2019 Annual Meeting

Seismological Society of America
Technical Sessions
23–26 April
The Westin Seattle
Seattle, Washington

PROGRAM COMMITTEE

The Co-Chairs of the 2019 SSA Annual Meeting are Joan Gomberg of the U.S. Geological Survey and Michael Bostock of the University of British Columbia.

Meeting Contacts

Technical Program Co-Chairs
Michael Bostock and Joan Gomberg
program@seismosoc.org

Abstract Submissions
Rikki Anderson
510.559.1784
abstracts@seismosoc.org

Exhibit and Sponsorship Opportunities
Sydni Schieber
510.559.1781
exhibits@seismosoc.org

Media Registration and Press Releases
Becky Ham
602.300.9600
press@seismosoc.org

Registration, Student Grants and Workshops
510.525.5474
registration@seismosoc.org

PRELIMINARY SCHEDULE

Tuesday, 23 April

- Workshops (see page 794).
- SSA Board of Directors Meeting.
- Registration. 3–7:30 PM, Grand Foyer.
- Welcome Reception, 4:30–6 PM, Grand Foyer.
- Opening Keynote by William B. Banerdt, InSight principal investigator. 5:10 PM, Grand Ballroom (see page 796).
- Town Hall Meeting. 6–7:30 PM, Cascade I & II (see page 792).

Wednesday, 24 April

- Technical Sessions. 8:30 AM–5:30 PM.
- SSA Annual Luncheon and Awards Ceremony. Noon–2 PM, Grand Ballroom.
- Lightning Talks. 6–7 PM, Grand Ballroom (see page 792).
- Early-Career and Student Reception. 7–8 PM, Cascade I.
- Special Interest Group: Offshore Facilities for Solid Earth Geoscience. 7:30–9 PM, Cascade II (see page 795).

Thursday, 25 April

- Student and Early-Career Mentoring Breakfast. 7–8:15 AM, Grand Ballroom.
- Technical Sessions. 8:30 AM–5:15 PM.
- Public Policy Luncheon. Speaker: Barb Graff, director, Office of Emergency Management, City of Seattle. Noon–1:30 PM, Grand Ballroom (see page 797).
- Joyner Lecture and Reception. Lecturer: Robert W. Graves, U.S. Geological Survey. 5:30–7:30 PM, Grand Ballroom (see page 797).
- Women in Seismology Reception. Speaker: Gail Atkinson, University of Western Ontario. 7:30–9 PM, Cascade I.
- Special Interest Group: Canadian Cordillera Array. 8–9:30 PM, Cascade II (see page 795).

Friday, 26 April

- Technical Sessions. 8:30 AM–5 PM.
- Luncheon. Noon–1:15 PM, Grand Ballroom.
- Special Interest Group: Seismic Instruments for the Coming Decade. Noon–1:15 PM, Cascade II (see page 795).

Saturday, 27 April

- Field Trips (see page 795).

EVENTS

Town Hall Meeting

On Tuesday, 23 April, 6–7:30 PM, we will hold a Town Hall Meeting titled "The Why, How, Where and What of Earthquake Early Warning" in Cascade I and II. The meeting will focus on earthquake early warning systems in the Pacific Northwest and California, including how they function, how they can prevent damage and injury and when they may be fully operational throughout the region.

Earthquake early warning experts will speak at the meeting, including:

- Sandi Doughton, Science Reporter, Seattle Times and author of *Full-Rip 9.0: The Next Big Earthquake in the Pacific Northwest*
- Scott Miles, Department of Human Centered Design and Engineering, University of Washington
- Rachel Lanigan, ShakeAlert program manager, RH2 Engineering
- Harold Tobin, director, Pacific Northwest Seismic Network, University of Washington
- Doug Toomey, co-director, Pacific Northwest Seismic Network, University of Oregon

This meeting is open to the public and is free to attend.

LIGHTNING TALKS

The Lightning Talks comprise an hour of 10 five-minute talks. The talks start at 6:00 PM on Wednesday, 24 April.

The Evolution of Rapid Response

Adam M. Pascale (quake@src.com.au)

Realtime telemetry of seismic data started to become affordable for small observatories in the 1980s and 90s, usually over leased phone lines using point-to-point modems. With the arrival of the world wide web, indirect data telemetry using Internet Protocols made connectivity simpler, and with expanding cellular network coverage and ever-reducing data costs, quality data telemetry is now commonplace.

The process of responding to earthquakes hasn't changed (get data, analyse, publish), but the approach and time frame has changed greatly. Over 30 years we have moved from: pagers that summoned us to the observatory; to SMS messages; carrying computers and modems to dial up the office to download data; using laptops with cellular data access; and finally tablets and mobile phones with customised apps for rapid response. The time from earthquake to initial reviewed solution has reduced from an hour or more (traffic permitting), to half an hour using laptops and traditional programs, to just minutes using apps.

To make a Duty Seismologist's life less stressful requires easy data access, and a simple analysis and publishing process. Distributing reviewed information rapidly is becoming more important in this age of instant social media sharing, and the tools need to adapt accordingly.

Century Old Induced Seismicity in LA

Susan E. Hough (hough@usgs.gov).

Induced earthquakes have received a great deal of attention in recent years, both within and outside of the scientific community. But can earthquakes also be induced by primary oil production? In general, uncompensated oil extraction will lower pore pressures, which will tend to stabilize nearby faults. Oil withdrawal can also, however, perturb subsurface stresses, which can potentially destabilize faults. We use a modern modeling approach to calculate the stress perturbation associated with oil production in the southwest Los Angeles Basin during the late 1930s through mid-1940s. Oil production ramped up sharply during this period, largely to meet the demands of the second World War. We show that, by 1941, significant stress perturbations from the Wilmington and other nearby fields extended about 2-3 km from a production horizon. For oil fields where wells were drilled to 2-4 km depth, signifcant stress perturbation thus extended to the top of the seismogenic crust. Thus, this mechanism can plausibly account for the occurrence of half-dozen moderate (magnitude 4-5) earthquakes in the Los Angeles Basin between 1938 and 1944. The advent of wide-spread water flooding, or fluid-injection recovery, methods around 1960 appears to have mitigated induced earthquake risk.

Visualization on Shaky Ground? How to Display an Aftershock Forecast

Max Schneider (maxs15@uw.edu).

Earthquake forecasts are based on statistical estimates of seismicity rates, which have multiple sources of uncertainty. How can we communicate a forecasted earthquake rate together with its uncertainty, to facilitate seismic decision-making under uncertainty? In an experiment, we evaluate the effectiveness of three competing visualizations of aftershock forecasts and their uncertainties. Subjects perform realistic judgment tasks and responses and response times are compared across visualizations. We discuss the design of such an experiment and provide first results.

Seismology From the Roof of the World to the Irrawaddy Delta

Emily Wolin (wolin.emily@gmail.com).

The active tectonics of the Himalaya and Indo-Burman regions produce some of the highest earthquake hazards and risks in the world. Efforts to improve seismic monitoring and earthquake hazard characterization face logistical, financial, and political challenges in developing and maintaining the high-quality real-time sensor networks and specialized staff needed to monitor local seismicity and to record and analyze strong ground motions. We present an overview of recent projects to expand and densify seismic networks and characterize ground motions for hazard assessment. In Myanmar, a new national seismic network comprising 19 broadband and strong-motion stations has recorded three $M \geq 6$ earthquakes in its first three years of operation, and continues to record 2-4 $M \geq 4.5$ earthquakes per month. In Nepal, a steadily expanding network of low-cost Raspberry Shake sensors installed in schools in the mountains of western Nepal and around the Kathmandu Valley is beginning to enable improved monitoring of local seismicity and further investigation of basin effects observed during the 2015 M7.8 Gorkha earthquake. Data from these rapidly-developing seismic networks are largely freely available. The expansion and operation of these networks is made possible by a dedicated and skilled group of scientists, engineers, teachers, and volunteer station hosts.

GNSS Global Seismic Monitoring

Timothy I. Melbourne (tim@geology.cwu.edu).

The ongoing global proliferation of real-time GNSS networks has blanketed many of Earth's tectonically active regions with receivers that straddle active crustal faults and tsunamigenic subduction zones, volcanoes, landslides, and many other sources of natural hazards. In some seismically active regions such as the western US, the number of GNSS receivers now rivals or exceeds seismometers available for earthquake and tsunami monitoring. A recent tally of public-facing casters yields over 3500 GNSS stations available for hazards mitigation through real-time positioning. CWU is currently point-positioning 850 stations globally and is working to expand that number to include all available stations, to make them available to the public via a variety of data-sharing interfaces, and to provide seismic point- and finite-fault estimation routines for the major subduction zones that can be used in real-time by earthquake and tsunami hazards monitoring agencies.

An Apples-to-Apples Comparison of Three Earthquake Early Warning Algorithms

Men-Andrin Meier (mmeier@caltech.edu).

How often, and under which circumstances, can Earthquake Early Warning (EEW) algorithms provide useful alerts? Although numerous EEW algorithms have been proposed and developed to date, we do not have a detailed understanding of how often they can provide useful ground motion alerts to end-users. To find out we have run the EPIC, PLUM and FinDer algorithms under realistic and identical conditions on the strong motion data of the 219 largest events in Japan since 1996 (Mw 3.4-9.1). We analyze how often they are able to provide correct and timely alerts. We find that for strong and medium ground motion (MMI~<7.5) a majority of sites can get useful alerts. Sites with more extreme ground motion can often be alerted successfully in the case of very large subduction zone earthquakes, but only in <20% of cases for shallow crustal events. Our results provide a detailed, quantitative and largely assumption-free insight into what EEW can and cannot do.

Practical Limitations of Earthquake Early Warning

David J. Wald (wald@usgs.gov).

EEW is coming to the U.S. West Coast, as it should. But, can it deliver on what's been promised? Basic principles, lessons learned from the EEW experience in Japan and an appraisal of the communication challenges along with the possible response actions associated with EEW, all point to more limited opportunities to warn and protect than envisioned. That is, potential warning times are less impressive—and possible mitigation actions are likely to be less effective—than often purported. In essence, seismic network operators have less than 5 sec to make a highly visible, critically important public decision––a serious technical challenge in its own right. Yet, widely communicating actionable warnings turns out to be even more difficult. Recent studies and events in the U.S. and Japan have shown that under most circumstances areas with damaging shaking levels are likely to receive almost no warning; moderately shaken areas will likely receive a short—a few sec—warning. Only lightly shaking areas will most likely receive a significant warning—10 sec or more. I illustrate how we might better communicate the concept of the no-warning zone by comparing warning timeliness—properly accounting for warning alerting, receipt, and response times—with maps of strongly shaken and affected areas.

Crisis + Time = Humor?

Sara K. McBride (drsaramcb@gmail.com).

When, where, how and with whom humor helps ease science communication during crisis.

Marijuana, Mother's Milk and Earthquake Precursors

David D. Jackson (djackson@g.ucla.edu).

In 1982, President Ronald Reagan and his wife, Nancy Reagan, joined the forces of the War on Drugs. In several public appearances, Nancy emphasized the dangers of marijuana because many hard drug users reported prior marijuana consumption. Marijuana was labeled a "gateway drug" to the hard stuff. Comedian George Carlin perceptively noted that by the same logic a more potent gateway drug would be mother's milk, since virtually all hard drug users had consumed that before their drug additions. Carlin apparently realized that the concern was based on observed conditional probability of prior marijuana use given later hard drug use, just the reverse of the relevant condition. We who deal with earthquake precursors wouldn't make that mistake, would we?

How Do You Get to Mars? Practice, Practice, Practice

William B. Banerdt (william.b.banerdt@jpl.nasa.gov).

Using seismology to study the interior structure and processes of the other planets of our solar system seems to be a no-brainer. Yet after a flurry of extraterrestrial seismometer deployments by Apollo and Viking in the 1970s, there was a 40-year seismic drought before SEIS was placed on the surface of Mars by InSight at the beginning of this year. This was despite no fewer than 14 landers being dispatched to the surface of Mars during that period. As it happens, this was not for lack of trying, as there were more than 15 serious proposals during that period either to include seismometers in Mars-bound payloads or even to launch dedicated geophysical missions. Having been involved in most of those, I will talk about some of my personal experiences in trying to "make it rain" during that long hiatus.

WORKSHOPS

Achieve Your Career Goals

Tuesday, 23 April, 1–4 PM, Elliott Bay
Instructor: Alaina Levine, Quantum Success Solutions

Whether you're a student or early-career scientist looking to advance your career, or an experienced researcher looking at getting back into the job market, learn how to create your dream career!

This three-hour workshop focuses on strategies and tactics to understand what you can, could and should be doing for your careers. Topics include how to conduct a job search in academia, consulting or government agencies; the pros and cons of working in each sector; how potential employers find job seekers and other career-related questions.

Attendees will also have the chance to learn and practice skills that can help them get a job and advance their careers, such as interview skills, having a polished social media presence and marketing their value.

Following the workshop, attendees have the opportunity of participating in one-on-one, 15-minute career consultations, which are available on a first-come, first-served basis.

Developing and Visualizing Community Seismic Velocity Models

Tuesday, 23 April, 1–5 PM, Pine
Instructors: Erin Wirth, U.S. Geological Survey; Philip Maechling, Southern California Earthquake Center; Manoch Bahavar, Incorporated Research Institutions for Seismology

Three-dimensional seismic velocity models play an important role in many aspects of seismological research, including strong ground motion modeling, earthquake location and inversions for Earth structure.

This workshop will discuss the challenges and best practices for developing and maintaining community velocity models, as well as explore software and tools for visualizing 3D models. Attendees will explore a variety of currently available community velocity models, learn scientific and technical differences between models and work with Southern California Earthquake Center (SCEC) and Incorporated Research Institutions for Seismology (IRIS) software tools to investigate properties of the models.

Attendees will examine SCEC's Unified Community Velocity Model (UCVM) framework, an open-source software developed to help researchers use velocity models for ground motion simulations. Using hands-on tutorials, attendees will learn how to use the UCVM software to investigate differences between velocity models, create plots showing model properties in geographical areas of interest, generate simulation meshes from a velocity model and define and query a velocity model for a large region by combining multiple velocity models together.

Attendees will also participate in hands-on tutorials using the IRIS Data Management Center's Earth Model Collaboration (EMC) ParaView Visualization Plugins. ParaView is an open-source data analysis and visualization application and these plugins are designed to extend and expand its functionalities so it can be used for 3D visualization of Earth models and spatial datasets. By the end of this tutorial, attendees will have a working knowledge of EMC-plugins for ParaView and how to prepare their own models/data for display.

Getting Published – Writing a Good Scientific Paper

Tuesday, 23 April, 1–4 PM, Pike
Instructors: John Ebel, Boston College; Roland Burgmann, University of California, Berkeley; Brent Grocholski, *Science*

Learn all the nuts-and-bolts of a good scientific paper.

In this workshop, attendees will learn the elements of a good scientific paper through group discussions and analyzing effective examples of writing, figures, tables, citations and supplementary material in published papers. The workshop will also cover what to do once the paper is finished, such as how to pick a publisher, as well as how to respond to reviewers' comments.

Machine Learning for Seismology

Tuesday, 23 April, 1–5 PM, Vashon
Instructors: Karianne Bergen, Harvard; Qingkai Kong, University of California, Berkeley; Zefeng Li, California Institute of Technology; Youzuo Lin, Los Alamos National Laboratory; Maruti Kumar Mudunuru, Los Alamos National Laboratory; Daniel Trugman, Los Alamos National Laboratory

Learn how to use machine learning in your research!

The increase in computational capability in the past decade has created new opportunities for machine learning and data science in the seismological fields. This workshop offers an introduction to machine learning concepts and a hands-on look at how to use them in seismological research.

The workshop will cover introductory machine learning topics such as regression, classification, clustering, data cleaning, feature engineering and automatic feature extraction with deep learning. Attendees will then learn about the practical issues that are encountered when applying these methods to waveform and seismicity data.

Laptops are recommended to follow along with the examples presented in class and become familiar with workflows that can easily be adopted in your future research. The example code and data will be provided so you can continue to experiment after the workshop.

Measuring Fault Parameters and Slip from Geodetic Imaging Data using GeoGateway Online Tools

Tuesday, 23 April, 1–5 PM, Puget Sound
Instructors: Andrea Donnellan, Jet Propulsion Laboratory; Lisa Grant Ludwig, University of California, Irvine; John Rundle, University of California, Davis

GeoGateway (http://geo-gateway.org) provides online tools for analysis, modeling, and response using geodetic imaging data. The main application of GeoGateway is to analyze and model crustal deformation related to earthquakes, and measure fault slip. The tools focus on airborne InSAR data from NASA's airborne UAVSAR platform and Global Positioning System (GPS) position time series, displacements, and velocities.

This workshop provides an overview of geodetic imaging and a hands-on experience working with the tools available through GeoGateway. Attendees will gain an understanding of GPS time series and produce GPS station velocities, displacements, coseismic offsets and postseismic motions. Attendees will also analyze UAVSAR data to measure fault slip and crustal deformation, as well as learn to identify signals reflecting solid Earth processes versus signal from error sources. The workshop is geared toward geologists and students who want to apply geodetic imaging data to their research.

SPECIAL INTEREST GROUPS

Offshore Facilities for Solid Earth Geoscience

Wednesday, 24 April, 7:30–9 PM, Cascade II
Conveners: Emily Roland, University of Washington; Anne Trehu, Oregon State University; Jackie Caplan-Auerbach, Western Washington University

This brief meeting will focus on the current state and future evolution of offshore facilities available for Solid Earth geoscience research. Topics include cutting-edge infrastructure that is and will continue to be instrumental for supporting seismic and other geophysical studies in the offshore environment, such as the U.S. Ocean Bottom Seismic Instrument Pool, the National Marine Seismic Research Facility and the Ocean Observatories Initiative. Collectively, these facilities represent a unique capability to sample the solid earth at variable spatiotemporal resolutions across the ~70% of the globe covered by the oceans.

We will provide brief overviews of the current state of several existing offshore facilities. Representatives from relevant oversight committees will be present during a Q&A session to discuss future priorities for existing and evolving frontier offshore facilities.

Canadian Cordillera Array (CCArray)

Thursday, 25 April, 8–9:30 PM, Cascade II
Conveners: David Eaton, University of Calgary; Roy Hyndman, University of Victoria; Pascal Audet, University of Ottawa

This brief meeting will provide an update on the Canadian Cordillera Array (CCArray) (www.ccarray.org). This new international initiative seeks to develop an integrated plate boundary observatory that bridges critical gaps in seismological and GNSS station coverage along the North American plate boundary region in western Canada. The goal of CCArray is to enable trans-disciplinary research focused on Earth systems processes and boundaries from the core to the magnetosphere.

Attendees are encouraged to contribute ideas to the design and implementation of the network and become involved in this research program at an early stage in its development.

Seismic Instruments for the Coming Decade

Friday, 26 April, Noon–1:15 PM, Cascade II
Conveners: Bob Woodward, Incorporated Research Institutions for Seismology

This group will explore recently developed seismic instrumentation technologies and discuss their observed (or projected) performance and usability. Participants will focus on instrumentation that is or will be implemented as part of the Incorporated Research Institutions for Seismology (IRIS) capabilities that serve the seismological community.

In recent years there have been a variety of developments in seismic instrumentation that are seeing wide use in research seismology, ranging from improved emplacement methods for broadband sensors to autonomous ("nodal") geophone sensors. IRIS has recently gained substantial experience with post hole-style sensor installations in Alaska and is presently embarking on a multi-year effort to enable a new level of wavefield imaging capability as part of the IRIS PASSCAL program.

Further, over the next several years IRIS will be implementing a system of instruments dedicated to rapid response efforts for geohazard events, considering such features as ultra-portable packaging concepts, mesh-network telemetry and combined seismic-GNSS capability.

We invite participation from those interested in instrument performance or capability and who would like to discuss the needs and requirements of the community's future instrumentation activities.

FIELD TRIPS

Cascadia Earthquakes by Canoe

Saturday, 27 April, 8 AM–10 PM
Trip leader: Brian Atwater, scientist emeritus, U.S. Geological Survey

Hardy participants will view iconic clues to great earthquakes on the Cascadia subduction thrust. The clues tell of recurrent subsidence and associated tsunamis in the past 2,000 years. Highlights include one of the estuarine ghost forests that identifies Cascadia as the likely source of a Pacific Ocean tsunami in January 1700 and provides tree-ring evidence for an unusually long recurrence interval before then.

The bus will depart The Westin Seattle promptly at 8 AM and will reach the Copalis River, on Washington's outer coast, three hours later. Participants will spend four hours paddling canoes, inspecting muddy river banks and walking in a ghost forest. The bus will stop for dinner on the way back to The Westin Seattle.

Earthquake Geology of Seattle

Saturday, 27 April, 8:30 AM–6:30 PM
Trip Leaders: Ralph Haugerud, U.S. Geological Survey; Elizabeth Barnett, Shannon & Wilson, Inc.; Bill Laprade, Shannon & Wilson, Inc.; Elizabeth Davis, University of Washington

This trip explores the geomorphology and stratigraphy of Seattle that record the history of crustal faulting and determine site response to earthquakes on all sources.

Participants will leave The Westin Seattle at 8:30 AM by bus to the South Beach of Discovery Park, which offers views of glacial stratigraphy and evidence for recent sea level change. From there, the tour heads to scenic Jose Rizal Park, where participants can see downtown Seattle and the lower Duwamish River delta, before continuing on to historic Alki Point for lunch and discussion of the last large earthquake on the Seattle fault.

After that, the tour visits Terminal 107 Park, where Duwamish stratigraphy and evidence of uplift from sediment peels can be seen alongside public art installations. Participants will follow a short trail to the edge of the park, where a dry outcrop displays uplifted tide flat and riverbed deposits.

The final stop of the tour is the Diagonal Avenue South Public Shoreline to view sand dikes and vented sand volcanoes. Waders or change of shoes/clothes are recommended due to sticky mud.

The bus will stop at The Pike Brewing Company at 6:30 PM before continuing directly to The Westin Seattle. Participants who wish to stay and visit the brewery will be dropped off and responsible for returning to the hotel (approximately a 10-minute walk).

Facilities Tour of University of Washington

Saturday, 27 April, 7:15–11 AM
Trip Leader: Ian Stone, University of Washington

Take a tour of the University of Washington (UW) campus and its seismic research facilities, including the Pacific Northwest Seismic Network (PNSN), the Rapid Response Research Facility and UW Oceanography's newest research vessel, the Rachel Carson.

Attendees will depart The Westin Seattle at 7:15 AM and ride the Link light rail to the UW campus. The tour starts at 8 AM at PNSN's headquarters. Attendees will learn about the daily operations of the seismic network, the seismic hazards unique to the region, as well as the network's ongoing projects, such as the implementation of earthquake early warning.

Next, attendees will visit the RAPID facility's equipment library, which houses items ranging from LIDAR and surveying equipment to unmanned aerial systems. Attendees will also learn about facility operations, including reconnaissance and data acquisition in post-disaster situations and software development.

The tour concludes with a look at the R/V Rachel Carson at the UW docks. Attendees will learn about its laboratory, specialized tools and the role it plays in UW's seismic exploration of the Puget Sound and surrounding coastal areas.

Attendees return to The Westin Seattle at 11 AM. Walking shoes are recommended. Be prepared for rain. Lunch is not provided. The PNSN and RAPID facility are both ADA accessible, but the R/V Rachel Carson is not.

TECHNICAL PROGRAM

The 2019 SSA Technical Program comprises oral and poster presentations presented over three days, 24–26 April. The session descriptions, detailed program schedule and all abstracts appear in the following pages.

LECTURES

Opening Keynote

Tuesday, 23 April, 5:10 PM, Grand Ballroom
William B. Banerdt, InSight Principal Investigator and Principal Research Scientist at NASA's Jet Propulsion Laboratory, will give an overview of the first few months of observations and the mission's goal of learning more about Mars' deep interior.

The InSight mission landed in Elysium Planitia on November 26, 2018, and 22 days later placed the first broadband seismometer on the surface of another planet.

In contrast to the 45 previous missions to Mars, which have thoroughly explored its surface features and chemistry, atmosphere, and searched for past or present life, InSight focuses on the deep interior of the planet, investigating the processes of terrestrial planet formation and evolution by performing the first comprehensive surface-based geophysical measurements on Mars using the "traditional" geophysical techniques of seismology (via a non-traditional single-station approach), geodesy (through precision tracking for rotational dynamics) and heat flow measurement.

It will provide key information on the composition and structure of an Earth-like planet that has gone through most of the evolutionary stages of the Earth up to, but not including, plate tectonics. Unlike the Earth, its overall internal structure appears to have been relatively unchanged for more than 4 By; unlike the Moon, it is large enough that the P-T conditions within the planet span an appreciable fraction of the terrestrial planet range. Thus chemical and structural evidence preserved in Mars' interior should tell us a great deal about the processes of planetary differentiation and heat transport.

President's Address

Wednesday, 24 April, Noon–2 PM, Grand Ballroom
Peter Shearer will present the President's Address at the Annual Luncheon.

Policy Speaker

Thursday, 25 April, Noon–1:30 PM, Grand Ballroom
Barb Graff, director of the Seattle Office of Emergency Management, will give a talk about the state of Seattle's earthquake readiness titled, "Seismic Retrofit of Unreinforced Masonry Buildings."

Graff is responsible for the team that manages the all-hazard community-wide emergency management program for the City of Seattle. Since 2005, the Seattle Emergency Operations Center has coordinated a city-wide response to 16 major exercises and 50 incidents, eight of which resulted in a Presidential Declaration.

Joyner Lecture

Thursday, 25 April, 5:30–6:30 PM, Grand Ballroom
Robert W. Graves, U.S. Geological Survey, will present the Joyner Lecture. The 2019 Joyner Lecture is titled "Simulating Realistic Earthquake Ground Motions?"

Ground motion simulations are an important resource for augmenting recorded motions, assessing impacts for scenario earthquakes and exploring parametric sensitivity. Providing confidence that simulations are realistic requires demonstrating that they not only reproduce motions from past earthquakes, but also that they can predict motions for future events. Ideally, simulations should capture effects due to complexities in the rupture process, as well as effects due to large-scale (*e.g.*, basins) and small-scale (*e.g.*, scattering or site effects) variations in the seismic velocity structure. Accounting for these features is challenging due to uncertainty in the expected ranges of the required parameters. Furthermore, adding increased detail to the model space increases the computational requirements. Simulation approaches have traditionally been classified as "deterministic" or "stochastic" depending on the level of complexity used to describe earthquake rupture and wave propagation effects. Because of knowledge limitations and computational cost, the deterministic approach is typically employed for lower frequencies (< 1 Hz) and the stochastic approach at higher frequencies (> 1Hz). This distinction naturally leads to a hybrid approach, where the separate low- and high-frequency responses are combined to produce a broadband response. In my talk, I will describe the features behind the hybrid simulation approach along with examples of its application to model recorded earthquake ground motions. I will also describe refinements to the deterministic approach that extend its range of applicability to higher frequencies. Finally, I will summarize those cases where simulations are most beneficial and explore some frontiers scientists are facing in ground motion simulations.

SSA CODE OF CONDUCT

SSA is committed to fostering the exchange of scientific ideas by providing a safe, productive, and welcoming environment for all SSA sponsored meeting participants, including attendees, staff, volunteers and vendors. We value the participation of every member of the community and want all participants to have an enjoyable and fulfilling experience.

All participants at SSA meetings are expected to be considerate and collaborative, communicating openly with respect for others, and critiquing ideas rather than individuals. Behavior that is acceptable to one person may not be acceptable to another, so use discretion to be sure that respect is communicated.

Unacceptable Behavior
Examples of unacceptable behavior include, but are not limited to:

- Physical or verbal abuse of any kind.
- Threatening or stalking any participant.
- Making inappropriate comments whether verbal or digital related to gender, gender identity and expression, age, sexual orientation, disability, physical appearance, body size, race, ethnicity, religion (or lack thereof), national origin, or other legally protected group status or characteristics.
- Inappropriate use of nudity and/or sexual images or language in public spaces or in presentations.
- Harassment intended in a joking manner still constitutes unacceptable behavior.
- Retaliation for reporting harassment is also a violation of this Code of Conduct, as is reporting an incident in bad faith.

Reporting Unacceptable Behavior
Any participant experiencing or witnessing behavior that at any time in their judgment constitutes an immediate or serious threat to public safety is advised to contact emergency services immediately (for hotel security, dial 0 from any house phone; or 911) and to notify on-site venue security and SSA staff.

If you are the subject of unacceptable behavior or have witnessed any such behavior, you are encouraged to notify an SSA staff member, call 408-647-5811, and write the Executive Director Nan Broadbent by emailing nbroadbent@seismosoc.org. Writing down the details of the incident is also recommended. Requests for confidentiality will be honored to the extent possible.

Consequences
SSA staff (or their designee) or security may take any action deemed necessary and appropriate for any unacceptable behavior, including but not limited to that described above. Possible actions include removal of a participant from the meeting, without refund. Suspension or termination of membership in SSA, denial to participate in future SSA events or meetings, or other action(s) may be taken in SSA's sole discretion, depending on the severity of the unacceptable behavior.

SSA is committed to handling all situations to the best of its ability. However, this Code of Conduct is informational and is not a contract.

Overview of Technical Program

ORAL SESSIONS

Wednesday 24 April

Time	*Grand Crescent*	*Vashon*	*Cascade I*	*Cascade II*	*Puget Sound*	*Pike*	*Pine*	*Elliott Bay*
8:30–9:45 AM	Photonic and Non-Inertial Seismology	Advances in Intraplate Earthquake Geology	…Advances in Improving Absolute Hypocenter Location Accuracy for Natural, Induced and Explosion Seismic Events	The Science of Slow Earthquakes from Multi-Disciplinary Perspectives	Characterizing Faults, Folds, Earthquakes and Related Hazards in the Pacific Northwest	U.S. Geological Survey National Seismic Hazard Model Components	Earthquake Ground Motions and Structural Response in Subduction Zones: A Focus on Cascadia	Machine Learning in Seismology
10:45–Noon	…Geophysical Research Using Dense Mixed Sensor and Broadband Seismology Arrays		Explosion Seismology Applications					
Noon–2 PM	SSA Annual Luncheon and Awards Ceremony, Grand Ballroom							
2:15–3:30	Evolving Best Practices for Station Buildout in EEW and New Permanent Networks	Frontiers in Earthquake Geology: Bright Futures and Brick Walls	Explosion Seismology Applications (*continued*)	The Science of Slow Earthquakes from Multi-Disciplinary Perspectives (*continued*)	Characterizing Faults, Folds, Earthquakes and Related Hazards in the Pacific Northwest (*continued*)	Better Earthquake Forecasts	Earthquake Ground Motions and Structural Response in Subduction Zones: A Focus on Cascadia (*continued*)	Machine Learning in Seismology (*continued*)
4:15–5:30	Advances in Ocean Floor Seismology			Science, Hazards and Planning in Subduction Zone Regions, Part I of II	Offshore Subduction Zone Structure and Seismicity Along the Pacific Northwest…		Modeling and Understanding of High-Frequency Ground Motion	Science Gateways and Computational Tools for Improving Earthquake Research
5:30–6:30	Posters and Break, Fifth Avenue and Grand Ballroom							
6:00–7:00	Lightning Talks, Grand Ballroom							
7:00–8:00	Early-Career and Student Reception, Cascade I							
7:30–9:00	Special Interest Group: Offshore Facilities for Solid Earth Geoscience, Cascade II							

Thursday 25 April

Time	*Vashon*	*Cascade I*	*Cascade II*	*Puget Sound*	*Pike*	*Pine*	*Elliott Bay*
7–8:15 AM	Student and Early-Career Mentoring Breakfast, Grand Ballroom						
8:30–9:45 AM	The InSight Mission – Seismology on Mars and Beyond	Earthquake Source Parameters: Theory, Observations and Interpretations	Science, Hazards and Planning in Subduction Zone Regions, Part II of II	Advances in Tectonic Geodesy	Explore the Fault2SHA Paradigms Across the Ponds	Current and Future Challenges in Engineering Seismology	Numerical Modeling of Earthquake Ground Motion, Seismic Noise, Rupture Dynamics and Seismic Wave Propagation
10:45–Noon	Facebook and Twitter and Snapchat, Oh My! The Challenges and Successes of Using Social Media to Communicate Science to the Public				Central and Eastern North America and Intraplate Regions Worldwide		
Noon–1:30 PM	Public Policy Luncheon, Grand Ballroom						
1:45–3:00		Earthquake Source Parameters: Theory, Observations and Interpretations (*continued*)	Imaging Subduction Zones	Recent Developments in High-Rate Geodetic Techniques and Network Operations for Earthquake and Tsunami Early Warning and Rapid Post-Earthquake Response	Central and Eastern North America and Intraplate Regions Worldwide (*continued*)	Current and Future Challenges in Engineering Seismology (*continued*)	Numerical Modeling of Earthquake Ground Motion, Seismic Noise, Rupture Dynamics and Seismic Wave Propagation (*continued*)
4:00–5:15				Next Generation Earthquake Early Warning Systems: Advances, Innovations and Applications		Problem Unsolved: Knowledge Gaps at the Intersection of Earthquake Engineering Practice and Research	Large Data Set Seismology: Strategies in Managing, Processing and Sharing Large Geophysical Data Sets
5:30–6:30	Joyner Lecture, Grand Ballroom						
6:30–7:30	Joyner Reception, Grand Foyer and Grand Crescent						
7:30–9:00	Women in Seismology Reception, Cascade I						
8:00–9:30	Special Interest Group: Canadian Cordillera Array (CCArray), Cascade II						

Friday 26 April

Time	*Vashon*	*Cascade I*	*Cascade II*	*Puget Sound*	*Pike*	*Pine*	*Elliott Bay*
8:30–9:45 AM	Building, Using and Validating 3D Geophysical Models	Injection-Induced Seismicity	Large Intraslab Earthquakes	The 2018 Eruption of Kīlauea Volcano, Hawai‘i	Seismology BC(d)E: Seismology Before the Current (digital) Era	Methods for Site Response Estimation	Next Generation Seismic Detection
10:45–Noon	Structural Seismology: From Crust to Core		The M7 Anchorage Earthquake: Testing the Resiliency of South-Central Alaska				New Frontiers in Global Seismic Monitoring and Earthquake Research
Noon–1:15 PM	Luncheon, Grand Ballroom						
Noon–1:15 PM	Special Interest Group: Seismic Instruments for the Coming Decade, Cascade II						
1:30–2:45	State of Stress and Strain in the Crust and Implications for Fault Slip Based on Observational, Numerical and Experimental Analysis	Advances, Developments and Future Research into Seismicity in Natural and Anthropogenic Fluid-Driven Environments	The M7 Anchorage Earthquake: Testing the Resiliency of South-Central Alaska (*continued*)	Observations of Volcanism in the Three Spheres: Land, Air and Sea	Seismology BC(d)E: Seismology Before the Current (digital) Era (*continued*)	Methods for Site Response Estimation (*continued*)	Using Repeating Seismicity to Probe Active Faults
3:45–5:00			Emerging Science from the EarthScope Transportable Array in Alaska and Western Canada	Causes and Consequences of the Columbia River Flood Basalts	Environmental Seismology: Glaciers, Rivers, Landslides and Beyond	Metamaterials, Resonances and Seismic Wave Mitigation, an Emerging Trend in Seismology	Non-Traditional Application of Seismo-Acoustics for Non-traditional Monitoring

POSTER SESSIONS

Wednesday 24 April

Fifth Avenue Room
- Advances in Intraplate Earthquake Geology
- Evolving Best Practices for Station Buildout in EEW and New Permanent Networks
- New Approaches to Geophysical Research Using Dense Mixed Sensor and Broadband Seismology Arrays
- Photonic and Non-Inertial Seismology

Grand Ballroom
- The Science of Slow Earthquakes from Multi-Disciplinary Perspectives
- Frontiers in Earthquake Geology: Bright Futures and Brick Walls
- Characterizing Faults, Folds, Earthquakes and Related Hazards in the Pacific Northwest
- Offshore Subduction Zone Structure and Seismicity Along Pacific Northwest: From the Gorda Plate to the Queen Charlotte Fault
- Earthquake Ground Motions and Structural Response in Subduction Zones: A Focus on Cascadia
- Better Earthquake Forecasts
- U.S. Geological Survey National Seismic Hazard Model Components
- Coseismic Ground Failure and Impacts on the Built and Natural Environment
- Explosion Seismology Applications
- From Drifting to Anchored: Advances in Improving Absolute Hypocenter Location Accuracy for Natural, Induced and Explosion Seismic Events
- Machine Learning in Seismology
- Modeling and Understanding of High-Frequency Ground Motion
- Science Gateways and Computational Tools for Improving Earthquake Research

Thursday 25 April

Fifth Avenue Room
- Earthquake Source Parameters: Theory, Observations and Interpretations
- Facebook and Twitter and Snapchat, Oh My! The Challenges and Successes of Using Social Media to Communicate Science to the Public
- The InSight Mission—Seismology on Mars and Beyond

Grand Ballroom
- Central and Eastern North America and Intraplate Regions Worldwide
- Next Generation Earthquake Early Warning Systems: Advances, Innovations and Applications
- Recent Developments in High-Rate Geodetic Techniques and Network Operations for Earthquake and Tsunami Early Warning and Rapid Post-Earthquake Response
- Advances in Tectonic Geodesy
- Science, Hazards and Planning in Subduction Zone Regions
- Imaging Subduction Zones
- Current and Future Challenges in Engineering Seismology
- Explore the Fault2SHA Paradigms Across the Ponds
- Metamaterials, Resonances and Seismic Wave Mitigation, an Emerging Trend in Seismology
- Numerical Modeling of Earthquake Ground Motion, Seismic Noise, Rupture Dynamics and Seismic Wave Propagation
- Large Data Set Seismology: Strategies in Managing, Processing and Sharing Large Geophysical Data Sets
- Building, Using and Validating 3D Geophysical Models

Friday 26 April

Fifth Avenue Room
- Advances, Developments and Future Research into Seismicity in Natural and Anthropogenic Fluid-Driven Environments
- Injection-Induced Seismicity
- Observations of Volcanism in the Three Spheres: Land, Air and Sea
- The 2018 Eruption of Kīlauea Volcano, Hawaiʻi
- Non-Traditional Application of Seismo-Acoustics for Non-Traditional Monitoring

Grand Ballroom
- Environmental Seismology: Glaciers, Rivers, Landslides and Beyond
- Using Repeating Seismicity to Probe Active Faults
- State of Stress and Strain in the Crust and Implications for Fault Slip Based on Observational, Numerical and Experimental Analysis
- The M7 Anchorage Earthquake: Testing the Resiliency of South-Central Alaska
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- New Frontiers in Global Seismic Monitoring and Earthquake Research
- Next Generation Seismic Detection
- Methods for Site Response Estimation
- Problem Unsolved: Knowledge Gaps at the Intersection of Earthquake Engineering Practice and Research
- Seismology BC(d)E: Seismology Before the Current (digital) Era

The 2018 Eruption of Kīlauea Volcano, Hawai'i

The 2018 volcano-seismic activity on Kīlauea, Hawai'i manifested in three distinct phases: (1) a magma intrusion along the Lower East Rift Zone, beginning 30 April, resulting in eruptive fissures that eventually produced the highest flow rates ever recorded at Kīlauea; (2) a M6.9 earthquake on 4 May located under the south flank of Kīlauea; the second largest event in Hawaii instrumented history; and (3) the episodic collapse of Halema'uma'u crater at the Kīlauea summit from mid-May to early-August. Advances in techniques to assess the temporal evolution of seismicity, seismic parameters and structure and to link changes to dynamic shifts in eruption behavior, are exciting advances in monitoring, particularly techniques that do so in a largely automated fashion. This session will focus on improving our scientific understanding of seismicity with respect to volcanic and tectonic activity at Kīlauea, the 2018 M6.9 event, caldera collapse processes and advances in techniques that address the temporal evolution of seismic parameters that may accompany these eruptive phases. We invite contributions that include new observations, modeling and other pertinent studies. Topics include, but are not limited to: automated or semi-automated location methods, source rupture processes, foreshock and aftershock studies, early warning systems and geophysical imaging. We seek contributions from diverse fields to facilitate a multi-disciplinary discussion.

Session Chairs: Jefferson C. Chang (jchang@usgs.gov), Charlotte A. Rowe (char@lanl.gov), Ellen M. Syracuse (syracuse@lanl.gov).

Advances in Intraplate Earthquake Geology

Paleoseismic studies of intraplate faulting in regions such as the Basin and Range Province, Walker Lane and crustal Pacific Northwest are often challenged by slow (<5 mm/yr) slip rates, long (> 1 k/yr) earthquake recurrence times, distributed faulting and limited event preservation because of episodic sedimentary and pedogenic processes. To address open questions about earthquake timing and rupture length in these regions, extract new information on potential seismic sources and better characterize intraplate faulting for seismic-hazard models, new techniques and dense and high-quality data are required.

This session will include invited and contributed presentations focused on how new data and methods in earthquake geology advance our understanding of intraplate faulting. In particular, we welcome presentations on (1) high-resolution and/or long-term earthquake timing, recurrence and slip rate constraints; (2) the application of Bayesian modeling to geochronological data; (3) methods of evaluating and propagating paleoseismic uncertainties; (4) spatial and temporal trends in rupture length and displacement from high-resolution surface topography (*e.g.*, from lidar and unmanned aircraft systems); and (5) techniques for synthesizing earthquake histories and developing fault-rupture scenarios.

Session Chairs: Christopher B. DuRoss (cduross@usgs.gov), Mark Zellman (mzellman@bgcengineering.com), Stephen Angster (sangster@usgs.gov).

Advances in Ocean Floor Seismology

Marine seismology has enjoyed a rapid growth in recent years, as significant advances have been realized in sensors, deployment and data recovery methods. Continued development of these technologies have led to greater capability to pose, and answer, more questions regarding the tectonics, seismicity and geodynamics associated with the ocean floors. We invite contributions detailing not only recent and ongoing seismological research on the ocean floors, but also focusing on hardware, software and deployment innovations that can facilitate new revelations for ocean bottom seismological research.

Session Chairs: Charlotte A. Rowe (char@lanl.gov), Susan M. Bilek (sbilek@nmt.edu), Michael Begnaud (mbegnaud@lanl.gov).

Advances in Tectonic Geodesy

Geodetic datasets such as GPS, InSAR and measurements of strain and tilt are critical to observing many tectonic processes. Geodetic data is often complementary to seismic data, with the ability to record aseismic transients such as slow slip events. Geodetic data record the active accumulation of tectonic strain across seismogenic faults, which are often used to create locking models used in seismic hazard mapping. These data are also critical to monitoring volcanic processes, such as inflation and deflation, which are useful in forecasting and monitoring eruptions. Significant recent advances have been made in the field of seafloor geodetic observations, which require novel instrumentation and techniques. Seafloor observations are key to constraining locking in shallow subduction environments and studying offshore volcanic processes. In addition, a wealth of land based geodetic data in many areas has enabled rapid progress in the study of various tectonic processes. In this session, we welcome contributions from any topic related to geodetic observations, modeling and interpretation of geodetic data and development of geodetic techniques as they relate to tectonics. Contributions may describe analyses of seismic or other complementary data in addition to geodetic data. We especially encourage contributions which focus on any of the following topics:

- Advances in geodetic measurement techniques, including seafloor geodesy
- Novel modeling, inversion or data processing approaches applicable to geodetic data

- Studies which rigorously explore the role of geodetic data in constraining hazards, including those that analyze GPS noise
- Geodetic studies of recent geophysical events, including the 2018 eruptive activity at Kilauea volcano
- Studies focusing on aseismic phenomena, including slow slip, post-seismic processes and viscoelastic mantle flow

Session Chairs: Noel M. Bartlow (nbartlow@berkeley.edu), Kang Wang (kwang@seismo.berkeley.edu).

Advances, Developments and Future Research into Seismicity in Natural and Anthropogenic Fluid-Driven Environments

Induced seismicity has been associated with many fluid-related anthropogenic activities, such as hydraulic fracturing, geothermal exploitation, waste-water injection and reservoir impoundment. However, fluid-induced seismicity can also be observed in natural environments, such as volcanic systems. Through recent advances in seismic monitoring, a closer examination of such seismicity can be achieved, particularly with regards to understanding the role of highly-pressurized fluids at depth and the consequences this may have at the surface. However, several fundamental questions remain, including: What factors control fluid-induced seismicity? What can be inferred from the seismicity in terms of ongoing processes? Can this information be used to inform hazard assessment, *e.g.*, forecast volcanic eruptions or large induced earthquakes? Can comparisons between fluid-induced seismicity from different environments improve our understanding of the source processes involved?

This session aims to bring together a variety of topics related to fluid-induced seismicity to further our understanding of the physics behind earthquakes that are both natural and anthropogenic. We welcome contributions relating to seismicity in any fluid-driven environment. We are looking for abstracts related to lab experiments, statistical analysis, field observations and novel techniques in data processing/interpretation that characterize the physical conditions and mechanisms of fluid-related seismicity."

Session Chairs: Rebecca O. Salvage (rebecca.salvage1@ucalgary.ca), Megan Zecevic (megan.zecevic@ucalgary.ca), Ruijia Wang (ruijia.wang@uwo.ca).

Better Earthquake Forecasts

Earthquake forecasts have a wide range of applications from short-term guidance during earthquake sequences and swarms to being an ingredient in long-term Probabilistic Seismic Hazards Assessments (PSHA). In this session, we will discuss what makes an earthquake forecast useful and how to improve them. For short-term forecasts of swarms and earthquake sequences, most current, official forecasts are based on statistical models of earthquake clustering such as the Reasenberg & Jones model or the ETAS (Epidemic Type Aftershock Sequences) model. Can we improve these by including physics-based models of stress transfer or results from numerical simulators of earthquake occurrence on fault networks? For long-term forecasts, PSHA often relies on seismicity rates obtained by smoothing declustered earthquake catalogs. Would other declustering methods improve the forecasts or should we abandon declustering altogether and include aftershocks in hazards assessments and building codes? Some PSHA now also includes deformation information from plate motions or geodetic monitoring. How do we best combine that information with the seismicity rates? For all forecasts, how do we include fault-based information and do we need better ways to address earthquake catalog incompleteness and uncertainty? A critical step is testing these forecasting methods and the forecasts themselves, for example using approaches from the Collaboratory for the Study of Earthquake Predictability (CSEP). As we develop tests we need to consider the role of local versus global tests, prospective versus retrospective tests and tests of forecast ingredients versus complete forecasts. Questions about testing are particularly timely as CSEP develops its second phase of operations. Finally, we need to communicate these forecasts with different users to help inform a variety of decisions. These communications methods range from hazard curves for engineers to simplified text or graphics for the people impacted by the earthquake, broadcast media, emergency managers and first responders. Working alongside our social science colleagues is an important step to understanding more about our users, the channels they prefer and what information they need most to inform their decisions. We seek contributions that address any of the questions posed above or other ideas on how to improve earthquake forecasts.

Session Chairs: Andrew J. Michael (ajmichael@usgs.gov), Camilla Cattania (camcat@stanford.edu), David D. Jackson (djackson@g.ucla.edu), Sara K. McBride (skmcbride@usgs.gov), Warner Marzocchi (warner.marzocchi@ingv.it), Maximilian J. Werner (max.werner@bristol.ac.uk).

Building, Using and Validating 3D Geophysical Models

Geophysical models, such as 3D geologic and seismic velocity models, are needed in three and sometimes four dimensions for a host of applications from predicting earthquake ground motions to locating natural resources to planning subsurface infrastructure. Many types of observations can be used to inform geophysical models including geologic mapping, borehole data, active and passive seismic imaging, potential field observations and observations from other direct and indirect methods. Geophysical theory or empirical models may also be used to solve for missing geophysical attributes given other related observations, for example, solving for S-wave velocity and density given the P-wave velocity. Further, some observations sample distinct locations while others average over volumes of varying size and different methods of informed interpolation and extrapolation may be used to reconcile observations, theory and empirical relationships into a single geophysical model. We seek contributions in which researchers have developed and/or applied methods for reconciling multiple datasets into a unified geophysical model. Discussion should address the advantages and disadvantages of various types of datasets and methods in an effort to improve and validate the next generation of geophysical models. Applications of geophysical models to improve assessment of hazard and risk, particularly in novel ways or for novel applications, are also encouraged.

Session Chairs: Oliver Boyd (olboyd@usgs.gov), William J. Stephenson (wstephens@usgs.gov), Brad Aagaard (baagaard@usgs.gov).

Causes and Consequences of the Columbia River Flood Basalts

Flood basalt eruptions represent the largest volcanic events on Earth and the most recent one occurred 16 million years ago. It covered most of eastern Oregon and parts of western Idaho and southern Washington. In many cases, flood basalts are associated with the presence of hotspots, such as in Yellowstone. While processes driving the flood basalt event originate in the asthenosphere, the connection between these processes and the subsequent modification of the lithospheric plate is still poorly understood.

This session welcomes studies focused on the origin, evolution and dynamics of the Columbia River flood basalts and the Yellowstone system. We welcome contributions from geology, geochemistry, geochronology and geophysics that explore the architecture and dynamics of the crust-mantle system in the Columbia River flood basalts region.

Session Chairs: A. Christian Stanciu (cstanciu@uoregon.edu), YoungHee Kim (younghkim@snu.ac.kr), Eugene D. Humphreys (genehumphreys@gmail.com), Robert W. Clayton (clay@gps.caltech.edu).

Central and Eastern North America and Intraplate Regions Worldwide

This session aims to be a home for a wide variety of presentations tied together by a shared intraplate setting. Submissions treating crustal to lithospheric imaging in cratonic regions such as new results from EarthScope data, paleoseismology of intraplate faults, geodynamic models of continental seismicity, geodetic observations in low strain-rate regions, ground-motion and attenuation models and any other studies focused away from active plate boundaries are warmly encouraged.

Session Chairs: Will Levandowski (will.levandowski@tetratech.com), Weisen Shen (weisen.shen@stonybrook.edu), Christine A. Powell (capowell@memphis.edu).

Characterizing Faults, Folds, Earthquakes and Related Hazards in the Pacific Northwest

This session will showcase recent advances in quantifying the activity and impacts of active faults and folds that accommodate oblique plate convergence along the Cascadia margin. We invite studies that characterize recent deformation related to the Juan de Fuca-North America plate boundary, including offshore structures, the plate interface and slab and upper plate structures from the forearc to the backarc. We welcome contributions from the fields of tectonic geomorphology, paleoseismology, geophysics and others that exploit lidar, bathymetry, seismic, potential field, GPS, InSAR and other high-resolution data to map active Cascadia structures and characterize their hazards.

Session Chairs: Scott E. K. Bennett (sekbennett@usgs.gov), Ashley R. Streig (streig@pdx.edu), Colin Amos (colin.amos@wwu.edu), Megan Anderson (megan.anderson@dnr.wa.gov).

Coseismic Ground Failure and Impacts on the Built and Natural Environment

In this session, we invite presentations on coseismic landslides and liquefaction, and their impacts on the built environment. We encourage submissions on empirical and analytical models, sensitivity analyses, data collection and analyses and scenario exercises. We welcome submissions focusing on both local and regional-scales, especially those addressing data or methods that bridge the gap between detailed local studies and generalized regional or global models. Submissions addressing the effect of frequency content, duration, or improved ground motion intensity measures on ground failure triggering are encouraged, as well as considerations of regional differences. Additionally, we encourage submissions on the collection and analysis of ground failure impacts and development of proxies for predicting the likelihood and the spatial distribution of earthquake ground failure impacts.

Session Chairs: Alex Grant (agrant@usgs.gov), Kate E. Allstadt (kallstadt@usgs.gov), Eric M. Thompson (emthompson@usgs.gov), Keith Knudsen (kknudsen@usgs.gov).

Current and Future Challenges in Engineering Seismology

The impressive ongoing densification of modern high-quality earthquake monitoring networks in most earthquake prone countries means that near-field strong ground motions—which dominate earthquake hazard—are increasingly recorded worldwide. Earthquake records are then made available to the seismological and engineering communities through open access databases and associated, state-of-the art web services. These high-quality earthquake waveforms are typically acquired at a variety of recording sites, ranging from rocklike ground to very soft sediments, with well characterized geotechnical and geophysical properties. This allows novel, physically sound representations of site terms in empirical ground-motion models and for reliably constraining reference rock ground motions. At the same time, tremendous advances in computational seismology allow physics-based numerical simulations of strong ground motions to reliably complement and further constrain ground-motion prediction efforts and hazard studies, by providing opportunities to model and test the impacts of complex source characteristics on expected ground motions. Ground-motion models are one of the key ingredients of seismic hazard assessments for tectonic and induced earthquakes, increasingly implemented also in real-time or rapid fashion to promptly identify potential associated impacts and losses and to optimize emergency response. Earthquake impact mitigation, that chiefly relies on modern earthquake resistant construction practice, requires effective translation of scientific investigation into building codes and requires continuous dialogue between the seismological and engineering communities. With this background, this session welcomes novel and multi-disciplinary contributions focusing on the current "grand challenges" in engineering seismology like: (a) prediction of near-field strong ground motions; (b) prediction of reference rock ground motions; (c) new approaches to empirical and computational ground motion modelling (including novel functional forms and predictors and attempts to reduce prediction uncertainties); (d) advanced site characterization (beyond the use of Vs,30 and site classes); (e) real-time/rapid earthquake hazard and impact assessment; and (f) translation of seismological science into building codes. We aim at a rich discussion that brings together experiences and ideas from the operational and research communities, and from empirical and numerical modelers. Students and early-career seismologists are encouraged to present their ongoing and recent works.

Session Chairs: Carlo Cauzzi (carlo.cauzzi@sed.ethz.ch), Ralph J. Archuleta (ralph.archuleta@ucsb.edu), Fabrice Cotton (fcotton@gfz-potsdam.de), Nicolas Luco (nluco@usgs.gov), Alberto Michelini (alberto.michelini@ingv.it), Stefano Parolai (sparolai@inogs.it), Ellen Rathje (e.rathje@mail.utexas.edu), David Wald (wald@usgs.gov).

Earthquake Ground Motions and Structural Response in Subduction Zones: A Focus on Cascadia

Accurate estimates of earthquake ground motions and structural response in subduction zone settings are critical to improving seismic hazard assessment and community resilience. This is especially true in the Cascadia subduction zone, with its susceptibility to multiple types of earthquake sources (*e.g.*, megathrust, crustal and intraslab), the presence of deep sedimentary basins and proximity to major cities such as Portland, Oregon; Seattle, Washington; and Vancouver, British Columbia.

We invite studies focusing on ground motion estimates using a variety of seismological approaches (*e.g.*, observational, theoretical, numerical modeling), as well as those that assess the response of man-made structures and the underlying local site due to earthquake ground motions. We welcome results from all subduction zone systems, with a particular focus on those that may improve our understanding of seismic hazard in Cascadia.

Session Chairs: Erin Wirth (ewirth@usgs.gov), Marine A. Denolle (mdenolle@fas.harvard.edu), Nasser A. Marafi (marafi@uw.edu), Valerie Sahakian (vjs@uoregon.edu).

Earthquake Source Parameters: Theory, Observations and Interpretations

Understanding origin and spatio-temporal evolution of seismicity needs a careful quantitative analysis of earthquake source parameters for large sets of earthquakes in studied seismic sequences. Determining focal mechanisms, seismic moment tensors, static stress drop, apparent stress and other earthquake source parameters provides an insight into tectonic stress and crustal strength in the area under study, material properties and prevailing fracturing mode (shear/tensile) in the focal zone, and allows investigating earthquake source processes in greater detail. In addition, studying relations between static and dynamic source parameters and earthquake size is essential for understanding the self-similarity of rupture processes and scaling laws and for improving our knowledge of ground motion prediction equations.

This session focuses on methodological as well as observational aspects of earthquake source parameters of natural or induced earthquakes in a broad range of magnitudes from large to small earthquakes, including acoustic emissions in laboratory experiments. Presentations of new approaches to determination of focal mechanisms, seismic moment tensors and other source parameters, as well as case studies related to analysis of earthquake source parameters are welcome. We also invite contributions related to scaling of static and dynamic source parameters, to self-similarity of earthquakes and inversions for stress and other physical parameters in the focal zone.

Session Chairs: Vaclav Vavrycuk (vv@ig.cas.cz), Douglas S. Dreger (dreger@seismo.berkeley.edu), Grzegorz Kwiatek (kwiatek@gfz-potsdam.de).

Emerging Science from the EarthScope Transportable Array in Alaska and Western Canada

The USArray Transportable Array deployment in Alaska and Western Canada was completed in the fall of 2017 with 194 telemetered broadband seismic and infrasound expected to collect data though the summer of 2020. This unprecedented systematic broadband coverage of the entirety of continental Alaska and far northwestern Canada provides the seismological community with a dataset intended to help illuminate long-standing questions and aid in new discoveries. The diverse tectonic environment of Alaska and northwest Canada provides a world-class setting for investigating seismicity, plate boundaries, distributed intraplate deformation, subduction, active volcanism, infrasound phenomena and a myriad of other Earth processes. This session welcomes emerging studies using all or part of this new community asset to investigate structures ranging from the crust to core, active tectonics, local, regional and teleseismic earthquakes or other elastic wave sources and seismic wave propagation.

Session Chairs: Natalia A. Ruppert (naruppert@alaska.edu), Kevin M. Ward (kevin.ward@sdsmt.edu), Meghan S. Miller (meghan.miller@anu.edu.au).

Environmental Seismology: Glaciers, Rivers, Landslides and Beyond

Environmental seismology is the study of seismic signals generated at and near the surface created by environmental forces in the atmosphere, hydrosphere or solid Earth. Contributions to this session are welcome on a wide variety of topics including (but not limited to) the seismic signals associated with landslides, rock falls, debris flows, lahars, snow avalanches, cliff or pinnacle resonance, bedload transport, fluid flow in open and confined channels, open water waves, tides, glacial stick-slip, iceberg calving, crevassing, extreme weather, other anthropogenic sources. In addition, other processes monitored by seismic waves such as permafrost, groundwater, soil moisture using seismometers or DAS data are welcome. Contributions that seek to conduct monitoring, create physical or statistical models of source processes or systems, detect events, characterize a wave propagation environment, or interact with other branches of the Earth or social sciences are additionally encouraged.

Session Chairs: Bradley Paul Lipovsky (brad_lipovsky@fas.harvard.edu), Marine A. Denolle (mdenolle@fas.harvard.edu), Rick Aster (rick.aster@colostate.edu).

Evolving Best Practices for Station Buildout in EEW and New Permanent Networks

On the U.S. West Coast, the U.S. Geological Survey and its partner institutions, University of California, Berkeley, Caltech, the University of Oregon and the University of Washington are focusing on completing the build-out of the infrastructure for initial implementation of ShakeAlert Earthquake Early Warning (EEW) in the United States. Over the next few years, the number of EEW-capable seismic stations must at least double from today's ~850 contributing stations. This effort requires planning regarding station density and type as well as complex logistics including siting, legal and environmental permitting, equipment specification and delivery. Other important topics include data quality and latency, continuous monitoring systems, delivery of alerts and other technical topics. This session invites contributions from any EEW system operator on all these topics related to EEW build, including case studies for current and planned seismic networks as well as new ideas for developing EEW deployments and collaborations with contributing networks that are novel for their design or approach in handling these issues.

Session Chairs: Fabia Terra (terra@seismo.berkeley.edu), Mouse Reusch (topo@uw.edu), Tim Parker (timparker@nanometrics.ca), Geoffrey Bainbridge (geoffreybainbridge@nanometrics.ca).

Explore the Fault2SHA Paradigms Across the Ponds

After the formalization of a Fault2SHA working group inside the European Seismological Commission (2016), some initiatives for presenting new data sets and the latest integration of fault sources in SHA models in Latin Americas were organized by the Executive Committee in the "Old Word" (http://fault2sha.net/what/) and at a fruitful session at SSA2018. This session aims at exploring differences and similarities in treating fault data in seismic hazard assessment across the Ponds (the Oceans). Descriptions of earthquake sources coming from field observations and from modelling, discussions on how to handle uncertainties in source representation for Seismic Hazard Assessment (*i.e.* probability of multi-fault ruptures) and contributions to the identification of 3D, geometrically complex fault systems and their incorporation in either physics-based or probabilistic seismic hazard results are welcome.

This session is jointly organized by the European Seismological Commission and SSA.

Session Chairs: Laura Peruzza (lperuzza@inogs.it), Edward H. Field (field@usgs.gov), Richard Styron (richard.styron@globalquakemodel.org), Alessandro Valentini (alessandro.valentini@unich.it).

Explosion Seismology Applications

Explosion sources are an important component of seismology and are used in everything from characterization of geologic environments to nuclear test identification. In regions of low natural background seismicity, mine blasting can dominate monitoring catalogs and finding and separating these sources from tectonic earthquakes is important for hazard estimation. Recent work using template matching, waveform modeling for moment tensors and combining seismic and acoustic data has shown great success in discriminating explosions from earthquakes and other sources. With the advent of inexpensive and easy to deploy arrays and networks of sensors, the wavefield produced by explosions is being studied with unprecedented detail. We welcome abstracts on explosion source physics, wave propagation, large-N network design, multi-physics data fusion and advanced processing techniques applied to explosion sources.

Session Chairs: William R. Walter (walter5@llnl.gov), Robert E. Abbott (reabbot@sandia.gov), Jessie L. Bonner (bonnerjl@nv.doe.gov), Catherine M. Snelson (snelson@lanl.gov).

Facebook and Twitter and Snapchat, Oh My! The Challenges and Successes of Using Social Media to Communicate Science to the Public

Social media is becoming a more important component of communicating science and local hazard information to the public. With the rise of this new media and the internet of things, scientists now have a more direct connection to communicate not only science information but also near real-time information about seismic hazards (*e.g.* tsunami alerts, earthquake information). However, this new communication avenue is a double-edged sword, as the same social media can be used to spread misinformation or create unrealistic expectations from the public regarding how and when local hazard information is disseminated. Here we invite presentations that relate to the use of social media as an education and outreach tool or as a method to disseminate hazard information including but not limited to: case studies of using social media to disseminate emergency information, applications of social media as an education and outreach tool, challenges and successes in using social media to communicate with the public and new methods or techniques that aim to improve interactions on social media.

Session Chairs: Elizabeth A. Vanacore (elizabeth.vanacore@upr.edu), Sara K. McBride (skmcbride@usgs.gov).

From Drifting to Anchored: Advances in Improving Absolute Hypocenter Location Accuracy for Natural, Induced and Explosion Seismic Events

Accurate, absolute geographic location of seismic event hypocenters is important for characterizing seismic activity and estimating seismic hazard. The increasing societal demands for robust and actionable hazard estimation of natural and induced earthquakes, the requirements for nuclear explosion monitoring and other social and economic needs require improved hypocenter accuracy and robust error estimation. But, in general, seismic event locations are not well anchored to the geographic Earth because they depend on poorly distributed and distant seismogram measurements, simplified and erroneous Earth models and approximated physical processes. While many common hypocenter relocation methods can precisely constrain relative locations, hypocenters remain poorly constrained in absolute geographic coordinates. Only in rare cases is there relatively direct and accurate “ground truth” (GT) information on location that can be derived from static source displacement or from the known source of a human caused event or explosion.

Error estimates for seismic location fall into at least three main classes: (1) True, absolute geographic error (hypocenter - GT); (2) Nominal absolute error (nominal hypocenter uncertainties output by location algorithms or other analyses without GT); and (3) Nominal relative location errors. Here we welcome observational, theoretical and methodological contributions addressing determination of absolute geographic location of seismic events. We specifically ask - is it possible to achieve true absolute hypocenter estimates with representative uncertainties? If yes, what methods and data are needed to achieve this goal? We also welcome contributions on absolute and relative location procedures and their nominal error estimates that relate to improving absolute geographic location accuracy.

Session Chairs: Alexandros Savvaidis (alexandros.savvaidis@beg.utexas.edu), Anthony Lomax (alomax@free.fr), William L. Yeck (wyeck@usgs.gov), Stephen C. Myers (myers30@llnl.gov).

Frontiers in Earthquake Geology: Bright Futures and Brick Walls

Since its infancy in the mid-1960s, the study of earthquake geology and paleoseismology has grown into a multi-disciplinary field. In concert, we have seen an increase in the precision and detail of coseismic earthquake observations and of complex fault behavior, including multi-fault rupture, earthquake triggering and fault interaction. In addition to the challenges of combining various geochronologic techniques, event stratigraphy and geomorphic surface reconstruction, paleoseismologic studies must also reconcile evidence from the upper several meters of the Earth with processes that initiate at several kilometers depth and with various models of rupture scenarios and earthquake recurrence. Despite these challenges, scientists are using new and improved methods and concepts to characterize both regional and local fault behavior, compare short term deformation rates with longer-term geologic slip rates, add critical constraints to dynamic rupture models and improve estimates of fault rupture length, earthquake magnitude and fault slip rates.

This session covers recent advancements, ongoing challenges and the future of earthquake geology. We welcome submissions focused on incorporating new concepts and methods that improve our understanding of short- and long-term fault behavior, place controls and insight on rupture modeling and provide new constraints on seismic hazard analyses.

Session Chairs: Lydia Staisch (lstaisch@usgs.gov), Brian L. Sherrod (bsherrod@usgs.gov), Stuart Nishenko (spn3@pge.com), H. Gary Greene (greene@mlml.calstate.edu).

Imaging Subduction Zones

Subduction zones host most of the deep earthquakes on Earth. The dynamic processes within subduction zones create volcanic arcs, control the global volatile cycle that impacts the climate and lead to orogeny that is responsible for the rise of mountains, *e.g.*, the Andes mountains along the Andean subduction zone. Although there have been tremendous advances in imaging subduction zones (especially in Japan and Cascadia) with increasing seismic data coverage and improved imaging theory and methods, it is still very challenging to obtain consistent 3D high-resolution seismic images of these systems. Such high-resolution images are critical in definitively answering questions such as how volatiles are recycled, what are the pathways of melt migration and whether or not serpentine exists in the “cold nose” of the mantle wedge or the cold core of the slab mantle. The goal of this session is to motivate discussion on the current state of subduction zone imaging with a special focus placed on new seismic array deployments (*e.g.*, OBS) and advanced seismic imaging methods (*e.g.*, ambient noise tomography, migration imaging and full waveform inversion) that can explore and fully utilize big seismic data sets to better image subduction zones. We welcome and encourage research topics on robust imaging method development and applications and image interpretations of global subduction zones.

Session Chairs: Min Chen (chenmi22@msu.edu), Eric D. Kiser (ekiser@email.arizona.edu), Zhongwen Zhan (zwzhan@caltech.edu).

Injection-Induced Seismicity

Induced seismicity related to oil and gas production has been a growing concern in the last few years. Although the majority of wastewater disposal and hydraulic fracturing operations do not generate seismicity or large magnitude events, there have been few reports of damaging earthquakes in North America, resulting in some damages to infrastructure and other properties. This led to an increased demand for appropriate risk assessment and management of induced seismicity and the development of effective risk mitigation strategies. Injection-induced seismicity and associated risk and hazard have been the subject of many studies and research. However, there are still many questions to answer. In this session, we welcome contributions on geomechanics, numerical modelings, case studies, induced seismicity forecasting and risk assessment techniques, estimating ground motions, assessing liquefaction, lateral spreading, site amplification and infrastructure damage.

Session Chairs: Sepideh Karimi (sepidehkarimi@nanometrics.ca), Zia Zafir (zzafir@kleinfelder.com), Dario Baturan (dariobaturan@nanometrics.ca), David Shorey (davidshorey@nanometrics.ca).

The InSight Mission—Seismology on Mars and Beyond

The InSight mission landed on Mars on November 26, 2018 and was the first to place an ultra-sensitive broad band seismometer on the surface of another planet. It will provide key information on the composition and structure of an Earth-like planet that has gone through most of the evolutionary stages of the Earth up to, but not including, plate tectonics. Using seismology, geodesy and heat flow measurement, InSight aims to determine the thickness and structure of the Martian crust and mantle, the size and state of the core, the planet's thermal state and the level of tectonic activity and rate of meteorite impacts.

The two-year (one Mars year) InSight mission ushers in a new era in planetary seismology. In the coming years and decades NASA may launch missions to explore the interiors of our Moon, Venus and the "Ocean Worlds" of the Solar System (*e.g.*, Europa, Enceladus and Titan). While the focus of these mission concepts vary from fundamental geophysics to detection of life and conditions for life, seismological exploration of planetary bodies' interiors is likely to play a key role in understanding planetary state and evolution by helping to determine their thermal and chemical make-up.

We invite contributions that provide overviews of the InSight mission, including description of its experiments, instruments, models, data access and services, as well as observations made in the first few months of operation. We also invite contributions that describe past and future seismological exploration of the Solar System.

Session Chairs: Sharon Kedar (sharon.kedar@jpl.nasa.gov), Mark P. Panning (mark.p.panning@jpl.nasa.gov), William B. Banerdt (william.b.banerdt@jpl.nasa.gov).

Large Data Set Seismology: Strategies in Managing, Processing and Sharing Large Geophysical Data Sets

As seismology grows increasingly data rich, studies are being designed that use ever larger volumes of available data. The strategies for collecting, processing and sharing these data are evolving accordingly. In cases when the traditional research pattern of downloading, managing and processing data locally becomes untenably slow, new approaches are required. These strategies may include employing a compute cluster, either operated by a research group, an institutional HPC resource or a cloud computing provider. Researchers may use new technologies and frameworks to orchestrate more advanced processing workflows aimed at large scale computation, *e.g.* Hadoop. Furthermore, they may employ stream processing, where data are processed as it is collected from a center, thus mitigating the local storage issues. Ultimately, working with large data sets challenges researchers to be more informed and deliberate about computation, data transmission, compression and storage. This shift in data processing scale has a number of implications for both data providers and research processing pipelines and a variety of approaches are being used to address these changes. We invite researchers and data providers to describe their experiences in collecting, managing and processing large data sets.

Session Chairs: Chad Trabant (chad@iris.washington.edu), Jonathan K. MacCarthy (jkmacc@lanl.gov).

Large Intraslab Earthquakes

The physical processes associated with intermediate-depth and deep-focus earthquakes are not well understood. However, understanding these events can provide insights into earthquake mechanics, subduction dynamics, mineral physics and mantle thermal structures. In addition, some intermediate-depth earthquakes can pose significant hazards to local communities. Therefore, investigating rupture processes of these earthquakes has both significant intellectual and societal relevance. Recently large intermediate-depth and deep-focus earthquakes have occurred at multiple subduction zones with distinct characteristics, including the 2013 M8.3 Sea of Okhotsk earthquake, the 2015 M7.5 Hindu Kush earthquake, the 2015 M7.8 Bonin Islands earthquake, the 2017 M8.2 Mexico earthquake and the 2018 M8.2 and M7.9 Fiji doublet. The high-quality seismic records of these events provide excellent opportunities to probe kinematic and dynamic processes of these earthquakes, to differentiate their associated physical mechanisms, to investigate geodynamics of different subduction zones and to understand the related seismic hazards. We welcome contributions on all aspects of intra-slab earthquakes, including but not limited to rupture process, foreshocks and aftershocks, dynamic triggering, geodynamic modeling, mineral laboratory experiments and seismic imaging of slabs.

Session Chairs: Zhongwen Zhan (zwzhan@caltech.edu), Wenyuan Fan (wfan@whoi.edu), Linda M. Warren (linda.warren@slu.edu).

The M7 Anchorage Earthquake: Testing the Resiliency of South-Central Alaska

The M7 Anchorage Earthquake of November 30, 2018 struck under Alaska's most densely populated urban area, and generated the strongest ground motions in south-central Alaska since the Great 1964 Alaska Earthquake. The Anchorage earthquake is the third Mw≥7 earthquake in the subducting Pacific Plate to impact south-central Alaska in the past three years. The rupture appears to have occurred inside the Pacific Plate and generally propagated upward and northward toward the plate interface. Strong ground motions across the Anchorage and Mat-Su Valley regions caused major impacts to the built environment and local economy, estimated in the hundreds of millions of dollars. Yet, despite the shaking severity most buildings, critical facilities and lifelines performed remarkably well. Damage was generally minor to moderate though spread across a large geographic area. In this session, we invite contributions from all fields addressing an array of topics including, but not limited to, the earthquake source, propagation and ground motion observations, geodetic observations, geotechnical impacts to the built environment and ground failures placed in the context of the local geology. We also seek perspectives that address community preparedness, mitigation measures, resiliency to seismic hazards and lessons learned.

Session Chairs: Michael West (mewest@alaska.edu), Robert C. Witter (rwitter@usgs.gov).

Machine Learning in Seismology

Recent advances in computer science and data analytics have brought machine-learning (ML) techniques, including deep learning, to the forefront of seismological research. While ML methods continue to produce impressive successes in conventional artificial intelligence (AI) tasks, they also start to show powerful applicability in augmenting big data analysis in seismology by improving accuracy and efficiency compared to the traditional methods. Successful ML applications in seismology include seismic event detection, seismic signal classification, earthquake parameter estimation, signal denoising, ground motion prediction, subsurface tomography, aftershock pattern recognition and efficient visualization. However, challenges remain in terms of discovering new ML methods that can be applied to seismic and other geophysical data to learn about Earth's subsurface structure and the underlying processes of Earth such as earthquakes. Furthermore, instead of considering ML models as "black boxes," developing human-interpretable ML models and learning about their decision-making process also remain as grand challenges in ML field. The goal of this session is to highlight some of most recent ML results in our seismology community to motivate discussions of new ML research directions in seismology and beyond.

This session is jointly organized by the Seismological Society of Japan and SSA.

Session Chairs: Youzuo Lin (ylin@lanl.gov), Sepideh Karimi (sepidehkarimi@nanometrics.ca), Takahiko Uchide (t.uchide@aist.go.jp), Qingkai Kong (kongqk@berkeley.edu), Dario Baturan (dariobaturan@nanometrics.ca), Zhigang Peng (zpeng@gatech.edu), Ting Chen (tchen@lanl.gov), Andrew Delorey (andrew.delorey@lanl.gov), Min Chen (chenmi22@msu.edu), Chengping Chai (chaic@ornl.gov), Paul Johnson (paj@lanl.gov).

Metamaterials, Resonances and Seismic Wave Mitigation, an Emerging Trend in Seismology

The study of the interaction between waves propagating in a medium and its structure continues to be one of the most active research areas of wave physics and notably seismology. After the introduction of a new class of artificially engineered media called "metamaterials" in electromagnetism and acoustics, the idea that full control on wave propagation can be achieved through an appropriate design of the medium's microstructure is now widely accepted. In elasticity for instance, several laboratory experiments have shown how waves can be stopped, converted or amplified using resonant inclusions or periodic arrangement of heterogeneities. This evokes the compelling question whether metamaterial concepts can be scaled up and work for seismic waves at earthquakes frequencies.

Major research directions are emerging in this area including the development of barriers for seismic waves, the design of periodic frames for buildings and, at a larger scale, the study of city layouts that exploit building resonances and site-city interaction (SCI) to mitigate the propagating seismic field.

We invite theoretical, numerical and experimental contributions dealing with metamaterials, site-city interaction and wave control applications, including ground borne vibrations, to the field of geophysics and seismic engineering.

Session Chairs: Andrea Colombi (andree.colombi@gmail.com), Philippe Gueguen (philippe.gueguen@univ-grenoble-alpes.fr), Antonio Palermo (palerman@caltech.edu).

Methods for Site Response Estimation

Assessing the influence of soil and rock properties on the strength of earthquake ground shaking is an area of active research because of the importance of such "site effects" to realistically quantify potential seismic risk to infrastructure. The hazards community is moving beyond simple measurements of Vs30 (average shear-wave velocity in the upper 30 m) to measuring, modeling and predicting more accurate site response. These approaches include inverting various datasets for shear wave velocities at a range of depths, identifying hard boundaries that influence site response and also developing methods for direct measurement of site response through, such as spectral ratios using earthquake or ambient noise signals. In this session we invite abstracts on innovative methods for site response characterization, data collection approaches needed for such characterizations, as well as case studies showing the application of these methods.

Session Chairs: Thomas L. Pratt (tpratt@usgs.gov), Lisa S. Schleicher (lisasschleicher@gmail.com), Lee M. Liberty (lliberty@boisestate.edu).

Modeling and Understanding of High-Frequency Ground Motion

Seismic wave attenuation is an important topic for both seismology and engineering, as it enters in the prediction of ground motions, site response analyses and the assessment of seismic hazards. In this session, we would like to bring in studies focusing on high-frequency ground motion and its attenuation, as this may have significant impact on the site response and engineering design. As physics-based broadband simulations can reach unprecedented high frequencies, such studies can be of help in understanding ground motion at high frequencies crucial to the seismic response of certain structures, especially for critical facilities.

This session aims at collecting contributions as to how physics-based and empirical modeling handle high-frequency ground motion. We welcome simulation studies that may shed light on the nature of high-frequency attenuation of ground motion, in particular considering also a proper statistical treatment of the uncertainties associated with data collected in the field, the laboratory and through analysis of ground motion records. Topics of interest include crustal attenuation studies, fmax, kappa, spectral analysis studies (stress drop and Q), potential trade-offs between kappa and source, path and site effects, rock and site characterization studies, as well as contributions on the quantification and interpretation of scattering and intrinsic attenuation. Further contributions that help quantify uncertainties in high-frequency attenuation and corresponding ground motion models are also particularly welcome.

Session Chairs: Marco Pilz (pilz@gfz-potsdam.de), Ashly Cabas (amcabasm@ncsu.edu), Olga Ktenidou (olga.ktenidou@noa.gr).

New Approaches to Geophysical Research Using Dense Mixed Sensor and Broadband Seismology Arrays

Researchers are deploying complementary geophysical instruments such as high and low gain seismic velocity sensors, accelerometers, infrasound, GNSS, MT in dense and sparse arrays along with broadband seismic sensors. Some of these techniques require longer-term deployments than others and contributors are encourage to discuss these constraints and tradeoffs when considering these types of combined instrument observations.

We would encourage session contributors to present their research, motivation and innovative approaches to geophysical studies using mixed sensor deployment techniques for Earth and climate sciences observations including: broadband and geophone velocity sensors, accelerometers, GNSS, tilt, pressure and infrasound, magnetotelluric instruments. Presentations may describe the results, challenges and discoveries of the multidisciplinary approach to geophysical studies.

Session Chairs: Tim Parker (timparker@nanometrics.ca), Ninfa Bennington (ninfa@geology.wisc.edu), Bruce Townsend (brucetownsend@nanometrics.ca).

New Frontiers in Global Seismic Monitoring and Earthquake Research

Driven by the societal expectation for timely, accurate information, the past decade has seen dramatic improvements as a result of increased computational efficiency, seismic data coverage and improved communication technology. While aspects of earthquake research have taken advantage of this evolution, the adoption of improvements in earthquake monitoring has not been fully leveraged. In real-time monitoring, earthquakes are characterized in a vacuum, without leveraging knowledge of past events. New data types may help characterize earthquakes more quickly and accurately. New opportunities exist for rapidly communicating information. With these advances, global seismic monitoring can improve the quality and timeliness of information shared with the public.

A U.S. Geological Survey Powell Center Working Group explored these issues at a recent meeting, attempting to prioritize future opportunities in earthquake monitoring and research. Areas of focus identified by the group included improved agency communication during earthquake response; leveraging insights from the nuclear monitoring community in processing array data for earthquake detection and association; use of machine learning techniques to improve the reliability of source characterization; compressing the timeline of rapid source characterization; and improving our use of social media and crowd-sourced data. We solicit contributions that further explore these and related issues. We seek to more clearly identify priorities of future monitoring efforts, what new technologies can improve the speed and accuracy of monitoring and how to improve communication and coordination between groups involved in earthquake response and research.

Session Chairs: Gavin P. Hayes (ghayes@usgs.gov), Paul Earle (pearle@usgs.gov), Kristine Pankow (pankow@seis.utah.edu), Alberto Michelini (alberto.michelini@ingv.it).

Next Generation Earthquake Early Warning Systems: Advances, Innovations and Applications

Recent scientific advances in real-time data processing, source characterization and ground motion prediction shape the future of earthquake early warning (EEW) systems. Machine-learning based techniques take conventional event detection algorithms to the next level by successfully identifying concurrent seismic radiations from multiple sources and reducing the number of false triggers. Integration of real-time seismic and GPS data reduce uncertainties on source characterization by providing additional insights on event magnitude, fault slip and rupture geometry. Ground-motion algorithms that make use of real-time observed amplitudes, regional wave propagation attributes and frequency-dependent site amplification allow for the reliable prediction of shaking intensities. Incorporation of building/facility inventory and associated vulnerabilities allows prediction of where damage potential is high for rapid aftermath response.

This session seeks contributions from the latest advances in the field of earthquake early warning, including (but not limited to):

- real-time earthquake location, rupture and ground motion characterization techniques/algorithms;
- insights gleaned from multi-disciplinary real-time data sets;
- challenges related to complex ruptures and concurrent events;
- characterization of prediction uncertainties and risk-oriented probabilistic early warnings;
- tsunami potential and early warning at local and global scales;
- case studies, testing and performance evaluation of existing systems;
- near real-time of damage predictions for post-disaster management.

This session is jointly organized by the Seismological Society of Japan and SSA.

Session Chairs: Angela I. Chung (aichung@berkeley.edu), Emrah Yenier (emrahyenier@nanometrics.ca), Men-Andrin Meier (mmeier@caltech.edu), Mark Novakovic (marknovakovic@nanometrics.ca), Mitsuyuki Hoshiba (mhoshiba@mri-jma.go.jp), Yuki Kodera (y_kodera@mri-jma.go.jp).

Next Generation Seismic Detection

A range of new technologies are revolutionizing how we can detect and characterize seismic events. These include the use of new types of sensors to record motion, as well as new algorithms to process the geophysical data that they generate. Real-time processing of geodetic data is now the norm as the number of GNSS receivers streaming continuous data is steadily increasing. Tens of millions of smartphones equipped with both GNSS and accelerometer sensors have been deployed throughout the western US, while hundreds of millions exist throughout tectonically regions globally, and these are increasingly being harnessed in myriad new ways through crowd-sourcing. Seismic detection by voice- and shaking-activated Internet of Things offer to push sensor density far higher still. Machine learning algorithms are being applied to a wide variety of geophysical data and are improving our capability to detect events of interest. We invite contributions from researchers developing new and innovative ways to detect and characterize seismic events.

Session Chairs: Timothy Melbourne (tim@geology.cwu.edu), Richard M. Allen (rallen@berkeley.edu), Gavin P. Hayes (ghayes@usgs.gov), Raymond J. Willemann (raywillemann@gmail.com), G. Eli Baker (glenn.baker.3@us.af.mil).

Non-Traditional Application of Seismo-Acoustics for Non-Traditional Monitoring

Seismo-acoustic measurements have been shown to be sensitive for detecting, locating and characterizing natural environmental phenomena, animal communications and military activities. There are however other phenomena and activities producing seismo-acoustic signals. For example, the operation of industrial facilities generates mechanical energy that potentially propagates into the air as acoustic and infrasonic waves and/or into the solid earth as seismic waves. The types and intensity of vibrational signals recorded at the sensors vary according to the specifics of the machinery and their relative location with respect to the sensors. Innovative analyses techniques can extract useful information from these signals and help us monitor the machinery or related activities. We welcome submissions on collection and application of seismo-acoustic data and techniques that shed light on non-traditional monitoring of facilities and activities.

Session Chairs: Monica Maceira (maceiram@ornl.gov), Chengping Chai (chaic@ornl.gov), Omar Marcillo (omarcillo@lanl.gov).

Numerical Modeling of Earthquake Ground Motion, Seismic Noise, Rupture Dynamics and Seismic Wave Propagation

Continuous development of numerical modeling methodology in seismology is driven by emerging requirements in the observational seismology, advances in the mathematical sciences, evolution of computer architectures and programming models, adaptation of methods originating in other scientific fields, as well as by practical applications including site-specific seismic hazard assessment. This session is a forum for presenting advances in numerical methodology, whether the principal context is observational, mathematical/numerical, computational or application.

We invite contributions focused on development, verification and validation of numerical-modeling methods and methodologically important applications especially to earthquake ground motion, seismic noise and rupture dynamics, including applications from field of induced seismicity with particular focus on multi-physics aspects. Examples may include combining fluid migration and stress transfer in porous media with rupture dynamics and wave propagation in poro-elastic media and full seismic cycle simulations. We encourage contributions on the analysis of methods, fast algorithms, high-performance implementations, large-scale simulations, non-linear behavior, multi-scale problems and confrontation of methods with data.

Session Chairs: Peter Moczo (moczo@fmph.uniba.sk), Steven M. Day (sday@sdsu.edu), Jozef Kristek (kristek@fmph.uniba.sk).

Observations of Volcanism in the Three Spheres: Land, Air and Sea

Volcanoes are naturally situated at the intersection of the solid Earth with the air and/or sea. As a result, we can probe the volcanic system using a diverse range of observable waves: seismic, infrasonic and hydroacoustic. While these waves can undergo conversions and move between spheres, information is typically lost in the conversion process and is best analyzed in the sphere where the source originates. Thus, observations in the different spheres may be necessary to fully characterize and understand volcanic activity.

Recent advances have been made using combinations of these observables in complementary ways to improve our understanding of volcanoes in eruption and repose. Monitoring networks are increasingly using infrasound to detect explosions, lahars and other subaerial activity. Underwater cabled networks, such as that at Axial Seamount and other instrumentation are opening new possibilities for monitoring and studying submarine volcanism. Additionally, new seismic technologies, such as large-N arrays, are allowing for more thorough seismic studies. New or improved methods—such as machine learning techniques—for processing, analyzing and combining the variety of data collected from volcanoes are also needed to improve our understanding of volcanism. In this session, we encourage interdisciplinary studies but also welcome new studies that showcase the diversity of advances in volcano seismology within a single sphere. Topics may include scientific studies as well as work focusing on techniques and instrumentation."

Session Chairs: Alicia J. Hotovec-Ellis (ahotovec@gmail.com), Gabrielle Tepp (gtepp@usgs.gov), Jackie Caplan-Auerbach (jackie.caplan-auerbach@wwu.edu), Mel Rodgers (melrodgers@usf.edu).

Offshore Subduction Zone Structure and Seismicity Along Pacific Northwest: From the Gorda Plate to the Queen Charlotte Fault

The Cascadia subduction zone extends along the Pacific Northwest from Cape Mendocino in the south to northern Vancouver Island in the north. However, convergence continues farther north beneath Haida Gwaii along the Queen Charlotte Fault, where the Pacific and North America plates meet. Across this entire area, several oceanic plates (Explorer, Juan de Fuca, Gorda, Pacific) and one continental plate (North America) interact forming a myriad of structures and a complex stress regime, with most of the important tectonic boundaries and associated seismicity located offshore. In this session we invite contributions that focus on investigating the offshore structure and convergent tectonics along the Cascadia subduction zone and the Queen Charlotte Fault using marine geophysical data, especially those that are centered on or include active and/or passive source seismic studies. We also welcome contributions that use other observational or modeling techniques to characterize stress or deformation along the margin and those that that summarize past, present and future offshore instrument deployments along the Pacific Northwest.

Session Chairs: Pascal Audet (pascal.audet@uottawa.ca), Mladen Nedimovic (mladen@dal.ca), Emily Roland (eroland@uw.edu), Shuoshuo Han (han@ig.utexas.edu), Suzanne Carbotte (carbotte@ldeo.columbia.edu).

Photonic and Non-Inertial Seismology

Emerging photonic and non-inertial seismic measurements of ground motion that use laser interferometery or a networked array of stationary receivers (*e.g.*, GNSS) instead of a classical "mass-on-a-spring" are expanding our capacity to observe the structure and dynamics of Earth systems. These photonic and non-inertial tools include fiber-optic and distributed fiber-optic strain sensors (*e.g.*, interferometers, Bragg grating methods, DAS) and ring-laser rotational sensors. There are key theoretical and practical differences (advantages and disadvantages) between inertial and non-inertial sensors, which are the present focus of many seismological and computational science research groups worldwide. These include measurement of strain and rotation, perhaps in addition to particle velocity, and the ability to record terabytes of Large-N seismic data with meter-scale sensor spacing. Also, seismogeodetic techniques such as GNSS precise point positioning increases the dynamic range and accuracy of (particularly large) ground displacements and strain. Because non-inertial data often contain information on displacement gradients of a seismic wavefield (*i.e.*, strain), there is a need to develop a fundamental theoretical framework to cope with this new data type. Moreover, the diverse advantages of non-inertial seismology make way for new data analysis methods, or the adaptation of existing methods to this new data type, with the potential to make novel observations of the planet. This session aims to crosscut the emerging space of photonic and other non-inertial seismological methods with contributions on sensor design, technical instrumentation aspects and current roadblocks, inertial/non-inertial comparisons, case studies involving theoretical and real datasets and applications ranging from basic science to engineering/monitoring.

Session Chairs: Nathaniel J. Lindsey (natelindsey@berkeley.edu), Patrick Paitz (patrick.paitz@erdw.ethz.ch), Paul Bodin (bodin@uw.edu), Jamie Steidl (steidl@eri.ucsb.edu), Eileen Martin (eileenrmartin@vt.edu), Zefeng Li (zefengli@gps.caltech.edu).

Problem Unsolved: Knowledge Gaps at the Intersection of Earthquake Engineering Practice and Research

Earthquake engineering is a perpetual balancing act between established methods and innovative techniques. Established best practices and existing code are backed by published research as well as engineering consensus, but for some cases may lead to unrealistic results. The engineer's desire to improve and optimize the design requires adoption of new practices and techniques that are actively being researched. These newer practices may expose deficiencies in scientific understanding of which the research community is unaware. Alternatively, the practitioner may not be aware of the full range of research on these techniques. The intent of this session is to promote a dialogue between the earthquake engineering research and practice communities, and to suggest possible directions for new research to fill in these gaps.

This session invites engineering practitioners and researchers to submit case studies that illustrate difficulties they have encountered in their practice, owing to gaps in scientific knowledge. The session also invites papers on recent research illuminating known gaps in understanding of earthquake engineering practice. Submissions highlighting any earthquake engineering problem are welcome, as are those in the area of risk analysis and mitigation for disaster resilience. Submissions in the areas of seismic risk/hazard analysis, ground response analysis, soil-structure interaction and liquefaction analysis are particularly encouraged.

Session Chairs: Youssef M. A. Hashash (hashash@illinois.edu), Shahriar Vahdani (shah.vahdani@gmail.com), Brady Cox (brcox@utexas.edu), Albert Kottke (albert.kottke@gmail.com), Recep Cakir (cakir.recep@gmail.com), Bahareh Heidarzadeh (bheidarzadeh@engeo.com), David P. Teague (dteague@engeo.com), Gilead Wurman (gwurman@engeo.com).

Recent Developments in High-Rate Geodetic Techniques and Network Operations for Earthquake and Tsunami Early Warning and Rapid Post-Earthquake Response

Over the past decade, geodetic techniques have become invaluable to rapid evaluation of earthquake hazards, both in real-time and for post-earthquake response. Techniques have included, but are not limited to, high-rate GNSS, strainmeters, ocean bottom pressure sensors, gravimeters and collocated seismic/geodetic instrumentation. These instruments and techniques are particularly useful for extracting moment release and rupture extent for large subduction earthquakes, although they have been shown to provide good source information for moderate sized events as well. Additionally, high-rate geodetic data and associated models can help improve ground motion characterization and prediction. This session seeks proposals that utilize geodetic instrumentation for the rapid modeling of earthquakes and tsunamis, both from the perspective of operational early warning and rapid post-earthquake response. We invite abstracts related to algorithm development, testing and validation of methodologies, machine-learning techniques to analyze GNSS data, analyses in combination with seismic data in real-time and more.

This session will also provide a venue for those involved in operating real-time GNSS networks to discuss current developments both in field operations and at data management centers. Building redundancy into critical data paths, efforts to lower latency and the upgrade of communications to meet the needs of systems being built for public-safety, methods for quantifying solution quality, as well seeking ways to integrate existing GNSS and seismic network infrastructure are topics of interest to this session. We also encourage presentations on the latest advances in the use of cloud architecture to manage the data and, the exploratory use of software such as Kafka and Elasticsearch at data operations centers."

Session Chairs: Brendan W. Crowell (crowellb@uw.edu), Kathleen Hodgkinson (hodgkinson@unavco.org), Alberto Lopez (alberto.lopez3@upr.edu), Benjamin A. Brooks (bbrooks@usgs.gov), Joe Henton (joe.henton@canada.ca), Jeffrey J. McGuire (jmcguire@usgs.gov), David J. Mencin (dmencin@unavco.org).

Science Gateways and Computational Tools for Improving Earthquake Research

Science gateways allow research communities to access shared data, software, computing services, instruments, educational materials and other resources. Advances in earthquake science are becoming increasingly tied to the ability to fuse and model multiple data types, requiring advances in computational infrastructure. Earthquake scientists must rely on computational laboratories to integrate disparate data sets and perform simulation experiments, particularly because earthquake processes span multiple spatial and temporal scales, ranging from microscopic, millisecond source physics to long-term, global tectonic scales. This session focuses on identifying best technologies and management strategies of science gateways for facilitating data access and science analysis through user interfaces, middleware and community networking capabilities. Abstracts discussing advances in computational infrastructure and data synthesis for enhancing earthquake science, including software, supercomputing, simulation models, sensor technology, heterogeneous data sets, cloud computing, management of huge data volumes and development of community standards are encouraged. Abstracts identifying management strategies and recommendations for analytics software to provide a feedback loop for making science gateways useful are also encouraged.

Session Chairs: Andrea Donnellan (andrea@jpl.caltech.edu), Lisa Grant Ludwig (lgrant@uci.edu), Philip J. Maechling (maechlin@usc.edu).

Science, Hazards and Planning in Subduction Zone Regions

Subduction zones host the Earth's largest faults and many of its active volcanoes. Subduction systems also play a central role in the formation and accretion of continental crust and are responsible for recycling oceanic crust and volatiles into the mantle. This session explores the latest multidisciplinary scientific advances in subduction zones around the world, including their mechanics, structure, evolution and dynamics from the trench to the backarc. We welcome studies that explore such topics as seismicity, tremor and deformation transients, including the slip behavior of faults and tsunami genesis, as well as studies that explore the geologic signatures of these processes. Below the arc, studies may explore volatile and magma migration, mantle wedge dynamics and melt production in the lower crust.

The dynamic processes inherent to subduction zones also challenge society's prosperity given the potential for natural disasters with broad regional impacts. These natural disasters are often compound events, as in the case where large earthquakes can trigger both landslides and tsunamis. The successful mitigation of these natural hazards requires a thorough scientific understanding of the underlying processes. Therefore, we also welcome studies that explore the recurrence, probability, potential impacts and mitigation strategies of these natural hazards.

Session Chairs: David Schmidt (dasc@uw.edu), Lori Dengler (lori.dengler@humboldt.edu), Will Levandowski (will.levandowski@tetratech.com), Kathy Davenport (davenpka@oregonstate.edu), Jamey Turner (jamey.turner@tetratech.com), Rick Wilson (rick.wilson@conservation.ca.gov), Brendan W. Crowell (crowellb@uw.edu).

The Science of Slow Earthquakes from Multi-Disciplinary Perspectives

Recognition of slow earthquake phenomena originated in Cascadia and Japan. Since the discovery of slow earthquakes, their study has continued to advance rapidly. Discussion in this joint session with Seismological Society of Japan (SSJ) is proposed to advance understanding of the phenomena not only in these two zones, but in many subduction zones around the Pacific Ocean, as well as other tectonic settings. The proximity of slow slip phenomena in subduction zones to great megathrust earthquakes highlights the importance of this topic for seismic hazard.

The goal of the session is to bring together research on slow earthquake phenomena that uses a variety of tools from seismology, geodesy, numerical modeling and laboratory studies, for various tectonic settings and spatial and temporal scales.

This session is jointly organized by the Seismological Society of Japan and SSA.

Session Chairs: Kazushige Obara (obara@eri.u-tokyo.ac.jp), Kenneth C. Creager (kcc@uw.edu), Heidi Houston (heidi.houston@gmail.com), Takanori Matsuzawa (tkmatsu@bosai.go.jp).

Seismology BC(d)E: Seismology Before the Current (digital) Era

We are in the early stages of the seismological digital era, and high-quality digital recordings of earthquakes are plentiful. But there is still much to learn from the early instrumental era with analog recordings on paper, film, or other media; from the pre-instrumental era with earthquake information through reported observations; and from pre-historic times through paleoseismological investigations. The digital era encompasses only a tiny fraction of recorded seismic history. The synthesis of information from the pre-digital eras, combined with modern analyses and modeling, presents new opportunities to learn and discover.

We invite presentations that highlight the finding, preserving and/or using of paleoseismological or historic observational data alone or in conjunction with modern data. Uses may include the exploration of key open questions concerning fault and earthquake processes, seismotectonics and seismic hazard; quantification of uncertainties in using historical and paleoseismological data. Presentations may highlight the use of seismic data to explore other phenomena such as slow slip events, ambient noise, storm surges, tectonic tremors, acoustic phases, induced seismicity, landslides, icequakes and avalanches, and describe recent efforts to develop durable and accessible archives of original sources and datasets. We will conclude the presentations with an open discussion of best practices and identification of actionable tasks to advance reuse of analog data and move preservation efforts forward.

Session Chairs: Susan E. Hough (hough@usgs.gov), Lorraine Hwang (ljhwang@ucdavis.edu), Allison L. Bent (allison.bent@canada.ca), Maurice Lamontagne (maurice.lamontagne@canada.ca), Emile Okal (e-okal@northwestern.edu), Brian Young (byoung@sandia.gov), Graziano Ferrari (graziano.ferrari@ingv.it).

State of Stress and Strain in the Crust and Implications for Fault Slip Based on Observational, Numerical and Experimental Analysis

Understanding the stress and strain distributions in the crust and specifically near fault zones is essential towards refining knowledge on deformation processes, fault mechanics and earthquake source physics. This session focuses on (1) the estimation of the state of stress/strain and (2) the analysis of stress/strain distributions at different spatial and temporal scales by soliciting works based on theory, observational data, modeling and laboratory experiments. Contributions are encouraged but not limited to address the following questions: 1) How are stress and strain distributed in lab experiments and nature and how can we bridge the two environments? 2) What are insights from numerical simulations on stress state and to what extent can models help in interpreting observations such as earthquakes or slow slip events? 3) What can we extract from geodetic, geologic, borehole and seismic data regarding the state of stress at regional and local scales? 4) How can spatial stress/strain variations from long-term data compilations improve our knowledge of fault zone structure, earthquake mechanics, aseismic slip? 5) How can information on the state of stress/strain be used to improve seismic hazard assessments?

Session Chairs: Niloufar Abolfathian (nabolfat@usc.edu), Patricia Martinez-Garzon (patricia@gfz-potsdam.de), Thomas H. W. Goebel (tgoebel@ucsc.edu).

Structural Seismology: From Crust to Core

Seismic imaging of the Earth's inaccessible interior, spanning from the lower crust to the deepest inner core, has achieved better resolution and accuracy due to improvements in data coverage, computational power, as well as modelling and inversion algorithms. We invite contributions highlighting results of analyses of new datasets as well as applications of new algorithms for revealing detailed Earth structure across length-scales, from local to global, and throughout the interior, from crust to core.

Session Chairs: Vedran Lekic (ved@umd.edu), Jessica C. E. Irving (jirving@princeton.edu), Andrew J. Schaeffer (andrew.schaeffer@canada.ca), Meghan S. Miller (meghan.miller@anu.edu.au).

U.S. Geological Survey National Seismic Hazard Model Components

The U.S. Geological Survey will soon complete the 2018 update to the National Seismic Hazard Model (NSHM) for the coterminous U.S. This update has begun an experiment with a more frequent update process that shortens the time between releases from six to three years on average. More frequent updates permit fewer model changes per update, more opportunities for adoption by a wide array of users and release of the latest models representing best-available science. For instance, the 2018 NSHM update mainly incorporated NGA-East for U.S. Geological Survey (Goulet *et al.*, 2017) in the central and eastern U.S. The NGA-East ground motion model marks a significant change in how we characterize the epistemic uncertainty in ground motions, and it is essential that we be able to evaluate and understand the model without the additional complexity of source model or implementation changes that are necessary to include in longer update cycles. This session focuses on the latest such models and the tools and techniques used to evaluate them. The 2014 update to NSHM for the conterminous U.S. saw the adoption of UCERF3, NGA-West2 and new adaptive smoothing techniques for gridded seismicity sources. The 2018 update brought in NGA-East and considered basin amplification effects in the western U.S. Forthcoming updates will consider NGA-Subduction, the use of the UCERF3 inversion methodology for Alaskan fault systems and further use of simulation-based ground motions. The latest models also commonly present implementation and application challenges. We invite submissions on, but not limited to, the NSHM components listed above. In particular, submissions should focus on sensitivity testing, comparative analysis, implementation techniques, new evaluation tools or metrics, new uses and applications of existing analyses (*e.g.* deaggregation) or uncertainty analysis.

Session Chairs: Peter M. Powers (pmpowers@usgs.gov), Allison M. Shumway (ashumway@usgs.gov), Mark D. Petersen (mpetersen@usgs.gov), Sanaz Rezaeian (srezaeian@usgs.gov), Richard W. Briggs (rbriggs@usgs.gov), Robert C. Witter (rwitter@usgs.gov), Charles S. Mueller (cmueller@usgs.gov).

Using Repeating Seismicity to Probe Active Faults

Repeating seismicity provides a novel means of monitoring fault zone processes at depths commonly inaccessible. Various forms of repeating seismicity exist, and we invite studies from the broad suite of repeating seismicity including earthquakes, long-period events and low-frequency earthquakes. Recent studies have shown that repeating seismicity can be used to infer fault slip-rates and physical properties at depths relevant to earthquake nucleation. With growing datasets and computationally efficient routines for detection of repeating seismicity it is now possible to probe faults in great detail and for long durations. Data from catalogs of repeating seismicity can provide the basis for physically realistic models of earthquake cycles and triggering and interaction of seismicity. We invite contributions relating to field and laboratory observations of repeating seismicity, advances in the detection and parameterization of repeating seismicity and the modelling of repeating seismicity.

Session Chairs: Calum J. Chamberlain (calum.chamberlain@vuw.ac.nz), Amanda M. Thomas (amt.seismo@gmail.com), William B. Frank (wbfrank@usc.edu).

Presenting author is indicated in bold.

Wednesday 24 April—Oral Sessions

Time	*Grand Crescent*	*Vashon*	*Cascade I*	*Cascade II*
	Photonic and Non-Inertial Seismology (see page 877).	**Advances in Intraplate Earthquake Geology** (see page 895).	**From Drifting to Anchored: Advances in Improving Absolute Hypocenter Location Accuracy for Natural, Induced and Explosion Seismic Events** (see page 864).	**The Science of Slow Earthquakes from Multi-Disciplinary Perspectives** (see page 868). Jointly organized by the Seismological Society of Japan and SSA
8:30 AM	Optical Measurements of Temperature and Strain of New Zealand's Alpine Fault. **Broderick, N. G. R.**, Loveday, J., van Wijk, K., Townend, J., Sutherland, R.	STUDENT: What Controls the Maximum Magnitude of Continental Normal Faulting Earthquakes? **Neely, J. S.**, Stein, S.	Absolute Hypocentral Location Improvements With 3D Velocity Model Optimization: Application to Duvernay, Western Canada. Vaezi, Y., Booterbaugh, A., Stacey, M., **Karimi, S.**, Baturan, D.	Slow Earthquake Segmentation as a Barrier to the 2011 Tohoku-Oki Earthquake Rupture. **Nishikawa, T.**, Matsuzawa, T., Ohta, K., Uchida, N., Nishimura, T., Ide, S.
8:45 AM	Fiber Optic Sensing of Local and Regional Earthquakes. **Mellors, R. J.**, Gok, R., Messerly, M., Pax, P., Yu, C., Mart, C., Morency, C., Sherman, C., Wang, H.	STUDENT: Towards Time-Dependent Modelling of Episodic Earthquake Occurrence on Intraplate Faults. **Griffin, J. D.**, Stirling, M. W., Wang, T., Clark, D.	Accuracy and Uncertainty of TexNet Absolute Seismic Event Location in West Texas. **Lomax, A.**, Savvaidis, A.	Short-Term Bidirectional Interaction between Slow Slip Events and Three Devastating Earthquakes in Mexico. **Cruz-Atienza, V. M.**, Tago, J., Villafuerte, C., Kostoglodov, V., Real, J., Ito, Y., Franco, S. I., Nishimura, T., Kazachkina, E., Santoyo, M. A., Zavala-Hidalgo, J.
9:00 AM	A Velocity-Based Earthquake Detection System Using Downhole DAS Arrays – Examples From SAFOD. Lellouch, A., Yuan, S., Spica, Z., Biondi, B., **Ellsworth, W.**	INVITED: Postglacial Paleoseismicity of the Teton Normal Fault Recorded by Lake Sediments in Grand Teton National Park, WY. **Larsen, D. J.**, Crump, S. E., Blumm, A.	Feature-Based Bayesian Inference for Seismic Event Monitoring. **Catanach, T. A.**, Downey, N. J., Young, C. J.	A Close Look at Slow and Fast Earthquakes Under the Aleutian Islands. **Ghosh, A.**, Li, B.
9:15 AM	Distributed Acoustic Sensing (DAS) for Continuous Monitoring of Near-Surface Properties Using Coda Wave Interferometry. **Rodríguez Tribaldos, V.**, Dou, S., Lindsey, N. J., Ulrich, C., Robertson, M., Freifeld, B. M., Daley, T. M., Monga, I., Tracy, C., Ajo-Franklin, J. B.	Paleoseismic History and Slip Rate of the Teton Fault at the Buffalo Bowl Site. **DuRoss, C. B.**, Gold, R. D., Briggs, R. W., Delano, J., Ostenaa, D., Zellman, M., Cholewinski, N., Wittke, S., Mahan, S.	Machine Learning for Emulation of Seismic-Phase Travel Times in 3D Earth Models. **Myers, S.**, Jensen, D., Simmons, N.	Slow Slip Events: Earthquakes in Slow Motion. **Michel, S.**, Avouac, J., Gualandi, A.

Time	Puget Sound	Pike	Pine	Elliott Bay
	Characterizing Faults, Folds, Earthquakes and Related Hazards in the Pacific Northwest (see page 891).	**U.S. Geological Survey National Seismic Hazard Model Components** (see page 882).	**Earthquake Ground Motions and Structural Response in Subduction Zones: A Focus on Cascadia** (see page 886).	**Machine Learning in Seismology** (see page 873). Jointly organized by the Seismological Society of Japan and SSA.
8:30 AM	A Kinematic Model for Late Cenozoic Fault Motion Within the Greater Cascadia Subduction System. **McCrory, P. A.**, Wilson, D. S.	2018 Update of the U.S. National Seismic Hazard Model. Petersen, M. D., Shumway, A. M., **Powers, P.**, Mueller, C. S., Moschetti, M. P., Frankel, A., Rezaeian, S., McNamara, D. E., Hoover, S. M., Luco, N., Boyd, O. S., Rukstales, K., Jaiswal, K., Thompson, E. M., Clayton, B., Field, E. H., Zeng, Y.	Downdip Extension of Large Intraslab Earthquakes and Its Engineering Implications. **Ji, C.**, Archuleta, R. J., Hao, J.	A Probabilistic Framework for Vs30. **Mital, U.**, Yong, A., Iwahashi, J., Savvaidis, A.
8:45 AM	INVITED: Evidence for a Quaternary-Active Fault Network in the Forearc of Southwestern British Columbia. **Morell, K.**, Regalla, C., Bennett, S. E. K., Leonard, L. J., Amos, C., Lynch, E., Harrichhaussen, N., Graham, A.	Additional Period and Site Class Maps for the 2018 USGS National Seismic Hazard Model. Shumway, A. M., Rezaeian, S., **Powers, P.**, Petersen, M. D.	Rupture Model of a Hikurangi Mw 8.6 Megathrust Earthquake for Strong Motion Simulations. **Somerville, P.**, Bayless, J., Pitarka, A., Skarlatoudis, A.	Using Machine Learning to Improve Ground Motion Prediction Equations. **Aagaard, B.**
9:00 AM	Near-Surface Geophysical, Geological and Geodetic Constraints on the Seismic Hazard of the Leech River Fault in the Northern Cascadia Forearc. **Leonard, L. J.**, Graham, A., Morell, K., Regalla, C., Harrichhausen, N., Elliott, J., Jiang, Y., Amos, C., Lynch, E.	Evaluation of Ground Motion Models for USGS Seismic Hazard Forecasts: NGA-Subduction. **McNamara, D. E.**, Wolin, E., Petersen, M. D., Shumway, A. M., Powers, P., Moschetti, M. P.	Using Noise Correlation to Improve the Seismic Velocity Model of the Seattle Basin and 3D Simulations of Large Earthquakes. **Frankel, A.**, Bodin, P.	STUDENT: Real-Time Earthquake Detection and Phase Picking Using Temporal Convolutional Networks. **Zhu, W.**, Mousavi, M., Beroza, G. C.
9:15 AM	STUDENT: An Earthquake Nest in Cascadia. **Merrill, R.**, Bostock, M. G.	Uncertainties in Probabilistic Seismic Hazard Analysis for a Poisson Earthquake Occurrence Model. **Zeng, Y.**, Petersen, M. D.	STUDENT: Topographic Response to Ground Motion From Modeled Seattle Fault Earthquakes. **Stone, I.**, Vidale, J. E.	INVITED: Smart Phone Based Bridge Seismic Monitoring and Vibration Status Realization by Time Domain Convolutional Neural Network. **Dang, J.**, Shrestha, A., Wang, X.

Time	*Grand Crescent*	*Vashon*	*Cascade I*	*Cascade II*
	Photonic and Non-Inertial Seismology...	**Advances in Intraplate Earthquake Geology**	**From Drifting to Anchored...**	**The Science of Slow Earthquakes...**
9:30 AM	Experimental Assessment of Rocking and Torsion in Civil Engineering Structures Using 3C and 6C Sensors. **Guéguen, P.**, Guattari, F., Laudat, T.	Paleoseismic Investigation of the Levan and Fayette Segments of the Wasatch Fault Zone, Central Utah. **McDonald, G. N.**, Hiscock, A. I., Hylland, M. D., Kleber, E.	The IASPEI Reference Event (GT) List (1959-2017) Maintained by the ISC. Lentas, K., **Storchak, D. A.**, Di Giacomo, D., Harris, J.	Seafloor Pressures, Temperatures, Ocean Circulation and Plate-Interface Slow Slip. **Gomberg, J.**, Hautala, S., Johnson, P., Chiswell, S., Wallace, L. M., Webb, S.
9:45–10:45 AM	Posters and Break, Fifth Avenue and Grand Ballroom			
	New Approaches to Geophysical Research Using Dense Mixed Sensor and Broadband Seismology Arrays (see page 878).	**Advances in Intraplate Earthquake Geology** (continued).	**Explosion Seismology Applications** (see page 865).	**The Science of Slow Earthquakes from Multi-Disciplinary Perspectives** (continued).
10:45 AM	Lessons From Two Years of Multi-Sensor Structural Monitoring at the UC San Diego Geisel Library. **Goldberg, D. E.**, Golriz, D., Bock, Y., Lo, E., De Vivo, L., Kuester, F., Wang, X., Hutchinson, T., Maher, R.	Late Quaternary Slip Rates and Holocene Paleoearthquakes of the Eastern Yumu Shan Fault, Northeast Tibet: Implications for Kinematic Mechanism and Seismic Hazard. **Ren, J.**, Xu, X., Zhang, S., Zhao, J., Ding, R.	Insights From the Source Physics Experiments on Seismic Waves Generated by Explosions. **Walter, W. R.**, Ford, S. R., Pitarka, A., Pyle, M., Pasyanos, M. E., Ichinose, G. A., Chiang, A., Mellors, R. J., Ezzedine, S. M., Vorobiev, O. Y., Dodge, D., Matzel, E., Wagoner, J., Hauk, T., Sullivan, D.	Interaction Between ETS (Episodic Tremor and Slip) and Long-Term Slow Slip Event in Nankai Subduction Zone. **Obara, K.**
11:00 AM	Clarifying the Distribution of Magmatic Fluids Within the Yellowstone Volcanic System: A Magnetotelluric and Seismic Study. **Bennington, N. L.**, Schultz, A., Bowles-Martinez, E., Thurber, C. H., Farrell, J., Lin, F.	INVITED: Recent Paleoseismic and Tectonic Geomorphic Studies of the Meers Fault, Oklahoma Reveal Longer Rupture Lengths and More Surface Deforming Earthquakes in the Last 6,000 Years. **Streig, A. R.**, Bennett, S. E. K., Hornsby, K. T., Chang, J. C., Mahan, S.	Relationship Between DPRK Nuclear Events and Near-Field Response to Chemical Explosions in the Source Physics Experiment Series. **Steedman, D. W.**, Bradley, C. R.	Characteristic Tectonic Tremor Activity Observed Over Multiple Slow Slip Cycles in the Mexican Subduction Zone. **Husker, A.**, Frank, W. B., Gonzalez, G., Kostoglodov, V., Kazachkina, E.

Time	Puget Sound	Pike	Pine	Elliott Bay
	Characterizing Faults, Folds, Earthquakes…	**U.S. Geological Survey National Seismic…**	**Earthquake Ground Motions…**	**Machine Learning in Seismology**
9:30 AM	Seismic Risk Assessment for British Columbia, Accessible Via Web Portal. **Bird, A. L.**, Journeay, J., Hastings, N., Cassidy, J. F., Wagner, C.	Impacts on Catastrophe Loss Modeling from Multi-Segment and Multiple Fault Ruptures in UCERF3. **Lee, Y.**, Graf, W.	INVITED: Nonlinear Broadband Simulations of M9 Megathrust Earthquakes in the Cascadia Subduction Zone. **Roten, D.**, Olsen, K. B., Takedatsu, R., Wang, N.	Robust Arrival Time Uncertainty Estimation Using Gaussian Blurring. **Peterson, M. G.**, Vollmer, C., Young, C. J., Stracuzzi, D.
9:45–10:45 AM	Posters and Break, Fifth Avenue and Grand Ballroom			
	Characterizing Faults, Folds, Earthquakes and Related Hazards in the Pacific Northwest (continued).	**U.S. Geological Survey National Seismic Hazard Model Components** (continued).	**Earthquake Ground Motions and Structural Response in Subduction Zones: A Focus on Cascadia** (continued).	**Machine Learning in Seismology** (continued).
10:45 AM	Mapping Coda Q Across Western Canada: From an Active Subduction Zone to a Stable Craton. Farahbod, A., **Cassidy, J. F.**	Updating the Seismic Source Model for a New USGS Earthquake Hazard Map of Alaska. **Haeussler, P. J.**, Bender, A. M., Witter, R. C., Brothers, D. S., Liberty, L. M.	An Overview of the NGA-Subduction Research Program. **Bozorgnia, Y.**, Abrahamson, N., Ahdi, S. K., Ancheta, T. D., Archuleta, R. J., Atkinson, G. M., Boore, D. M., Campbell, K. W., Chiou, B. S. J., Contreras, V., Darragh, R. B., Gregor, N., Idriss, I., Ji, C., Kamai, R., Kishida, T., Kuehn, N. M., Magistrale, H., Mazzoni, S., Parker, G. A., Si, H., Silva, W., Stewart, J. P., Walling, M., Wooddell, K. E., Youngs, R. R.	A Deep Neural Network to Identify Foreshocks in Real Time. **Karunanidhi, V.**
11:00 AM	STUDENT: Slip and Strain Accumulation Along the Sadie Creek Fault, Northern Olympic Mountains, WA. **Duckworth, W. C.**, Amos, C., Schermer, E. R., Loveless, J. P., Rittenour, T. M., Perez, Y. E.	Deformation in the August 2018 Mw 6.4 Kaktovik (North Slope), Alaska Earthquake. **Rollins, C.**, Meyer, F., Xue, X., Holtkamp, S. G., Freymueller, J. T.	NGA-Subduction Database. Ahdi, S. K., Ancheta, T. D., Bozorgnia, Y., Chiou, B. S. J., Contreras, V., Darragh, R. B., Kishida, T., Kuehn, N. M., Kwok, A. O., Lin, P., Youngs, R. R., **Stewart, J. P.**	Realistic Synthetic Broadband Ground Motions by Machine Learning. **Li, Z.**, Zhu, W., Hauksson, E., Beroza, G. C.

Time	*Grand Crescent*	*Vashon*	*Cascade I*	*Cascade II*
	New Approaches to Geophysical Research…	**Advances in Intraplate Earthquake Geology…**	**Explosion Seismology Applications…**	**The Science of Slow Earthquakes…**
11:15 AM	New High Resolution Very Low Powered Broadband Digitizer System, Pegasus. **Townsend, B.**, Moores, A., Pelyk, N., Parker, T.	High-Resolution Seismic Reflection Imaging of the Low-Angle Panamint Valley Normal Fault System, Eastern California. **Gold, R. D.**, Stephenson, W. J., Kirby, E., Woolery, E. W., Briggs, R. W., DuRoss, C. B., Delano, J., Odum, J., Leeds, A., Paris, D., Sethanant, I., von Dassow, W.	Distributed Acoustic Sensing Observations and Modeling of the DAG Series of Chemical Explosions. **Abbott, R. E.**, Mellors, R. J., Pitarka, A.	Periodic Occurrence of the Slow Slip Events Off Kyushu Island, Southwest Japan, Based on Spatial Gradients of Displacement Rate Field and Activities of Small Repeating Earthquakes. **Iinuma, T.**, Uchida, N.
11:30 AM	STUDENT: Aftershock Monitoring with a Heterogeneous Seismic Network. **Pearson, K. M.**, Lekic, V., Pratt, T. L., Roman, D. C., Wagner, L. S., Kim, W.	Paleoseismic Investigation of the Freds Mountain Fault and the Western Lemmon Valley Fault Zone, North Valleys-Reno, Nevada. **Dee, S.**, Ramelli, A. R., Koehler, R. D., Mahan, S., De Masi, C.	Surface Ground Motion Prediction for Chemical Explosions in Alluvium. **Bonner, J. L.**, Zeiler, C. P., White, R. L., McLin, K. L., Steedman, D. W., Ezzedine, S. M.	Low-Frequency Earthquake Slip Model Using the Northern Cascadia Array of Arrays. **Creager, K. C.**, Chestler, S. R.
11:45 AM	STUDENT: Calibrating the 2016 IRIS Community Wavefields Experiment Nodal Sensors for Amplitude Statics and Orientation Errors. **Bolarinwa, O. J.**, Langston, C. A.	STUDENT: Geometry and Geomorphic Expression of Strike-Slip Faulting in the Central Walker Lane. **Pierce, I. K. D.**, Wesnousky, S. G., Owen, L. A.	Beyond Perret & Bass: Data Analysis and Simulation of DAG-1 & DAG-2 Chemical Explosions. **Ezzedine, S. M.**, Vorobiev, O. Y., Steedman, D. W., Bonner, J. L., Antoun, T. H., Bradley, C. R., Walter, W. R.	STUDENT: Spectra and Mechanics of Slow to Fast Contained Laboratory Earthquakes. **Wu, B.**, McLaskey, G.
Noon–2:00 PM	SSA Annual Luncheon and Awards Ceremony, Grand Ballroom			
	Evolving Best Practices for Station Buildout in EEW and New Permanent Networks (see page 879).	**Frontiers in Earthquake Geology: Bright Futures and Brick Walls** (see page 898).	**Explosion Seismology Applications** (continued).	**The Science of Slow Earthquakes from Multi-Disciplinary Perspectives** (continued).
2:15 PM	Network Expansion Challenges in Alaska. **Dalton, S. M.**	Earthquake and Tsunami Hazards in the Inland Sea of the San Juan Archipelago, Salish Sea of Washington State. **Greene, H.**, Barrie, J., Todd, B. J., Nishenko, S.	Reconstruction of the Three-Dimensional Acoustic Wavefield Induced by SPE Explosions and Implications for Explosion Yield Estimation. **Kim, K.**, Ford, S. R., Chiang, A., Bowman, D. C.	Slow Slip and Tremor: A Review of the Role of Water Expelled From Subducting Plate. **Hyndman, R. D.**

Time	Puget Sound	Pike	Pine	Elliott Bay
	Characterizing Faults, Folds, Earthquakes...	**U.S. Geological Survey National Seismic...**	**Earthquake Ground Motions...**	**Machine Learning in Seismology...**
11:15 AM	Connectivity of Holocene Fault Network Between the Southern Olympic Mountains and the Puget Lowland. **Bennett, S. E. K.**, Scharer, K., Delano, J.	An Integrated Geodetic Tectonic Model for Alaska. **Elliott, J.**, Freymueller, J. T.	Cascadia-Specific NGA-Subduction Ground Motion Models for Interface and Intraslab Events with Regionalized Site Response. **Parker, G. A.**, Stewart, J. P., Hassani, B., Atkinson, G. M., Boore, D. M.	Seismic Signal Clustering Using Deep-Self-Supervised Networks. **Mousavi, M.**, Zhu, W., Beroza, G. C.
11:30 AM	STUDENT: Shallow Offshore Deformation in the Seattle Fault Zone: Insights From High Resolution Seismic Reflection Imagery. **Moore, G. L.**, Roland, E., Bennett, S. E. K., Watt, J., Kluesner, J., Brothers, D. S.	Updated GK17 Ground Motion Prediction Equation for Shallow Crustal Continental Earthquakes and Use of Proper Terminology. **Graizer, V.**	A Partially Non-Ergodic NGA Subduction Ground Motion Prediction Equation and Its Application to Cascadia. **Kuehn, N. M.**, Bozorgnia, Y., Campbell, K. W., Gregor, N.	STUDENT: Rapid Prediction of Earthquake Ground Shaking Intensity Using Raw Waveform Data and a Convolutional Neural Network. **Jozinovic, D.**, Lomax, A., Michelini, A.
11:45 AM	The Gales Creek Fault – Active Northward Migration of an Oregon Forearc Sliver. **Wells, R. E.**, Blakely, R. J., Redwine, J., Bemis, S.	Alaska Megathrust Source Characterization for Tsunami Hazard. **Thio, H.**	Subregional Attenuation of Ground Motion Amplitudes for Japan Megathrust Earthquakes. **Campbell, K. W.**	Sequencing Seismic Data and Models. **Lekic, V.**, Kim, D., Baron, D., Menard, B.
Noon–2:00 PM	SSA Annual Luncheon and Awards Ceremony, Grand Ballroom			
	Characterizing Faults, Folds, Earthquakes and Related Hazards in the Pacific Northwest (continued).	**Better Earthquake Forecasts** (see page 884).	**Earthquake Ground Motions and Structural Response in Subduction Zones: A Focus on Cascadia** (continued).	**Machine Learning in Seismology** (continued).
2:15 PM	INVITED: STUDENT: Crustal Deformation Near the Mendocino Triple Junction Inferred From GPS-Derived Strain Rate Maps. **Nuyen, C.**, Schmidt, D. A., Crowell, B. W.	INVITED: STUDENT: Improving Physics-Based Earthquake Forecasts for the 2016-2017 Central Italy Earthquake Sequence. **Mancini, S.**, Segou, M., Werner, M. J., Cattania, C.	Comparison of NGA-Sub Developed Ground Motion Models for Subduction Earthquakes. **Gregor, N.**, Abrahamson, N., Al Atik, L., Atkinson, G. M., Boore, D. M., Bozorgnia, Y., Campbell, K. W., Chiou, B. S. J., Gulerce, Z., Hassani, B., Kishida, T., Kuehn, N. M., Midorikawa, S., Mazzoni, S., Parker, G. A., Si, H., Stewart, J. P., Youngs, R. R.	Non-Negative Tensor Factorization for Interpretable Unsupervised Signal Discovery in Continuous Seismic Data. **Nebgen, B. T.**, MacCarthy, J. K., Alexandrov, B.

Time	*Grand Crescent*	*Vashon*	*Cascade I*	*Cascade II*
	Evolving Best Practices for Station Buildout…	**Frontiers in Earthquake Geology…**	**Explosion Seismology Applications…**	**The Science of Slow Earthquakes…**
2:30 PM	Oregon's Multi-Hazard Monitoring Network: Recent Growth and Future Directions. **Toomey, D.**, O'Driscoll, L. J., Walsh, L. K., Meyer, S.	Recurrence of Large Upper Plate Earthquakes in the Puget Lowland. **Sherrod, B. L.**, Styron, R. H., Angster, S.	Infrasound Source Modeling and Data Inversion Using Coupled Seismo-Acoustic Simulations. **Poppeliers, C.**, Preston, L.	Offshore Seismic Attenuation Heterogeneity and Implications for Pore-Fluid Pressure in Gisborne Slow-Slip Region, Northern Hikurangi Margin, North Island, New Zealand. **Nakai, J.**, Sheehan, A. F., Abercrombie, R. E., Eberhart-Phillips, D.
2:45 PM	Expanding the Berkeley Digital Seismic Network for Earthquake Early Warning (EEW): Operations, Installation and Upgrades to Seismic Monitoring. Terra, F., **Hellweg, M.**, Merritt, J. M., Allen, R. M., Ferry, D., Arba, R.	Mw 7.8 2016 Kaikoura, New Zealand Earthquake: Hundalee Fault Paleoseismology. **Stirling, M. W.**, Barrell, D. J. A., Williams, J. N., Sauer, K. M., van den Berg, E. J.	Explosion Source Models and the Scattering Origin of Regional Phases From SPE Phase 1 Coda Spectral Ratios. **Phillips, W. S.**, Patton, H. J., Cleveland, K. M., Larmat, C., Stead, R. J.	Probing Fault Frictional Properties During Afterslip Up- and Down-Dip of the 2017 Mw 7.3 Iran-Iraq Earthquake With Space Geodesy. **Wang, K.**, Bürgmann, R.
3:00 PM	Optimizing Borehole Station and Array Performance, Enabled by the Trillium Slim Borehole 120 Seismometer. **Bainbridge, G.**, Parker, T., Townsend, B.	A Multi-Fault Model Estimation From Tsunami Data: An Application to the 2018 M7.9 Kodiak Earthquake. **Hossen, M.**, Sheehan, A. F., Satake, K.	Testing Explosion Source Models From Yield and Depth Analysis of Chemical Explosions Conducted in Alluvium. **Pasyanos, M. E.**, Walter, W. R., Ford, S. R.	A Meso-Scale Take on the Modeling of Fault Zone Faulting Behaviors. **Fitzenz, D. D.**, Maury, V., Piau, J.
3:15 PM	Testing the Readiness of Strong Motion Sensors for Earthquake Early Warning. **Massin, F.**, Clinton, J., Racine, R., Rossi, Y.	INVITED: Slip Rates Are Dead. Long Live Slip Rates. **Briggs, R. W.**, Gold, R. D.	Application of Advanced Numerical Techniques to Improve the Estimation of Explosion Yield and Quantify Its Uncertainty. **Yoo, S.**	Aseismic Slip Phenomena in Southern Cascadia. **Bartlow, N. M.**, Materna, K., Bürgmann, R.
3:30–4:15 PM	Posters and Break, Fifth Avenue and Grand Ballroom			

Time	*Puget Sound*	*Pike*	*Pine*	*Elliott Bay*
	Characterizing Faults, Folds, Earthquakes…	**Better Earthquake Forecasts…**	**Earthquake Ground Motions…**	**Machine Learning in Seismology…**
2:30 PM	Geodetic and Geologic Observations Along the Southern Cascadia Subduction Zone: Implications for Strain Accumulation in the North America Plate – the Lahsāsēte Fault. **Patton, J. R.**, Leroy, T. H., Williams, T. B., Hemphill-Haley, M., McPherson, R. C.	STUDENT: Aftershock Decay in Space and Time in Regions with Induced Seismicity in Oklahoma. **Rosson, Z.**, Walter, J., Goebel, T. H. W., Chen, X.	INVITED: Development of Basin Depths and VS30-Depth Centering Models for the Pacific Northwest. **Ahdi, S. K.**, Ancheta, T. D., Stewart, J. P.	INVITED: High-Resolution Seismic Tomography of Long Beach, CA, Using Machine Learning. **Olsen, K. B.**, Bianco, M., Gerstoft, P., Lin, F.
2:45 PM	INVITED: Quaternary Faults and Folds of the Northern Sacramento Valley: Accommodating Transpressional Strain in the Northern Sierra and Southern Cascadia Transition Zone. **Angster, S.**, Wesnousky, S. G., Figueirdo, P., Owen, L. A., Sawyer, T.	A Forecast of Peak Ground Motion Due to Aftershocks Based on the Extreme-Value Analysis of Seismograms. **Sawazaki, K.**	Implementation of Basin Effects in Seismic Hazard of the Greater Seattle Region. **Walling, M.**, Puangnak, H., Abrahamson, N.	STUDENT: Convolutional Neural Networks & Deep Learning on Spectrograms for Earthquake Detection. **Audretsch, J.**, Mai, P., Parisi, L.
3:00 PM	A Kinematic Model of Offshore Strike-Slip Faults in the Cascadia Accretionary Prism. **Schmidt, D. A.**	A Stress-Similarity Aftershock Forecast Model. **Hardebeck, J.**	Earthquake Source-Dependent Amplification of Ground Motions in the Puget Lowland Sedimentary Basins. **Wirth, E.**, Vidale, J. E., Frankel, A., Pratt, T. L., Marafi, N. A., Thompson, M., Stephenson, W. J.	Event and Noise Discrimination Using Deep Learning. **Karunanidhi, V.**, Córdova Pérez, G., Rodriguez, A.
3:15 PM	STUDENT: Does Subslab Buoyancy Govern Segmentation of Cascadia's Forearc Topography? **Bodmer, M.**, Toomey, D., Roering, J. J., Karlstrom, L.	Aftershock Forecasts Following the M7.0 Anchorage, Alaska Earthquake. **McBride, S. K.**, Hardebeck, J., Michael, A. J., Page, M., van der Elst, N., Martinez, E. M.	Effects of Simulated Magnitude 9 Earthquake Motions on Reinforced Concrete Wall Structures in the Pacific Northwest. **Marafi, N. A.**, Berman, J., Eberhard, M.	STUDENT: A Convolutional-Neural-Network-Based Damage Detection Method and Its Application to a Shake Table Test of an 18-Story Steel Frame Building Structure. **Wang, L.**, Dang, J., Wang, X.
3:30–4:15 PM	Posters and Break, Fifth Avenue and Grand Ballroom			

Time	*Grand Crescent*	*Vashon*	*Cascade I*	*Cascade II*
	Advances in Ocean Floor Seismology (see page 880).	**Frontiers in Earthquake Geology: Bright Futures and Brick Walls** (continued).	**Explosion Seismology Applications** (continued).	**Science, Hazards and Planning in Subduction Zone Regions, Part I** (see page 872).
4:15 PM	Millihertz Ground Motion at the Seafloor Excited by Large Regional Earthquakes. **Ito, Y.**, Webb, S., Kaneko, Y., Wallace, L. M., Hino, R.	INVITED: Slip-Rates, Obliquity Estimates and Plate Boundary Localization Along the Queen Charlotte Fault Based on Submarine Tectonic Geomorphology. **Brothers, D. S.**, Miller, N., Barrie, J., Haeussler, P. J., Greene, H., Zielke, O., Andrews, B., Dartnell, P.	Large-N Seismic Recordings at the Source Physics Experiment (SPE) Phase II Site. **Chen, T.**, Snelson, C.	Subduction-Related Stress Field in Central America and Intraplate Stress in Costa Rica. **Levandowski, W.**, Turner, J.
4:30 PM	STUDENT: Teleseisms and Microseism Generation Observed by an Ocean-Bottom Distributed Acoustic Sensing Array Offshore Belgium. **Williams, E. F.**, Fernandez Ruiz, M. R., Fidalgo Martins, H., Zhan, Z., Gonzalez Herraez, M., Vanthillo, R., Magalhaes, R.	STUDENT: Expanding the Cascadia 1700 CE Paleogeodetic Database With Subsidence Estimates From Northern California and Washington. **Padgett, J. S.**, Engelhart, S. E., Sypus, M., Wang, K., Hawkes, A. D., Cahill, N., Witter, R. C., Nelson, A. R., Hong, I., Horton, B. P., Kelsey, H. M.	STUDENT: Azimuthally Dependent Scattering of High Frequency Vertical Component Seismic Data at the Large N Array, Source Physics Experiment. **Darrh, A.**, Poppeliers, C., Preston, L.	INVITED: Translating Megathrust Behavior Into the Nicoya Crust, Revealing a Dynamic Dance Across the Seismic Cycle. **Newman, A.**, Hobbs, T. E., Kyriakopoulos, C., Protti, M., Dixon, T. H., Schwartz, S. Y.
4:45 PM	Seismo-Tectonic Monitoring of Endeavour: Recent and Future Expansion of Ocean Networks Canada's NEPTUNE Observatory on the Juan de Fuca Ridge. **Farrugia, J. J.**, Heesemann, M., Wilcock, W. S. D., Baillard, C., Mihaly, S. F., Scherwath, M.	INVITED: Prehistoric, Headwater-Basin-Encompassing Debris-Avalanches, Northern California Coast Ranges: Temporal Association With Plate Boundary Earthquakes. **Kelsey, H. M.**, Sherrod, B. L., Padgett, J. S., Brocher, T., Angster, S.	Analysis of Local Explosion Waveforms for 1D Crustal Structure Using Interactive Non-Linear Block Thresholding and Phased Array Methods. **Langston, C. A.**, Zeiler, C. P.	The March 2012 Mw 7.4 Ometepec and February 2018 Mw 7.2 Pinotepa Earthquakes in Mexico Ruptured Small Patches of the Cocos Megathrust. **Fielding, E. J.**, Gombert, B., González Ortega, J., Duputel, Z., Liang, C., Bekaert, D. P. S., Samsonov, S. V., Jolivet, R., Ampuero, J.
5:00 PM	STUDENT: Ambient Noise Analysis Near Hikurangi Margin, New Zealand Using an Amphibious Array. Sheehan, A. F., **Wang, H.**	STUDENT: Bayesian Diatom-Based Estimates of Coastal Deformation During Megathrust Earthquakes at the Cascadia Subduction Zone. **Hong, I.**, Cahill, N., Engelhart, S. E., Hawkes, A. D., Nelson, A. R., Padgett, J. S., Horton, B. P.	STUDENT: Modeling 0-2 Hz 3D Wave Propagation of the North Korean Nuclear Tests Across the Sea of Japan. **Yeh, T.**, Olsen, K. B.	The Role of Afterslip and Slow Slip Events in Subduction-Related Earthquake Triggering: The Case Studies of the 2017 M7.1 Mexico City (Puebla) and the 2018 M7.0 Anchorage Earthquakes. **Segou, M.**, Parsons, T.

Time	Puget Sound	Pike	Pine	Elliott Bay
	Offshore Subduction Zone Structure and Seismicity Along Pacific Northwest: From the Gorda Plate to the Queen Charlotte Fault (see page 894).	**Better Earthquake Forecasts** (continued).	**Modeling and Understanding of High-Frequency Ground Motion** (see page 889).	**Science Gateways and Computational Tools for Improving Earthquake Research** (see page 876).
4:15 PM	INVITED: Constraints on Juan De Fuca Plate Hydration From Controlled-Source Wide-Angle Seismic Studies. **Canales, J.**, Boulahanis, B., Carbotte, S. M., Nedimović, M.	A Geodesy- and Seismicity-Based Local Earthquake Likelihood Model for Central Los Angeles. **Rollins, C.**, Avouac, J.	INVITED: Decomposing Source and Path Terms in High-Frequency Ground Motion Data. **Baltay, A. S.**, Hanks, T. C.	INVITED: Science Gateways for Enhancing Earthquake Science. **Pierce, M.**
4:30 PM	STUDENT: The Evolution of the Hydration State of the Juan De Fuca Plate From Ridge to Trench Offshore Washington State. **Boulahanis, B.**, Canales, J., Carbotte, S. M., Carton, H., Han, S., Nedimović, M.	San Andreas Rupture Gates? **Jackson, D. D.**	INVITED: Investigations on the Kappa Parameter Using Empirical and Numerical Approaches and Application for Site-Specific Ground Motion Assessment. **Gelis, C.**, Bonilla, L., Calvet, M., Colvez, M., Gatti, F., Laurendeau, A., Lopez-Caballero, F., Margerin, L., Mayor, J., Provost, L., Beucler, E., Bonnin, M., Courboulex, F., Froment, B., Guéguen, P., Mocquet, A., Monfret, T., Tchawe Nziaha, F.	INVITED: OpenTopography, a Science Gateway to High Resolution Topography for Earthquake Research. **Crosby, C. J.**, Arrowsmith, R., Scott, C., Nandigam, V.
4:45 PM	INVITED: Three-Dimensional Variations of the Slab Geometry Correlate With Earthquake Distributions at the Cascadia Subduction System. **Gao, H.**	STUDENT: Characterizing the Spatial Uncertainty of Coseismic Slip for Past and Future Cascadia Subduction Zone Full-Margin Events. **Paige, J. L.**, Guttorp, P., Schmidt, D. A.	Modeling Anelastic Effects Within the Near Surface. **Morozov, I.**	INVITED: Enhancing Seismology and Earthquake Engineering Research Through the DesignSafe Cyberinfrastructure. **Rathje, E.**, Arduino, P., Brandenberg, S. J., Lowes, L., Mosqueda, G., Padgett, J.
5:00 PM	Plate Deformation at Cascadia's Northern Terminus. **Bostock, M. G.**, Savard, G., Hutchinson, J., Kao, H., Christensen, N. I.	STUDENT: Implications of Temporal Clustering and Long-Term Fault Memory for Earthquake Forecasting. **Salditch, L.**, Stein, S., Spencer, B., Brooks, E. M.	Capturing Regional Variations of Hard-Rock Attenuation in Europe. **Pilz, M.**, Cotton, F., Zaccarelli, R.	Seamless Access to Data From Multiple Data Centers Through Federation. **Trabant, C.**, Van Fossen, M., Casey, R., Clark, A., Falco, N., Ahern, T., Carter, J.

Time	*Grand Crescent*	*Vashon*	*Cascade I*	*Cascade II*
	Advances in Ocean Floor Seismology…	**Frontiers in Earthquake Geology…**	**Explosion Seismology Applications…**	**Science, Hazards and Planning…**
5:15 PM	Güralp Aquarius, The Future of Ocean Seismology. **Allardice, S.**, Hill, P.	Microfossil Measures of Subsidence During Past Plate-Boundary Earthquakes: Their Accuracy Revealed by a Sudden Tidal-Flooding Experiment in Cascadia. **Dura, T.**, Horton, B. P., Milker, Y., Wang, K., Bridgeland, W. T., Brophy, L., Ewald, M., Khan, N., Engelhart, S. E., Nelson, A. R., Witter, R. C.	Local and Regional Seismic Characteristics of Chemical Explosions in Eastern Margin of the Junggar Basin, Northwest China. **Zhao, L.**, Xie, X., Ma, X., Zhang, L., Zhen-Xing, Y.	STUDENT: Double Benioff Zones Along the Hikurangi Subduction Zone, New Zealand, Based on Nested Regional-Global Seismic Tomography and Precise Earthquake Relocation. **Aziz Zanjani, F.**, Lin, G., Thurber, C. H.
5:30–6:30 PM	Posters and Break, Fifth Avenue and Grand Ballroom			
6:00–7:00 PM	Lightning Talks, Grand Ballroom			
7:00–8:00 PM	Early-Career and Student Reception, Cascade I			
7:30–9:00 PM	Special Interest Group: Offshore Facilities for Solid Earth Geoscience, Cascade II			

Time	*Puget Sound*	*Pike*	*Pine*	*Elliott Bay*
	Offshore Subduction Zone Structure…	**Better Earthquake Forecasts…**	**Modeling and Understanding…**	**Science Gateways and Computational Tools…**
5:15 PM	STUDENT: Cross-Correlation Beamforming for Simultaneous Event Detection and Location in Conjunction With Logistic Regression for Event Discrimination. **Mosher, S. G.**, Audet, P.	Can Earthquake Clustering Explain the Paleo-Event Hiatus in California? **Page, M.**, van der Elst, N., Field, E. H., Milner, K. R.	Attenuation Estimation With Uncertainty for Seismic Noise Interferometry: Application to a Dense 3C Array in Groningen, Netherlands. **Liu, X.**, Beroza, G. C., Nakata, N., Spica, Z.	Computational Tools to Support Large-Scale CyberShake PSHA Simulations. **Callaghan, S.**, Maechling, P. J., Goulet, C. A., Milner, K. R., Su, M., Vahi, K., Deelman, E., Graves, R. W., Olsen, K. B., Cui, Y., Jordan, T. H.
5:30–6:30 PM	Posters and Break, Fifth Avenue and Grand Ballroom			
6:00–7:00 PM	Lightning Talks, Grand Ballroom			
7:00–8:00 PM	Early-Career and Student Reception, Cascade I			
7:30–9:00 PM	Special Interest Group: Offshore Facilities for Solid Earth Geoscience, Cascade II			

Poster Sessions

Fifth Avenue Room

Advances in Intraplate Earthquake Geology (see page 900).

1. Strike-Slip in Transtension: Complex Crustal Architecture of the Warm Springs Fault Zone, Northern Walker Lane, Nevada. **Briggs, R. W.**, Stephenson, W. J., McBride, J., Odum, J., Reitman, N., Gold, R. D.
2. Student: Spatiotemporal Aftershock Analysis of the M5.8 Lincoln, Montana Event. **Smith, E. M.**
3. Student: Quaternary Geologic Mapping and Paleoseismic Assessment of the Warm Springs Valley Fault, Washoe County, Nevada. **Chupik, C. M.**, Koehler, R. D.
4. Student: Paleoseismic Trench Investigation of the Petersen Mountain Fault, North Valleys-Reno, Nevada. **De Masi, C.**, Koehler, R. D., Dee, S., Chupik, C. M., Castillo, C., Kleber, E., Keen-Zebert, A.
5. Evidence for Large Earthquakes About A.D. 0 and B.C. 1050 in the New Madrid Seismic Zone. Tuttle, M. P., **Wolf, L. W.**, Starr, M., Lafferty, III, R. H., Villamor, P.
6. Lidar-Based Evaluation of Faulting in the Northern Walker Lane, Upper Feather River Watershed, Plumas County, California. **Hitchcock, C.**, Hoirup, D. F., Kozaci, O.
7. Is the Antelope Flats Fault an Antithetic Rupture of the Teton Fault? **Thackray, G. D.**, DuRoss, C. B., Zellman, M., Wittke, S., Gold, R. D., Delano, J., Jobe, J. A. T., Hille, M., Grasso, K., Mahan, S.

Evolving Best Practices for Station Buildout in EEW and New Permanent Networks (see page 902).

8. Station Quality Monitoring for the Pacific Northwest Seismic Network and Shakealert. **Hutko, A.**, Reusch, M., Marczewski, K., Connolly, J., Hartog, J. R., Bodin, P.
9. Station Building Strategies Developed During Earthscope Transportable Array – A Retrospective. **Busby, R.**, Frassetto, A. M., Aderhold, K., Hafner, K., Woodward, R. L.
10. Noise Characteristics of Alaska Transportable Array Posthole Sensor Emplacements. **Frassetto, A. M.**, Aderhold, K., Busby, R.
11. From Boutique to Wholesale Seismic Monitoring: Performance Evaluation Tools to Prepare a Traditional Regional Seismic Network for Earthquake Early Warning. Bodin, P., **Connolly, J.**, Marczewski, K., Hutko, A.
12. Station Service Statistics for Alaska Transportable Array: Suspected Causes and Potential Mitigation Approaches. **Enders, M.**, Bloomquist, D., Aderhold, K.
13. Shakealert: The Journey From Research to Implementation. **Steele, W. P.**, Walsh, L. K.
14. What Would You Do if You Received a ShakeAlert Earthquake Early Warning Right Now? The Strategy for Education, Training and Outreach in the Pacific Northwest. **Terbush, B. R.**
15. Multi-Sensored Small Diameter Cased Borehole for EEW – Turn an EEW Station Into an Greater Capability Long Term Observatory and Monitoring Solution. **Parker, T.**, Bainbridge, G.
16. The State of PNSN and Growth to Meet ShakeAlert Requirements. **Meyer, S.**, UW, P., UO, P.
17. Using Shakealert to Protect Water and Sewer Systems in the Pacific Northwest. Steele, W. P., **Ervin, D.**
18. Student: Towards Understanding the Effects of Atmospheric Pressure Variations on Long-Period Horizontal Seismic Data: A Case Study. **Alejandro, A. C. B.**, Ringler, A. T., Wilson, D. C., Anthony, R. E., Moore, S. V.
19. A Fault Hazard Based Expected Value Metric for Earthquake Early Warning Seismic Network Stations. **Biasi, G.**, Stubailo, I., Alvarez, M.
20. Scsn Advanced System Monitoring and Telemetry Planning Tools. **Stubailo, I.**, Alvarez, M., Biasi, G., Bhadha, R., Watkins, M., Bruton, C., Hauksson, E., Thomas, V.

New Approaches to Geophysical Research Using Dense Mixed Sensor and Broadband Seismology Arrays (see page 904).

21. Delineating the Near-Surface West Napa Fault in St. Helena, California Using Vp/Vs and Guided Waves. **Goldman, M. R.**, Catchings, R. D., Chan, J. H., Philibosian, B., DeLong, S., Sickler, R. R., Criley, C. J.
22. Geophysical Studies of the Subsurface Structure of the Castle Mountain Fault System, Upper Cook Inlet, Alaska. Ziwu, F. D., **Doser, D. I.**, Schinagel, S. M.
23. Invited: Evolution of the IRIS Portable Facility: New Tools for Wavefield Imaging, Rapid Response and Magnetotellurics. **Sweet, J. R.**, Anderson, K., Frassetto, A. M., Beaudoin, B. C., Bilek, S., Woodward, R. L.
24. Velocities and Upper Crustal Structure of the Hayward Fault Zone: Results From the 2016 East Bay Seismic Experiment. **Strayer, L. M.**, Catchings, R. D., Chan, J. H., Richardson, I. S., McEvilly, A. T., Goldman, M. R., Criley, C. J., Sickler, R. R.
25. High Resolution Imaging of the San Andreas Fault System in Baja California Using Triple-Difference Tomography. **Share, P.**, Castro, R. R., Vidal, A., Mendoza, L., Ben-Zion, Y.
26. Student: Time-Dependent Earthquake Tomography in Southern California. **Hu, J.**, Share, P., Qiu, H., Zhang, H., Ben-Zion, Y.
27. Installation and Performance of a Small Aperture Posthole Array at Albuquerque Seismological Laboratory. **Anthony, R. E.**, Ringler, A. T., Wilson, D. C., Rodd, R. L., Maharrey, J. Z.

28. Seismic Fault Exploration in Urban Fault Zones, Los Angeles, California. **Catchings, R. D.**, Hernandez, J. L., Olson, B. P. E., Goldman, M. R., Chan, J. H., Sickler, R. R., Criley, C. J.

Photonic and Non-Inertial Seismology (see page 906).

29. Student: Towards Multi-Observational Full-Waveform Inversion. **Paitz, P.**, Sager, K., Schmelzbach, C., Doetsch, J., Chalari, A., Fichtner, A.
30. Distributed Fiber-Optic Sensing on Infrastructure Installations. **Karrenbach, M.**, Cole, S., Minto, C., Godfrey, A.
31. Quantitative Assessment of Earthquake Detection Capability of DAS, MEMS and Broadband Networks in Pasadena, CA. **Li, Z.**, Zhan, Z., Kohler, M. D., Hauksson, E.
32. Student: How Broadband is DAS? Two Empirical Evaluations of Instrument Response. **Lindsey, N. J.**, Rademacher, H., Dreger, D. S., Titov, A., Ajo-Franklin, J. B.
33. Student: High-Resolution Mapping and Monitoring of Shallow Shear-Wave Velocity in Urban Pasadena with Distributed Acoustic Sensing. **Williams, E. F.**, Zhan, Z., Karrenbach, M., Cole, S., LaFlame, L.
34. Preliminary Analysis of Distributed Acoustic Sensing at the Kafadar Commons Geophysical Laboratory. **Trainor, W. J.**, Titov, A., LaFlame, L., Sullivan, B., Hannum, C., Huxel, Z., Binder, G., Cole, S., Karrenbach, M.
35. Small Giant Gyroscope: BlueSeis_1c, Ultimate but Affordable Ground Rotation Sensor. Guattari, F., Laudat, T., **de Toldi, E.**, Jolly, O., Lefèvre, H.

Grand Ballroom

The Science of Slow Earthquakes from Multi-Disciplinary Perspectives (see page 908).

36. Student: Earthquake Swarms and Slow Slip on a Sliver Fault in the Mexican Subduction Zone. **Fasola, S.**, Brudzinski, M. R., Holtkamp, S. G., Graham, S. E., Cabral-Cano, E., Skoumal, R. J.
37. Seafloor Borehole Observation Network in the Nankai to Observe Slow Slip Events and Slow Earthquakes. **Araki, E.**, Kimura, T., Machida, Y., Yokobiki, T., Nishida, S., Kodaira, S.
38. Numerical Modeling of Long- and Shallow Slow Slip Events Including Shallow Region in Hyuganada and Western Nankai, Japan. **Matsuzawa, T.**, Shibazaki, B.
39. Quantitative Relationship Between Aseismic Slip Propagation Speed and Frictional Properties. **Ariyoshi, K.**, Ampuero, J., Bürgmann, R., Matsuzawa, T., Hasegawa, A., Hino, R., Hori, T.
40. Student: Long-Range Dependence in Low-Frequency Earthquakes Catalogs? **Ducellier, A.**, Creager, K. C.
41. Student: Variable Slow Slip Speeds at Sub-Daily Timescales: Constraints From High-Rate GPS Records. **Hall, K.**, Schmidt, D. A., Houston, H., Crowell, B. W.
42. Student: Stress Regime of the Nankai Trough Megathrust: A Stress Analysis Incorporating Geodetic and Seismic Fault Slip. **Newton, T. J.**, Lin, J., Thomas, A. M.
43. High-Resolution Imaging of Slow Earthquake Source Processes Resulting From the Cholame Dense Array Experiment. **Thomas, A. M.**, Inbal, A., Bürgmann, R.
44. Student: Uncovering the Physical Controls of Slow Slip Events Using Machine Learning. **McLellan, M.**
45. Slow Slip and Potential Earthquake Triggering Near Guerrero, Mexico From Geodetic Remote Sensing. **Maurer, J.**, Bekaert, D. P. S., González Ortega, J., Gualandi, A., Huang, M., Fattahi, H.
46. Using Earthquake Focal Mechanisms to Investigate Slow Slip Driving Forces in the Northern Hikurangi. **Warren-Smith, E.**, Fry, B., Wallace, L. M.

Frontiers in Earthquake Geology: Bright Futures and Brick Walls (see page 910).

47. Dispersion of Alluvial Fan Scarp Ages and Epistemic Uncertainty of Cumulative Vertical Separation, Cucamonga Fault, Southern California. **McPhillips, D.**, Scharer, K.
48. 10Be Exposure Age of the Third Terrace in Bingzhongluo Reach of Nujiang River. **Lv, Y.**, Ren, J.
49. Stereopaired Morphometric Protection Index Red Relief Image Maps (Stereo MPI-RRIMs): Effective Visualization of High-Resolution Digital Elevation Models for Interpreting and Mapping Small Tectonic Geomorphic Features. **Kaneda, H.**, Chiba, T.
50. Slip Rate and Paleoseismic History of the Tianjingshan Fault, Northeast Tibet, China. **Pierce, I. K. D.**
51. Core Penetrometer Tests, Continuous Cores and Paleoseismic Trenching Combined to Infer a Mid-Holocene Slip Rate for the Imperial Fault, California. **Rockwell, T. K.**, Klinger, Y., Jerrett, A., Wessel, K., Singleton, D. M., Levy, Y., Štěpančíková, P., Wechsler, N., Okumura, K., Stemberk, J.
52. Student: Refining the Spatial and Temporal Signatures of Creep and Co-Seismic Slip Along the Southern San Andres Fault, Coachella Valley, California. **Blanton, C. M.**, Rockwell, T. K., Gontz, A., Kelly, J. T.
53. Evaluating the Reliability of Reported Deep Seismicity Beneath Long Beach by Back-Projection of Randomized Traces. **Yang, L.**, Liu, X., Beroza, G. C.
54. Student: Structural Architecture of the Western Transverse Ranges and Potential for Large Earthquakes – Initial Results of 3D Trishear Forward Modeling. **Levy, Y.**, Rockwell, T. K.
55. Student: Combining Geologic and Geophysical Techniques to Study Fault Geometry Beneath a Major Coastal Metropolitan Area. **Singleton, D. M.**, Maloney,

J. M., Agnew, D. C., Rockwell, T. K., Brothers, D. S., Kluesner, J., Sliter, R.

56. A Database and Working Group for Cascadia Earthquake Research: Synthesizing Existing Knowledge to Answer Outstanding Questions. Walton, M. A. L., **Staisch, L.**, Gomberg, J., Perkins, J., Watt, J., Witter, R. C.
57. Paleoseismology of the Colton Site, Northern San Jacinto Fault, San Bernardino County, Southern California. **Kendrick, K.**, Fumal, T.

Characterizing Faults, Folds, Earthquakes and Related Hazards in the Pacific Northwest (see page 913).

58. Neotectonic Investigation of the Chehalis Basin, Southwestern Washington, USA. **Reedy, T. J.**, von Dassow, W., Anderson, M., Lau, T., Cakir, R., Steely, A.
59. Student: Finite-Difference Wave Simulation of High-Frequency Seismic Waveforms in the Cascadia Subduction Zone. **Rathnayaka, S.**, Gao, H.
60. Student: Seismic Source Characterization of Faults in the Portland and Tualatin Basins and a Paleoseismic Study of the Gales Creek Fault, OR. **Horst, A. E.**, Streig, A. R., Wells, R. E., Guilderson, T. P.
61. A Post-Glacial Record of Large, Strike-Slip Earthquakes on the Sadie Creek Fault, Northern Olympic Peninsula, WA. **Amos, C.**, Schermer, E. R., Angster, S., Delano, J., Duckworth, W. C., Nelson, A. R., Sherrod, B. L.
62. Fault Investigation in Western Washington Using 2D Ambient Noise Tomography. **Hayashi, K.**, Cakir, R.
63. Student: Wedge Plasticity and Coupled Simulations of Dynamic Rupture and Tsunami in the Cascadia Subduction Zone. **Wilson, A. L.**, Ma, S.
64. Student: Two Seattle Earthquakes: Evidence From the Duwamish Waterway. **Davis, E. J.**
65. Student: Vertical Land Motion in Western Washington: Separating Cascadia Locking From Other Sources. **Newton, T. J.**, Weldon, R. J., Schmidt, D. A., Miller, I. M.
66. Leech River Fault Array. **Mulder, T. L.**

Offshore Subduction Zone Structure and Seismicity Along Pacific Northwest: From the Gorda Plate to the Queen Charlotte Fault (see page 914).

67. Student: Seismic Imaging of the Gorda Slab Subduction Interface Near the Mendocino Triple Junction Using Converted Phases. **Gong, J.**, Guo, H., McGuire, J. J.
68. Student: Lithospheric Structure of the Juan De Fuca and Gorda Plates From Ambient Noise. **Wang, H.**, Ritzwoller, M., Zhong, S.
69. Décollement initiation at Cascadia Subduction Zone from Full-Waveform Inversion. **Han, S.**, Arnulf, A. F., Canales, J., Carbotte, S. M., Nedimović, M.
70. Student: Onshore/Offshore Shear-Wave Velocity Structure Along the West Coast of British Columbia from Surface-Wave Tomography. **Gosselin, J.**, Audet, P., Schaeffer, A.
71. Pn Tomography of the Juan De Fuca and Gorda Plates: Constraints on Mantle Deformation and Hydration in Young Oceanic Lithosphere. VanderBeek, B. P., **Toomey, D.**
72. New Constraints on Mantle Shear Velocity Structure Offshore Cascadia From the Joint Analysis of Teleseismic Body and Rayleigh Wave Data. VanderBeek, B. P., Forsyth, D. W., **Toomey, D.**
73. Northern Cascadia Subduction Zone Observatory. **Heesemann, M.**, Wang, K., Davis, E., Chadwell, D. C., Nissen, E., Jiang, Y.

Earthquake Ground Motions and Structural Response in Subduction Zones: A Focus on Cascadia (see page 916).

74. Feasibility of Uniformly Applicable Basin Amplification Models for the United States. **Skarlatoudis, A.**, Bayless, J., Somerville, P.
75. Predicting Ground Motion for Hypothetical Earthquakes in the Cascadia Region Using Virtual Earthquakes. **Ma, Z.**, Denolle, M. A.
76. Proposed Break in Magnitude Scaling of Earthquake Ground Motion and Source Dimensions for Subduction Mega-Earthquakes. **Campbell, K. W.**
77. Development of NGA-Sub Ground Motion Model of 5%-Damped Pseudo-Spectral Acceleration Based on Database for Subduction Earthquakes in Japan. **Si, H.**, Midorikawa, S., Kishida, T.
78. Generic Ground Motion Model for Subduction Earthquakes in Japan; Implication for Cascadia Subduction Zone. **Hassani, B.**, Atkinson, G. M.
79. Student: Characterizing Strong Shaking Hazard in Puget Sound Using Ambient Noise Seismology. **Toghramadjian, N.**, Denolle, M. A.
80. Student: Challenges and Consequences of Input Motion Selection for Subduction Zone Environments: Seattle, Washington. **Chowdhury, I.**, Cabas, A., Kaklamanos, J., Kottke, A. R., Gregor, N.
81. Trans-Boundary Earthquakes of the Himalayan Thrust Region and Their Bearing on Hazard Potential in Around Geographical Boundaries. **Sharma, B.**, Mishra, O. P.
82. New Earthquake Classification for the NGA-Subduction Project. **Wooddell, K. E.**, Abrahamson, N., Bozorgnia, Y., Campbell, K. W., Stewart, J. P., Chiou, B. S. J., Youngs, R. R.
83. Student: The Period-Dependent Effects on the Amplification of Observed Ground Motions Within the Seattle Basin. **Rekoske, J.**, Moschetti, M. P., Thompson, E. M.
84. Using Noise Correlation to Improve the 3D Seismic Velocity Model of the Seattle Basin. **Hutko, A.**, Reusch, M., Gibbons, D., Bodin, P.

Better Earthquake Forecasts (see page 918).

85. A New Application of Operational Aftershock Forecasting: Sequence Duration. **Michael, A. J.**, McBride, S. K.
86. Student: Towards Improved Uncertainty Quantification and Visualization for Aftershock Forecasts in the Pacific Northwest. **Schneider, M.**, Guttorp, P.
87. Student: A Comparison of Probabilistic Seismic Hazard Maps to Shakemap Footprints in Indonesia. **Pothon, A.**, Guéguen, P., Bard, P., Buisine, S.
88. Earthquake and Tsunami Nowcasting and Forecasting Using Shannon Information Theory. **Rundle, J. B.**, Nanjo, K., Turcotte, D. L., Donnellan, A., Crutchfield, J.
89. Bayesian Inference on the Magnitude of the Largest Expected Earthquake. **Shcherbakov, R.**, Zhuang, J., Zoeller, G., Ogata, Y.
90. The Collaboratory for the Study of Earthquake Predictability Version 2 (CSEP2): Testing Forecasts That Generate Synthetic Earthquake Catalogs. **Savran, W.**, Maechling, P. J., Werner, M. J., Jackson, D. D., Schorlemmer, D., Rhoades, D., Marzocchi, W., Yu, J., Jordan, T. H.
91. Numerical Simulation of Stress Evolution and Earthquake Sequence of the Sichuan-Yunnan Region, China. **Dong, P.**
92. Effects of Low-Magnitude Earthquakes' Focal Mechanisms on the Evolution of Aftershock Sequences. **Townend, J.**
93. Uncertainties on Fault Parameters and Seismotectonic Source Zones for Site-Specific PSHA in Southeastern France. **Duverger, C.**, Vallage, A., Bollinger, L.
94. Revisiting Source Modeling in Complex Tectonic Environments for PSHA: A Taiwan Case Study. **Velasquez, J.**, Fitzenz, D. D., Porto, N. M.
95. Student: Assessments of the Performance of the 2017 One-Year Seismic Hazard Forecast for the Central and Eastern United States via Simulated Earthquake Shaking Data. Brooks, E. M., **Neely, J. S.**, Stein, S., Spencer, B., Salditch, L., Petersen, M. D., McNamara, D. E.
96. Seismogenic Zones and their Influence on Seismic Hazard Assessments – Case Studies from the Caucasus. **Onur, T.**, Gok, R., Godoladze, T., Buzaladze, A., Gunia, I.
97. New Software for Computing Time Dependent Seismic Hazard During Aftershock Sequences Using the Opensha Platform. **van der Elst, N.**, Milner, K. R., Page, M., Field, E. H., McBride, S. K.
98. The Current Unlikely Earthquake Hiatus at California's Transform Boundary Paleoseismic Sites. **Scharer, K.**, Biasi, G.

U.S. Geological Survey National Seismic Hazard Model Components (see page 921).

99. Student: Coseismic Deformation of the 2018 Kaktovik Earthquakes Illuminate Active Tectonics in Alaska's Brooks Range. **Gaudreau, É.**, Nissen, E., Bergman, E.
100. Landslide and Megaturbidite Records Reveal a 2.5 Kyr History of Seismic Shaking in Skilak Lake, Alaska. Praet, N., **Van Daele, M.**, Moernaut, J., Mestdagh, T., Vandorpe, T., Haeussler, P. J., De Batist, M.
101. Regionally Optimized Background Earthquake Rates from ETAS (ROBERE) for Probabilistic Seismic Hazard Assessment. **Llenos, A.**, Michael, A.
102. Recent Trends in Seismicity Catalogs for the USGS National Seismic Hazard Model. **Mueller, C. S.**, Hoover, S. M.
103. A Comprehensive Offshore Quaternary Fault Database for California. **Papesh, A. G.**, Walton, M. A. L., Conrad, J. E., Johnson, S., Brothers, D. S., Kluesner, J.

Coseismic Ground Failure and Impacts on the Built and Natural Environment (see page 922).

104. The New USGS Near-Real-Time Ground Failure Product and Its Performance for Recent Earthquakes. **Allstadt, K. E.**, Thompson, E. M., Hearne, M., Wald, D. J., Fee, J. M., Martinez, E. M., Hunter, E., Brown, J. D.
105. Student: Past and Future Coseismic Landslides Triggered by Seattle Fault Earthquakes. **Herzig, E.**, Duvall, A.
106. The Next-Generation Liquefaction Database Project: Current Status and Future Goals. **Zimmaro, P.**, Brandenberg, S. J., Bozorgnia, Y., Stewart, J. P., Kwak, D., Cetin, K., Franke, K. W., Moss, R. E. S., Kramer, S. L., Stamatakos, J., Juckett, M.
107. West Shore Lake Oroville Lineament Geologic Investigation, Northern California, Part 1 of 2. **Hoirup, D. F.**, Kozaci, O.
108. Liquefaction Loss Estimation for the United States. **Baise, L. G.**, Rashidian, V.
109. West Shore Lake Oroville Lineament Geologic Investigation, Northern California, Part 2 of 2. **Kozaci, O.**, Hoirup, D. F., Zachariasen, J., Bloszies, C., Hitchcock, C., Koehler, R. D., Lindvall, S., McDonald, E., Feigelson, L., Abramson-Ward, H., Hartleb, R., Huebner, M.
110. Estimating the Likelihood and Impact of Seismically Induced Landslides in Near Real-Time. **Nowicki Jessee, A.**, Hamburger, M. W.
111. An Open Repository of Earthquake-Triggered Ground-Failure Inventories. Schmitt, R., **Allstadt, K. E.**, Godt, J., Jibson, R. W., Wald, D. J., Knudsen, K. L., Tanyas, H., Thompson, E. M., Van Westen, C., Gorum, T., Nowicki Jessee, A., Rathje, E., Biegel, K., Xu, C., Sato, H., Zhu, J.

Explosion Seismology Applications (see page 924).

112. Finite-Difference Algorithm for 3D Orthorhombic Elastic Wave Propagation. **Jensen, R. P.**, Preston, L.
113. Physics-Based Simulations of Aftershock Productivity From Explosion and Earthquake Sources. **Kroll, K.**, Pitarka, A., Ford, S. R., Walter, W. R., Richards-Dinger, K. B.
114. Nonlinear Effects on Linear Seismic Source Inversions From Simulations of Underground Chemical Explosions. **Preston, L.**, Eliassi, M., Gullerud, A., Poppeliers, C.
115. Microseismicity Associated With the DAG-2 Chemical Explosion. **Holland, A. A.**, Abbott, R. E., Preston, L., Larmat, C., Morton, E. A.
116. Student: Analysis of Simulated and Recorded Far-Field Ground Motions for the SPE and DAG Underground Chemical Explosions. **Dunn, M.**, Pitarka, A., Louie, J. N., Smith, K., Eckert, E.
117. Constraining Stochastic Variability of the Velocity Model Using Large-N Data. **Pitarka, A.**, Mellors, R. J., Ezzedine, S. M., Walter, W. R., Matzel, E., Wagoner, J.
118. Mechanisms of Near Field Non-Radial Motion From Underground Explosions in Various Geologies. **Vorobiev, O. Y.**
119. Comparison of Seismic Detectors Applied to an Explosion Aftershock Sequence. **Rowe, C. A.**, Carmichael, J. D., Phillips, W. S., Stead, R. J.
120. High-Frequency Rg Modeling at the SPE Site Using Accelerated Weight Drop Sources. **Rowe, C. A.**, Patton, H. J.
121. Testing the Effects of Velocity Models for Seismic Location in the DNE18 Virtual Experiment. **Begnaud, M.**, Syracuse, E. M., Gammans, C., MacCarthy, J. K.
122. Characterization of Spall in Hard-Rock From Observations and Simulations of the Source Physics Experiment Phase I. **Ford, S. R.**, Vorobiev, O. Y.
123. Simulation of Underground Explosions in Anisotropic Media Using GEODYN-SW4 Coupling Scheme. **Ezzedine, S. M.**, Hirakawa, E. T., Vorobiev, O. Y., Antoun, T. H.
124. Variations in Aftershock Behavior Following a Large Underground Chemical Explosion in Alluvium. **Syracuse, E. M.**, Phillips, W. S., Euler, G. G., Rowe, C. A.
125. Chemical Explosion/Nuclear Explosion Equivalences and Differences as Identified in the Near-Field Data From the SPE Program. Steedman, D. W., **Euler, G. G.**, Bradley, C. R., Bonner, J. L.

From Drifting to Anchored: Advances in Improving Absolute Hypocenter Location Accuracy for Natural, Induced and Explosion Seismic Events (see page 927).

126. Obtaining Accurate Earthquake Location with Cabled Seismic Networks on the Juan de Fuca Spreading Center. **Baillard, C.**, Wilcock, W. S. D., Arnulf, A. F., Tolstoy, M., Waldhauser, F., Heesemann, M., Farrugia, J. J.
127. Exploring Hypocenter Uncertainty in the Fort Worth Basin, North Texas. **DeShon, H. R.**, Quinones, L., Sufri, O., Arrowsmith, S., Savvaidis, A., Hayward, C.
128. Investigating Seismicity and Structure With a 25-Node 3-Component, 5-Hz Geophone Network in the Delaware Basin Around Pecos, TX. **Karplus, M.**, Veitch, S. A., Doser, D. I., Faith, J. L., Savvaidis, A.
129. Student: Feasibility of Detecting Shallow Events in Dense Array Data With the Source Scanning Method. **Cheng, Y.**, Li, F., Ben-Zion, Y.

Machine Learning in Seismology (see page 928).

130. Invited: Student: What Triggered the Tremors in Nigeria on Sept 5-7, 2018? **Lu, Y.**, Adepelumi, A. A., Kolawole, F., Olugboji, T. M.
131. Detecting Low Magnitude Seismic Events Using Convolutional Neural Networks. **Forrest, R.**, Young, C. J.
132. Automatic Phase Picking by Deep Learning. **Uchide, T.**
133. An Automated Station Assessment Based on Deep Learning. Seo, K., **Sheen, D.**, Kim, G., Lee, H., Kwak, D.
134. Student: Network Analysis to Characterize Seismic Ground Motion Variability. **Sheng, Y.**, Kong, Q., Beroza, G. C.
135. Operational Real-Time Automatic Seismic Catalog Generator Utilizing Machine Learning: Performance Review Over a One Year Period in Production. Reynen, A., **Karimi, S.**, Baturan, D.
136. Student: A Machine Learning Approach to Identify Landslides With Seismic Waves Using Support Vector Machine Method. **Chuang, L. Y.**, Peng, Z., Zhu, L., McClellan, J.
137. Automatic Waveform Quality Control for Surface Waves Using Machine Learning Techniques. **Chai, C.**, Kintner, J., Cleveland, K. M., Luo, J., Maceira, M., Ammon, C. J., Santos-Villalobos, H. J.
138. Invited: Convolutional Neural Network for Seismic Phase Picking, Performance Demonstration in the Absence of Extensive Training Data. **Woollam, J.**, Rietbrock, A., Bueno, A., De Angelis, S.
139. A Neural Network Based Multi-Component Earthquake Detection Method. **Lin, Y.**, Zhang, Z., Chen, T.
140. Inversionnet: A Real-Time and Accurate Full Waveform Inversion With CNNs and Continuous CRFs. **Lin, Y.**, Wu, Y.
141. Machine Learning Models for Classifying Variations in Emergent and Impulsive Seismic Noise. **Johnson, C.**, Vernon, F. L., Ben-Zion, Y.
142. Two Combinatorial Optimization Methods That Determine On-Fault Earthquake Magnitude Distributions. **Geist, E.**, Parsons, T.

Modeling and Understanding of High-Frequency Ground Motion (see page 931).

143. Nonlinear Attenuation at PS10 During the 2002 Denali Earthquake Associated With Interaction of High-Frequency S Waves With the Near-Field Velocity Pulse. **Sleep, N. H.**
144. Validation of Two Approaches for Expressing Spectral Decay Characteristics of Ground Motions in High Frequency Range - Fmax and Kappa Models -. **Tsurugi, M.**, Tanaka, R., Kagawa, T., Irikura, K.
145. Student: Comparing Eastern and Western Canada Kappa Values. **Palmer, S. M.**, Atkinson, G. M.
146. Student: A New Ground Motion Model for Iran. **Farajpour, Z.**, Pezeshk, S.
147. Student: Spatial Characteristics of High Frequency Ground Motion Along the Chilean Subduction Zone. **Aziz Zanjani, A.**, Herrmann, R. B.
148. Attenuation of Ground Motion Spectral Amplitudes in the Longmenshan Belt and Its Surrounding Regions in Southwestern China. **Wei-Min, W.**, Jian-Kun, H., Zhao, L., Xie, X., Zhen-Xing, Y.
149. Student: Numerical Investigations on the Effect of Crustal Heterogeneities on the High Frequency Attenuation. **Colvez, M.**, Gatti, F., Lopez-Caballero, F., Cottereau, R., Bonilla, L., Gelis, C.
150. Student: Within Station Variability and Uncertainty in Kappa Estimations: Insights From Various KiK-Net Downhole Arrays. **Ji, C.**, Cabas, A., Cotton, F., Pilz, M., Bindi, D.
151. Student: Inclusion of Frequency-Dependent Spatial Correlation into the SDSU Broadband Ground-Motion Generation Method. **Wang, N.**, Takedatsu, R., Olsen, K. B., Day, S. M.
152. Student: A Seismic Intensity Survey of the 16 April, 2016 Mw 7.8 Muisne, Ecuador Earthquake and a Comparison With Strong Motion Data. **Smith, E. M.**, Mooney, W. D.
153. Influence of Coupling and Installation Depth of Accelerometric Station on Signal High-Frequency Content. **Hollender, F.**, Maufroy, E., Roumelioti, Z.

Science Gateways and Computational Tools for Improving Earthquake Research (see page 933).

154. Processing and Review Interface for Strong Motion Data: Prism Software Version 2.0. **Kalkan, E.**, Jones, J., Stephens, C., Ng, P., Steidl, J. H., Brody, J., Gee, L.
155. MUSTANG: Advances in a Resource for Seismic Noise Measurements and Data Quality Metrics. **Sharer, G.**, Weertman, B. R., Keyson, L., Templeton, M. E., Casey, R., Ahern, T.
156. Developing a Web-Based Interface to the SCEC Community Fault Model (CFM). **Su, M.**, Maechling, P. J., Marshall, S. T., Hearn, E., Nicholson, C., Plesch, A., Shaw, J., Pauk, E.
157. Developing a GeoGateway User Community. **Grant Ludwig, L.**, Mirkhanian, M., Donnellan, A.

Thursday 25 April—Oral Sessions

Time	Vashon	Cascade I	Cascade II	Puget Sound
	The InSight Mission – Seismology on Mars and Beyond (see page 961).	**Earthquake Source Parameters: Theory, Observations and Interpretations** (see page 934).	**Science, Hazards and Planning in Subduction Zone Regions, Part II** (see page 938).	**Advances in Tectonic Geodesy** (see page 956).
8:30 AM	SEIS: Overview, Deployment and First Science on the Ground. **Lognonné, P.**, Banerdt, W. B., Pike, W. T., Giardini, D., Banfield, D., Christensen, U., Bierwirth, M., Calcutt, S., Clinton, J., Kedar, S., Garcia, R., de Raucourt, S., Hurst, K., Kawamura, T., Mimoun, D., Panning, M. P., Spiga, A., Zweifel, P.	Bayesian Dynamic Finite-Fault Inversion of the 2016 Mw 6.2 Amatrice, Italy, Earthquake. **Gallovic, F.**, Valentova, L., Ampuero, J., Gabriel, A.	STUDENT: Sediments From Lower Squaw Lake, OR, Contain Evidence of the 1700 AD Cascadia and 1873 AD Intraplate Earthquakes and Suggest a New Method for the Precise Dating of Earthquake Deposits. **Morey, A. E.**	Deformation Model Inversion Dependency on GNSS Series Characteristics. **Parker, J.**, Donnellan, A., Gross, R., Heflin, M., Moore, A.
8:45 AM	Initial Results From the Heat Flow and Physical Properties Package (Hp3) on InSight. **Hudson, T. L.**, Spohn, T. C., Grott, M., Smrekar, S. E., Knollenberg, J., Krause, C., Mueller, N., Plesa, A. C., Golombek, M. P., Siegler, M. A., Picqueux, S., Nagihara, S., King, S. D., Banerdt, W. B.	Uncertainty Analysis of Back-Projection Methods. **Zeng, H.**, Wei, S., Wu, W.	Calibrating Cascadia Paleoearthquake Magnitudes and Ground Motions From the Paleoseismic Record. **Goldfinger, C.**	A 3D Finite Element Model to Investigate Elastic Heterogeneity and Topography Effects on 2010 Mw 7.2 El-Mayor Cucapah Earthquake Coseismic Deformation Using Space Geodetic Data. **Pulvirenti, F.**, Liu, Z., Aloisi, M.
9:00 AM	Detecting and Locating Quakes on Mars. **Giardini, D.**, Lognonne, P., Banerdt, W. B., Böse, M., Ceylan, S., Clinton, J., van Driel, M., Garcia, R., Khan, A., Stähler, S., Kawamura, T., Panning, M. P., Pike, T.	An Objective Method for Estimating Earthquake Rupture Dimensions From Early Aftershock Distributions Across a Wide Magnitude Range. **Meier, M.**, Ampuero, J., Ross, Z. E., Hauksson, E.	Complicated Kinematics in the Southern Cascadia Subduction Zone. **McPherson, R. C.**, Smith, S. W., Williams, T. B., Patton, J., Hemphill-Haley, M.	Fusing GNSS, InSAR and Imagery to Improve Spatio-Temporal Measurement of Crustal Deformation in the Salton Trough. **Donnellan, A.**, Parker, J., Heflin, M., Granat, R., Lyzenga, G., Glasscoe, M., Grant Ludwig, L., Rundle, J. B., Wang, J., Pierce, M.
9:15 AM	Mars Structure Service: Single-Station and Single-Event Marsquake Inversion for Structure Using Synthetic Martian Waveforms. **Panning, M. P.**, Beucler, E., Drilleau, M., Khan, A., Lognonné, P., Beghein, C., Xu, H., Menina, S., Barkaoui, S., Lekic, V., Stähler, S., van Driel, M., Kenda, B., Murdoch, N., Clinton, J., Giardini, D., Smrekar, S. E., Stutzmann, E., Schimmel, M.	STUDENT: Seismic Source Inversion Using Hamiltonian Monte Carlo and a 3D Earth Model for the Japanese Islands. **Simute, S.**, Fichtner, A.	STUDENT: Repeating Earthquakes in the Cascadia Subduction Zone and Their Ties to Seismogenic Zone Heterogeneities. **Morton, E. A.**, Bilek, S., Rowe, C. A.	STUDENT: Differential Lidar Derived Geometry and Kinematics of the Papatea Fault (Kaikoura, New Zealand). **Diederichs, A.**, Nissen, E., Lajoie, L.

Time	*Pike*	*Pine*	*Elliott Bay*
	Explore the Fault2SHA Paradigms Across the Ponds (see page 947). Jointly organized by the European Seismological Commission and SSA	**Current and Future Challenges in Engineering Seismology** (see page 952).	**Numerical Modeling of Earthquake Ground Motion, Seismic Noise, Rupture Dynamics and Seismic Wave Propagation** (see page 943).
8:30 AM	Developing Next Generation PFDHA and Confidence Limits on Geologic Slip Rates Using High-Resolution Geodetic Imaging Data. **Milliner, C. W. D.**, Chen, R., Dawson, T. E., Madugo, C., Dolan, J.	Physics of Near-Source Strong Ground Motions. **Koketsu, K.**	The Internal Structure of the Dead Sea Transform and Ground Motions in Northern Israel. **Tsesarsky, M.**, Shimony, R., Gvirtzman, Z.
8:45 AM	Fault2SHA Working Group: Linking Faults to Seismic Hazard Assessment. **Peruzza, L.**, Scotti, O.	What Is Fling Step?—Its Physics, Theoretical Simulation Method and Applications to Strong Ground Motion Near Surface Fault. **Hisada, Y.**, Tanaka, S.	3D Simulation of Large San Andreas Scenario Earthquakes Using a Multi-Surface Plasticity Model. **Roten, D.**, Olsen, K. B., Day, S. M.
9:00 AM	Presenting the 2018 Gem Global Seismic Hazard Map and Global Active Faults Database. **Styron, R. H.**, Pagani, M., García-Pelaez, J., Poggi, V., Gee, R., Johnson, K.	Double-Corner Source Spectrum Explains Earthquake Duration, Energy and High-Frequency Ground Motion. **Archuleta, R. J.**, Ji, C., Crempien, J. G. F.	Effects of Structural Parameters on Characteristics of Earthquake Ground Motion in Water-Saturated Sedimentary Basins. **Moczo, P.**, Kristek, J., Stripajova, S., Gregor, D., Bard, P., Kristekova, M.
9:15 AM	Simple Faults With Complex Slip Patterns: Theoretical Arguments for Non-Characteristic Ruptures on Homogeneous Planar Faults. **Cattania, C.**, Segall, P., Hainzl, S.	Looking at the Between-Event Variability From the Source Parameters Point of View: A Test Case in Central Italy. **Bindi, D.**, Picozzi, M., Spallarossa, D., Cotton, F., Kotha, S.	STUDENT: Validation of Ground Motions From a Deterministic Earthquake Sequence Simulator. **Milner, K. R.**, Shaw, B. E., Richards-Dinger, K. B., Goulet, C. A., Callaghan, S., Meng, X., Gilchrist, J. A., Dieterich, J. H., Maechling, P. J., Jordan, T. H.

Time	*Vashon*	*Cascade I*	*Cascade II*	*Puget Sound*
	The InSight Mission…	**Earthquake Source Parameters…**	**Science, Hazards and Planning…**	**Advances in Tectonic Geodesy…**
9:30 AM	Constraining Mars Crust and Mantle Structure From Waveform Inversion of Fundamental and Higher Mode Surface Waves. Xu, H., **Beghein, C.**, Irving, J. C. E., Drilleau, M., Kenda, B., Lognonné, P., Murdoch, N., Panning, M. P., Böse, M., Brinkman, N., Ceylan, S., Clinton, J., Euchner, F., Giardini, D., Horleston, A. C., Kawamura, T., Khan, A., van Driel, M., Stähler, S.	Comprehensive Analysis of the 2010 Mw 7.2 El Mayor-Cucapah Foreshock Sequence. **Yao, D.**, Huang, Y., Peng, Z., Castro, R. R.	INVITED: Repeating Earthquakes Record Fault Weakening and Healing Following a Megathrust Earthquake. **Chaves, E. J.**, Schwartz, S. Y., Abercrombie, R. E.	In Situ Calibration for Geodetic Measurements on the Seafloor and in Oceanic Drill Holes. **Wilcock, W. S. D.**, Manalang, D. A., Harrington, M. J., Fredrickson, E. K., Cram, G., Tilley, J., Burnett, J., Martin, D., Kobayashi, T., Paros, J. M.
9:45–10:45 AM	Posters and Break, Fifth Avenue and Grand Ballroom			
	Facebook and Twitter and Snapchat, Oh My! The Challenges and Successes of Using Social Media to Communicate Science to the Public (see page 962).	**Earthquake Source Parameters: Theory, Observations and Interpretations** (continued).	**Science, Hazards and Planning in Subduction Zone Regions, Part II** (continued).	**Advances in Tectonic Geodesy** (continued).
10:45 AM	Hazards Communication in the Age of Social Media: Now, Now, Now! **Bohon, W.**, Bartel, B.	INVITED: Representation of Complex Seismic Sources by Orthogonal Moment Tensor Fields. **Jordan, T. H.**, Juarez, A.	Probabilistic Tsunami Hazard Maps for Application Through the California Seismic Hazard Mapping Act. **Wilson, R.**, Thio, H., McCrink, T.	Total Variation Regularization of Geodetically Constrained Block Models in Southwestern Taiwan. **Huang, M.**, Evans, E. L.
11:00 AM	The "Seismo Blog" at the UC Berkeley Seismological Laboratory. **Rademacher, H.**, Hellweg, M.	STUDENT: Representation of the 2016 Mw 7.8 Kaikoura Earthquake by Orthogonal Moment Tensor Fields. **Juarez, A.**, Jordan, T. H.	Efficient Methods for Site-Specific Probabilistic Tsunami Hazard Analysis. **Thio, H.**, Polet, J.	A Logarithmic Model Based Simultaneous Co and Postseismic Slip Inversion Method with an Application to the 2017 Mw 7.3 Sarpol Zahāb Earthquake, Iran. **Xu, W.**, Liu, X.
11:15 AM	Exercises vs Real Events: Caribe Wave, ShakeOut and Real Earthquakes in Social Media. **Báez-Sánchez, G.**, Feliciano-Ortega, A. J., Cordero-Nieves, H., Ventura-Valentín, W. A., Cáliz-Padilla, R. M.	STUDENT: Quasi-Automated Estimates of Directivity and Related Source Properties of Small to Moderate Southern California Earthquakes With Second Seismic Moments. **Meng, H.**, McGuire, J. J., Ben-Zion, Y.	The Effect of Kinematic Earthquake Rupture on Tsunami Hazards Along Subduction Zones. **Williamson, A. L.**, Melgar, D., Rim, D., LeVeque, R.	STUDENT: Recent Slow Slip Events in Costa Rica Detected by GPS. **Afra, M.**, Muller, C., Voss, N., Protti, M., Malservisi, R., Dixon, T. H., Hastings, M.

Time	*Pike*	*Pine*	*Elliott Bay*
	Explore the Fault2SHA Paradigms Across the Ponds	**Current and Future Challenges in Engineering Seismology**	**Numerical Modeling of Earthquake Ground Motion…**
9:30 AM	How Physics-Based Earthquake Simulators Might Help Improve Earthquake Forecasts. **Field, E. H.**	INVITED: Insights From Residual Analyses for an Improved Parametrization of Ground Motion Models. **Kotha, S.**, Cotton, F., Bindi, D., Weatherill, G.	Homogenization and Very High Degree Spectral Elements for Elastic and Acoustic Waves Propagation in Multi-Scale Geological Media. **Capdeville, Y.**, Chao, L.
9:45–10:45 AM	Posters and Break, Fifth Avenue and Grand Ballroom		
	Central and Eastern North America and Intraplate Regions Worldwide (see page 948).	**Current and Future Challenges in Engineering Seismology** (continued).	**Numerical Modeling of Earthquake Ground Motion, Seismic Noise, Rupture Dynamics and Seismic Wave Propagation** (continued).
10:45 AM	A Comprehensive Seismological Investigation of the Anninghe-Zemuhe Fault Zone With a Dense Array. **Fang, L.**, Wu, J., Wang, W., Wang, C.	Investigation of Ground Motion Variability Due to Source Complexities. **Sivasubramonian, J.**, Mai, P.	STUDENT: Dynamic Rupture and Strong Ground Motion Simulations Performed on the Northern and Eastern Boundaries of the Sichuan-Yunnan Block, China. **Yu, H.**, Zhang, Z., Chen, X.
11:00 AM	STUDENT: Seismic Evidence of Thickened Crust Beneath Eastern Part of Chhotanagpur Plateau, India. **Das, M. K.**, Agrawal, M., Patel, A.	Application of Directivity in PSHA and the Effect of Centering. **Watson-Lamprey, J.**, Murphy, D.	Pushing the Limits of Regional-Scale Fully Deterministic Large Earthquake Ground Motion Simulations on High-Performance Computers with Three-Dimensional Earth Structure and Topography: Hayward Fault Scenarios and Generic Ruptures in Simple Models. **Rodgers, A. J.**, Pitarka, A., Petersson, A., McCallen, D. B.
11:15 AM	Crustal Underplating Beneath the Mid-Continental Rift System Imaged by USArray and SPREE. **Shen, W.**, Wiens, D. A., van der Lee, S., Darbyshire, F., Frederiksen, A., Revenaugh, J., Wysession, M., Aleqabi, G., Stein, S., Jurdy, D., Wolin, E., Bollmann, T.	INVITED: Overcoming Limitations of Ergodic GMPEs: Properly Separating Earthquake Source and Path Terms. **Wooddell, K. E.**, Abrahamson, N.	The Existence and Cessation of the Free-Surface-Induced Supershear Rupture: Depth-Dependent Stress Effects. **Hu, F.**, Wu, B., Chen, X., Oglesby, D.

Time	*Vashon*	*Cascade I*	*Cascade II*	*Puget Sound*
	Facebook and Twitter and Snapchat, Oh My!...	**Earthquake Source Parameters≥**	**Science, Hazards and Planning...**	**Advances in Tectonic Geodesy**
11:30 AM	Rapid Earthquake Information Dissemination on Social Media: Lessons Learnt From Lastquake. **Bossu, R.**, Fallou, L., Steed, R., Roussel, F., Roch, J., Landes, M.	STUDENT: Relative Moment Tensors Revisited. **Plourde, A. P.**, Bostock, M. G.	Building a Geologic Record of Earthquakes and Tsunamis of the Guerrero Seismic Gap, Mexican Subduction. **Ramírez-Herrera, M.**, Cerny, J., Sugawara, D., Corona, N., Caballero, M., Dura, T., Machain, M., Gogichaishvili, A., Ruiz-Fernández,, A.	Sentinel-1 Time Series of Transient Creep on the Concord Fault, Eastern Bay Area. **Tymofyeyeva, E.**, Fattahi, H., Bekaert, D. P. S., Agram, P.
11:45 AM	Social Media and the Alaska Earthquake Center's Response to the November 30, 2018 7.0 Mw Anchorage Earthquake. **Dickson, I. J.**, Gardine, L., Gardine, M., Merz, D. K., Ruppert, N., West, M. E.	Green's Functions Determined From Moment Tensors. **Vavrycuk, V.**, Adamova, P., Doubravova, J.	Ground Motions From Tsunami Earthquakes: An Example From Indonesia and Implications for Hazard and Warning. **Sahakian, V. J.**, Melgar, D., Muzli, M.	Chaos and Slow Earthquakes Predictability. **Gualandi, A.**, Michel, S., Avouac, J., Faranda, D.
Noon–1:30 PM	Public Policy Luncheon, Grand Ballroom			
		Earthquake Source Parameters: Theory, Observations and Interpretations (continued).	**Imaging Subduction Zones** (see page 941).	**Recent Developments in High-Rate Geodetic Techniques and Network Operations for Earthquake and Tsunami Early Warning and Rapid Post-Earthquake Response** (see page 959).
1:45 PM		INVITED: Near-Field Observations of the Rupture for the M5.5 Orkney, South Africa Earthquake. **Mori, J.**, Yasutomi, T., Ogasawara, H., Somala, S. N., Sangaraju, S.	Significant Bulk Attenuation in the Tonga-Lau Mantle Wedge. **Wei, S.**, Wiens, D. A.	INVITED: Ocean Networks Canada's EEW System: An Efficient System Architecture to Make Use of Both GNSS and Accelerometer Data. **Pirenne, B.**
2:00 PM		STUDENT: Observational Evidence of the Early and Persistent Supershear Rupture of the 2018 Mw 7.5 Palu Earthquake. **Bao, H.**, Ampuero, J., Meng, L., Fielding, E. J., Liang, C., Milliner, C. W. D., Feng, T., Huang, H.	INVITED: Autocorrelation Reflectivity Imaging of the Magmatic Plumbing System Under Mount St. Helens. **Levander, A.**, Kiser, E., Ulberg, C. W., Creager, K. C., Schmandt, B., Hansen, S., Delph, J. R., Abers, G. A.	Modernization of the Network of the Americas to Support Earthquake and Tsunami Early Warning. **Feaux, K.**, Hodgkinson, K., Mattioli, G., Mencin, D.

Time	*Pike*	*Pine*	*Elliott Bay*
	Central and Eastern North America and Intraplate Regions…	**Current and Future Challenges in Engineering Seismology**	**Numerical Modeling of Earthquake Ground Motion…**
11:30 AM	STUDENT: Seismic Characteristics of the Eastern North American Crust With Ps Converted Waves: Terrane Accretion and Modification of Continental Crust. **Li, C.**, Gao, H., Williams, M. L., Yang, X.	A Non-Ergodic GMPE for Europe and the Middle East With Spatially Varying Coefficients. **Kuehn, N. M.**, Landwehr, N., Kotha, S.	Stick-Slip Induced Source Ground Vibration in Sheared Granular Fault. **Gao, K.**, Rougier, E., Guyer, R., Johnson, P.
11:45 AM	INVITED: Imaging the Cratonic Lithosphere Beneath the Illinois Basin and the Adirondack Mountains. **Yang, X.**, Gao, H., Pavlis, G. L.	Hybrid Ground Motion Prediction Equations for Southern Italy. **Lanzano, G.**, D'Amico, M., Santulin, M.	Numerical Modeling of Experimental Rock Friction Data for Rough Surfaces. **Tal, Y.**, Avouac, J., Goebel, T. H. W.
Noon–2:00 PM	Public Policy Luncheon, Grand Ballroom		
	Central and Eastern North America and Intraplate Regions Worldwide (continued).	**Current and Future Challenges in Engineering Seismology** (continued).	**Numerical Modeling of Earthquake Ground Motion, Seismic Noise, Rupture Dynamics and Seismic Wave Propagation** (continued).
1:45 PM	STUDENT: Wave Propagation Analysis of the SP Headwave Observed in the Charlevoix Seismic Zone and Its Application for Constraining Source Depth. **Fadugba, O. I.**, Langston, C. A., Powell, C. A.	Which Is a Better Proxy, Site Period or Depth, in Modelling Linear Site Response in Addition to the Average Shear-Wave Velocity? **Zhu, C.**, Cotton, F., Pilz, M.	Mechanical Weakening of Near-Surface Rock Layers Due to the Scattering of Seismic Waves. **Mohammadi, K.**, Asimaki, D.
2:00 PM	Earthquakes and Faults of the Western Quebec Seismic Zone and Their Relationship With the Great Meteor Hot Spot Track. **Lamontagne, M.**, Brouillette, P., Kjarsgaard, B., Ashoori Pareshkoohi, A.	Evidence on the Effect of Weather Seasons on Soil Response. Roumelioti, Z., **Hollender, F.**, Guéguen, P.	A CyberShake PSHA Model for Northern California. **Callaghan, S.**, Maechling, P. J., Goulet, C. A., Milner, K. R., Su, M., Graves, R. W., Olsen, K. B., Cui, Y., Aagaard, B., Wooddell, K. E., Kottke, A. R., Jordan, T. H.

Time	Vashon	Cascade I	Cascade II	Puget Sound
		Earthquake Source Parameters…	**Imaging Subduction Zones**	**Recent Developments in High-Rate Geodetic…**
2:15 PM		Regional Estimates of Radiated Energy for Crustal Japanese Earthquakes. **Ross, Z. E.**, Kanamori, H., Rivera, L.	Insights Into the Transitions in the Banda Arc-Australian Continental Collision From Seismic Imaging of Deep Slab Structures. **Miller, M. S.**, Harris, C. W., Porritt, R. W., Sun, D., Zhang, P., Supendi, P., Widiyantoro, S., Becker, T. W.	INVITED: Merged Real Time GNSS Positioning and Seismic Moment Estimation in Support of NOAA Operational Tsunami Warning. **Melbourne, T. I.**
2:30 PM		STUDENT: New IRIS Data Product: Dynamic Surface Wave Radiation Patterns. **Roesler, B.**, van der Lee, S., Elavsky, F., Bahavar, M.	INVITED: Seismic Evidence of Mantle Wedge Controls on Volcano Distribution Along Aleutian-Alaska. **Yang, X.**, Gao, H.	Scaling of Peak Ground Displacement With Seismic Moment Above the Mexican Subduction Thrust. Singh, S. K., **Perez-Campos, X.**, Ordaz, M., Iglesias, A., Kostoglodov, V.
2:45 PM		High Resolution Imagery at the Source Physics Experiment Using Large Seismic Arrays. **Matzel, E.**, Mellors, R. J., Magaña-Zook, S. A.	Lithospheric Structure of the Pampean Flat Slab Region From Double-Difference Tomography. **Linkimer, L.**, Beck, S., Zandt, G., Alvarado, P., Anderson, M., Gilbert, H., Zhang, H.	Intercomparisons Between Geodetic and Seismic Algorithms for ShakeAlert. **Crowell, B. W.**
3:00–4:00 PM	Posters and Break, Fifth Avenue and Grand Ballroom			
		Earthquake Source Parameters: Theory, Observations and Interpretations (continued).	**Imaging Subduction Zones** (continued).	**Next Generation Earthquake Early Warning Systems: Advances, Innovations and Applications** (see page 960). Jointly organized by the Seismological Society of Japan and SSA
4:00 PM		STUDENT: Resolving Stress Drop Variation Along San Andreas Fault at Parkfield and Its Implication. **Zhang, J.**, Chen, X., Abercrombie, R. E.	Three Dimensional Seismic Velocity Structure Beneath Japanese Islands From Sea of Japan to Pacific Ocean Including NIED S-Net Data. **Matsubara, M.**, Sato, H., Uehira, K., Mochizuki, M., Takahashi, N., Suzuki, K., Kamiya, S., Kanazawa, T.	The First-Year Operation of the Plum Algorithm in the Earthquake Early Warning System of the Japan Meteorological Agency. **Kodera, Y.**, Hayashimoto, N., Moriwaki, K.

Time	Pike	Pine	Elliott Bay
	Central and Eastern North America and Intraplate Regions…	**Current and Future Challenges in Engineering Seismology**	**Numerical Modeling of Earthquake Ground Motion…**
2:15 PM	Structure and Anisotropy of the Crust and Upper Mantle Along the St. Lawrence Corridor, Eastern Canada, From the Charlevoix Seismic Zone to the Gulf of St. Lawrence. **Bent, A. L.**, Kao, H., Darbyshire, F.	Application of Mean Spectral Matching of Time Histories. **Hudson, K. S.**, Hudson, M. B., Mazzoni, S., Lew, M.	Dynamic Rupture Modeling on the Hayward Fault, Northern California – Estimating Coseismic and Postseismic Hazards of Partially Creeping Faults. **Lozos, J.**, Funning, G.
2:30 PM	Improving Magnitude Consistency in Eastern Canada Through Regionally Appropriate Attenuation Relations. **Perry, C.**, Bent, A. L.	Extension of the Adaptable Seismic Data Format (ASDF) for Applications in Engineering Seismology. **Kottke, A. R.**, Thompson, E. M., Steidl, J. H., Aagaard, B.	Finite Frequency Sensitivity Kernel for the Differential Measurements of Ambient Noise Correlations: Theory and Numerical Tests. **Liu, X.**, Beroza, G. C.
2:45 PM	NGA-East: A Ground Motion Characterization Model for Central and Eastern North America. **Goulet, C. A.**, Bozorgnia, Y., Abrahamson, N., Kuehn, N. M., Al Atik, L., Youngs, R. R., Graves, R. W., Atkinson, G. M.	The New Shakemap in Italy: Progress and Advances in the Last 10 Years. **Michelini, A.**, Faenza, L., Lanzano, G., Puglia, R., Lauciani, V., Russo, E., Luzi, L.	Broad Band Trajectory Mechanics. **Vasco, D. W.**, Nihei, K. T.
3:00–4:00 PM	Posters and Break, Fifth Avenue and Grand Ballroom		
	Central and Eastern North America and Intraplate Regions Worldwide (continued).	**Problem Unsolved: Knowledge Gaps at the Intersection of Earthquake Engineering Practice and Research** (see page 955).	**Large Data Set Seismology: Strategies in Managing, Processing and Sharing Large Geophysical Data Sets** (see page 946).
4:00 PM	The 2018 Lake Muir Earthquakes: Australia's Ninth Surface Rupturing Earthquake Sequence in 50 Years. **Allen, T.**, Clark, D., Lawrie, S., Brenn, G., Dimech, J., Garthwaite, M., Glanville, H., Kemp, T., Lintvelt, C., Lumley, D., Pejic, T., Saygin, E., Standen, S.	Bridging the Gap Between Input Motion Selection Protocols and Geotechnical Engineering Analyses. **Cabas, A.**, Chowdhury, I., Kaklamanos, J., Kottke, A. R., Gregor, N.	INVITED: Efficient Storage and Processing of Segmented Waveform Data for the Generation of a Signal Quality Machine Learning Classifier. **Magaña-Zook, S. A.**

Time	Vashon	Cascade I	Cascade II	Puget Sound
		Earthquake Source Parameters...	**Imaging Subduction Zones**	**Next Generation Earthquake Early...**
4:15 PM		STUDENT: Uncertainties in Stress Drop Estimates and Their Tectonic Consequences. **Neely, J. S.**, Stein, S.	INVITED: Searching for the Deep Roots of Arc Volcanoes: Results From IMUSH Seismic Imaging in the Washington Cascades. **Abers, G. A.**, Mann, M., Crosbie, K. J., Soto Castaneda, R., Ulberg, C. W., Creager, K. C.	Finder Templates for the Pacific Northwest. **Hartog, R.**, Andrews, J. R., Böse, M.
4:30 PM		STUDENT: Determination of Focal Depths, Moment Magnitudes and Focal Mechanisms of Small Magnitude Local and Regional Earthquakes Recorded by a Sparse Seismic Network. **Dahal, N.**, Ebel, J. E.	STUDENT: Investigating Anomalous Crustal Thickness of the Subducting Iquique Ridge. **Myers, E. K.**, Tréhu, A., Davenport, K., Roland, E.	Earthquake Early Warning Using MyShake Global Smartphone Seismic Network. **Kong, Q.**, Short, R. M., Allen, R. M.
4:45 PM		Empirical Green's Functions Analysis of Induced Earthquakes in the Duvernay Play Near Fox Creek, Alberta. **Zecevic, M.**, Eyre, T. S., Eaton, D. W.	INVITED: Synthesis of Results From a Dense Nodal Geophone Array Deployed Along the Cascadia Subduction Zone. **Ward, K. M.**, Wang, Y., Dunham, A. M., Lin, F., Kiser, E., Schmandt, B.	Quantifying the Value of Real-Time Geodetic Constraints for Earthquake Early Warning Using a Global Seismic and Geodetic Dataset. **Ruhl, C. J.**, Melgar, D., Chung, A., Grapenthin, R., Allen, R. M.
5:00 PM		Working Towards Including Rotational Ground Motions for Regional Long Period Full-Moment Tensor Inversion. **Ichinose, G. A.**, Ford, S. R., Mellors, R. J.	STUDENT: Seismic Attenuation Structure of Nazca Plate Subduction Zone in Southern Peru. **Jang, H.**, Kim, Y., Clayton, R. W.	The Potential of Using Strain Data in Earthquake Early Warning: Near-Source Characteristics. **Farghal, N. S.**, Barbour, A. J.
5:30 PM	Joyner Lecture, Grand Ballroom			
6:30 PM	Joyner Reception, Grand Foyer and Grand Crescent			
7:30–9:00	Women in Seismology Reception, Cascade I			
8:00–9:30	Special Interest Group: Canadian Cordillera Array (CCArray), Cascade II			

Time	*Pike*	*Pine*	*Elliott Bay*
	Central and Eastern North America and Intraplate Regions…	**Problem Unsolved: Knowledge Gaps…**	**Large Data Set Seismology: Strategies…**
4:15 PM	High-Resolution Topographic Analysis of the Late Quaternary Deformation of Crowley's Ridge, New Madrid Seismic Zone. **Jobe, J. A. T.**, Gold, R. D., Briggs, R. W., Delano, J., Stephenson, W. J., Williams, R.	Comparison of the Seismic Design Procedures of ASCE 7-16 With Non-Ergodic Site Response Analyses. **Heidarzadeh, B.**, Teague, D. P.	STUDENT: Ambient Noise Processing With Julia. **Clements, T.**, Denolle, M. A., Yu, E., Ross, Z. E., Hauksson, E.
4:30 PM	New Constraints on Reelfoot Fault Rupture, New Madrid Seismic Zone. **Delano, J.**, Briggs, R. W., Jobe, J. A. T., Gold, R. D., Engelhart, S. E.	Washington State School Seismic Safety Project: Soil Seismic and Structural Assessments at 220 K–12 School Buildings. **West, L. T.**, Nielson, T., Cakir, R., Forson, C.	Managing Large Data Sets for British Columbia Earthquake Early Warning. **Kreimer, N.**, Jenkyns, R., Parker, G., Timmerman, R., Schlesinger, A., Rosenberger, A., Ferguson, E., Wagner, S., Dorocicz, J., Hembroff, D., Key, R., Gunderson, C., Robinson, J., Pirenne, B., Morley, M., Heesemann, M., Li, M., Nykolaishen, L., Lu, Y., Brillon, C., Collins, P., Caissy, M.
4:45 PM	Progress in Understanding the Geodynamics of the Eastern Tennessee Seismic Zone. **Levandowski, W.**, Powell, C. A.	Importance of Rotational Ground Motions on Seismic Response of Tall Buildings. **Safak, E.**, Çaktı, E.	Putting the Commercial Cloud to Work for Seismology. **MacCarthy, J. K.**, Marcillo, O.
5:00 PM	Discussion	Rotational Motions Extracted From Delaney Park Downhole Array in Anchorage, Alaska. **Graizer, V.**, Kalkan, E.	INVITED: The Promise of the Cloud and the IRIS DMC. Trabant, C., **Ahern, T.**, Watson, I., Weekly, R., Carter, J.
5:30 PM	Joyner Lecture, Grand Ballroom		
6:30 PM	Joyner Reception, Grand Foyer and Grand Crescent		
7:30–9:00	Women in Seismology Reception, Cascade I		
8:00–9:30	Special Interest Group: Canadian Cordillera Array (CCArray), Cascade II		

Poster Sessions

Fifth Avenue Room

Earthquake Source Parameters: Theory, Observations and Interpretations (see page 963).

1. Student: Data-Driven Earthquake Detection, Localization and Source Mechanism Estimation Based on Wavefield Extrapolation and 2D Deconvolution in High-Noise Environments. **Vinard, N. A.**, Drijkoningen, G. G., Verschuur, D. J.
2. Student: Source Properties of Repeating Earthquakes in Aftershocks of the 2016 ML 5.8 Gyeongju Earthquake Sequences. **Woo, J.**, Rhie, J., Kim, S.
3. Earthquake Source Mechanisms and Relationship to an Updated Fault Framework of the Greater Permian Basin in West Texas. **Huang, D.**, Horne, E., Savvaidis, A., Hennings, P., Young, B., Whittaker, S., Martone, P.
4. Student: Stress Drops and Directivity of Induced Earthquakes in Western Canada Sedimentary Basin. **Holmgren, J. M.**, Atkinson, G. M., Ghofrani, H.
5. Student: Relocations and Tectonic Implications of the Nine Mile Ranch Sequence From 2016-2018: 3 Mw 5.4-5.6 Near Hawthorne, Nevada. **Hatch, R.**, Smith, K., Abercrombie, R. E., Ruhl, C. J., Hammond, W., Pierce, I. K. D.
6. Self-Adapting Bayesian Fault Slip Inversion With Green Functions Uncertainty: Demonstration on the 2016 M7 Kumamoto, Japan, Earthquake. **Hallo, M.**, Gallovic, F.
7. Rupture Behavior and Interaction of the 2018 Hualien Earthquake Sequence and Its Tectonic Implication. **Jian, P.**, Hung, S., Meng, L.
8. Characterizing Moderate-Magnitude Earthquakes and Their Aftershocks Using Montana Regional Seismic Network Data. **Stickney, M. C.**
9. Stress Drops for Microseismicity in Asperity-Like Dynamic Fault Models: Actual Values vs. Estimates From Spectral Fitting and Second-Moment Approaches. **Lin, Y.**, Lapusta, N.
10. The 2007 Ning'er Mw 6.1 Earthquake: A Shallow Rupture in Southwest China Revealed by Insar Measurements. **Chen, W.**, Qiao, X.
11. Student: Long-Period Velocity Pulses at Near-Fault Region During the 2016 Kumamoto Earthquake, Japan. **Kido, T.**, Nagano, M.
12. Student: Differences Between Main-Shock and Aftershock Ground Motions Using the Japan's Kik-Net Database. **Lee, H.**, Park, H., Kim, B.
13. Rupture Initiation of Small Earthquakes in the Corinth Rift, Greece. **Duverger, C.**, Collombelli, S., Bernard, P., Zollo, A.
14. Frequency-Dependent Moment Tensors of Induced Microearthquakes. Yu, C., **Vavrycuk, V.**, Adamova, P., Bohnhoff, M.
15. Student: Fault Failure in Oklahoma Is Anything but Simple. **Pennington, C. N.**, Uchide, T., Chen, X.
16. Student: Multiple Point Source Inversions on Teleseismic Waveform Data Reveal the Complex Super-Shear Rupture Process of the 2018 Mw 7.5 Palu Earthquake. **Shi, Q.**, Wei, S., Zeng, H.
17. Finite-Source Inversion of the 14 December 2016 M5 Geysers Geothermal Field Earthquake, Post-Earthquake Velocity Changes and Finite-Source Scaling. **Dreger, D. S.**, Boyd, S., Taira, T., Gritto, R.
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21. Communicating Earthquake Science in Real Time: Tweets From the Berkeley Seismology Lab. Taggart, J., Strauss, J., Allen, R. M., **Hellweg, M.**
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23. Comparison of the InSight Seismometer Characteristics on Mars With Tests on Earth. **Hurst, K.**, Verdier, N., Bierwirth, M., Fayon, L., Kedar, S., Knapmeyer-Endrun, B., Tillier, S., Widmer-Schnidrig, R., Banerdt, W. B., Calcutt, S., de Raucourt, S., Garcia, R., Giardini, D., Lognonné, P., Mimoun, D., Panning, M. P., Pike, W. T., Zweifel, P., Charalambous, C., Clinton, J., Drilleau, M., Mance, D., McClean, J. B., Murdoch, N., Nebut, T., Stähler, S., ten Pierick, J., Warren, T.
24. Marsquake Service for InSight: Methods to Locate Events in a 3D Planet. **Clinton, J.**, van Driel, M., Stähler, S., Giardini, D., Böse, M., Ceylan, S., Khan, A., Kemper, J., Munch, F., Afanasiev, M., Wieczorek, M.
25. Marsquake Service for InSight: Preliminary Observations and Operations. **Ceylan, S.**, Clinton, J., Stähler, S., Giardini, D., Böse, M., van Driel, M., Horleston, A. C., Kawamura, T., Kedar, S., Khan, A., Euchner, F., Banerdt, W. B., Lognonné, P.
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27. Innovative Ground Motion Sensors for Planets and Asteroids: Pioneers H2020-Space European Project. Garcia, R., Shariati, S., **Guattari, F.**, Bonnefois, J., Mimoun, D., Bernauer, F., Wassermann, J. M., Igel, H., de Raucourt, S., Lognonné, P., Karatekin, O., Ritter, B., Dehant, V., Schmelzbach, C., Giardini, D., Ferraioli, L.
28. Characterization of the InSight Landing Site Near Surface Properties Using the Heat Flow and Physical Properties Probe (Hp3) Mole as a Seismic Source. **Kedar, S.**, Banerdt, W. B., Brinkman, N., Delage, P., Fayon, L., Grott, M., Horleston, A. C., Hudson, T. L., Hurst, K., Kiely, A. B., Knapmeyer-Endrun, B., Krause, C., Lognonné, P., Pike, W. T., Robertsson, J. O. A., Schmelzbach, C., Schmerr, N. C., Spohn, T. C., Sollberger, D., Stähler, S., Teanby, N. A., van Driel, M., Vrettos, C.
29. Towards Planetary Remote-Sensing Seismology: Modeling the Airglow Signature of Venus Quakes. Kenda, B., **Lognonné, P.**, Komjathy, A., Banerdt, W. B., Sutin, B. M., Cutts, J. A., Jackson, J. M.
30. InSight Lessons on Science Potential From On-Deck Operation of a Broadband Seismometer. **Panning, M. P.**, Pike, W. T., Lognonné, P., Banerdt, W. B., Banfield, D., Charalambous, C., Kedar, S., McClean, J. B., Murdoch, N., Stott, A., Warren, T.
31. The Seismic Experiment for Interior Structure (SEIS) Experiment Data Distribution. Pardo, C., **Weber, R. C.**, Lognonné, P., Pike, T., Giardini, D., Christensen, U., Banerdt, W. B., Bandfield, D., Berenguer, J., Bravo, T., Conejero, V., Drilleau, M., Gabsi, T., Luno, L., Labrot, P., Slavney, S., Sauron-Sornette, A., Stutzmann, E.
32. Probabilistic Source Inversion Using Body Wave Coda From a Single Seismic Station (InSight). **Stähler, S.**, Brinkman, N., Böse, M., Khan, A., van Driel, M., Giardini, D., Clinton, J., Ceylan, S.
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52. Student: Envelope-Based, Real-Time Nested Grid Search: Estimates for Earthquake Early Warning. **Roh, B. H.**, Heaton, T. H., Ross, Z. E.
53. A New Multi-Sensor Network Developed for the China Earthquake Early Warning System (EEWs). Wang, H., **Mooney, W. D.**, Gao, J., Mao, G., Hu, B.

54. Investigating the Effect of Finite Source Processes in Single Station Based On-Site Earthquake Early Warning System. **Kwak, S.**, Song, S., Park, J.
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59. An Amphibious Subduction Zone Earthquake Early Warning System for British Columbians — Introduction, Design and First Results. **Schlesinger, A.**, Rosenberger, A., Ferguson, E., Wagner, S., Kreimer, N., Dorocicz, J., Collins, P., Hembrof, D., Key, R., Henton, J. A., Nykolaishen, L., Lu, Y., Pirenne, B., Morley, M., Heesemann, M., Jenkyns, R., Moore, T., Crosby, B.
60. Too-Late Warnings by Estimating Mw: Earthquake Early Warning in the Near-Fault Region. **Hoshiba, M.**
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62. ElarmS/EPIC Earthquake Early Warning System: 2018-2019 Development and Performance. **Chung, A.**, Henson, I., Allen, R. M.
63. Social Science and ShakeAlert. **McBride, S. K.**, deGroot, R. M.
64. Finite-Fault Rupture Detector (Finder): Rapid Line-Source Models for Large Crustal Earthquakes in Sichuan, China. Böse, M., Li, J., Hutchison, A., **Clinton, J.**, Wu, Z., Zhou, S.
65. An Automatic S-Phase Arrival Time Picker. **Kalkan, E.**
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69. Tsunami Early Visualization and Warning System. **Johnson, C.**
70. Platform-Based Testing of Station-Based GNSS-Positioning, Accelerometer and Ensemble Streams for Early Warning Applications With the 'HERB-SE'. **Henton, J. A.**, Collins, P., Rosenberger, A., Ferguson, E., Lu, Y., Caissy, M., Perera, D.
71. Developing Real-Time Strainmeter Data to Supplement GNSS and Seismically Determined Rapid Earthquake Magnitude Estimates. **Gottlieb, M. H.**, Hodgkinson, K., Mencin, D., van Boskirk, L., Mattioli, G., Johnson, W., Pyatt, C.
72. Ionoseis: A Package to Model Coseismic Ionospheric Disturbances. **Mikesell, T. D.**, Rolland, L.
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77. Tsunami Generation From Coseismic Deformation During the 2018 Mw 7.5 Palu Earthquake. **Williamson, A. L.**, Melgar, D., Xu, X., Milliner, C. W. D.
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84. Preparing Communities in Western Nepal for Their Next Major Earthquake, Using Scenarios and Action Plans. Acharya, A., Bhatta, L., Clahan, K., Jomo, J., Joshi, D., Khan, M., Kumar, H., Lizundia, B., Ojha, U., Rodgers, J., Sethi, P., **Stenner, H.**, Tlau, L., Wald, D. J.
85. MARACAS ANR Project Presentation: Marine Terraces Along the Northern Andean Coast as a Proxy for Seismic Hazard Assessment. **Saillard, M.**, Regnier, M., Cisneros, A. L., Michaud, F., Vaca, S., Proust, J., Chlieh, M., Hassani, R., Braucher, R., Espurt, N., Font, Y., Hernandez-Salazar, M., Alvarado, A., Benavente Escobar, C. L., Martillo Bustamante, C. E., Segovia, M., Ponce, G., Nicolas-Cabane, C.
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87. The Seismic Strong Motion Array Project (SSMAP) and September 5, 2012 (Mw 7.6) Nicoya, Costa Rica Earthquake Investigation During 2006-18. **Simila, G.**, Quintero, R.
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90. Seismic Velocity Structure and Geologic Controls on Seismicity Surrounding the April 1, 2014 Pisagua, Chile Earthquake. **Davenport, K.**, Tréhu, A.
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108. ORFEUS Products and Services for Strong Motion Seismology. Luzi, L., Çaktı, E., **Cauzzi, C.**, Clinton, J., Kalafat, D., Kalogeras, I., Marmureanu, A., Michelini, A., Maufroy, E., Shahvar, M., Sleeman, R., Tepeuğur, E., Theodoulidis, N., Roumelioti, Z., Rupakhety, R., Weatherill, G.
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148. Three-Dimensional Tomography of the Crust and Uppermost Mantle of Eastern Nepal. **Ho, T.**, Priestley, K., Roecker, S., Gupta, R.
149. High Resolution 3D Wavespeed Model of the Iranian Plateau Lithosphere. **Irandoust, M.**, Priestley, K., Sobouti, F.
150. Building a Three Dimensional Model of Plio-Quaternary Basin of Argostoli (Cephalonia Island, Greece) From an Integrated Geophysical and Geological Approach to Perform Numerical Simulations of Seismic Motion. **Cushing, E. M.**, Touhami, S., Hollender, F., Lopez-Caballero, F., Moiriat, D., Guyonnet-Benaize, C., Theodoulidis, N., Pons-Branchu, E., Sepulcre, S., Bard, P., Cornou, C., Dechamp, A., Marsical, A., Roumelioti, Z.
151. Student: Ambient Noise Empirical Green's Function Full Waveform Tomography for the Northern Mississippi Embayment. **Yang, Y.**, Liu, C., Langston, C. A.
152. Updates to the Regional Seismic Travel Time (RSTT) Tomography Model. **Begnaud, M.**, Myers, S., Young, B. A.
153. Student: A Bayesian Approach to Regional Phase Blockage Imputation at the Iranian Plateau. **Hui, H.**, Sandvol, E. A., Aldossary, H., Holan, S. H.
154. Recent Improvements to the SCEC Unified Community Velocity Model (UCVM) Software Framework. **Maechling, P. J.**, Su, M., Plesch, A., Shaw, J., Taborda, R.

Friday 26 April—Oral Sessions

Time	*Vashon*	*Cascade I*	*Cascade II*	*Puget Sound*
	Building, Using and Validating 3D Geophysical Models (see page 1025).	**Injection-Induced Seismicity** (see page 998).	**Large Intraslab Earthquakes** (see page 1003).	**The 2018 Eruption of Kīlauea Volcano, Hawai'i** (see page 1020).
8:30 AM	The Western Australia Modeling (WAMo) Project: Geomodel Building and Seismic Validation. **Shragge, J. C.**, Lumley, D., Bourget, J.	STUDENT: Seismicity Induced by Waste Water Injection in Complex Fault Systems. **Szafranski, D.**, Duan, B., Meng, Q.	STUDENT: A Tale of Two Earthquakes: Two Mw 7.1 Earthquakes in Alaska Reveal the Importance of Deep Earth Structure on Ground Motion. **Mann, M.**, Abers, G. A.	Evolution of Seismicity During the 2018 Kīlauea Volcano Eruption. **Chang, J. C.**, Shiro, B., Dotray, P. J., Burgess, M., Okubo, P., Antolik, L., Thelen, W., Waite, G. P.
8:45 AM	Progress on Building a USGS National Crustal Model for Seismic Hazard Studies. **Boyd, O. S.**, Shah, A. K., Sowers, T.	The Effect of Aseismic Slip on the Timing and Size of Induced Seismicity. **Lui, S. K. Y.**, Huang, Y., Young, R.	INVITED: Deep Embrittlement and Complete Rupture of the Lithosphere During the M8.2 Tehuantepec, Mexico Earthquake. **Melgar, D.**, Ruiz-Angulo, A., Garica, E. S., Manea, M., Manea, V. C., Xu, X., Ramirez-Herrera, M. T., Zavala-Hidalgo, J., Geng, J., Corona, N., Pérez-Campos, X., Cabral-Cano, E., Ramírez-Guzmán, L.	Seismic Velocity Changes Associated With the 2018 Collapse of Kīlauea's Summit. **Hotovec-Ellis, A. J.**, Shiro, B., Haney, M., Shelly, D. R., Thelen, W., Montgomery-Brown, E., Anderson, K. R., Johanson, I.
9:00 AM	Validation of Seismic Crustal and Mantle Models of the Contiguous U.S. **Chen, M.**, Zhou, T., Xi, Z.	Hydraulic Properties of Injection Formations in Eastern Texas Constrained by Surface Deformation. **Shirzaei, M.**, Manga, M., Zhai, G.	Complex and Diverse Rupture Processes of the 2018 Mw 8.2 and Mw 7.9 Tonga-Fiji Deep Earthquakes. **Fan, W.**, Wei, S., Tian, D., McGuire, J. J., Wiens, D. A.	Anatomy of a Caldera Collapse: Kilauea 2018 Summit Seismicity Sequence in High Resolution. **Shelly, D. R.**, Thelen, W., Okubo, P.
9:15 AM	Evaluation of the USGS 3D Seismic Model of the San Francisco Bay Area From Moderate Earthquake Waveform Modeling. **Rodgers, A. J.**, Kottke, A. R., Abrahamson, N.	Increased Detections Through Array Design and Processing. **Witten, B.**, Booterbaugh, A., Segstro, R.	INVITED: Seismogenic Characteristics and Dynamic Triggering in the Slab Penumbra. **Wiens, D. A.**, Luo, Y.	Understanding Summit Failure Processes During the 2018 Kilauea Eruption Through Analysis of Earthquake Swarms. **Tepp, G.**, Hotovec-Ellis, A. J., Shiro, B., Haney, M., Thelen, W.
9:30 AM	STUDENT: Combining Geotechnical and Geophysical Data to Build a 3D Model of the Var Valley, Nice (France). **Ophélie, R.**, Bertrand, E., Mercerat, D., Langlaude, P., Régnier, J.	Hide and Seek: Identification and Analysis of Operational Micro-Seismicity Below the Noise Level During a Hydraulic Stimulation Experiment. **Salvage, R. O.**, Eaton, D. W.	STUDENT: Source Variations in Intraslab Earthquakes From Data and Modelling. **Chu, S.**, Beroza, G. C., Ellsworth, W.	How Did the 2018 Kilauea Eruption Affect the Volcano's Submarine South Flank? Preliminary Results From an Ocean Bottom Seismometer Deployment Offshore Kilauea. **Caplan-Auerbach, J.**, Shen, Y., Morgan, J. K., Soule, S. A.
9:45–10:45 AM	Posters and Break, Fifth Avenue and Grand Ballroom			

Time	*Pike*	*Pine*	*Elliott Bay*
	Seismology BC(d)E: Seismology Before the Current (digital) Era (see page 1012).	**Methods for Site Response Estimation** (see page 1016).	**Next Generation Seismic Detection** (see page 1008).
8:30 AM	INVITED: From Historical Seismology to Seismogenic Source Models to Seismic Risk: 20 Years On, Results and Challenges. **Valensise, G.**	Common Best Practice Procedures for Site and Seismic Station Characterization: A European Initiative. Di Giulio, G., **Cornou, C.**, Cultrera, G., Bard, P.	A Deep Learning Pipeline for Earthquake Detection. **Ross, Z. E.**, Hauksson, E.
8:45 AM	INVITED: Himalaya – A Present-Day Evaluation of Its Thousand-Year Seismic Slip Potential. **Bilham, R.**	Resolving S-Wave Velocity Structure from Weak-Motion S-Wave HVSR. **Carpenter, S.**, Wang, Z., Woolery, E. W.	Cone Detectors That Operate at IMS Arrays Screen Background Seismicity at the DPRK Test Site. **Carmichael, J. D.**, Wagner, G.
9:00 AM	INVITED: Whither the Big One: Dynamic Rupture Modeling of Large Historic San Andreas-System Earthquakes. **Lozos, J.**	Quantifying Site Response of the Atlantic Coastal Plain Strata in the Eastern United States Using Horizontal to Vertical Spectral Ratios. **Schleicher, L. S.**, Pratt, T. L.	Analyzing Data From MyShake Smartphone Seismic Network. **Kong, Q.**, Inbal, A., Allen, R. M.
9:15 AM	STUDENT: A Bayesian Approach to Estimating the Source of Historical Earthquakes From Intensity Data: Application to the Eastern Sunda Arc, Indonesia, 1681-1877. **Griffin, J. D.**, Nguyen, N., Cummins, P., Cipta, A.	Direct Evaluation of Horizontal Amplification Factor HHbR From Earthquake HVR and Empirical Vertical Amplification Factor VHbR. **Kawase, H.**, Nakano, K., Nagashima, F., Ito, E.	Smartphone App Earthquake Detections: How Combined Analysis of Crowdsourced and Seismic Data Can Improve Performance of Existing Seismic Networks. **Bossu, R.**, Steed, R., Landes, M., Roch, J., Roussel, F.
9:30 AM	STUDENT: Toward a Database of Consistently Reinterpreted Intensities in California. **Salditch, L.**, Hough, S. E., Stein, S., Spencer, B., Brooks, E. M., Neely, J. S., Gallahue, M.	Estimation of EMR Correction Factor in the Grenoble Basin; an Attempt to Establish a Simple Method to Get Earthquake HVR From Microtremors. **Ito, E.**, Kawase, H., Cornou, C., Nagashima, F.	Global Seismic Monitoring With Real-Time GNSS. **Szeliga, W.**, Melbourne, T. I., Scrivner, C., Santillan, V. M.
9:45–10:45 AM	Posters and Break, Fifth Avenue and Grand Ballroom		

Time	*Vashon*	*Cascade I*	*Cascade II*	*Puget Sound*
	Structural Seismology: From Crust to Core (see page 1026).	**Injection-Induced Seismicity** (continued).	**The M7 Anchorage Earthquake: Testing the Resiliency of South-Central Alaska** (see page 1004).	**The 2018 Eruption of Kīlauea Volcano, Hawai‘i** (continued).
10:45 AM	Seismic Images of the North American Upper Mantle From S-to-P Converted Waves. **Mooney, W. D.**, Kind, R., Yuan, X.	Seismicity Induced by Hydraulic Fracturing in the Central and Eastern United States. **Brudzinski, M. R.**, Skoumal, R. J., Ries, R., Fasola, S., Friberg, P., Currie, B.	Aftershock Analysis of the Mw 7 November 30, 2018 Anchorage Earthquake: Locations and Regional Moment Tensors. **Ruppert, N.**, Richards, C., Tape, C., West, M. E.	Interseismic Quiescence and Triggered Slip of Active Normal Faults of KīLauea Volcano's South Flank During 2001-2018. **Wang, K.**, MacArthur, H., Johanson, I., Montgomery-Brown, E., Poland, M., Cannon, E. C., d'Alessio, M., Bürgmann, R.
11:00 AM	STUDENT: Teleseismic Traveltime Tomography of the Crust and Upper Mantle Beneath the Southern U.S. Continental Margin. **Netto, A.**	STUDENT: Identifying and Forecasting Induced Seismicity Due to Wastewater Injection. **Grigoratos, I.**, Rathje, E., Bazzurro, P., Savvaidis, A.	Preliminary Geodetic Analysis of 2018 M7 Anchorage Earthquake. **Elliott, J.**, Grapenthin, R., Freymueller, J. T., Rollins, C., Kaufman, A. M., Witter, R. C., Wech, A.	STUDENT: Inter-Event Seismicity Statistics Associated With the 2018 Quasi-Periodic Collapse Events at Kīlauea, HI, USA. **Fildes, R. A.**, Kellogg, L. H., Turcotte, D. L., Rundle, J. B.
11:15 AM	Imaging Terranes and Structure of the Southern South Island, New Zealand, With Joint Earthquake Travel-Time and Ambient-Noise Tomography. **Eberhart-Phillips, D.**, Upton, P., Reyners, M., Fry, B., Bourguignon, S.	The Application of High-Quality Seismic Catalogs in Forecasting Induced Seismicity: A Risk Management System. **Karimi, S.**, Baturan, D.	Impact of Flat Slab Subduction on Earthquake Ground Motions in South Central Alaska Including the 2018 M7.0 Anchorage Inslab Earthquake. **Cramer, C. H.**, Jambo, E.	Six Axis Measurements at Kilauea – More Riddles to Be Solved? **Wassermann, J. M.**, Bernauer, F., Shiro, B., Johanson, I., Igel, H., Guarttari, F.
11:30 AM	Receiver Function HV Ratio: A New Single Station Seismic Measurement for Imaging Crustal Structure. **Chong, J.**, Ni, S., Chu, R.	Seismic Network Development for Monitoring an Engineered Geothermal System in Finland. Malin, P. E. A., **Passmore, K.**, Heikkinen, P., Ader, T., Kwiatek, G., Saarno, T.	Ground Failures Induced by Seismic Shaking During the 2018 Anchorage, Alaska M7 Earthquake. **Witter, R. C.**, Allstadt, K. E., Bender, A. M., Grant, A., Jibson, R. W., Thompson, E. M.	STUDENT: Hindcasting May 2018 Kīlauea Summit Explosions With Atmospheric Remote Sensing, Geophysical Monitoring and 3D Eruptive Plume Simulations. **Crozier, J. A.**, Karlstrom, L., Thelen, W., Anderson, K. R., Dufek, J., Liang, C., Benage, M.
11:45 AM	Direct Observations of Surface-Wave Eigenfunctions at the Homestake 3D Array. Meyers, P., **Tsai, V. C.**, Bowden, D. C., Prestegard, T., Mandic, V., Pavlis, G. L., Caton, R.	Impacts of Induced Seismicity on Geotechnical Aspects of Infrastructure Systems. **Zafir, Z.**	USGS Near-Real-Time Ground Failure Product for the 2018 Anchorage Earthquake. **Thompson, E. M.**, Allstadt, K. E., Grant, A., Jibson, R. W., Bender, A. M., Witter, R. C., Hearne, M., Wald, D. J., McBride, S. K.	What Lies Ahead for Kilauea? Perhaps Lo`ihi Knows. Remarkable Parallels Between the 1996 Eruption of Lo`ihi Seamount and the 2018 Kilauea Eruption. **Caplan-Auerbach, J.**, Thurber, C. H.
Noon–1:15 PM	Luncheon, Grand Ballroom		Seismic Instruments for the Coming Decade	Luncheon, Grand Ballroom

Time	Pike	Pine	Elliott Bay
	Seismology BC(d)E: Seismology Before the Current (digital) Era (continued).	**Methods for Site Response Estimation** (continued).	**New Frontiers in Global Seismic Monitoring and Earthquake Research** (see page 1009).
10:45 AM	INVITED: The Potential of Analogue Seismograms for Science and Education. **Ishii, M.**, Morinaga, T., Lee, T. A.	Shallow Shear Wave Velocities for Downtown Salt Lake City: Relationships With Surface Topography, Basin Depth and Earthquake Site Amplifications. **Liberty, L. M.**, St Clair, J., Gribler, G., McDonald, G. N., Pechmann, J. C.	INVITED: Semi-Supervised Learning for Seismic Monitoring Applications. **Linville, L.**, Anderson, D., Michalenko, J., Galasso, J., Draelos, T.
11:00 AM	The Large Andaman Islands Earthquake of 26 June 1941: Why No Significant Tsunami? **Okal, E. A.**	Evaluation of Vs30 at Southern California Edison Substations Using S-Wave Refraction Tomography and Multichannel Analysis of Surface Waves. **Chan, J. H.**, Catchings, R. D., Goldman, M. R., Criley, C. J., Sickler, R. R., Strayer, L. M.	Comparison of Pick-Based and Waveform-Based Event Detectors for Local to Near-Regional Distance Data From Utah. **Heck, S.**, Young, C. J., Brogan, R.
11:15 AM	Comparison of Three Mw ~7 Pre-Digital Era Intraplate Alaska Earthquakes to the November 30, 2018 Anchorage Event. **Doser, D. I.**	New Geotechnical Maps and 3D Basin Velocity Model for Central Wellington, New Zealand, Following the Mw 7.8 Kaikoura Earthquake: Explaining Site Effects in a Shallow, Steep-Sided Sedimentary Basin. **Kaiser, A. E.**, Hill, M., Wotherspoon, L., Bourguignon, S., Bruce, Z., McVerry, G., Morgenstern, R., Giallini, S.	Regional Earthquake Relocation Using Multiple Seismic Arrays: Case Examples From Offshore Eastern Taiwan and Yellow Sea Between China and South Korea. **Chiu, J.**, Kim, K., Chiu, S. C., Kang, S., Han, J., Hwang, B., Chen, K.
11:30 AM	Source Processes of the Complex 1932 M7.6 Changma Earthquake in Gansu, China, From Early Seismic Records and Modern Photogrammetric Geomorphology. **Elliott, A. J.**, Kulikova, G., Ou, Q., Walker, R. T., Parsons, B.	Estimation of Bedrock Depth in the Kathmandu Valley, Nepal, Using Long-Term Ambient Noise and Teleseismic Data. **Hayashida, T.**, Yokoi, T., Bhattarai, M., Dhakal, S., Shrestha, S., Pokharel, T., Maharjan, N., Timsina, C.	INVITED: Rapid Characterisation of Large Earthquakes in New Zealand. **Fry, B.**, Gledhill, K., Kaiser, A. E., Holden, C.
11:45 AM	Examining Taiwanese Historical Earthquakes From Literature Intensity to Synthetics for the Understanding of Fault System, Multiple Fault Segments Rupture and Seismic Hazard Analysis. **Ma, K.**, Yen, M., Liao, Y.	Bias and Uncertainty of Depth Parameters Extracted From a Regional Velocity Model and Its Implications on Ground Motion Prediction. **Zhu, C.**, Cotton, F., Pilz, M.	Update From the Powell Center Working Group on Future Opportunities in Regional and Global Seismic Network Monitoring and Science. **Hayes, G. P.**, Earle, P.
Noon–1:15 PM	Luncheon, Grand Ballroom		

Time	*Vashon*	*Cascade I*	*Cascade II*	*Puget Sound*
	State of Stress and Strain in the Crust and Implications for Fault Slip Based on Observational, Numerical and Experimental Analysis (see page 1027).	**Advances, Developments and Future Research into Seismicity in Natural and Anthropogenic Fluid-Driven Environments** (see page 1001).	**The M7 Anchorage Earthquake: Testing the Resiliency of South-Central Alaska** (continued).	**Observations of Volcanism in the Three Spheres: Land, Air and Sea** (see page 1023).
1:30 PM	Heterogeneity of Shallow Crustal Stress Estimated From Borehole Breakouts and Local Earthquake Focal Mechanism Inversions in the Los Angeles Basin. **Luttrell, K.**, Hardebeck, J.	Controlling Induced Seismicity During Hydraulic Stimulation of a 6 km Deep Enhanced Geothermal System in Finland. **Kwiatek, G.**, Saarno, T., Ader, T., Bluemle, F., Bohnhoff, M., Chendorain, M., Dresen, G., Heikkinen, P., Kukkonen, I., Leary, P., Leonhardt, M., Malin, P. E. A., Martinez-Garzon, P., Passmore, P., Passmore, K., Wollin, C., Valenzuela, S.	Initial Observations From the GEER Reconnaissance Evaluation of the 2018 M7.0 Anchorage Alaska Earthquake. **Koehler, R. D.**, Franke, K. W., Beyzaei, C. Z., Cabas, A., Pierce, I. K. D., Stuedlein, A. W., Yang, Z.	Ancillary Land, Sea and Air Records of the Krakatau Eruption and Tsunami of 22 December 2018. **Okal, E. A.**, Hyvernaud, O., Paris, A., Hebert, H., Heinrich, P.
1:45 PM	Influence of Coseismic and Postseismic Stress Induced by the 2011 M9.0 Tohoku-Oki Earthquake on Regional Medium Properties and Seismicity. **Hong, T.**, Lee, J., Kim, I., Park, S., Kim, W.	Investigating the Origin of the Mw 5.4 Pohang, Korea, Earthquake of 15 November, 2017: The Investigations and Conclusions of the Overseas Research Advisory Committee (ORAC). **Ellsworth, W.**, Ge, S., Giardini, D., Shimamoto, T., Townend, J.	Ground Motion and Hazard Context for the Anchorage Earthquake. **West, M. E.**, Ruppert, N., Gardine, M.	INVITED: Explosion Volume Flux Comparison Using Seismically Derived Tilt, Infrasound and Gas Data at Stromboli Volcano, Italy. **McKee, K. F.**, Fee, D., Waite, G. P., Roman, D. C., Ripepe, M., Aiuppa, A., Carn, S., Le Mével, H., Delle Donne, D., Bitetto, M., Lacanna, G., Sealing, C., Cigala, V., Tamburello, G.
2:00 PM	Spectral and Temporal Evolution of Surface Creep Events in Parkfield, 1990-Present. **Mencin, D.**, Bilham, R., Hodgkinson, K., Mattioli, G.	Microseismicity Recorded in the Geothermal Areas of Mt. Amiata (Italy). **Braun, T.**, Cesca, S., Caciagli, M., Famiani, D., Dahm, T.	Using the M7.0 Anchorage Earthquake to Validate Ground Response Modeling at the Delaney Park Downhole Array in Anchorage, Alaska. **Thornley, J.**, Dutta, U., Yang, Z., Douglas, J.	Seismic Imaging of Magmatic- and Subduction-Related Structures Beneath Arc Volcanoes: A Case Study at Mount Cleveland, Alaska. **Janiszewski, H. A.**, Wagner, L. S., Roman, D. C.
2:15 PM	Nonlinear Rheology of the Shallow Crust Inferred From Multi-Year Borehole Strain Time Series. **Roeloffs, E.**	Rapid Tremor Migration and Pore-Pressure Waves in Subduction Zones. **Cruz-Atienza, V. M.**, Villafuerte, C., Bhat, H.	A Twenty-Story Instrumented Building Response to M7 Anchorage, Alaska Earthquake. Wen, W., **Kalkan, E.**	Combining Active- and Passive-Source Seismic Observations to Image Magma Storage Beneath Mount St. Helens. **Ulberg, C. W.**, Kiser, E., Creager, K. C., Levander, A., Schmandt, B., Hansen, S., Abers, G. A.

Time	*Pike*	*Pine*	*Elliott Bay*
	Seismology BC(d)E: Seismology Before the Current (digital) Era (continued).	**Methods for Site Response Estimation** (continued).	**Using Repeating Seismicity to Probe Active Faults** (see page 1010).
1:30 PM	Status and Future of Macroseismic Information in Canada. **Lamontagne, M.**, Burke, K. B. S.	Shallow Vs Structure Imaged With the Ambient Noise Recorded by a Telecommunication Fiber-Optic Cable in Urban Area. **Zeng, X.**, Wang, B., Li, X., Xu, W., Xu, S., Song, Z.	The Initiation of Dynamic Rupture on a 3-m Laboratory Earthquake Experiment. **McLaskey, G.**
1:45 PM	The New Version of the Catalogue of Strong Earthquakes in Italy and in the Extended Mediterranean Area (CFTI5Med): A Fundamental Seismological Tool for Learning, Discovering and Predicting. **Ferrari, G.**, Guidoboni, E., Mariotti, D., Comastri, A., Tarabusi, G., Sgattoni, G., Valensise, G.	STUDENT: Imaging and Monitoring Temporal Changes of Shallow Seismic Velocities at the Garner Valley Near Anza, California, in Relation to the M7.2 2010 El Mayor – Cucapah Earthquake. **Qin, L.**, Ben-Zion, Y., Bonilla, L., Steidl, J. H., Vernon, F. L.	Spatial and Temporal Evolution of Microseismicity of the Rattlesnake Ridge Landslide. **Thomas, A. M.**, Toomey, D., Chamberlain, C. J., Newton, T. J., Malone, S.
2:00 PM	A Discussion of Efforts Needed to Extract Key Information From Important Old Seismograms. **Richards, P.**, Kim, W., Wilding, J. D.	Soil Seismic Non-Linear Behavior Inferred by Analysis of Vertical Arrays Recordings. Castro Cruz, D., **Bertrand, E.**, Régnier, J., Courboulex, F.	INVITED: Modeling High Stress Drops, Scaling, Interaction and Irregularity of Repeating Earthquake Sequences Near Parkfield. **Lui, S. K. Y.**, Lapusta, N.
2:15 PM	Historical (Pre-Digital) Earthquake Information at the UC Berkeley Seismological Lab. **Hellweg, M.**	Site Characterization Based Upon Body-Wave Polarization. **Park, S.**, Ishii, M., Tsai, V. C.	Slow Slip Happens Every Day. **Frank, W. B.**, Brodsky, E. E.

Time	Vashon	Cascade I	Cascade II	Puget Sound
	State of Stress and Strain in the Crust…	**Advances, Developments and Future Research…**	**The M7 Anchorage Earthquake…**	**Observations of Volcanism…**
2:30 PM	INVITED: Stress From Plate Bending in the Nankai Trough. **Hardebeck, J.**, Loveless, J. P.	INVITED: Untangling the Web of Fluids and Faulting in Earthquake Swarms. **Shelly, D. R.**	The M7.0 November 30, 2018, Anchorage, Alaska, Earthquake and Response of the USGS Earthquake Hazards Program. **Knudsen, K. L.**, Haeussler, P. J., Witter, R. C., Thompson, E. M., Blanpied, M. L., Hayes, G. P.	Insights Into Shallow Submarine Explosion Dynamics at Bogoslof Volcano From Infrasound, Hydroacoustic and Seismic Data. **Lyons, J. J.**, Wech, A., Tepp, G., Haney, M., Fee, D., Waythomas, C.
2:45–3:45 PM	Posters and Break, Fifth Avenue and Grand Ballroom			
	State of Stress and Strain in the Crust and Implications for Fault Slip Based on Observational, Numerical and Experimental Analysis (continued).	**Advances, Developments and Future Research into Seismicity in Natural and Anthropogenic Fluid-Driven Environments** (continued).	**Emerging Science from the EarthScope Transportable Array in Alaska and Western Canada** (see page 1006).	**Causes and Consequences of the Columbia River Flood Basalts** (see page 1024).
3:45 PM	INVITED: Post-Large Earthquake Seismic Activities Mediated by Aseismic Deformation Processes. **Gualandi, A.**, Liu, Z., Rollins, C.	STUDENT: Hydraulic-Fracturing, Induced Seismicity and the Characteristic Earthquake Hypothesis: Observations and Implications. **Igonin, N.**, Zecevic, M., Eaton, D. W.	The Future of the Alaska Transportable Array. **Busby, R.**, Aderhold, K., Enders, M.	INVITED: Origin of the Columbia River Flood Basalts: Geochemical Evidence. **Wolff, J. A.**, Steiner, A. R., Ramos, F. C.
4:00 PM	Assimilating Stress and Strain in an Energy-Based PSHA Workflow. **Ziebarth, M. J.**, Heidbach, O., Cotton, F., Anderson, J. G., Weatherill, G., von Specht, S.	STUDENT: Source Parameters of the Nov 30, 2018, ML 4.5 Hydraulic Fracturing Induced Earthquake and Aftershock Sequence in Northeast BC, Canada. **Onwuemeka, J.**, Peña-Castro, A., Roth, M. P., Liu, Y., Harrington, R. M., Kao, H.	Contributions of USArray Stations to Regional Earthquake Monitoring in Alaska. **Ruppert, N.**, West, M. E.	Crustal Seismic Structure Beneath the Source Area of the Columbia River Flood Basalt: Bifurcation of the Moho Driven by Lithosphere Delamination. **Gao, H.**
4:15 PM	STUDENT: Spatial Variations of Stress Patterns Near the South Central Transverse Ranges in Southern California. **Abolfathian, N.**, Martinez-Garzon, P., Ben-Zion, Y.	INVITED: Controls of Structural Complexity and Earthquake Rupture Process on Spatiotemporal Evolution of Induced Earthquake Sequences. **Chen, X.**, Qin, Y., Wu, Q., Kolawole, F., Dangwal, D.	Toward a Community Seismic Velocity Model for Alaska. **Thurber, C. H.**, Eberhart-Phillips, D., Nayak, A., Ruppert, N., Driskell, M., Fang, H.	Wallowa Seismic Anomaly: Lithospheric Delamination and Northward Rollback Triggered by the Yellowstone Plume, Along the Western Edge of Precambrian North America. **Stanciu, A.**, Humphreys, E. D., Clayton, R. W.

Time	Pike	Pine	Elliott Bay
	Seismology BC(d)E: Seismology Before the Current (digital) Era	**Methods for Site Response Estimation**	**Using Repeating Seismicity to Probe Active Faults**
2:30 PM	Preserving Ohio's Historic Seismogram Collection: 83 Years of Global Seismology: 1909–1992. **Fox, J.**	STUDENT: Mapping Near-Surface Rigidity Structure Using Co-Located Pressure and Seismic Sensors From the Earthscope Transportable Array. **Wang, J.**, Tanimoto, T.	INVITED: STUDENT: Aseismic Slip at the Mendocino Triple Junction From Repeating Earthquakes. **Materna, K.**, Taira, T., Bürgmann, R.
2:45–3:45 PM	Posters and Break, Fifth Avenue and Grand Ballroom		
	Environmental Seismology: Glaciers, Rivers, Landslides and Beyond (see page 1015).	**Metamaterials, Resonances and Seismic Wave Mitigation, an Emerging Trend in Seismology** (see page 1019).	**Non-Traditional Application of Seismo-Acoustics for Non-Traditional Monitoring** (see page 1011).
3:45 PM	INVITED: Glacial Dynamics From Sequences of Long-Lived Repeating Glacial Stick-Slip Events. **Winberry, J. P.**, Huerta, A., Anandakrishnan, S., Aster, R., Conway, H., Koutnik, M., Nyblade, A., Wiens, D. A.	STUDENT: 3D Finite Difference Simulation for Evaluating the Possibility of Buildings as Metastructures. **Joshi, L.**, Narayan, J. P.	Mapping the Harmonic Tonal Noise in the Continental U.S. **Marcillo, O.**, MacCarthy, J. K.
4:00 PM	Multiple Constituents of Solid Earth Tides Observed With Ambient Seismic Noise. **Sens-Schönfelder, C.**, Eulenfeld, T.	Passive Redirection of Seismic Waves Through the Use of Gradient Index Metamaterial Barriers. **Shakalis, A. J.**, Ghisbain, P., Milner, D., Cipolla, J. L.	The 2016 Infrasound Wanaka Balloon Flight: What Have We Learned? **Lees, J. M.**, Bowman, D. C., Lamb, O., Traphagan, J. W.
4:15 PM	Simulation of Asteroids Impacting Earth: Tsunami Generation and Consequences on U.S. Major Cities for Disaster Response and Management Preparedness. **Ezzedine, S. M.**	Experimental Analysis of the Concept of Meta-City Considering a Geophysical Scale Analog City-Like Environment. **Guéguen, P.**, Touma, R.	Unconventional Seismic Monitoring in the Built Environment, From Canal Integrity to Coal Seam Fires. **Levandowski, W.**, O'Connell, D. R., Steele, L., Johnson, M., Nuttall, J., Isaacson, M., Turner, J.

Time	Vashon	Cascade I	Cascade II	Puget Sound
	State of Stress and Strain in the Crust…	**Advances, Developments and Future Research…**	**Emerging Science from the EarthScope…**	**Causes and Consequences of the Columbia River…**
4:30 PM	STUDENT: Surface-Wave Induced Dynamic Stresses on Arbitrary Faults in a Layered Earth. **Roesler, B.**, van der Lee, S., Chao, K.	Rainwater and Aquifer Factors of Seasonally Induced Seismicity in Southeast Brazil. **Convers, J.**, Assumpção, M., Barbosa, J. R.	Alaska Amphibious Community Seismic Experiment: Update and Outlook. **Roland, E.**, Abers, G. A., Adams, A. N., Bécel, A., Haeussler, P. J., Shore, P. J., Schwartz, S. Y., Sheehan, A. F., Shillington, D. J., Webb, S., Wiens, D. A., Worthington, L. L.	INVITED: STUDENT: Imaging the Crust and Upper Mantle Beneath Columbia River Flood Basalts With Ambient Seismic Noise, Regional and Teleseismic Events and Converted Phases. **Castellanos, J. C.**, Clayton, R. W., Kim, Y., Humphreys, E. D.
4:45 PM	Contemporary Stress and Strain Field Data in the Mediterranean From Surface to Depth: Resolution, Correlations and Contradictions. **Martinez-Garzon, P.**, Heidbach, O., Bohnhoff, M.	Snowmelt-Triggered Earthquake Swarms at the Margin of Long Valley Caldera, California. **Montgomery-Brown, E.**, Shelly, D. R., Hsieh, P., Silverii, F.	Nature and Thermal State of the Cordilleran Lithosphere in Northwestern Canada From a Compilation of Broadband Seismic Studies. **Audet, P.**, Schaeffer, A. J., Currie, C., Clement, E., Schutt, D., Aster, R., Freymueller, J. T., Cubley, J., Khare, A.	Deep Seismic Crustal Structure Beneath Wallowa, Columbia River Flood Basalt Province. **Kim, Y.**, Clayton, R. W., Kang, H., Humphreys, E. D.

Poster Sessions

Fifth Avenue Room

Advances, Developments and Future Research into Seismicity in Natural and Anthropogenic Fluid-Driven Environments (see page 1030).

1. A Wastewater Disposal Reservoir Sensitive to Teleseismic Waves. **Barbour, A. J.**
2. Evolution of Faulting Induced by Deep Fluid Injection, Paradox Valley, Colorado. **Denlinger, R. P.**, O'Connell, D. R.
3. Rupture Model of the 2016 M5.8 Pawnee Earthquake From Regional and Teleseismic Waveforms: Potential Influence of Pore Pressure Perturbations on Rupture Dynamics. **Moschetti, M. P.**, Hartzell, S., Herrmann, R. B.
4. The Similarity Between Induced and Natural Earthquakes: A View From the Non-Double-Couple Component. **Wang, R.**, Gu, Y., Schultz, R., Chen, Y.
5. Moment Tensors of Waste-Water Disposal Induced Seismicity in Southern Kansas. **Martinez-Garzon, P.**, Amemoutou, A., Rubinstein, J., Kwiatek, G., Bohnhoff, M.
6. Tidally Triggered Earthquakes at the Geysers in Northern California. **Delorey, A. A.**, Chen, T.
7. Hydraulic-Fracturing Induced Seismicity Driven by Accelerated Fault Creep. Eyre, T. S., **Eaton, D. W.**, Garagash, D., Venieri, M., Weir, R., Lawton, D.
8. Seismicity of Bull Shoals Lake Area of Missouri and Arkansas. **Kopper, M. T.**, Ausbrooks, S. M., Horton, S. P.
9. Stress State Inferred From Moment Tensors of Induced Events Near Fox Creek, Alberta: Implications for Fault Criticality. Zhang, H., **Eaton, D. W.**, Rodriguez Pradilla, G., Jia, S.

Injection-Induced Seismicity (see page 1031).

10. Analysis of the 29 November 2018 ML 4.5 Earthquake Near Fort St. John, BC. **Eaton, D. W.**, Kao, H., Esmaeilzadeh, Z.
11. Stochastic Modelling of Induced Seismicity Clusters in Central Alberta. **Wang, R.**, Shcherbakov, R., Atkinson, G. M., Assatourians, K.
12. The 16 December 2018 Mw 5.3 Earthquake in the Southern Sichuan Basin of China Was Likely Caused by Hydraulic Fracturing. **Meng, L.**, McGarr, A.
13. Seismicity Induced by Hydraulic Fracturing in Ohio in 2016: Case Study of the Conotton Sequence in Harrison County. **Friberg, P.**, Brudzinski, M. R., Fasola, S., Ries, R., Kozlowska, M., Skoumal, R. J.
14. STUDENT: Comparing Seismicity-Inferred Fault Structures to Local Basement Fault Structures in Oklahoma. **Tripplehorn, T. J.**, Ruhl, C. J., Roche, S. L.
15. Infrasound Generated by Fluid-Induced Seismicity in Finland. **Lamb, O.**, Lees, J. M., Malin, P. E. A., Saarno, T.
16. Seismology and Drilling, Characterizing and Hydraulic Stimulation of the OtN-3 EGS Well in Finland. **Malin, P. E. A.**, Kwiatek, G., Saarno, T.

Time	*Pike*	*Pine*	*Elliott Bay*
	Environmental Seismology: Glaciers, Rivers, Landslides…	**Metamaterials, Resonances and Seismic Wave Mitigation…**	**Non-Traditional Application of Seismo-Acoustics…**
4:30 PM	STUDENT: Seismic Detection of Internal Gravity Waves at the Dongsha Atoll, South China Sea. **Shaddox, H. R.**, Brodsky, E. E., Davis, K.	STUDENT: Resonant Metasurfaces for Surface Shear Horizontal Wave Attenuation in Unconsolidated Granular Media. **Zaccherini, R.**, Colombi, A., Palermo, A., Dertimanis, V. K., Marzani, A., Chatzi, E. N.	Detecting and Monitoring Operational Events Around a Nuclear Reactor Using Seismo-Acoustic Signals. **Chai, C.**, Marcillo, O., Ramirez, C. A., Maceira, M.
4:45 PM	INVITED: Seismic Recordings Reveal the Timing and Extent of Subglacial Water Pressurization. **Bartholomaus, T. C.**, Labedz, C., Amundson, J. M., Gimbert, F., Veitch, S. A., Tsai, V. C., Karplus, M.	Periodic Excavations, Hills and Inclusions as Seismic Metamaterials: Can They Be Used as Wave Barriers Protecting Structures From Seismic and Anthropogenic Sources of Vibrations? **Todorovska, M. I.**, Ba, Z., Ozmutlu, A., Gao, X.	Monitoring a Nuclear Research Reactor with Traditional and Non-Traditional Vibration Measurements. **Parikh, N. K.**, Flynn, G. S., Casleton, E., Ray, W.

17. STUDENT: Assessing the Applicability of Ground Motion Models for Induced Seismicity Application in Central and Eastern North America. **Farhadi, A.**, Pezeshk, S.
18. Mapping Temporal Stress Evolution in Pawnee and Cushing Oklahoma Using Ambient Noise. **Ogwari, P. O.**

Observations of Volcanism in the Three Spheres: Land, Air and Sea (see page 1033).

19. STUDENT: Melt Evolution Beneath Axial Volcano Imaged Using Continuous Seafloor Compliance Data. **Doran, A. K.**, Crawford, W. C.
20. Repeating Deep Long-Period Earthquakes Beneath Mauna Kea Volcano. **Wech, A.**, Thelen, W.
21. Next-Generation Volcano Monitoring at Mount Rainier, Washington. **Moran, S. C.**, Thelen, W., Lockhart, A., Pauk, B., Kramer, R., Lockett, C.
22. Hydroacoustic and Seismic Observations of the 2016-17 Bogoslof Eruption, Alaska. **Tepp, G.**, Power, J., Dziak, R., Searcy, C., Lyons, J. J., Haney, M., Wech, A., Haxel, J., Matsumoto, H.
23. Preliminary Earthquake Detections From Seismic Stations Installed on Bioko Island, Equatorial Guinea. **Lough, A. C.**, Sealing, C.
24. Conjugate Flow, Heat and Chemical Transport Processes in Underground Cavities Partially Filled With Molten Rock: A Numerical Investigation. **Ezzedine, S. M.**, Nguyen, J. S., Rose, T. P., Cassata, W., Antoun, T. H., Walter, W. R.
25. STUDENT: Seismic Structure of Tanaga and Takawangha Volcanoes, Tanaga Island, Alaska. Caplan-Auerbach, J., **Lally, K. F.**, Power, J.
26. STUDENT: Eruption Dynamics and Variations in Earthquake Stress Drop With the 2015 Eruption of Axial Seamount. **Moyer, P.**, Boettcher, M. S., Bohnenstiehl, D. R., Abercrombie, R. E.
27. Velocity Changes Associated With the Three Year Buildup of Activity at Great Sitkin Volcano, Alaska – Are Precursory Signals Detectable? **Bremner, P.**, Tepp, G., Haney, M., Woo, H., Power, J.

The 2018 Eruption of Kīlauea Volcano, Hawai'i (see page 1035).

28. Verification of Sub-Faults Division in the Numerical Evaluation Precision of Near-Fault Seismic Ground Motions Accompanied by Surface Rupture. **Nagano, M.**, Kido, T.
29. STUDENT: Interpretation of and Proposed Model for Progressive Decorrelation of Auto-Correlation Functions on the East Rift Zone of Kīlauea during the Volcanic Activity of 2018. **Lee, T. A.**, Ishii, M.
30. STUDENT: Mechanism of the 4 May 2018 East Hawaiian Earthquake and Tsunami: Evidence of Progressive Volcanic Flank Failure? **Lin, J.**, Melgar, D., Thomas, A. M.
31. Source Mechanism of Caldera Collapse Events During the 2018 Kīlauea Volcano Eruption. **Dawson, P.**

Non-Traditional Application of Seismo-Acoustics for Non-Traditional Monitoring (see page 1036).

32. On the Use of Seismo-Acoustic Signatures for Power-Level Classification at an Industrial Facility. **Ramirez, C. A.**, Chai, C., Maceira, M., Marcillo, O.
33. STUDENT: A New Approach for Lightning Infrasound Detection Using Ground and Balloon-Based Instruments. **Traphagan, J. W.**, Lees, J. M., Lamb, O.
34. Seismo-Acoustic Responses of Explosions, Mining and Machining in Different Geological Materials: A Parametric Study of Different Emplacements and Different Energy Depositions. **Ezzedine, S. M.**, Vorobiev, O. Y., Yoder, M. K., Rodgers, A. J., Antoun, T. H., Walter, W. R.
35. Monitoring of Industrial Facilities With Telecom Fiber Optics. **Ray, W.**, Ramirez, C. A., Poska, M.
36. Non-Traditional Application of Seismo-Acoustics for Non-Traditional Monitoring. **Ahuja, K. K.**

Grand Ballroom

Environmental Seismology: Glaciers, Rivers, Landslides and Beyond (see page 1037).

37. Geochemical Characteristics of Underground Fluid Observation Points in the North Tianshan. **Gao, X.**
38. STUDENT: Estimations of Ambient Seismic Noise Sources Around Antarctica From Waveform Inversions of Multi-Component Rayleigh-Wave Crosscorrelations. **Xu, Z.**, Mikesell, T. D., Mordret, A., Gribler, G.
39. STUDENT: Tidally Induced Cryoseismicity Observed Along the Periphery of the Ross Ice Shelf, Antarctica. **Cole, H.**, Aster, R., Baker, M. G., Chaput, J., Wiens, D. A., Stephen, R. A., Nyblade, A., Bromirski, P. D., Gerstoft, P.
40. Glacier Sliding, Seismicity and Sediment Entrainment. **Lipovsky, B. P.**, Meyer, C. R., Zoet, L. K., Hansen, D. D., Gimbert, F., Rempel, A. W.
41. A Multidisciplinary Study of Shallow Water Microseisms in Yellowstone Lake. **Koper, K. D.**, Farrell, J., Burlacu, R., Sohn, R. A.
42. Sea Ice and the Alaska Transportable Array. **Aderhold, K.**, Bradley, A. C., Busby, R.
43. Monitoring Seismic Velocity Changes in the Coastal and Sinking Sedimentary Basin of Jakarta, Indonesia. **Denolle, M. A.**, Clements, T., Cummins, P.
44. STUDENT: Seismic Observations of Precipitation and Recharge-Related Signals in the Floridan Aquifer at Santa Fe River Sink and Rise, Florida. **Gochenour, J. A.**, Bilek, S., Grapenthin, R., Luhmann, A. J., Martin, J. B., Barbosa, S. A.
45. Towards a Probabilistic Model of Fluid Pressure Changes During Earthquakes. Weaver, K. C., Arnold, R., **Townend, J.**, Cox, S. C.
46. Using Ambient-Noise Based Ellipticity and Delay Times to Probe Groundwater Changes in Southern California. **Syracuse, E. M.**, Delorey, A. A., Goldberg, H., Muir, J. B.
47. STUDENT: Seismoacoustic Insights From the May 22nd, 2016 Iliamna Volcano Rock and Ice Avalanche. **Toney, L. D.**, Fee, D., Haney, M., Matoza, R. S., Allstadt, K. E.
48. STUDENT: Seismic Monitoring of Mass Wasting Events Following the 2017 Brian Head Wildfire in Southern Utah. **Forbes, N. M.**, Koper, K. D., Burlacu, R., Jewell, P.
49. Microseismicity Detection Across the Antarctic Continent. **Walter, J.**, Peng, Z., Rosson, Z., Hansen, S.

Using Repeating Seismicity to Probe Active Faults (see page 1040).

50. A Repeating Earthquake Catalog for New Zealand. **Chamberlain, C. J.**, Townend, J., Hughes, L., Thomas, A. M.
51. Systematic Search for Repeating Earthquakes Along Haiyuan Fault in Northeast Tibet. Deng, Y., **Peng, Z.**, Yang, Z.

State of Stress and Strain in the Crust and Implications for Fault Slip Based on Observational, Numerical and Experimental Analysis (see page 1040).

52. Uppermost Mantle Velocity and Anisotropy Beneath Mongolia and Its Adjacent Regions. **He, J.**
53. STUDENT: Localizing Interseismic Deformation With Far-Field Loading Around Locked Strike-Slip Faults. **Zhu, Y.**, Wang, K., He, J., Nissen, E., Cao, J.
54. A Seismic Event From a Limestone Mine Collapse in Southern Korean Peninsula. **Kim, G.**, Cho, C., Che, I.
55. The 2015 Plainfield, CT Earthquake Swarm: Induced Earthquakes Due to an Abandoned Quarry? **Ebel, J. E.**, Starr, J., Aubin, P. W., Thomas, M. A.
56. 22 May 1971 and 1 May 2003 Bingöl Earthquakes in Eastern Turkey. **Kalafat, D.**, Cakir, R.
57. Optimized Moment Tensor Inversion in Effective Three-Dimensional Seismic Earth's Model. **Burgos, G.**, Guillot, L., Landes, M., Capdeville, Y., Shapiro, N.
58. Seismicity in the Region of the Gulf of California, Mexico From 1900 to 2018. **Castro, R. R.**, Mendoza, A., Pérez-Vertti, A.
59. STUDENT: Focal Mechanisms of Microseismicity in the San Jacinto Fault Zone Region of Southern California. **White, M. C. A.**, Ben-Zion, Y., Vernon, F. L.
60. Joint Analysis of Seismic, Geologic, Resistivity and Topographic Data Collected Within the San Jacinto Fault Zone Trifurcation Area Near Anza, California. **Share, P.**, Štěpančíková, P., Tábořík, P., Stemberk, J., Rockwell, T. K., Wade, A., Arrowsmith, R., Donnellan, A., Vernon, F. L., Ben-Zion, Y.
61. Remote Triggering of Microseismicity at Mt. Erubus, Antarctica. **Peng, Z.**, Li, C., Walter, J., Ji, M., Liu, G., Aster, R.

62. Interseismic Velocity Data Along the Conjugate Strike-Slip Faults From Sentinel-1 Satellite. **Li, Y.**

The M7 Anchorage Earthquake: Testing the Resiliency of South-Central Alaska (see page 1043).

63. A Cursory Study of Behavior of Three Instrumented Buildings During the Recent M7.0 Anchorage, AK, Earthquake of November 30, 2018. **Celebi, M.**
64. Intraslab Deformation in the 30 November 2018 Anchorage, Alaska Mw 7.0 Earthquake. **Liu, C.**, Lay, T.
65. Effect of Surficial Geology on Earthquake Ground Motions From the 2018 Mw 7.0 Anchorage Earthquake in Anchorage, Alaska. **Cannon, E. C.**, Dutta, U., Thornley, J.
66. Student: Co-Seismic Vertical Deformations of the 30 November 2018 M7.0 Anchorage Earthquake, Alaska. Köksal, D., **Cakir, R.**, Eronat, H. A.
67. Impacts on School Resilience Caused by the M7 November 30, 2018 Anchorage Earthquake. Hassan, W., Motter, C., **Thornley, J.**, Rodgers, J.
68. Analysis of Spatial Variation of Seismic Ground Motions in the Anchorage Bowl From 30th November, 2018 Anchorage Earthquake (Mw 7.0). **Dutta, U.**, Thornley, J., Uddin, M. S., Yang, Z.
69. Student: Stochastic Modeling of the November 30th M7.0 Anchorage Earthquake. **Dow, S. K.**, Dutta, U.
70. Delaney Park Downhole Array in Anchorage, Alaska—Site Properties Inferred From M7 Anchorage, Alaska Earthquake. **Kalkan, E.**, Wen, W.
71. USGS—FEMA Collaboration on Post-Earthquake Loss Estimates and Assessments: A Case Study of the November 30, 2018 M7.0 Anchorage, Alaska Earthquake. **Bausch, D.**, Burns, J., Wald, D. J., Jaiswal, K., Marano, K., Rozelle, J., Chatman, A.
72. Comparisons of Site-Specific Ground Motion Estimates and Observations in the 2018 Anchorage M 7.0 Earthquake. **Wong, I. G.**, Thomas, P.

Large Intraslab Earthquakes (see page 1045).

73. Student: Remote Dynamic Triggering of Intermediate-Depth Earthquakes in the Mariana Subduction Zone Following the 2012 Indian Ocean Earthquake. **Price, A.**, Wiens, D. A.
74. Student: One Doublet in Two Slabs: The 2018 Mw 8.2 and 7.9 Fiji Deep Earthquakes. **Jia, Z.**, Shen, Z., Zhan, Z., Li, C., Peng, Z., Gurnis, M.
75. Aftershock Sequences of Intermediate-Depth Earthquakes Beneath Japan. Baez, C. M., **Warren, L. M.**
76. The September 19, 2017 (Mw 7.1), Intermediate-Depth Mexican Earthquake: A Slow and Energetically Inefficient Deadly Shock. Mirwald, A., **Cruz-Atienza, V. M.**, Díaz-Mojica, J., Iglesias, A., Singh, S. K., Villafuerte, C., Tago, J.
77. Intraslab Versus Megathrust Earthquakes: Spectral Characteristics Result in Distinct Lacustrine Deposits. **Van Daele, M.**, Vanneste, K., Moernaut, J., Araya-Cornejo, C., Pille, T., Schmidt, S., Kempf, P., Meyer, I., Cisternas, M.
78. Student: Stress Drop Estimates of Deep Earthquakes Based on Empirical Green's Function Analysis. **Liu, M.**, Huang, Y., Ritsema, J.
79. Student: Matched Filter Detection of the 2018 Fiji Deep Doublet Sequences. **Li, C.**, Peng, Z., Zhan, Z., Jia, Z., Shen, Z.
80. Student: Precise Relocation of Deep Double Earthquake Subevents. **Liu, J.**, Warren, L. M.

Structural Seismology: From Crust to Core (see page 1046).

81. Surface Wave Tomography via Higher-Order Interferometry. Zhang, S., Feng, L., Wang, H., **Ritzwoller, M.**
82. Student: Radial Anisotropy of Antarctica From Surface Wave Ambient Noise Tomography. **Zhou, Z.**, Wiens, D. A., Shen, W., Hansen, S., Aster, R., Nyblade, A.
83. Different Patterns of Northward Advancing Indian Plate Beneath Western Tibet Revealed by Anisotropy Tomography. **Zhang, H.**, Li, Y.
84. Seismic Anisotropy of the Crust and Upper Mantle Beneath the Northeastern Margin of the Tibetan Plateau. **Ju, C.**, Zhang, H., Zhao, J.
85. Seismological Explorations of Earth's Outer Core: Normal Mode and Body Wave Analyses. **Irving, J. C. E.**, Cottaar, S., Lekic, V., Wu, W.
86. Student: Crustal Seismic Discontinuities Under Mexico City Observed With Receiver Functions. **Pita-Sllim, O. D.**, Perez-Campos, X., Aguilar-Velázquez, M. J., Rodríguez, M., González, A., Espinosa, V. H., Bello, D., Quintanar, L., Ramírez-Guzmán, L., Cárdenas, A., Pérez, J., Rodríguez-Rasilla, I.
87. Student: Seismic Crustal Velocity and Structure of the Texas-Gulf of Mexico Passive Margin From Waveform Inversion Using Global Optimization. **Thangraj, J.**, Pulliam, J.
88. Mantle Discontinuities From Reflected Phases in the Tonga Subduction Zone. Hrubcova, P., **Vavrycuk, V.**
89. Student: Inversions of Teleseismic P-Wave Coda Autocorrelations for Estimating Crustal Structure Below a Floating Ice Platform. **Baker, M. G.**, Aster, R., Wiens, D. A., Nyblade, A., Bromirski, P. D., Gerstoft, P., Stephen, R. A.
90. Pattern of Seismic Anisotropy in the Crust and Upper Mantle Around the Margin Zone of Eastern Tibetan Plateau. **Gao, Y.**, Shi, Y., Wang, Q.
91. Student: SSsPmp: Can We Expand the Applicable Epicentral Distance (Δ) for Virtual Deep Seismic Sounding? **Wang, S.**, Klemperer, S.
92. Student: Shear Wave Velocity Model of the Southeastern United States From Ambient Noise

Tomography With Double Beamforming. **Barman, D.**, Pulliam, J., Quiros, D.

93. Ambient Noise Tomography of the Saudi Arabian Shield. **Civilini, F.**, Mooney, W. D., Zahran, H. M.
94. On the Application of Phase-Weighted Stacking to Suppression of Sediment Reverberations in Receiver Functions. **Ball, J. S.**, Schulte-Pelkum, V.

Emerging Science from the EarthScope Transportable Array in Alaska and Western Canada (see page 1049).

95. Student: A High-Resolution 3D Vs Model of Alaska Revealed by Surface Waves. **Feng, L.**, Ritzwoller, M., Liu, C., Shen, W.
96. Student: The Investigation of the Alaskan Interior Using Ambient Seismic Noise. **Boschelli, J.**, Herrmann, R. B.
97. Student: Identification and Relocation of Earthquakes in the Sparsely Instrumented Mackenzie Mountain Region, Yukon and Northwest Territories, Canada. **Heath, D. C.**, Aster, R., Schutt, D., Freymueller, J. T., Cubley, J.
98. Multi-Scale Lithospheric Architecture of Alaska Inferred From Receiver Functions. **Miller, M. S.**, O'Driscoll, L. J., Porritt, R. W., Roeske, S. M.
99. Mapping the Alaskan Moho: An Exercise in Reproducible Science. **Moresi, L.**, Miller, M. S.
100. New Constraints on Crust and Mantle Structure Surrounding the Beaufort Sea, Western Canadian Arctic. **Schaeffer, A. J.**, Audet, P., Cairns, S., Elliott, B., Falck, H., Bostock, M. G., Darbyshire, F., Esteve, C., Snyder, D.

New Frontiers in Global Seismic Monitoring and Earthquake Research (see page 1051).

101. Global and Local Scale High-Resolution Seismic Event Catalogs for Algorithm Development and Testing. **Young, C. J.**, Linville, L., Aur, K. A., Brogan, R.
102. Recent Upgrade of the ISC Bulletin and Associated Datasets. **Storchak, D. A.**, Di Giacomo, D., Lentas, K., Brown, L., Harris, J.
103. First Results of CISA, The New Central Italy Seismic Array. **Braun, T.**, Caciagli, M., Famiani, D., Govoni, A., Handerek, K., Mariotti, M., Martini, M., Thorossian, W., Wassermann, J. M.
104. IRIS DMC's Latest Data Products. **Bahavar, M.**, Trabant, C., Van Fossen, M., Ahern, T., Carter, J.
105. Performance and Future Development of the Chilean Seismic Network. **Barrientos, S. E.**
106. Oklahoma Geological Survey Regional Network. **Walter, J.**, Ogwari, P. O.
107. The Advanced National Seismic System Comprehensive Earthquake Catalog. **Earle, P.**, Ambruz, N. B., Fee, J. M., Martinez, E. M.
108. Exploring the Use of Deep-Learning to Aid Global Earthquake Monitoring at the NEIC. **Yeck, W. L.**, Patton, J. M., Ross, Z. E., Earle, P., Benz, H. M.

Next Generation Seismic Detection (see page 1052).

109. Applying Waveform Correlation to Aftershock Sequences Using a Global Sparse Network. **Sundermier, A.**, Tibi, R., Young, C. J.
110. Real-Time In-Situ Seismic Imaging. Song, W., **Kedar, S.**
111. Student: A Progress Report on a Large MERMAID Deployment Into the Pacific Ocean. **Simon, J. D.**, Simons, F. J., Nolet, G.
112. Student: Is the Sangre de Cristo Fault in the Rio Grande Rift Reawakening? **Bell, J. P.**, Sheehan, A. F., Kirkham, R. M., Harris, D., Yeck, W. L.
113. Incorporating AI in Routine Seismic Network Operations in Southern California. **Hauksson, E.**, Ross, Z. E., Bhadha, R., Yu, E., Andrews, J. R.

Methods for Site Response Estimation (see page 1053).

114. Strong Ground Motion Site Effects in the Central United States: Issues and Alternatives. **Wang, Z.**, Carpenter, S., Woolery, E. W.
115. A Graphical Dispersion Curve Editing Tool for Seismic Site Characterization Using Surface Waves. **Yong, A.**, McPhillip, D., Martin, A. J.
116. Site Response of Levees From a 4 Element Accelerometer Array at Sherman Island, CA. **Fletcher, J.**, Erdem, J.
117. Student: An Examination of Low-Frequency Amplification and High-Frequency Attenuation Effects in the Gulf and Atlantic Coastal Plain Using Spectral Ratios. **Guo, Z.**, Chapman, M. C.
118. Basement Topography of Kathmandu Valley by Array Microtremor Observations. **Poovarodom, N.**, Jirasakjamroonsri, A., Chamlagain, D., Warnitchai, P.
119. Exploring Alternative Pathways for Modelling Site Response for Seismic Risk at a Regional Scale using Insights from Strong Motion Databases. Weatherill, G., **Kotha, S.**, Cotton, F.
120. Seismic and Liquefaction Hazard Maps for Dyer County, Northwestern Tennessee. **Cramer, C. H.**, Van Arsdale, R. B., Arellano, D., Pezeshk, S., Horton, S. P., Weathers, T., Nazemi, N., Tohidi, H., Bhattarai, R., Reichenbacker, R.
121. Seismic Response Estimation of the Site of the Italian Accelerometric Station IT.CSA. **Famiani, D.**, Cara, F., Bordoni, P., Brunori, C., Di Giulio, G., Felicetta, C., Mercuri, A., Pizzimenti, L., Todrani, A., Cultrera, G.
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From Drifting to Anchored: Advances in Improving Absolute Hypocenter Location Accuracy for Natural, Induced and Explosion Seismic Events

Oral Session · Wednesday · 8:30 AM · 24 April · Cascade I
Session Chairs: Alexandros Savvaidis, Anthony Lomax, William L. Yeck, Stephen C. Myers.

Absolute Hypocentral Location Improvements With 3D Velocity Model Optimization: Application to Duvernay, Western Canada

VAEZI, Y., Nanometrics Inc., Ottawa, Canada, yoonesvaezi@nanometrics.ca; BOOTERBAUGH, A., Nanometrics Inc., Ottawa, Canada, aaronbooterbaugh@nanometrics.ca; STACEY, M., Nanometrics Inc., Ottawa, Canada, markstacey@nanometrics.ca; KARIMI, S., Nanometrics Inc., Ottawa, Canada, sepidehkarimi@nanometrics.ca; BATURAN, D., Nanometrics Inc., Ottawa, Canada, dariobaturan@nanometrics.ca

The reliability of absolute hypocentral locations is of paramount importance as they form the basis for characterizing natural and induced seismicity. Apart from acquisition geometry and phase picking errors, velocity model errors are the main source of event location uncertainty, especially on local arrays, commonly used for induced seismic monitoring. We present a methodology for constructing and further calibrating/optimizing a 3D velocity model to reduce uncertainty in event locations recorded in the Duvernay Subscription Array (DSA) in Alberta, Canada. The method involves building an initial 3D velocity model by interpolating numerous P- and S-phase sonic logs from nearby wells. The model is constrained by structural horizon surfaces and formation tops obtained from surface seismic to ensure agreement with actual Earth's subsurface velocities and their physical complexity. A combination of cross-validation driven outlier removal and a smoothing operator via an elliptical inverse distance weighted exponential function, help remove poor data and limit unrealistic velocity contrasts. We also calculate station statics and include them in a grid search location algorithm utilizing the new 3D model to relocate the existing event catalog in the DSA network that had initially been located using a simple 1D velocity model. The relocated events show higher precision as they result in tighter clusters with reduced RMS residuals and lower station phase residuals. They also show higher accuracy as they provide better agreement with common events in well-constrained microseismic catalogs. As expected for surface monitoring, the velocity model optimization affects the depths of the events more severely than their lateral positions, which are more stable. The azimuthal coverage and redundancy from addition of potential extra stations can further lower the location uncertainty caused by the configuration bias and arrival-time picking errors.

Accuracy and Uncertainty of TexNet Absolute Seismic Event Location in West Texas

LOMAX, A., ALomax Scientific, Mouans-Sartoux, France, anthony@alomax.net; SAVVAIDIS, A., University of Texas at Austin, Texas, USA, alexandros.savvaidis@beg.utexas.edu

Likely induced seismicity has been recorded in the central U.S., including in Texas. This seismicity, possibly associated with hydrocarbon production and associated wastewater disposal, has led to substantial public discussion regarding cause, public safety, and potential infrastructure damage. To monitor this seismic activity the 84th Texas Legislature funded the statewide, Texas Seismological Network (TexNet).

High accuracy and realistic uncertainty estimates for absolute location of seismic events is critical to TexNet monitoring, especially when seismic sources must be associated with known locations of human activity. Error in absolute location has many causes, including error in the seismic velocity model used for calculating travel-times, error or mis-identification of phase onset picks, and inadequacies of the network station geometry.

Here we consider absolute location accuracy and uncertainty estimates for TexNet monitoring of the West Texas area around Pecos, Texas. We seek to improve absolute location accuracy considering: use of realistic 3D models, robust location algorithms, additional stations, and station travel-time corrections. We investigate location uncertainty estimates through mapping and assessment of spatial location error considering: picking errors, network geometry, different station sub-sets and velocity models, and station travel-time corrections. Additionally, in the absence of accurate ground-truth events, we probabilistically associate the seismicity with hydraulic fracturing space-time information to generate pseudo ground-truth station corrections and we examine their effect on absolute locations.

Feature-Based Bayesian Inference for Seismic Event Monitoring

CATANACH, T. A., Sandia National Laboratories, New Mexico, USA, tacatan@sandia.gov; DOWNEY, N. J., Sandia National Laboratories, New Mexico, USA, njdowne@sandia.gov; YOUNG, C. J., Sandia National Laboratories, New Mexico, USA, cjyoung@sandia.gov

Robustly detecting and locating relatively weak seismic events from noisy waveforms requires moving beyond pick-based methods and processing more information from the waveform. Further, because these events push the limits of our detection abilities, new methods must account for modeling and sensor uncertainties when making predictions about an event. This requirement motivates the use of Bayesian methods. An ideal method would assess the likelihood of a candidate event given the data based upon how well that event could predict the observed waveform data. This requires a model that predicts a seismic waveform at a monitoring station given an event hypothesis. Unfortunately, generative waveform models are computationally expensive and have many unquantified uncertainties. Methods like SIGVISA (Moore *et al.* 2017) have worked to bridge this gap by learning a generative model from historic data that does not require full simulations. This approach has been shown to significantly reduce location errors and improve event detection at the cost of needing to learn and then infer a complex generative signal model that can replicate the seismic waveform.

In contrast to predicting the waveform, we can design a Bayesian method that predicts waveform features. Using historic data or simulations, building models that predict features given a seismic event can be easier and more computationally tractable than direct waveform prediction while doing inference. Inspired by the WCEDS event detection and location method (Arrowsmith *et al.* 2016), the waveform features we consider are P and S wave arrival time and duration and the integrated power of the signal during the P, S, and pre-signal background intervals of the waveform. Our framework is general, and hence can use different features and/or transformed data, *e.g.* after STA/LTA processing. We demonstrate the feature-based framework and evaluate its performance on synthetic and real datasets for regional seismic event monitoring.

Machine Learning for Emulation of Seismic-Phase Travel Times in 3D Earth Models

MYERS, S., Lawrence Livermore National Laboratory, California, USA, myers30@llnl.gov; JENSEN, D., Lawrence Livermore National Laboratory, California, USA, jensen54@llnl.gov; SIMMONS, N., Lawrence Livermore National Laboratory, California, USA, simmons27@llnl.gov

Seismic-phase travel time prediction errors are the predominant source of bias in estimates of event locations. Seismic-phase travel times computed using a global 3-D Earth model can reduce travel-time prediction error to approximately 0.6 seconds on average, leading to median event epicenter error of approximately 6 km for a global or regional network with azimuth gap less than 120°. However, using a generalized 3-D model can be cumbersome because computation of travel times through a 3-D model can take 0.1 to 1.0 seconds, which is orders of magnitude too slow for real-time monitoring systems. Alternatively, travel times can be precomputed, but this approach is difficult to implement for a network comprised of a constantly evolving station set.

In an effort to make 3-D models easier to utilize, we develop a machine learning approach to emulate seismic-phase travel time calculation through a 3-D model. Our goal is to establish a computationally efficient way to implement 3-D models in real-time monitoring systems and enable routine utilization of 3-D models in basic research. We demonstrate this approach by training a gradient-boosted regressor using travel times computed through the LLNL-G3D model. The training set is millions of travel times from randomly selected event locations to each network station, as well as randomly selected station locations to provide predictive capability to new stations. Preliminary tests find that machine learning effectively captures global effects like ellipticity and event depth. The effects of the 3-D model can be emulated with average errors of approximately 0.38 seconds which is well below the error of the 3-D model itself. With computation time on the order of 10 micro-seconds, the machine learning emulator may be a practical way to utilize 3-D models in event locators. *Prepared by LLNL under Contract DE-AC52-07NA27344.*

The IASPEI Reference Event (GT) List (1959-2017) Maintained by the ISC

LENTAS, K., International Seismological Centre, Thatcham, United Kingdom, kostas@isc.ac.uk; STORCHAK, D. A., International Seismological Centre, Thatcham, United Kingdom, dmitry@isc.ac.uk; DI GIACOMO, D., International Seismological Centre, Thatcham, United Kingdom, domenico@isc.ac.uk; HARRIS, J., International Seismological Centre, Thatcham, United Kingdom, james@isc.ac.uk

As part of its mission, the International Seismological Centre (ISC) maintains the IASPEI Reference Event List (Ground Truth, GT). This is a database of earthquakes and explosions, for which epicentres are known with high confidence, with an error typically up to 10 km that is defined by the 95% confidence level. Specifically, the events are defined as GTX, where the source is known within X km, to a 95% confidence level.

The GT database currently contains ~9,500 events that occurred between 1959 and 2017. These events are large enough to be recorded at teleseismic distances but small enough to be considered as point source (mb/MS < 6.0). The GT events are associated with over 1 million seismic phases recorded from local/regional to teleseismic distances, and therefore, is an ideal dataset for velocity model/location calibration purposes. In particular, the new ISC location method (Bondar & Storchak, 2011) has been extensively tested using GT events and shown acceptable fit before it was put in operation at the ISC.

The database is maintained by the ISC under the supervision of the IASPEI working group on Improved Locations. The ISC routinely searches for candidate events in line with (Bondár et al, 2008) or (Bondár & McLaughlin, 2009), relocates and validates them accordingly, based on selection criteria with respect to phase arrivals in local distances, azimuthal gap and secondary azimuthal gap metrics.

Useful GT events are also proposed as a result of RSTT (regional seismic travel times) workshops held by the CTBTO where participants from seismological networks in a specific region bring together the results of their analysis of waveforms that are often not openly available.

Typically, events with a 95% confidence level within the 0-5 km range are nuclear and chemical explosions, rock bursts, mine-induced events, as well as a few earthquakes, whereas GT5 events are typically earthquakes with crustal depths.

We encourage the use of this dataset for testing and validation of new location algorithms, velocity models and corresponding location uncertainties.

Explosion Seismology Applications

Oral Session · Wednesday · 10:45 AM · 24 April · Cascade I
Session Chairs: William R. Walter, Robert E. Abbott, Jessie L. Bonner, Catherine M. Snelson.

Insights From the Source Physics Experiments on Seismic Waves Generated by Explosions

WALTER, W. R., Lawrence Livermore National Laboratory, California, USA, walter5@llnl.gov; FORD, S. R., Lawrence Livermore National Laboratory, California, USA, ford17@llnl.gov; PITARKA, A., Lawrence Livermore National Laboratory, California, USA, pitarka1@llnl.gov; PYLE, M., Lawrence Livermore National Laboratory, California, USA, pyle4@llnl.gov; PASYANOS, M. E., Lawrence Livermore National Laboratory, California, USA, pasyanos1@llnl.gov; ICHINOSE, G. A., Lawrence Livermore National Laboratory, California, USA, ichinose1@llnl.gov; CHIANG, A., Lawrence Livermore National Laboratory, California, USA, chang4@llnl.gov; MELLORS, R. J., Lawrence Livermore National Laboratory, California, USA, mellors1@llnl.gov; EZZEDINE, S. M., Lawrence Livermore National Laboratory, California, USA, ezzedine1@llnl.gov; VOROBIEV, O. Y., Lawrence Livermore National Laboratory, California, USA, vorobiev1@llnl.gov; DODGE, D., Lawrence Livermore National Laboratory, California, USA, dodge1@llnl.gov; MATZEL, E., Lawrence Livermore National Laboratory, California, USA, matzel1@llnl.gov; WAGONER, J., Lawrence Livermore National Laboratory, California, USA, wagoner1@llnl.gov; HAUK, T., Lawrence Livermore National Laboratory, California, USA, hauk1@llnl.gov; SULLIVAN, D., Lawrence Livermore National Laboratory, California, USA, sullivan42@llnl.gov

The Source Physics Experiments (SPE) are a large multi-institutional (LANL, LLNL, SNL, MSTS and UNR) endeavor to improve our understanding of how explosions generate seismic waves, particularly shear waves to improve nuclear monitoring capabilities. The SPE includes a series of chemical explosions in southern Nevada in two different boreholes in contrasting geologies. The explosions vary in size and depth and for each borehole they are recorded on a common network, allowing ratios between events to be formed, canceling path and site effects and illuminating near source effects due to size, depth, and media. In Phase I, six chemical explosions ranging from about 0.1 to 5 tons in TNT equivalent yield were detonated between 2011 and 2016 in the same granite borehole. In Phase II, four chemical explosions will be detonated in the same borehole, but in a dry alluvium geology (DAG). The first explosion, DAG-1, was conducted on July 20, 2018 at depth of 385 m and had a TNT equivalent yield of approximately 1 ton. The second explosion, DAG-2 was successfully executed on December 19, 2018 at a depth of 300 m with a TNT equivalent yield of about 51 tons.

Comparing large-to-small spectral ratios shows the explosion media has a very large effect on the seismic waves generated. We show the spectral ratios are not well matched by existing explosion models, and that the dry alluvium geology produces smaller amplitudes and appears deficient in high frequency energy relative to explosions in granite. Here we report on the initial results of comparing and contrasting explosions characteristics in wet granite and dry alluvium, examining factors such as absolute depth and scale depth effects, shear wave generation, P/S and low/high frequency amplitude discrimination performance, and correlation behavior. These results are being used to develop a new explosion spectral model, to better predict the effects of small, over-buried explosions in both low and high gas porosity media.

Relationship Between DPRK Nuclear Events and Near-Field Response to Chemical Explosions in the Source Physics Experiment Series

STEEDMAN, D. W., Los Alamos National Laboratory, New Mexico, USA, dwsteed@lanl.gov; BRADLEY, C. R., Los Alamos National Laboratory, New Mexico, USA, cbradley@lanl.gov

The Source Physics Experiment (SPE) is developing a greater understanding of explosion phenomenology. In particular we are identifying mechanisms for generating shear which can complicate event discrimination. The program consists of two phases: Phase I in granite and Phase II in dry alluvium. Each phase included a series of chemical explosions of varying yield and depth to provide a range of scaled depth of burial (SDOB).

The test data reveal a near-field shear mechanism in the granite testbed due to slippage along natural joint sets that occurs as the shock wave passes. Specifically, compressive shock causes joint closure during loading with the combined joint surface resistance and in situ stress preventing slippage. Unloading creates an extensional state allowing joint dilation and release of stored shear energy. Evidence is provided by numerous velocity records from the test events indicating unexpectedly large tangential motion. We support this hypothesis using results from explicitly jointed finite element simulations. Phase II data from the unjointed alluvium testbed lack any character indicating a near-field source of shear content, providing a clear contrast between propagation in jointed and in unjointed media.

The composite Phase I data set indicates three regimes. Deeply overburied events do not generate sufficient energy to overcome resistance to slippage due to high confining stress. At "nominal" SDOB there is insufficient confinement stress to lock the joints. Moderately overburied tests provide the condition for shear release. We indicate a notional relationship between SDOB and the likelihood of shear release in SPE. We then link this observation to the recognized DPRK nuclear events that are observed to have large shear magnitudes and are estimated to range from nominally buried to moderately overburied. The comparison suggests an explanation for the confusion identifying the DPRK events as explosions as oppposed to earthquakes.

Distributed Acoustic Sensing Observations and Modeling of the DAG Series of Chemical Explosions

ABBOTT, R. E., Sandia National Laboratories, New Mexico, USA, reabbot@sandia.gov; MELLORS, R. J., Lawrence Livermore National Laboratory, California, USA, mellors1@llnl.gov; PITARKA, A., Lawrence Livermore National Laboratory, California, USA, pitarka1@llnl.gov

The Dry Alluvium Geology (DAG) series of chemical explosions aim to increase our understanding of explosion-source seismic, acoustic, and electromagnetic phenomenology. The explosion series takes place on the Nevada National Security Site (NNSS) in an alluvium geology. As of December 2018, two of the planned four explosions have been detonated in a common borehole on Yucca Flat: 1,000 kg TNT-equivalent at 385-m depth-of-burial and 50,000 kg TNT-equivalent at 300 m. A component of the DAG diagnostic instrumentation consists of surface-laid and downhole fiber optic distributed acoustic sensing (DAS) cables. A helically-wound fiber installed in two vertical boreholes 80-m from ground zero (GZ) and a traditional surface-laid straight fiber extending from GZ to 2 km recorded the explosions. We present both modeling and observations of the explosions. Phenomenology observed thus far include near-source generated S waves, post-event microseismicity, and surface spall. Sandia National Laboratories is a multimission laboratory managed and operated by National Technology and Engineering Solutions of Sandia, LLC, a wholly owned subsidiary of Honeywell International Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525.

Surface Ground Motion Prediction for Chemical Explosions in Alluvium

BONNER, J. L., Nevada National Security Site, Nevada, USA, bonnerjl@nv.doe.gov; ZEILER, C. P., Nevada National Security Site, Nevada, USA, zeilercp@nv.doe.gov; WHITE, R. L., Nevada National Security Site, Nevada, USA, whiterl@nv.doe.gov; MCLIN, K. L., Nevada National Security Site, Nevada, USA, mclinkl@nv.doe.gov; STEEDMAN, D. W., Los Alamos National Laboratory, New Mexico, USA, dwsteed@lanl.gov; EZZEDINE, S. M., Lawrence Livermore National Laboratory, California, USA, ezzedine1@llnl.gov

The Dry Alluvium Geology (DAG) experiment is the second phase of the Source Physics Experiments (SPE) at the Nevada National Security Site (NNSS). The SPE program is examining the phenomenology of explosions in granite (Phase I) and dry alluvium (Phase II). The DAG experiment seismo-acoustic networks and support infrastructure locations were selected based on ground motion predictions from the Perret and Bass (1975) alluvium regressions (PB75), which are based on free-field recordings of nuclear explosions in that medium. The PB75 model predicts two regimes, the initial non-linear regime, which is dominated by extremely high attenuation to scaled ranges from 30 to 150 m/kt$^{1/3}$, followed by a linear region of less attenuation. For the DAG predictions we extrapolated the model to scaled ranges beyond those covered by the PB75 dataset, and then doubled those values to account for surface reflection. The data recorded from the DAG-1 (1 ton) and DAG-2 (50 tons) explosions indicate that this methodology does not correctly predict the observed surface ground motions for these chemical explosions. The observed ground motions at near-source distances (<1 km) are significantly stronger than predicted by PB75, while at farther ranges, the data were below predictions. We will provide new predictive relationships for three-component ground motion in alluvium for chemical explosions at near-source distances. This work was done by Mission Support and Test Services, LLC, under Contract No. DE-NA0003624 with the U.S. Department of Energy. DOE/NV/03624—0346

Beyond Perret & Bass: Data Analysis and Simulation of DAG-1 & DAG-2 Chemical Explosions

EZZEDINE, S. M., Lawrence Livermore National Laboratory, California, USA, ezzedine1@llnl.gov; VOROBIEV, O. Y., Lawrence Livermore National Laboratory, California, USA, vorobiev1@llnl.gov; STEEDMAN, D. W., Los Alamos National Laboratory, New Mexico, USA, dwsteed@lanl.gov; BONNER, J. L., Mission Support and Test Services, Nevada, USA, bonnerjl@nv.doe.gov; ANTOUN, T. H., Lawrence Livermore National Laboratory, California, USA, antoun1@llnl.gov; BRADLEY, C. R., Los Alamos National Laboratory, New Mexico, USA, cbradley@lanl.gov; WALTER, W. R., Lawrence Livermore National Laboratory, California, USA, walter5@llnl.gov

The Source Physics Experiment (SPE) is an ongoing effort to improve explosion monitoring by conducting a series of chemical explosions at the Nevada National Security Site (NNSS) and using the resulting observations to improve and validate physics-based simulations of explosion phenomena. Four chemical explosions are being conducted in dry alluvium geology (DAG) as part of SPE Phase II. Two first explosions, DAG-1 & DAG-2 have been successfully executed in 2018. Perret & Bass in 1975 compiled free-field triplet peak accelerations, velocities and displacements of several historical nuclear shots. Using regressions, Perret & Bass inferred different regimes and correlations of the peak responses as a function of the scaled depth of burial. Peak responses of alluvium is characterized by two regimes: an initial non-linear regime followed by a linear one. The linear-regime onset in alluvium is at ~110 m kt$^{-1/3}$ and the largest scaled depth data point is ~350 m kt$^{-1/3}$. It is worth noting that beyond 350 m kt$^{-1/3}$ field designers are left at the mercy of the extrapolations of the suggested inferred regressions based on very limited data beyond the linear regime onset. Here, we will, first, address the pos and cons of Perret & Bass analyses and we will highlight inconsistencies. Second, Perret & Bass regressions are used for surface accelerometer emplacements using scaled slant distances and doubling the peak triplets to account for the effect of free surface. This has been proving successful for strong material, such as granite. It has, however, data collected during DAG-1 and DAG-2 have proved that the latter approach is non-reliable in alluvium. Using physics-based coupled numerical codes, Geodyn-L for non-linear regime and WPP for the linear regime, we develop a new sets of surface peak accelerations, velocities and displacements attenuation curves and their functional correlation forms to be used for the subsequent DAG-3 and DAG-4 experiments. Third, we assess the statistical differences and significances of the newly developed correlations versus Perret and Bass.

Reconstruction of the Three-Dimensional Acoustic Wavefield Induced by SPE Explosions and Implications for Explosion Yield Estimation

KIM, K., Lawrence Livermore National Laboratory, California, USA, kim84@llnl.gov; FORD, S. R., Lawrence Livermore National Laboratory, California, USA, ford17@llnl.gov; CHIANG, A., Lawrence Livermore National Laboratory, California, USA, chiang4@llnl.gov; BOWMAN, D. C., Sandia National Laboratories, New Mexico, USA, dbowman@sandia.gov

Underground explosions induce surface ground motions, which can generate acoustic waves in the atmosphere. Since the excitation of epicentral acoustic waves depends on the ground motion, acoustic signals may contain valuable information about explosion source parameters including explosion yield and emplacement (*e.g.*, depth of burial). Previous studies showed that the extent of the epicentral area may not be compact with respect to acoustic wavelengths of interest and the consequent wavefield may not be represented by a simple point source. This finite-size source is expected to excite directional acoustic wavefield whose amplitude strongly depends on azimuth and elevation angle. While the theory predicts complex wavefields, ground-motion induced acoustic wavefield in 3D has not thus far been fully measured nor explored comprehensively. While horizontal variation of the wavefield can be readily recorded by the ground-based acoustic sensor network, vertical variation is very difficult to capture using traditional microphone deployments. This study investigates the three-dimensional properties of the local acoustic wavefield induced by buried explosions during the Source Physics Experiment (SPE) Phase I. As acoustic measurements are limited to the ground for SPE Phase I, we infer the 3-D wavefield by the Rayleigh integral method with epicentral ground motions measured during the experiment. The synthetic wavefield predicted by the ground motion shows remarkably good agreement with the acoustic observations on the ground, which demonstrates that the acoustic wave is a direct response to the epicentral ground motion. We further investigate the directional properties of the induced acoustic waves in the vertical direction and their relationship with the yield and the depth-of-burial of the explosions.

Infrasound Source Modeling and Data Inversion Using Coupled Seismo-Acoustic Simulations

POPPELIERS, C., Sandia National Laboratories, New Mexico, USA, cpoppel@sandia.gov; PRESTON, L., Sandia National Laboratories, New Mexico, USA, lpresto@sandia.gov

Buried explosions are known to produce infrasonic signals in the atmosphere. The phenomena responsible for the generation of the infrasound include seismic-to-acoustic coupling at the Earth's free surface, surface waves, and spall. In a previous study, we inverted infrasonic data collected as part of the Source Physics Experiment and determined that the majority of the infrasound energy was generated by the spall. This determination was made by inverting the observed infrasound where the source model was characterized by a spall term as well as a buried isotropic explosion. The inversion suggests that the spall term explained about 99% of the observed data. However, the forward model was acoustic throughout, meaning that the elastic energy produced by the buried isotropic source was not correctly simulated, nor was the seismic-to-acoustic coupling at the Earth's surface. In this study, we investigate the degree to which this acoustic approximation influenced our initial conclusions. Specifically, we use a Sandia-developed finite difference code that contains both elastic and acoustic model regimes to produce axially symmetric models with source parameters similar to our previous work. Because the code properly simulates elastic and acoustic waves, we can generate more realistic Green's functions for the linear inversion of the data. We discuss 1) the effects that the more realistic Green's functions have on the inversion of the data, 2) the accuracy of our initial conclusions based on the purely acoustic model, and 3) whether low-cost, purely acoustic models are adequate for linear source inversions with observed infrasound data. Sandia National Laboratories is a multimission laboratory managed and operated by National Technology & Engineering Solutions of Sandia, LLC, a wholly owned subsidiary of Honeywell International Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525.

Explosion Source Models and the Scattering Origin of Regional Phases From SPE Phase 1 Coda Spectral Ratios

PHILLIPS, W. S., Los Alamos National Laboratory, New Mexico, USA, wsp@lanl.gov; PATTON, H. J., Los Alamos National Laboratory, New Mexico, USA, patton@lanl.gov; CLEVELAND, K. M., Los Alamos National Laboratory, New Mexico, USA, mcleveland@lanl.gov; LARMAT, C., Los Alamos National Laboratory, New Mexico, USA, carene@lanl.gov; STEAD, R. J., Los Alamos National Laboratory, New Mexico, USA, stead@lanl.gov

The Source Physics Experiment (SPE) chemical explosions provide comprehensive ground truth information, and near-source recordings that are rarely available in typical monitoring scenarios. Here, we analyze these data together with local and regional distance recordings to isolate source and propagation effects, and to potentially improve monitoring at distance. Manual inspection of SPE waveforms shows strong P and Rg phases in the near source region, with distinct crustal shear phases emerging at far-local distances (100 km). Near-local distance secondary phases are indistinct at high frequencies (*e.g.* 4-8 Hz), likely due to intense Rg-to-Rg scattering. We examine source spectral ratios, which can be measured to high precision by taking advantage of many SPE and independently operated stations, as well as the redundancy available from coda waves. Classical source models (Mueller and Murphy, 1971, MM71; Denny and Johnson, 1991, DJ91) predict the source ratios poorly; however, a hybrid model (MM71 with DJ91 cavity radii) performs better, and by varying cavity and elastic radii we obtain models that fit spectral ratios to within measurement precision. Finally, we observe a distinct spectral modulation at 6-9 Hz that is not predicted by classical models, most likely caused by short period surface waves (Rg) interfering with those produced by spallation of near surface layers. The same modulation is observed for compressional (P) and shear (S) waves at distance, indicating that local and regional phases originate as near-source Rg that is scattered into body waves. The scattering process must be accounted for quantitatively to best use remotely recorded signals to monitor treaty compliance, discriminate event types, and estimate explosion yields over broad regions.

Testing Explosion Source Models From Yield and Depth Analysis of Chemical Explosions Conducted in Alluvium

PASYANOS, M. E., Lawrence Livermore National Laboratory, California, USA, pasyanos1@llnl.gov; WALTER, W. R., Lawrence Livermore National Laboratory, California, USA, bwalter@llnl.gov; FORD, S. R., Lawrence Livermore National Laboratory, California, USA, sean@llnl.gov

We have developed the envelope yield method (Pasyanos *et al.*, 2012) to estimate explosion source parameters for a variety of sources (chemical and nuclear), yields (sub-ton to ktons), depths (deeply buried to above surface) and distances (local and regional). Using the method, observed coda levels are tied to direct phase amplitudes. When corrected for propagation, these amplitudes have a physical basis to yield and depth through explosion source models such as Mueller-Murphy, Denny-Johnson, and Walter-Ford. While these models have been developed and validated using hard rock, the models are less mature for explosions in alluvium, which show important differences in the low-frequency moment rate level as well as in the high-frequency roll-off above the corner frequency. Changes in the material properties also affect the far-field displacement. Variations among the various source models and properly accounting for material properties have important implications for yield determination and source identification of small events and in uncalibrated media. In Phase II of the Source Physics Experiment (SPE), chemical explosions are now being conducted in Dry Alluvium Geology (DAG). We use local and regional data for DAG-1 (908 kg equivalent TNT @ 385 m depth) and DAG-2 (50997 kg TNT @ 300 m depth), and legacy U.S. nuclear tests conducted in alluvium (*e.g.* Riola) for which we have ground truth (announced yields and depths from DOE NV-209). We use the recordings to test several variations of the material model of alluvium for existing source models to best match the known GT.

Application of Advanced Numerical Techniques to Improve the Estimation of Explosion Yield and Quantify Its Uncertainty

YOO, S., Weston Geophysical Corp., Massachusetts, USA, syoo@westongeo.com

Improved characterization of low-yield underground explosion sources has become an increasingly active research topic in the last decade. We are addressing this research problem by developing a new yield estimation technique that incorporates improved predictions of seismic waveform envelopes, calibrated propagation models and realistic uncertainty estimates. To improve seismic waveform prediction, we have developed a new hybrid computational technique that models both multiple-forward and wide-angle scattering effects. The results indicate that we improve the predicted envelope fits over the entire waveform and account for direct-wave and early coda complexity. To generate calibrated models of wave propagation, we compute high-resolution tomographic attenuation models for P_g, P_n, S_n and L_g regional phases. We are also applying numerical methods to estimate the uncertainties of the waveform envelope modeling parameters and our attenuation models. For example, we apply a Bayesian inversion technique based on Markov-Chain Monte Carlo sampling methods to determine posterior distributions of the envelope modeling parameters. We also assess the non-uniqueness and quantitative bounds of our tomographic attenuation models using a null-space shuttle method. Our goal is to incorporate the estimated uncertainties in measured amplitudes, propagation and site amplification effects, as well as prior information and bounds on source parameters, in a Bayesian inference scheme to estimate a maximum *a posteriori* solution for explosion yield and depth, with quantified uncertainties. We will demonstrate the new techniques with regional seismic records from the Nevada National Security Site in the United States and the Punggye-ri Nuclear Test Site in North Korea.

Large-N Seismic Recordings at the Source Physics Experiment (SPE) Phase II Site

CHEN, T., Los Alamos National Laboratory, New Mexico, USA, tchen@lanl.gov; SNELSON, C., Los Alamos National Laboratory, New Mexico, USA, snelsonc@lanl.gov

The Source Physics Experiment (SPE) is a multi-institutional, multi-disciplinary project that consists of a series of chemical explosions conducted at the Nevada National Security Site (NNSS). The goal of SPE is to understand the complicated effect of geological structures on seismic wave propagation and source energy partitioning, develop and validate physics-based modeling, and ultimately better monitor nuclear explosions. The SPE program is multi-phase with the completion of Phase I located in hard rock (granite) in 2017 and the initiation of Phase II (DAG – Dry Alluvium Geology) located in weak rock (alluvium) in 2018. A large-N seismic array was deployed at the SPE Phase II site to image the full 3-D wavefields from multiple planned explosions. The large-N seismic array consists of 500 three-component geophones covering an area of approximately 2 x 2 km. This array started operation in December 2018 and will continue into 2019. The recordings include the DAG-2 chemical explosion (50 tons on Dec 19, 2018), earthquakes, ambient noise and a series of weight drops. In this work, we present first analysis of the data recorded at the DAG large-N array and compare them with predictions. We investigate how well the large-N array may improve our understanding of subsurface structure and source characteristics.

Azimuthally Dependent Scattering of High Frequency Vertical Component Seismic Data at the Large N Array, Source Physics Experiment

DARRH, A., Sandia National Laboratories, New Mexico, USA, adarrh@mymail.mines.edu; POPPELIERS, C., Sandia National Laboratories, New Mexico, USA, cpoppel@sandia.gov; PRESTON, L., Sandia National Laboratories, New Mexico, USA, lpresto@sandia.gov

The Large-N array of the Source Physics Experiment (SPE) consisted of 496 vertical component geophones that recorded the seismic wave field produced by the SPE-5 buried chemical explosion. One of the goals of the Large-N experiment was geophysical characterization of the subsurface, which relies on coherent wave field processing methods. However, preliminary observations of the data showed a high degree of azimuthally dependent seismic scattering, hindering surface wave analysis. For the work presented here, we quantify the azimuthal dependence of the wave field scattering to guide future coherent wave field processing methods. Specifically, we form ten linear arrays, with various source-receiver azimuths, from a subset of the Large-N stations. For each linear array, we evaluate wave field coherence as a function of frequency and inter-station distance. For P waves, we observe that there is a strong azimuthal dependence of wave coherence, with the highest degree of scattering occurring in a northwest/southeast propagation direction. This suggests that there are structural elements beneath the Large-N array that affect the direct source to receiver body wave ray path. We also observe that the scattering of the post-P energy displays a coherence that is dependent on both frequency and azimuthal direction. This energy is preferentially coherent in the southwest-to-northeast propagation direction, consistent with the strike of the steeply dipping boundary fault adjacent to the northeast side of the Large-N array at low frequencies (<10 Hz). At higher frequencies, the azimuthally dependent wave coherence diminishes, suggesting that the scattering of high frequency portion of the post-P wave field is independent of the large-scale geologic structure at this site.

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Analysis of Local Explosion Waveforms for 1D Crustal Structure Using Interactive Non-Linear Block Thresholding and Phased Array Methods

LANGSTON, C. A., University of Memphis, Tennessee, USA, clangstn@memphis.edu; ZEILER, C. P., Mission Support and Test Services, Nevada, USA, zeilercp@nv.doe.gov

The 2016 IRIS Wavefields experiment geometry allows for an interesting variety of seismological techniques for inferring local crustal structure from a dataset of 12 well-timed and positioned explosions near the array. Contracted by the Air Force Research Laboratory, explosions ranged from 2000 lbs to 250 lbs charge size with four explosions at each of three locations 15, 35, and 67 km from the center of the IRIS experiment. Subarrays of the 381 three-component elements are used to accurately determine wave phase velocities and azimuths for a variety of distinct, local wave phases and the relatively broad bandwidth of the 5Hz nodal sensors produces waveforms rich in frequency-dependent wave propagation information. Noise is suppressed using a non-linear block thresholding scheme on the continuous wavelet transform of the data. In addition, scale-time windowing before inverse transforming cleanly separates the fundamental mode Rayleigh wave from the first higher mode, allowing for independent measures of both group and phase velocity as a function of frequency for each mode. Removing the modes from the data via scale-time windowing exposes local P and S phases for better analysis with the phased subarrays. Observations of relative P and S wave travel times, phase velocities, and Rayleigh mode dispersion curves are combined with a nearby acoustic well log of the Paleozoic sediments and shallow crystalline basement to produce a 1D starting model for full waveform inversion. Use of phased array and wavelet transform thresholding techniques produces many constraints on the structure model that are essential for understanding the source excitation of local and regional seismic phases from small explosions.

Modeling 0-2 Hz 3D Wave Propagation of the North Korean Nuclear Tests Across the Sea of Japan

YEH, T., San Diego State University/University of California, San Diego, California, USA, tyyeh316@gmail.com; OLSEN, K. B., San Diego State University, California, USA, kbolsen@sdsu.edu

We have simulated 0-4 Hz wave propagation for the 2009 nuclear test on the Korean Peninsula in the SALSA3D velocity model developed by Sandia and LANL (Begnaud, 2015). The simulations are carried out using the highly scalable 4th-order finite-difference GPU-enabled code AWP-ODC code with discontinuous mesh capabilities. Broadband observations at regional distances (~500 km) are well modeled when appropriate statistical distributions of small-scale heterogeneities are included in the crust. We find that at INCN, the phase amplitudes and Pn/Lg, Pg/Lg and Pn/Sn ratios for data fall within the standard deviation of those calculated from the synthetic ensembles for an isotropic source at the North Korea Nuclear Test Site (NKNTS) for almost all frequencies between 0.5 and 4 Hz. This result is then used to calculate P/S ratios for isotropic and double-couple sources at all distances from NKNTS to station INCN. We carried out array analysis for KSRS data and synthetics for the 2009 event. Our results suggest that crustal small-scale heterogeneities with parameters constrained by our study are needed to reproduce the coherence from the data, and that array analysis is capable of constraining the properties of the velocity structure in this region. We find that a different scattering behavior appears to be associated with the two different source types (*e.g.*, P-S versus S-P scattering), indicating that the predominant S wave train for the double-couple source is very efficiently generating converted S-P scattered waves after Pn. We also model broadband stations in Japan for the 2017 mb=6.3 event at NKNTS (~1200 km) to better understand the leakage of Lg energy at the transition between the continental and oceanic crustal layers, as well as the formation of the long-period Rayleigh waves widely observed at stations in Japan. We show the contributions in the synthetics from both isotropic and non-isotropic moment tensor components to address S-wave generation in the source area.

Local and Regional Seismic Characteristics of Chemical Explosions in Eastern Margin of the Junggar Basin, Northwest China

ZHAO, L., Institute of Geology and Geophysics, Chinese Academy of Sciences, Beijing, China, zhaolf@mail.iggcas.ac.cn; XIE, X., Institute of Geophysics and Planetary Physics, University of California, Santa Cruz, California, USA, xxie@ucsc.edu; MA, X., Key Laboratory of Earth and Planetary Physics, Institute of Geology and Geophysics, Chinese Academy of Sciences, Beijing, China, maxiao100@mail.iggcas.ac.cn; ZHANG, L., Key Laboratory of Earth and Planetary Physics, Institute of Geology and Geophysics, Chinese Academy of Sciences, Beijing, China, seisleslay@mail.iggcas.ac.cn; ZHEN-XING, Y., Key Laboratory of Earth and Planetary Physics, Institute of Geology and Geophysics, Chinese Academy of Sciences, Beijing, China, yaozx@mail.iggcas.ac.cn

Between September 6 and October 10, 2018, 13 chemical explosions for seismic deep sounding purpose were detonated in the eastern margin of Junggar basin, Northwest China. The source parameters of these explosions, *e.g.*, their locations, depth of charges, property and yield of explosive, were known. They provided immediate constraints for seismic source characteristics, as well as for local and regional seismic wave propagations. In typical cases, three tons of specially designed ammonium nitrate explosive with about 30% trinitrotoluene (TNT) was detonated to generate seismic waves. We roughly assume that 1ton ammonium nitrate explosive equals to 0.5 ton of TNT. According to the result from Non-Proliferation Experiment, the chemical explosions are more efficient at generating seismic signals by a factor of approximately 2 compared to nuclear explosions. Therefore, the explosion effects are equal in TNT equivalent between both chemical and nuclear explosions. Within local and regional distances, these explosions generated abundant broadband digital seismograms, which were used to investigate event attributes, including the discrimination, yield estimation, and epicenter relocations. The spectral ratios Pg/Lg, Pn/Lg, and Pn/Sn were calculated for all 13 explosions and 5 nearby nature earthquakes. The explosion and earthquake sources showed apparently different features in their spectral ratios. Stacked spectral ratios provided a robust discriminant between explosions and natural earthquakes above 2.0 Hz. We calculated body-wave and Rayleigh wave magnitudes for explosions and natural earthquakes, and determined the relationship between mb(Lg) and explosive yield. Relation obtained in this region is consistent to those obtained in East Kazakhstan. This research was supported by the National Key Research and Development Program of China (2017YFC0601206) and the National Natural Science Foundation of China (grants 41630210, 41674060).

The Science of Slow Earthquakes from Multi-Disciplinary Perspectives

Oral Session · Wednesday · 8:30 AM · 24 April · Cascade II
Session Chairs: Kazushige Obara, Kenneth C. Creager, Heidi Houston, Takanori Matsuzawa.

Slow Earthquake Segmentation as a Barrier to the 2011 Tohoku-Oki Earthquake Rupture

NISHIKAWA, T., Disaster Prevention Research Institute, Kyoto University, Uji, Japan, nishikawa.tomoaki.68s@st.kyoto-u.ac.jp; MATSUZAWA, T., National Research Institute for Earth Science and Disaster Resilience, Tsukuba, Japan, tkmatsu@bosai.go.jp; OHTA, K., Disaster Prevention Research Institute, Kyoto University, Uji, Japan, ohta.kazuaki.7e@kyoto-u.ac.jp; UCHIDA, N., Tohoku University, Sendai, Japan, naoki.uchida.b6@tohoku.ac.jp; NISHIMURA, T., Disaster Prevention Research Institute, Kyoto University, Uji, Japan, nishimura.takuya.4s@kyoto-u.ac.jp; IDE, S., University of Tokyo, Tokyo, Japan, ide@eps.s.u-tokyo.ac.jp

Subduction zone megathrust earthquakes result from the interplay between fast dynamic rupture and slow deformation processes, which are directly observed as various slow earthquakes, including tectonic tremors, very low-frequency earthquake (VLFs) and slow slip events (SSEs), and indirectly suggested by a temporal change in the frequency of repeating earthquakes and the occurrence of episodic earthquake swarms. Some megathrust earthquakes have been preceded by slow earthquakes and terminated near the areas where slow earthquakes were frequently observed. While capturing the entire spectrum of slow earthquake activity is crucial for estimating the occurrence time and rupture extent of future megathrust earthquakes in a given subduction zone, such an observation is generally difficult, and slow earthquake activity is poorly understood in most subduction zones, including the Japan Trench, which hosted the 2011 M_w 9.0 Tohoku-Oki earthquake. Here we reveal the slow earthquake activity in the Japan Trench in detail using tectonic tremors, which we detected in the seismograms of a new ocean-bottom seismograph network, VLFs, SSEs, repeating earthquakes, and earthquake swarms. We show that the slow earthquake distribution is complementary to the rupture area of the Tohoku-Oki earthquake and correlates with the structural heterogeneity along the Japan Trench. Concentrated slow earthquake activities were observed in the afterslip area of the Tohoku-Oki earthquake, which is located to the south of the fore-arc geological segment boundary. Our results suggest that the megathrust in the Japan Trench is divided into three segments that are characterised by different frictional properties, and that the rupture of the Tohoku-Oki earthquake, which nucleated in the central segment, was terminated by the two adjacent segments.

Short-Term Bidirectional Interaction between Slow Slip Events and Three Devastating Earthquakes in Mexico

CRUZ-ATIENZA, V. M., Universidad Nacional Autónoma de México, Mexico City, Mexico, cruz@geofisica.unam.mx; TAGO, J., Universidad Nacional Autónoma de México, Mexico City, Mexico, josue.tago@gmail.com; VILLAFUERTE, C., Universidad Nacional Autónoma de México, Mexico City, Mexico, villafuerte.cd@gmail.com; KOSTOGLODOV, V., Universidad Nacional Autónoma de México, Mexico City, Mexico, vladikost@gmail.com; REAL, J., Universidad Nacional Autónoma de México, Mexico City, Mexico, jorge8428@gmail.com; ITO, Y., Disaster Prevention Research Institute, Kyoto University, Kyoto, Japan, ito.yoshihiro.4w@kyoto-u.ac.jp; FRANCO, S. I., Universidad Nacional Autónoma de México, Mexico City, Mexico, ivonne@igeofisica.unam.mx; NISHIMURA, T., Disaster Prevention Research Institute, Kyoto University, Kyoto, Japan, nishimura.takuya.4s@kyoto-u.ac.jp; KAZACHKINA, E., Universidad Nacional Autónoma de México, Mexico City, Mexico, kazachkina3007@gmail.com; SANTOYO, M. A., Universidad Nacional Autónoma de México, Mexico City, Mexico, santoyo@geofisica.unam.mx; ZAVALA-HIDALGO, J., Universidad Nacional Autónoma de México, Mexico City, Mexico, jzavala@atmosfera.unam.mx

Triggering of dynamic instabilities in a fault hosting aseismic slip or, inversely, triggering of slow earthquakes by seismic waves far from the source have been a major research topic in the last years mainly from the theoretical and experimental points of view. Only a few observations of one kind or the other plausibly suggest that such interactions actually happen in nature. In this study we show that the recent 2017-2018 devastating earthquakes in central Mexico (*i.e.* Mw8.2 of September 8, 2017; Mw7.1 of September 19, 2017; and Mw7.2 of February 16, 2018), two of them intraslab events, can be explained as a cascade of events causally related with slow slip transients in the plate interface at a regional scale, in the states of Guerrero and Oaxaca, that preceded or succeeded their ruptures. By means of newly developed and powerful methods, we analyze continuous nationwide geodetic and seismological data (*i.e.* GNSS and strong motion records onshore, and ocean bottom pressure gauges offshore) for (1) imaging the temporal evolution of aseismic slip and interseismic coupling in a period including and spanning beyond the 5 months comprising the three earthquakes; (2) imaging the evolution of Coulomb failure stresses in the plate interface and the seismogenic faults; and (3) estimating the dynamic stresses and strains at the interface produced by the seismic waves of the events. Our results suggest that both co-seismic and slow crustal deformations during the 1.5-years analyzed period are the consequence of quasi-static or dynamic bidirectional interactions between slow and devastating earthquakes in an unprecedented short-term cascade of events that killed more than 471 people in central and southern Mexico.

A Close Look at Slow and Fast Earthquakes Under the Aleutian Islands

GHOSH, A., University of California, Riverside, California, USA, aghosh.earth@gmail.com; LI, B., University of California, Riverside, California, USA, bli017@ucr.edu

We use four mini seismic arrays and additional standalone seismic stations in the Unalaska and Akutan Island, Alaska, to capture the details of slow and fast earthquakes. The arrays are strategically placed to simultaneously image both subduction zone and volcanic seismicity. We find a prolific activity of tremor and repeating low frequency earthquakes (LFE). Interestingly, tremor occurs near-continuously in three patches generating the majority of the tremor on the plate interface. The tremor patches are located at the down-dip edge of the past large megathrust event. The tremor patches are separated by well-defined tremor gaps indicating strong lateral heterogeneity possibly in frictional properties. Unlike in other subduction zones, no clear episodic nature of tremor activity is observed. LFE families are located in the tremor zone, but occur in bursts. Tremor shows interesting slow and rapid migration patterns, in most cases, with both along-strike and along-dip components. Rapid tremor streaking is observed with velocities of several tens on kms per hour. Interestingly, tremor streaks are often characterized by abrupt reversals of migration direction without a significant change in velocity. In addition, tremor also migrates slowly at a velocity of 1 km/day for 3 months mostly along-strike but also with a significant along-dip component. Some of the migration features we see here have not been observed elsewhere. This area is also active in terms of regular fast earthquakes, making it an ideal place to study possible interaction between slow and fast earthquakes. We are exploring correlation between tremor/LFE activity and regular seismicity in space and time. Understanding their dynamics can provide new insights into the processes controlling a broad range of behaviors of fault slip.

Slow Slip Events: Earthquakes in Slow Motion

MICHEL, S., Ecole Normale Superieure, Paris, France, sylvain_michel@live.fr; AVOUAC, J., California Institute of Technology, California, USA, avouac@gps.caltech.edu; GUALANDI, A., Jet Propulsion Laboratory, California Institute of Technology, California, USA, adriano.geolandi@gmail.com

Faults can slip episodically during earthquakes, but also during transient aseismic slip events, commonly called Slow Slip Events (SSEs). The mechanisms at the origin of SSEs might be investigated based on their scaling properties. Previous compilation of SSE characteristics from various area suggested their moment, *M0*, is proportional to their duration, *T*, suggesting a different physics from regular earthquakes which obey *M0* proportional to T^3. Thanks to a new catalog of SSEs on the Cascadia megathrust consisting of 64 events between 2007.0 and 2017.632, we find that SSEs actually follow the same scaling laws as regular earthquakes: *M0* proportional to T^3, *M0* proportional to $A^{3/2}$, where A is the rupture area, and the Gutenberg-Richter frequency-magnitude relationship, with a b-value of ~0.8. These scaling properties are to be expected if slow slip events, like regular earthquakes, are frictional instabilities on faults embedded in an elastic medium, though with much lower stress drop that we estimated to ~5 kPa. SSE might therefore be considered as earthquakes in slow motion.

Seafloor Pressures, Temperatures, Ocean Circulation and Plate-Interface Slow Slip

GOMBERG, J., U.S. Geological Survey, Washington, USA, gomberg@usgs.gov; HAUTALA, S., University of Washington, Washington, USA, hautala@uw.edu; JOHNSON, P., University of Washington, Washington, USA, paulj@uw.edu; CHISWELL, S., National Institute of Water & Atmospheric Research, Wellington, New Zealand, steve.chiswell@niwa.co.nz; WALLACE, L. M., The University of Texas at Austin, Texas, USA, lwallace@utexas.edu; WEBB, S., Lamont-Doherty Earth Observatory, New York, USA, scw@ldeo.columbia.edu

Seafloor pressure measurements made above the slipping subduction zone plate-interface have elucidated transient aseismic slow fault slip. Primary evidence for slow slip has come from onshore displacement measurements made using satellite data, after removal of signals attributable to atmospheric processes. Offshore pressure data similarly require elimination of large hydrostatic pressure signals generated by variations in the height and density of the ocean water column, but only accomplished with far poorer sampling and resolution than for onshore. We demonstrate a novel approach to reduce water column and some instrumental noise from seafloor pressures. This approach is based on correlations between seafloor temperature and pressure changes recorded at the same location and the assumption that tectonic deformation affects only seafloor pressures. In this case, the signal common to both pressure and temperature changes are due to water column processes and can be estimated and removed. If recorded within a single logging system, instrumental noise also may be estimated and reduced. Relative to methods that eliminate water column signals by subtracting reference site pressures and instrumental noise by subtracting fit parametric functions, this approach does not rely on assumptions about the spatial scale of water column processes nor on availability of data from a site unaffected by the slow slip. The approach also benefits from the minimal cost, high accuracy, and ease with which temperatures are recorded. We test the assumptions and illustrate the potential and limitations of all these approaches using measurements and model calculations of seafloor temperatures and pressures from the New Zealand Hikurangi subduction zone.

Interaction Between ETS (Episodic Tremor and Slip) and Long-Term Slow Slip Event in Nankai Subduction Zone

OBARA, K., Earthquake Research Institute, University of Tokyo, Tokyo, Japan, obara@eri.u-tokyo.ac.jp

ETS (Episodic tremor and slip), composed of low frequency tremor, very low frequency earthquake and short-term slow slip event (SSE), is one of slow earthquake phenomena occurring at the downdip side of the locked zone typically observed in Cascadia and Nankai subduction zones. ETS activity style is characterized commonly in both subduction zones by along-strike segmentation and along-dip gradual shortening of recurrence interval with increasing the depth. A big difference of ETS activity in both regions is existence of interaction with the long-term SSE at the gap between locked and ETS zones. The long-term SSE was originally detected in Tokai and Bungo channel at eastern and western edges of ETS zone; however, recently has been detected ubiquitously along the gap. The long-term SSE clearly interacts with surrounding ETS and other slow earthquakes. During the Bungo channel long-term SSE in 2003 and 2010, the tremor was activated for a few months at a narrow width of 10 km in the updip edge of ETS zone which is the adjacent region of the SSE source fault. On the other hand, the deeper tremor activity was stable irrespective of the SSE. Similar pattern of interaction between the long-term SSE and ETS tremor is also observed in Tokai and Mexico.

In the east side of the tremor region clearly triggered by the Bungo channel SSE, tremor activity seems to slightly increase after 2003 and 2010 SSEs. Such 7-year period variation in tremor activity is observed in only shallower part of

the ETS zone and seems to migrate eastward at a speed of a few 10 km per year. This long-term variation of tremor activity is well coincident with a sequence of long-term SSEs with eastward migration detected between locked and ETS zones after Bungo channel SSEs. It also indicates interaction between ETS tremor and long-term SSE. Therefore, tremor activity is considered as a sensitive indicator for slipping at surrounding area.

Characteristic Tectonic Tremor Activity Observed Over Multiple Slow Slip Cycles in the Mexican Subduction Zone

HUSKER, A., Universidad Nacional Autónoma de México, Mexico City, Mexico, allen@igeofisica.unam.mx; FRANK, W. B., University of Southern California, California, USA, wbfrank@usc.edu; GONZALEZ, G., Universidad Nacional Autónoma de México, Mexico City, Mexico, geomem.gg@gmail.com; KOSTOGLODOV, V., Universidad Nacional Autónoma de México, Mexico City, Mexico, vladimir@geofisica.unam.mx; KAZACHKINA, E., Universidad Nacional Autónoma de México, Mexico City, Mexico, kazachkina@igeofisica.unam.mx

We develop a single-station tremor spectrum template detection method that we applied to continuous seismic data recorded by the Mexican National Seismological Service broadband stations. This allows for an unprecedented long-term analysis of tectonic tremor in Mexico over multiple slow slip events (SSEs). We only detect tremor that are within previously discovered tremor regions, thereby extending the catalog in time but not space. The resulting catalog demonstrates the strong correlation of bursts of tremor activity and aseismic slip over multiple slow slip cycles. The M~7 long-term SSEs in the states of Guerrero and Oaxaca are associated with the longest sequences of tremor bursts. Each of these tremor bursts are made up of a series of smaller bursts. In between the large M7 SSEs, there are shorter duration, isolated tremor bursts. In Guerrero, these shorter bursts were found to accompany M~6 short-term SSEs. The occurrence of these short-duration tremor bursts in Oaxaca demonstrates that small short-term SSEs occur in both major slow slip regions in Mexico. The discrete range of tremor burst sizes and rates suggests that slow slip events in the Mexican subduction zone are organized into characteristic moment and moment rates. The catalog also reveals other aseismic transients, such as post-seismic slip in Oaxaca after the February 16, 2018 Mw 7.2 Pinotepa Nacional earthquake. We highlight that such long-term catalogs are a useful tool together with geodetic observations to monitor slow slip activity that potentially plays a role in the subduction megathrust cycle.

Periodic Occurrence of the Slow Slip Events Off Kyushu Island, Southwest Japan, Based on Spatial Gradients of Displacement Rate Field and Activities of Small Repeating Earthquakes

IINUMA, T., Japan Agency for Marine-Earth Science and Technology, Yokohama, Japan, iinuma@jamstec.go.jp; UCHIDA, N., Tohoku University, Sendai, Japan, naoki.uchida.b6@tohoku.ac.jp

Periodic changes in the interplate locking in the northeast Japan subduction zone were revealed based on the activity of small repeating earthquakes and the change in the spatial gradient of horizontal displacement rate field. Speaking of the southwest (SW) Japan subduction zone, large earthquakes such as Tokai, Tonankai, and Nankai earthquakes repeatedly occur that rupture the plate interface fault between the Philippine Sea plate and the continental plate (Eurasia or Amurian plate). Long- and short-term slow slip events on the plate interface are also found in the SW Japan subduction zone and the relationship between the occurrence of the SSEs and the generation process of the mega-thrust earthquakes are under discussion. In this study, we focused on the spatio-temporal change in the interplate locking along the plate boundary in SW Japan based both on the geodetic and seismic data. We applied the monitoring method for spatial and temporal variation of the degree of the interplate locking proposed by Iinuma [2018] to the southwest Japan. The spatial gradient of the surface displacement rate field in each swath region that is configured along the direction normal to the Nankai Trough for time windows such as one and two years being shifted by one week. The also utilized the activities of small repeating earthquakes that occur east off Kyushu Island to estimate the average cumulative slip within several sub-areas assuming the underlying slow slip is similar in each area. The results show that temporal changes in the spatial gradients of surface displacement rates and in the cumulative slip estimated from the small repeating earthquakes mostly coincide. The temporal changes show 5 to 6 peaks within ~14 years suggesting quasi-periodic occurrence of SSEs on the plate boundary. These SSEs are located to the south of the locked areas for previous large interplate earthquakes and suggesting non-stationary slow–slip behavior in this area.

Low-Frequency Earthquake Slip Model Using the Northern Cascadia Array of Arrays

CREAGER, K. C., University of Washington, Washington, USA, kcc@uw.edu; CHESTLER, S. R., rover.com, Washington, USA, schesty11@gmail.com

Using the 200-seismometer Array of Arrays we have identified 34,000 low-frequency earthquakes (LFEs) on the plate interface below the Olympic Peninsula, Washington and determined their seismic moments. The LFEs spatially cluster into 45 families with horizontal dimensions of hundreds of meters and separated by gaps ranging from 1 to 20 km. Individual LFEs vary from Mw 0.7 to 2.1 and unlike regular earthquakes, follow an exponential magnitude-frequency distribution with a characteristic moment of 2.0×10^{11}N-m (Mw=1.5). An exponential moment-frequency distribution implies a scale-limited source process. Seismic Moment equals the shear modulus (which we know) * area (A) * average slip (s). Thus, we have a constraint on the characteristic (mean) value of A * s for individual LFEs within each family. We do not have any direct constraints on A or s for individual LFEs, but we have geodetic constraints on the total slip (S_{ETS}) during Episodic Tremor and Slip (ETS) events and we have an estimate of the area of a family patch based on the distribution of individual LFE locations. We consider two end-member models: (1) connected patch model in which individual LFEs rupture different portions of the LFE family patch, but when summed over all LFEs every part of the patch slips the same amount. (2) For the ductile matrix model the patch is divided into regions with no LFE slip, and regions with LFE slip summing to S_{ETS}. We explore the implications of these models in terms of stress drop and geologic observations. We find that 0.2% of the geodetically inferred slip is accommodated by LFEs. Down-dip LFE slip occurs through a larger number (800–1,200) of smaller LFEs, while updip LFE slip occurs primarily during ETS events through a smaller number (200–600) of larger LFEs. This could indicate that the plate interface is stronger and has a higher stress threshold updip.

Spectra and Mechanics of Slow to Fast Contained Laboratory Earthquakes

WU, B., Cornell University, New York, USA, sw842@cornell.edu; MCLASKEY, G., Cornell University, New York, USA, gcm8@cornell.edu

We report a spectrum of slow to fast contained laboratory earthquakes generated on a dry, nominally homogeneous 3-meter granite fault. Using a newly constructed biaxial friction apparatus at Cornell University, we study the slow events using measurements of local stress, slip, and ground motions, and we find many similarities to low frequency earthquakes (LFEs) or tremor sources. In our experiments, spontaneous fault rupture events at 4 to 12 MPa stress levels are similar to M -3 to M -2 earthquakes. Prior to these dynamic rupture events that propagate across the entire fault, we observe contained earthquakes that nucleate and arrest within the sample. Closer to natural earthquakes than standard stick-slip events, these contained events rupture a patch of the fault with length P = 0.4 to 2 m. Their slip speeds range from 0.07 - 100 mm/s. The fastest events are similar to regular M -2.5 earthquakes, with a single distinct corner frequency and w^{-2} spectral falloff at high frequencies. They are well fit by the Brune earthquake source model with a 0.4 MPa stress drop. Events with intermediate slip speeds (2 – 10 mm/s) have 50 kPa to 100 kPa stress drops and weakly radiate tremor-like signals. Their source spectra are depleted near the corner frequency relative to a Brune model. The slowest events (<1 mm/s slip rates) have a w^{-1} spectral shape, similar to slow slip events observed in nature. Our results show that a fault patch P can radiate in vastly different ways, just from small changes in the ratio of a critical nucleation length (Lc) to P. In the lab, the patch P is set up from stress conditions. In the field, patch P is likely set up by fault structure or rheology such as a velocity weakening patch surrounded by velocity strengthening fault. LFE “families” and tremor locations that are persistent over many years support this view.

Slow Slip and Tremor: A Review of the Role of Water Expelled From Subducting Plate

HYNDMAN, R. D., SSA - BSSA, Sidney, Canada, rhyndman@nrcan.gc.ca

Sporadic seismic tremor and slow slip (ETS) occur in many subduction zones; I deal with the ~35 km deep continuous band that occurs in hot subduction zones, including Cascadia and SW Japan. Important conclusions are: (a) there is a gap on the thrust between the downdip limit of the seismogenic zone and the ETS, not a continuous transition, (b) the ETS temperatures are 500-550C, too hot for normal earthquake rupture. What is the process of ETS and what controls the location? A critical observation is the close spatial coincidence between ETS and the forearc mantle corner. We have proposed that downdip of the corner, fluid dehydrated from the oceanic plate is blocked from rising vertically by the low permeability forearc mantle serpentinite inferred by very high Poisson’s Ratio. The fluid is channelled updip in the high permeability oceanic crust until it is released upward at the corner. Concentrated fluid expulsion above the corner is indicated by: (a) Poisson's Ratio evidence for quartz deposition in the overlying forearc crust; (b) A high electrical conductivity plume above the corner from magnetotelluric data. Slip and tremor may occur in spite of the high temperatures because of "fault valve" buildup and simultaneous release of high pore pressure and shear stress. Buildup and release of pore pressure may give the slow slip and tremor, mainly at the thrust (LFEs) but also in the overlying crust. Near-lithostatic pore pressures are inferred by: (a) high Poisson's ratio in a dipping low velocity zone in the upper oceanic crust, (b) tremor sensitivity to small tidal and surface wave stresses, (c) Evidence for crack-seal and quartz deposition structures in exhumed subduction thrust zones.

Offshore Seismic Attenuation Heterogeneity and Implications for Pore-Fluid Pressure in Gisborne Slow-Slip Region, Northern Hikurangi Margin, North Island, New Zealand

NAKAI, J., University of New Mexico, New Mexico, USA, jenakai@unm.edu; SHEEHAN, A. F., University of Colorado Boulder, Colorado, USA, anne.sheehan@colorado.edu; ABERCROMBIE, R. E., Boston University, Massachusetts, USA, rea@bu.edu; EBERHART-PHILLIPS, D., GNS Science, Lower Hutt, New Zealand, d.eberhart-phillips@gns.cri.nz

The Hikurangi subduction margin offshore Gisborne, North Island, New Zealand hosts large slow-slip events (SSEs) every 18-24 months. The May 2014–June 2015 HOBITSS (Hikurangi Ocean Bottom Investigation of Tremor and Slow Slip) deployment of ocean-bottom seismometers (OBS) and pressure gauges was designed to overlie the source region of the Gisborne SSEs, and successfully recorded two SSEs with maximum displacement of ~20 cm. Hypotheses on the cause of the SSEs focus on high interface pore-fluid pressure, a fluid-filled and fractured overriding plate, and frictional properties of the plate interface. The degree of heterogeneity of these properties is important for understanding why slip varies spatially and why the depth of the brittle-viscous transition zone (where many SSEs are presumed to occur) varies widely from north (shallow) to south (deep). We aim to resolve the attenuation of P- and S-waves from local earthquakes. We determine ~2,700 t* (integrated path attenuation) values for 153 earthquakes (> M_L 2.5), mostly within the subducting plate, located with 12 OBS and 24 land stations. The addition of OBS expands the resolvable model region of attenuation with additional raypaths, which has thus far been limited by measurements from onshore stations. Initial results suggest ~90% of the path-averaged Qs values for earthquakes shallower than 25 km are <500, which agrees with existing onshore Q tomography (Eberhart-Phillips *et al.*, 2017). The majority of path-averaged Qs from shallow earthquakes at OBS are <300. These regions of lower Qs lie within and updip of high Vp/Vs (Eberhart-Phillips and Bannister, 2015), inferred to be associated with high pore-fluid pressure in the overlying plate. Variable Qs/Qp ratios (Eberhart-Phillips *et al.*, 2017) suggest heterogeneity in pore-fluid pressures in and above the interface and spatially coincides with variable slip rate deficit and topography of the incoming plate. We aim to further resolve the offshore attenuation structure to determine whether significant changes in seismic attenuation occur along the margin strike.

Probing Fault Frictional Properties During Afterslip Up- and Down-Dip of the 2017 Mw 7.3 Iran-Iraq Earthquake With Space Geodesy

WANG, K., University of California, Berkeley, California, USA, kwang@seismo.berkeley.edu; BÜRGMANN, R., University of California, Berkeley, California, USA, burgmann@seismo.berkeley.edu

On November 12th, 2017, an earthquake of Mw 7.3 occurred near the Iran-Iraq border, causing hundreds of deaths in both countries. The earthquake occurred along the Zagros mountain range, a broad and complex zone of continental collision between the Arabian and Eurasian plates. We use Interferometric Synthetic Aperture Radar (InSAR) data collected by the Sentinel-1 mission to study the co- and postseismic deformation of this earthquake. The fault geometry and coseismic slip distribution are exceptionally well determined, thanks to the excellent quality of the InSAR observations. Most of the coseismic moment release is found to be at a depth range between 15 and 21 km, well beneath the boundary between the sedimentary cover and underlying basement. Data from all four tracks also reveal robust postseismic deformation during ~1 year after the mainshock. Aftershocks during the same time period exhibit a similar temporal evolution as the InSAR time series, with most of the aftershocks being located within and around the area of maximum surface deformation. Both kinematic inversions and stress-driven afterslip simulations show that the observed postseismic InSAR LOS displacements are well explained by oblique (thrust + dextral) afterslip, both updip and downdip of the coseismic peak slip area. Assuming that the afterslip evolution is governed by rate-and-state friction, we estimate the value of $(a\text{-}b)\sigma$ (where a and b are the rate and state friction-law parameters and σ is the effective normal stress) updip and downdip of the coseismic rupture. We find that the $(a\text{-}b)\sigma$ updip of the coseismic rupture is significantly higher than downdip, suggesting either different effective normal stress, or heterogeneous fault frictional properties.

A Meso-Scale Take on the Modeling of Fault Zone Faulting Behaviors

FITZENZ, D. D., Risk Management Solutions, California, USA, delphine.fitzenz@rms.com; MAURY, V., IFP School, Reuil-Malmaison, France, vincent.maury2@wanadoo.fr; PIAU, J., IFSTTAR, Nantes, France, jean-michel.piau@ifsttar.fr

From strike-slip fault cores to subductions "interfaces" exhibiting rotated blocks, breccia, (silt, clay) deformation bands, those dilatant/contractant places where aseismic slip, slow-slip and seismic slip occur are far from simple. Locating each type of event is hard work, but examples are showing up where seismic and aseismic events are not just neighbors (hinting at triggering relationships) but may actually be collocated.

It seems important, in this context, to look at larger spectrum alternatives to purely frictional models that focus on thin interfaces, where (a-b) values need to be chosen, prescribing to a large extent whether the local behavior will be seismic or aseismic.

We propose that mesoscale empirical/conceptual fault core models that can be calibrated from geophysical data, are used to lead to new insights. Such a model was applied to oceanic transform faults and we are presenting here a generic study on the conditions that can lead to/from SSE to/from seismic. The model includes an original poro-plastic hardening/softening standard interface constitutive law with an end cap criterion, as well as a (currently simple) structural model that approximates the various scales involved in geological faults. It spontaneously produces contractant or dilatant behavior of fault areas at a large range of time scales from seconds to days to years, as a function of absolute stress magnitude, tectonic loading and fluid compressibility. Current results show that zones generating SSE and seismogenic areas are not mutually exclusive and a whole continuum of behaviors can happen on the same fault, including in short succession, depending namely on fault maturity, current deformation regime and on-going fluid conditions.

Case studies are needed to calibrate the model parameters and check the model predictions against monitoring data. For more realistic simulations, the interface model could be plugged into 2D or 3D crustal fault or subduction interface models.

Aseismic Slip Phenomena in Southern Cascadia

BARTLOW, N. M., University of California, Berkeley Seismology Lab and University of California, Santa Cruz, California, USA, nbartlow@berkeley.edu; MATERNA, K., University of California, Berkeley, California, USA, kmaterna@berkeley.edu; BÜRGMANN, R., University of California, Berkeley, California, USA, burgmann@seismo.berkeley.edu

Southern Cascadia experiences an array of interesting aseismic phenonema. Here we report on both a new technique used to study Episodic Tremor and Slip (ETS) in Cascadia, along with it's application to constraining local tectonics, and a novel observation of a new aseismic phenomenon: enduring coupling changes induced by dynamic stresses associated with regional earthquakes. Using daily GNSS timeseries provided by UNAVCO and the Pacific Northwest Seismic Network Cascadia tremor database, we estimate the ETS velocities at GNSS stations in southern Cascadia averaging over the full timeseries at each station (~10-14 years). We invert this velocity field to obtain the long-term average ETS slip rate on the plate interface, accounting for elastic heterogeneity. We find that ETS produces up to 40 mm/year of westward motion, far above the 25 mm/year of convergence predicted by the Juan de Fuca – North America Euler pole given by MORVEL. The direction of convergence is also not well described by the Euler pole, with a difference of >30° at the southern end. This implies significant internal deformation of the subducting Gorda sub-plate, which is likely to be an important effect in assessing earthquake hazards in the region.

Modeling of velocity changes detected in the GNSS time series not associated with ETS suggests the existence of a "spot" updip from the ETS zone on the southern Cascadia interface which experiences abrupt changes in coupling. The inferred increases and decreases in coupling are co-incident with the times of large (M_W ≥6.5) offshore earthquakes. Known postseismic processes, such as afterslip and mantle relaxation following these events, cannot explain our observations. Mechanically, it appears that the plate interface undergoes enduring changes in strength triggered by dynamic stresses. This phenomenon, which has not previously been reported, implies that plate interface coupling models may need to be periodically re-assessed.

Science, Hazards and Planning in Subduction Zone Regions (Part I)

Oral Session · Wednesday · 4:15 PM · 24 April · Cascade II
Session Chairs: David Schmidt, Lori Dengler, Will Levandowski, Kathy Davenport, Jamey Turner, Rick Wilson, Brendan W. Crowell.

Subduction-Related Stress Field in Central America and Intraplate Stress in Costa Rica

LEVANDOWSKI, W., Tetra Tech, Inc., Colorado, USA, will.levandowski@tetratech.com; TURNER, J., Tetra Tech, Inc., Colorado, USA, jamey.turner@tetratech.com

Along-strike stress variations in subduction zones reflect along-strike variations in subduction processes, and down-dip stress variations illuminate the driving mechanisms of convergence. Using more than 2500 moment tensors, we systematically map the 3D stress field along the Middle America Subduction Zone from southern Mexico to Panama. Results in the oceanic plate are readily interpreted as the hallmarks of slab pull. Margin-normal extension near the trench reflects slab bending, and events below 50 km reveal down-dip extension. By contrast, trench-perpendicular shortening to a few tens of km depth results from slab-continent coupling. As previously documented, the subducting plate shallows abruptly beneath central Costa Rica, and this geometric change has a profound impact on the continental stress field. Grossly, escape-style tectonics manifest as monotonic counterclockwise rotation of maximal compression from NE–SW in Panama in southern Central America, to NNW–SSE in Guatemala in northern Central America, with convergence-parallel stress in central Costa Rica, and a progression from transpression in Panama to thrust faulting in Costa Rica and back to strike-slip and even normal faulting in Nicaragua and northward. In Costa Rica, higher data density reveals a complex, roughly toroidal intraplate stress field. The reason for this complexity is not presently understood, but it may derive from kinematic interactions within the Central Costa Rica Deformed Belt and/or from topographical and rheological heterogeneities including seamounts and the Cocos Ridge of the underthrusting plate.

Translating Megathrust Behavior Into the Nicoya Crust, Revealing a Dynamic Dance Across the Seismic Cycle

NEWMAN, A., Georgia Institute of Technology, Georgia, USA, anewman@gatech.edu; HOBBS, T. E., Georgia Institute of Technology, Georgia, USA, tieganh@gatech.edu; KYRIAKOPOULOS, C., University of California, Riverside, California, USA, christos@ucr.edu; PROTTI, M., OVSICORI, UNA, Heredia, Costa Rica, marino.protti@gmail.com; DIXON, T. H., University of South Florida, Florida, USA, thd@usf.edu; SCHWARTZ, S. Y., University of California, Santa Cruz, California, USA, syschwar@ucsc.edu

The relatively unique geometry of the Nicoya Peninsula directly over the seismogenic megathrust in northwestern Costa Rica has allowed a unique opportunity for the development of a rich 20-year geodetic time history of behavior. The geodetic and seismic network operated in the region is jointly operated by University of South Florida, University of California Santa Cruz, and Georgia Tech, and is called the Nicoya Seismic Cycle Observatory (NSCO). Starting in the 1990s, we've observed approximately 15 years of interseismic strain accumulation centered beneath the peninsula, with frequent, nearly biennial slow-slip events outlining the locked regions. These events varied in size occurring both down-dip and up-dip, going offshore and becoming difficult to constrain. We then captured the 2012 Mw 7.6 Nicoya earthquake, which we anticipated, having ruptured the area previously locked. The afterslip and aftershocks tell a story of coexistence, but not colocation, with most aftershocks occurring at the periphery of afterslip, and not account their cumulative moment not accounting for the geodetic one of afterslip. Finally, following afterslip, we then see a very strange postseismic sliver transient during the recoupling period. This sliver transient is concurrent, but not necessarily dependent on transient locking near the coastline. Finally, the interface completely relocks itself, making it hardly distinguishable from the pre-2012-event. We will explain the totality of the locking in relationship to other behaviors over time, and discuss the relative similarities between relocking and old locking. By completing the cycle, we are getting at understanding the complete geodetic moment budget allowable from tectonic convergence rather than the 10-20% allowable from seismic only estimates.

The March 2012 Mw 7.4 Ometepec and February 2018 Mw 7.2 Pinotepa Earthquakes in Mexico Ruptured Small Patches of the Cocos Megathrust

FIELDING, E. J., Jet Propulsion Laboratory, California Institute of Technology, California, USA, eric.j.fielding@jpl.nasa.gov; GOMBERT, B., University of Oxford, Oxford, United Kingdom, baptiste.gombert@earth.ox.ac.uk; GONZÁLEZ ORTEGA, J., Centro de Investigación Científica y de Educación Superior de Ensenada, Ensenada, BC, Mexico, aglez@cicese.mx; DUPUTEL, Z., IPGS, Université de Strasbourg/EOST, CNRS, Strasbourg, France, zacharie.duputel@unistra.fr; LIANG, C., Seismological Laboratory, California Institute of Technology, California, USA, cunrenl@caltech.edu; BEKAERT, D. P. S., Jet Propulsion Laboratory, California Institute of Technology, California, USA, david.bekaert@jpl.nasa.gov; SAMSONOV, S. V., Canada Centre for Mapping and Earth Observation, Natural Resources Canada, Ottawa, Canada, sergey.samsonov@canada.ca; JOLIVET, R., École Normale Supérieure, Paris, France, romain.jolivet@ens.fr; AMPUERO, J., Université Côte d'Azur, IRD, CNRS, Observatoire de la Côte d'Azur, Géoazur, France, ampuero@geoazur.unice.fr

The megathrust of the Cocos Plate beneath Southern Mexico has major variations in the geometry and behavior. The segment beneath the Mexican state of Oaxaca has relatively frequent magnitude 7–7.5 earthquakes on the shallow part of the megathrust and within the subducting slab, and it also has large aseismic slow-slip events. The slab geometry includes part of the subhorizontal "flat-slab" zone extending far from the trench beneath Guerrero and the beginning of its transition to more regular subduction geometry to the southeast. We study the ruptures of the 20 March 2012 Mw 7.4 Ometepec earthquake near the Guerrero-Oaxaca border and the16 February 2018 Mw 7.2 Pinotepa earthquake near Pinotepa Nacional in Oaxaca that were both megathrust events. The 2012 Ometepec and 2018 Pinotepa earthquake epicenters were located about 45 km apart by the Mexican Servicio Sismológico Nacional (SSN).

We use geodetic measurements from interferometric analysis of synthetic aperture radar (InSAR) and GPS coseismic offsets to estimate finite-fault slip models for the M7.4 Ometepec and M7.2 Pinotepa earthquakes. We analyzed InSAR data from Copernicus Sentinel-1A and -1B satellites and JAXA ALOS-2 satellite for 2018 Pinotepa and Canadian RADARSAT-2 for 2012 Ometepec. Our Bayesian (AlTar) static slip models for both earthquakes shows all of the slip confined to very small (10-20 km diameter) ruptures, similar to some early seismic waveform fits, and the two ruptures do not overlap. The earthquakes ruptured part of the Cocos megathrust that has been previously mapped as partially coupled; at least small asperities in that zone of the subduction interface are fully coupled and fail in high stress-drop earthquakes. Preliminary analysis of GPS data after the Pinotepa earthquake indicates rapid afterslip on the megathrust in the region of coseismic slip. Previous analysis by Graham *et al*. (2014) and others showed afterslip after the 2012 Ometepec event, largely down-dip. This part of the megathrust may have areas of low coupling that have afterslip or slow slip between the locked patches.

The Role of Afterslip and Slow Slip Events in Subduction-Related Earthquake Triggering: The Case Studies of the 2017 M7.1 Mexico City (Puebla) and the 2018 M7.0 Anchorage Earthquakes

SEGOU, M., British Geological Survey, Edinburgh, United Kingdom, msegou@bgs.ac.uk; PARSONS, T., U.S. Geological Survey, California, USA, tparsons@usgs.gov

The complex environment of subduction zones offer opportunities to investigate earthquake-to-earthquake interactions. However, examples where non-episodic events may triggered a significant earthquake are sparse. We analyse two cases where ruptures occurred on low-angle normal faults at the hinge of the diving plate; the 2017 M7.1 Puebla earthquake in Mexico, and the 2018 M7.0 Anchorage earthquake in Alaska. We focus on the identification of interaction links incorporating both previous seismic and non-seismic deformation sources. The more landward epicentres of these earthquakes, located above the bending part of the subducting plate, enables the incorporation of extended afterslip and/or slow-slip events (SSEs) recorded by the existing land-based geodetic networks. The 2017 M7.1 Puebla earthquake occurred 11 days after the M=8.1 Chiapas earthquake, setting off public concern about their potential connection. However, no evidence suggests that dynamic triggering or static stress interaction played a role in the nucleation of the second event. The M7.1 Puebla rupture was rooted at the western extension of the afterslip area of the 2012 M7.5 Oaxaca shock that loaded the fault plane by 0.01-0.1 MPa. The 30 November 2018 Anchorage earthquake is the strongest one felt in Alaska since the 1964 M=9.2 Prince William Sound and the 2002 M=7.9 Denali earthquakes. The 1964 coseismic perturbations on the Anchorage plane are estimated >0.5 MPa, though this stress increase occurred more then 54 years ago. We find that recent deformation features of the subduction zone, such as long-lasting slow slip events under Cook Strait exert additional influence. Both recent slow slip episodes the 1992-2004 and 2009-2011 loaded the Anchorage fault plane approximately by 0.1 and 0.05-0.3 MPa, respectively. While the SSEs' predictive value remains questionable as precursory phenomena to megathrust events, their interaction together with extended postseismic deformation patterns with subduction bending earthquakes requires a closer examination.

Double Benioff Zones Along the Hikurangi Subduction Zone, New Zealand, Based on Nested Regional-Global Seismic Tomography and Precise Earthquake Relocation

AZIZ ZANJANI, F., University of Miami, Florida, USA, fzanjani@rsmas.miami.edu; LIN, G., University of Miami, Florida, USA, glin@rsmas.miami.edu; THURBER, C. H., University of Wisconsin–Madison, Wisconsin, USA, cthurber@wisc.edu

The exact mechanism for the genesis of the Double Benioff Zone (DBZ) and intermediate-depth earthquakes is an unresolved question. Several hypotheses have been proposed including dehydration-embrittlement and thermal shear instability. Here, we investigate the variation of the DBZs along the strike of Hikurangi trench, New Zealand. We obtain local and regional seismic data from the Geonet for over 70,000 events in magnitude range of 2 to 5 between 2013 and July 2017. In addition, we download teleseismic P arrival times reported by the International Seismological Center for the distance range between 30 and 90 degrees. We apply the teletomoDD algorithm (Pesicek *et al.*, 2014), which uses a nested regional-global parameterization with a finely gridded regional model embedded in a coarser global model. We obtain a 3-D P-wave velocity model based on 16,000 master events from the regional dataset and 5,660 events from the global dataset and use this velocity model to relocate the whole dataset. A differential-time relocation method based on waveform cross-correlation is then used to improve the accuracy of relative locations. Our results show a clear DBZ with separated upper and lower planes of seismicity in the north part of the Hikurangi subduction zone. Spatial distribution of seismicity in accordance with zones of low P-wave velocities supports the dehydration of the subducting slab. The slab is torn at about 80 km depth and the DBZ disappears below this depth, where the dip of the subducting slab increases. In the central North Island, there is no clear DBZ and the seismicity is more concentrated in the upper part of the subducting slab that may suggest a different degree of hydration. The DBZ reappears in the southern part of the North Island, where the layer separation is smaller compared to the DBZ in the northern part. These observations imply along strike changes in the geometrical, thermal, and/or hydration state of the subducting slab.

Machine Learning in Seismology

Oral Session · Wednesday · 8:30 AM · 24 April · Elliott Bay
Session Chairs: Youzuo Lin, Sepideh Karimi, Takahiko Uchide, Qingkai Kong, Dario Baturan, Zhigang Peng, Ting Chen, Andrew Delorey, Min Chen, Chengping Chai, Paul Johnson.

A Probabilistic Framework for Vs30

MITAL, U., California Institute of Technology, California, USA, umital@caltech.edu; YONG, A., U.S. Geological Survey, California, USA, yong@usgs.gov; IWAHASHI, J., Geospatial Information Authority of Japan, Tsukuba, Japan, iwahashi-j96pz@mlit.go.jp; SAVVAIDIS, A., The University of Texas at Austin, Texas, USA, alexandros.savvaidis@beg.utexas.edu

The time-averaged shear-wave velocity (V_S) in the upper 30 m from the surface (V_{S30}), is used as an index to quantify seismic site effects and model ground motions. V_{S30} is typically derived from in-situ recordings of V_S; however, proxies, as a function of topography, geology, and terrain properties, are used where observations are sparse, or not readily available. Recently, Iwahashi et al (2018) developed a map where global terrain was classified using a 280-m digital elevation model (DEM) down-scaled from the Multi-Error-Removed Improved-Terrain (MERIT) DEM (Yamazaki *et al.*, 2017). In this study, we present a framework to predict the most-probable value of V_{S30} for each terrain class. Our framework is grounded in the fundamental principles of geostatistics and probability and uses maximum-likelihood-estimates to optimally identify the non-gaussian distribution of V_{S30}. We show that a non-gaussian distribution of V_{S30} is to be expected and is not a sign of measurement error or sampling bias. This implies that a simplistic approach of using the mean to quantify V_{S30} can overestimate the most probable value. Our framework also lends itself to provide probabilistic bounds on the variation of V_{S30} for a given terrain class. Quantifying uncertainty in V_{S30} distribution can reduce uncertainty involving site effects and ground motion models. Our future work entails using machine learning to generate a synthetic V_{S30} database which can complement field measurements by increasing resolution and providing estimates where field observations are not available.

Using Machine Learning to Improve Ground Motion Prediction Equations

AAGAARD, B., U.S. Geological Survey, California, USA, baagaard@usgs.gov

I assess the potential for artificial neural networks to capture complex relationships among input parameters in ground-motion prediction equations (GMPEs) that may be difficult to describe in traditional empirical regressions. I construct a suite of GMPEs for California using a convolution artificial neural network model with data from the Pacific Earthquake Engineering Research Center's Next Generation Attenuation West2 ground-motion database. I consider different parameterizations for capturing the spatial variations in ground motion associated with the earthquake mechanism, site characterization, and distance from the rupture. For the inputs associated with each effect, I assess how the neural network weights the combination of parameters, the effect on the uncertainty in the resulting GMPE, and compare the functional form to traditional empirical regression-based GMPEs. For example, using continuous independent variables, such as fault dip and slip rake, rather than classifying earthquakes into discrete mechanism types (*e.g.*, strike-slip, reverse, and normal faulting) results in slightly smaller residuals. Additionally, complex variations in amplitude associated with hanging wall/footwall effects can be captured using a combination of Joyner-Boore distance and rupture distance. The artificial neural network provides a generalized form that remains the same for all of these different parameterizations, thereby facilitating exploration of how to best represent complex spatial variations of ground-motion amplitude in GMPEs.

Real-Time Earthquake Detection and Phase Picking Using Temporal Convolutional Networks

ZHU, W., Stanford University, California, USA, zhuwq@stanford.edu; MOUSAVI, M., Stanford University, California, USA, smousavi05@gmail.com; BEROZA, G. C., Stanford University, California, USA, beroza@stanford.edu

Real-time earthquake monitoring has high requirements on both accuracy and speed. The STA/LTA method for phase arrival identification is widely used by seismic networks due to its low computational cost, but it suffers from both missed events and false predictions. Recently, deep-learning-based methods have achieved significantly higher accuracies for earthquake detection. Although these algorithms perform much faster than search-based methods, they are not still fast enough for real-time applications. Sliding windows are needed for basic convolutional neural networks to achieve real-time prediction. This will introduce extensive computations due to the overlap among sliding windows, and making up for this by using a short sliding window will decrease neural networks' performance. Moreover, basic convolutional neural networks do not focus on the edges of the window, which reduces sensitivity to new events emerging from the front end of the time series. In this work, we build a deep neural network for real-time earthquake detection and phase picking using a dilated causal convolutional architecture. The network maps a continuous seismic waveform to a sequence of three classes: P, S, and noise. The network is designed to make real-time prediction for each new data point from a real-time data stream, making it hundreds of times faster than basic convolutional neural networks. The network learns long-range temporal dependencies and features based on a large receptive field, which achieves higher prediction accuracy than STA/LTA method. Our network has a good balance of speed and accuracy and can be used in real-time earthquake monitoring.

Smart Phone Based Bridge Seismic Monitoring and Vibration Status Realization by Time Domain Convolutional Neural Network

DANG, J., Saitama University, Saitama, Japan, dangji@mail.saitama-u.ac.jp; SHRESTHA, A., Saitama University, Saitama, Japan, ashishduwaju@hotmail.com; WANG, X., Tokyo University of Science, Noda, Japan, wangxin@rs.tus.ac.jp

In this study, a bridge seismic monitoring system was developed using smart phones as sensor nodes. Connected smart phones together in the same project as a sensor network, this system provides an easy way for bridge vibration sensing method. A long-term field test of this system was performed on a PC bridge in Japan. Smart phones with the monitoring application were deployed at six different locations inside the bridge's box girder. The system was connected to a cloud server for real-time data uploading and remote control. Inconsistent sampling rates and faulty sensor readings were identified to be two major problems with the use of the proposed system. A few seismic acceleration response records of the Takamatsu Bridge were captured during the more than one-year operation period. Dynamic properties extracted from this system were compared with those of reference seismometers to verify its viability and accuracy. To recognize vibration wave form from those sensor faulty data included data, a simple neural network was trained with data measure from the bridge. Combining with original time domain data as input layer, 2 one dimensional Convolutional Neural

Network layers, Pooling layer, and 2 Fully Connected Layers, the proposed model serves fast vibration classification of device faulty, transportation vibration, earthquake event and ambient noise in very high accuracy.

Robust Arrival Time Uncertainty Estimation Using Gaussian Blurring

PETERSON, M. G., Sandia National Laboratories, New Mexico, USA, mgpeter@sandia.gov; VOLLMER, C., Sandia National Laboratories, New Mexico, USA, cvollme@sandia.gov; YOUNG, C. J., Sandia National Laboratories, New Mexico, USA, cjyoung@sandia.gov; STRACUZZI, D., Sandia National Laboratories, New Mexico, USA, djstrac@sandia.gov

The uncertainty of the arrival time of a picked seismic phase directly controls both the detection and characterization of the associated event, yet relatively little work has been done on developing robust uncertainty estimation methods, and the standard approach is to use a simple algebraic scaling relationship based on signal-to-noise ratio (SNR). We present a case study in seismic onset detection, comparing statistically computed multi-band distributions over possible signal onset times to a range of onset times determined by an expert seismic analyst (best time, earliest possible time, latest possible time). Importantly, the uncertainty distributions sometimes identify subtle changes in the seismic waveform that are missed by both point estimate calculations and by analysts.

We generate our statistically computed distribution for each band by first creating a large set of Gaussian Blurred samples of the band-passed version of our original signal. We then use each sample to determine the best onset detection time by fitting statistical models to noise and signal data separately, then finding the point in time where the summation of the noise and signal fit scores is best. Once we have determined the onset time for all our Gaussian Blurred samples within a band using this method, we aggregate the results into a likelihood distribution over possible onset times, which we then compare to the range of pick times estimated by our expert analyst.

A Deep Neural Network to Identify Foreshocks in Real Time

KARUNANIDHI, V., ChiriNet, Chennai, India, mail@vikramank.com

Identifying foreshocks, prior to the occurrence of big earthquakes, is crucial and will make this process a valuable precursor. However, until now foreshock events are only identified retrospectively. The motive of this paper is to identify them in real-time.

I curated a new dataset that contains time series data of around 200 events of foreshock, mainshock and aftershock events each. I created a novel method, based on deep learning, that can classify seismic data into the aforementioned categories. The AI model achieves high accuracy while tested in the curated dataset. This is a big breakthrough as it can forecast the occurrence of massive earthquakes that are imminent.

Realistic Synthetic Broadband Ground Motions by Machine Learning

LI, Z., California Institute of Technology, California, USA, zefengli@gps.caltech.edu; ZHU, W., Stanford University, California, USA, zhuwq@stanford.edu; HAUKSSON, E., California Institute of Technology, California, USA, hauksson@caltech.edu; BEROZA, G. C., Stanford University, California, USA, beroza@stanford.edu

High frequency ($f > 1$ Hz) ground motions play an important role in seismic hazard for most structures; however, accurately simulation of high frequency ground motion requires details of crustal structure that we do not have and the computation expense of such simulations grow rapidly with frequency. At present, seismologists can only deterministically simulate ground motions with acceptable accuracy up to 1 Hz; above that, ground motion is typically simulated using stochastic or semi-stochastic methods. Here, we attempt to simulate high-frequency ground motions using a machine- learning-based approach. Because the low frequency component ($f < 1$ Hz) can be physically modeled, we train a deep neural network that takes input of the low frequency component and generates the broadband ground motions from it. We train the network using low frequency waveforms as input, so that the source, path and site effects are all included. The training and test data consist of broadband waveforms of 4,700 M>3 local earthquakes recorded by the Caltech/USGS Southern California Seismic Network (SCSN) from 2000 to 2018. Specifically, the 1-Hz lowpass filtered waveforms serve as input to the network, while the 20-Hz lowpass filtered waveforms are the prediction targets. We evaluate the accuracy of the synthetic broadband waveforms by comparing their key characteristics to a validation subset of the field recordings that were not used to train the network. This provides an alternative approach to generate realistic synthetic broadband ground motions across the frequency range of primary earthquake engineering interest.

Seismic Signal Clustering Using Deep-Self-Supervised Networks

MOUSAVI, M., Stanford University, California, USA, mmousavi@stanford.edu; ZHU, W., Stanford University, California, USA, zhuwq@stanford.edu; BEROZA, G. C., Stanford University, California, USA, beroza@stanford.edu

We present a method for unsupervised clustering of seismic signals using deep neural networks. In this approach, the clustering is performed in the feature space and the feature learning and clustering are optimized simultaneously resulting in learning feature representations that are more suitable for specific clustering tasks. The training process is done in a self-supervised fashion where the targets are generated from the input data. To demonstrate the application of this method for seismic signal processing, we designed two different networks mainly consist of full convolution and pooling layers for discriminating the waveforms with different polarities of first motions and hypocentral distances. Our method resulted in precisions close to those of supervised methods but without a need for labeled data and using much smaller datasets.

Rapid Prediction of Earthquake Ground Shaking Intensity Using Raw Waveform Data and a Convolutional Neural Network

JOZINOVIC, D., Istituto Nazionale di Geofisica e Vulcanologia, Rome, Italy, dario.jozinovic@ingv.it; LOMAX, A., ALomax Scientific, Mouans-Sartoux, France, alomax@free.fr; MICHELINI, A., Istituto Nazionale di Geofisica e Vulcanologia, Rome, Italy, alberto.michelini@ingv.it

Effective early-warning, emergency response and information dissemination for earthquakes and tsunamis require rapid characterization of an earthquake's location, size, ground shaking and other parameters, usually provided by real-time seismogram analysis using established, rule-based, seismological procedures. Powerful, new machine learning (ML) tools analyze basic data using little or no rule-based knowledge, allows us to process the information we have about the earthquake in a new way. A ML deep convolutional neural network (CNN) can operate directly on seismogram waveforms with little pre-processing and without feature extraction.

Here we examine the application of CNN's to rapidly predict ground shaking intensity, using the Engineering Strong Motion Database (Luzi *et al.* (2016)) of accelerometric waveforms and event meta-data for local earthquakes (up to 700 km epicentral distance). Lomax *et al.* (2019) used a CNN to predict earthquake parameters (distance, azimuth, depth and magnitude) using three-component single station waveforms for local, regional and teleseismic distances.

We extend the algorithm of Lomax *et al.* (2019) by exploring new machine learning techniques and data transformations. We find several ways to improvement the CNN algorithm for predict ground shaking intensity. Firstly, we separate the input of the normalized waveforms from the metadata, and then analysed these by separate networks which were then concatenated in an ensemble. Secondly, we use a LSTM (Long-short term memory network) which gave similar results to a CNN. Thirdly, we use an ensemble of a CNN and a LSTM to allow the network to learn local patterns (CNN) and the order of the patterns (LSTM) on the waveform. Additional improvement may be obtained with the use of two or more station waveforms to give even more information to the machine learning model. The ML CNN and classical methods will be compared for algorithm efficiency and accuracy of shaking intensity predictions.

Sequencing Seismic Data and Models

LEKIC, V., University of Maryland, District of Columbia, USA, ved@umd.edu; KIM, D., University of Maryland, Maryland, USA, dk696@umd.edu; BARON, D., Tel Aviv University, Tel Aviv, Israel, dalyabaron@gmail.com; MENARD, B., Johns Hopkins University, Maryland, USA, menard@jhu.edu

Long-term operations of high-quality networks, completion of the *EarthScope* project, continuing temporary deployments, and dense arrays enabled by new technology, have yielded massive datasets of seismic waveforms ripe for analysis and interpretation. In tandem, tomographic models across scales have proliferated, as have structural constraints from scattered and converted waves and ambient noise correlations. Gleaning insights into Earth structures and processes from these vast and heterogeneous datasets requires approaches flexible enough to detect with little-to-no user supervision robust patterns within and across different types of measurements made under various observing conditions. Here, we present results from a completely new sequencing-based unsupervised approach for identifying patterns and trends in seismic models and data. The algorithm arranges the data along a 1D manifold to form a sequence that minimizes differences between neighboring data in the sequence as well as globally across the entire sequence. A datum's position in the sequence can be used to visualize geographic patterns in the dataset – as we illustrate using group velocity dispersion curves and velocity profiles drawn from topographic models – and to identify anomalous signals and place them in context – as we do using waveforms of diffracted waves. We present results of sequencing of Love and Rayleigh dispersion curves across the conterminous United States, which show that the algorithm is able to map out large- and small-scale geographic patterns corresponding to structural boundaries within the crust and to physiographic provinces. Finally, we discuss the utility of sequencing and its advantages over more traditional techniques for exploring large datasets and identifying patterns within them.

Non-Negative Tensor Factorization for Interpretable Unsupervised Signal Discovery in Continuous Seismic Data

NEBGEN, B. T., Los Alamos National Laboratory, New Mexico, USA, bnebgen@lanl.gov; MACCARTHY, J. K., Los Alamos National Laboratory, New Mexico, USA, jkmacc@lanl.gov; ALEXANDROV, B., Los Alamos National Laboratory, New Mexico, USA, boian@lanl.gov

Discovering novel signals in continuous seismic data, particularly those that aren't characterized by common attributes like transience, high amplitudes, or narrow frequencies, is difficult. Unsupervised machine learning offers ways to discover novel signals, but many techniques suffer from the problem of non-interpretability. Non-negative tensor factorization (NTF) is an unsupervised learning approach that can extract hidden features from within data, subject to non-negativity constraints, which makes these features more physically interpretable than comparable techniques like principal component analysis. We present results of applying NTF to continuous seismic polarization and power spectrum data, towards physically interpretable automated feature discovery.

High-Resolution Seismic Tomography of Long Beach, CA, Using Machine Learning

OLSEN, K. B., San Diego State University, California, USA, kbolsen@mail.sdsu.edu; BIANCO, M., Scripps Institution of Oceanography, University of California, San Diego, California, USA, mbianco@ucsd.edu; GERSTOFT, P., Scripps Institution of Oceanography, University of California, San Diego, California, USA, pgerstoft@ucsd.edu; LIN, F., University of Utah, Utah, USA, u0919412@utah.edu

We use a machine learning-based tomography method to obtain high-resolution subsurface geophysical structure in Long Beach, CA, from seismic noise recorded on a "large-N" array with 5204 geophones (~13.5 million travel times). This method, called locally sparse travel time tomography (LST), exploits the dense sampling obtained by ambient noise processing on large arrays by learning dictionaries of local, or small-scale, geophysical features from the data. These features are obtained in LST using dictionary learning, an unsupervised machine learning method. Without the need for smoothing constraints often required in conventional tomography, dictionary learning in LST models both discontinuous and smooth slowness features and helps provide high-resolution slowness estimates as permitted by the data. Using LST, we obtain a high-resolution 1 Hz Rayleigh wave phase speed map of Long Beach. Among the geophysical features shown in the map, the important Silverado aquifer is well isolated relative to previous surface wave tomography studies. The 1 Hz Rayleigh wave sensitivity depth range (~100-500 m) is occupied by Pleistocene and Holocene deposits, which contain most of the ground water resources in the area. Specifically, the Silverado formation (Lower Pleistocene age, 300-580 ka), accounts for nearly 90% of the total ground water extraction in the region considered here. The Silverado unit is characterized by relatively high-density and high-velocity coarse-grained sediments, which result in high phase-speed anomalies detectable by the method. Our results show promise for LST in obtaining detailed geophysical structure in travel time tomography studies. In this particular application, we have potentially further characterized the structure of the important Silverado aquifer in Long Beach, CA.

Convolutional Neural Networks & Deep Learning on Spectrograms for Earthquake Detection

AUDRETSCH, J., King Abdullah University of Science and Technology, Thuwal, Saudi Arabia, james.audretsch@kaust.edu.sa; MAI, P., King Abdullah University for Science and Technology, Thuwal, Saudi Arabia, martin.mai@kaust.edu.sa; PARISI, L., King Abdullah University of Science and Technology, Thuwal, Saudi Arabia, laura.parisi@kaust.edu.sa

Continuous seismic waveform data recorded by a seismometer may potentially contain many events undetected by conventional techniques like STA/LTA or cross correlation. It is challenging to identify low signal-to-noise ratio seismic events when using conventional methods. The benchmark technique, autocorrelation, requires exponentially higher run time over longer time periods - it is infeasible to apply autocorrelation to even weeks of data. With recent advances in computing power and widespread access to large seismic datasets, machine learning can be applied to develop more robust seismic detection algorithms.

Data has been growing exponentially, with access to global seismic databases like IRIS enabling big data innovation. Our novel seismic window detection technique leverages advances in deep learning in order to achieve state of the art seismic event detection. Specifically, we use convolutional neural networks (CNN) to discriminate seismic events from noise. Instead of using raw seismic waveforms as the input, a series of preprocessing strategies constructs modified spectrograms. CNNs are well established in the image domain, having essentially "solved" image classification problems like handwriting recognition. This makes CNNs well suited to be used with spectrograms.

Our technique achieves very high detection accuracy even with low signal-to-noise ratio events. When the training data is from the same source as the test, performance is excellent, achieving 99%+ accuracy with linearly scaling runtime. Furthermore, this technique has potential to be generalized. Using event training data from a broad curation of different event sources can be used to train a model that can detect events in test data originating from a completely different source. We use 100+ stations in 30 locations in order to build a more generalized model, albeit with less consistency than the single source model. Current work involves increasing accuracy of the generalized detection model.

Event and Noise Discrimination Using Deep Learning

KARUNANIDHI, V., ChiriNet, Chennai, India, mail@vikramank.com; CÓRDOVA PÉREZ, G., ChiriNet, Volcan, Panama, geerardoprsz@gmail.com; RODRIGUEZ, A., ChiriNet, Volcan, Panama, angel@volcanbaru.com

We are surrounded by noises originating from a myriad of sources. Short period geophone based seismometers like Raspberry Shake are sensitive to vibrations between .5 to 25 Hz which coincides with urban and cultural noise. Discriminating small to medium events from noise in urban settings by an automatic AI system is the next important step to having usable data from short period geophones.

Detecting local and regional seismic events with conventional amplitude ratio techniques is challenging due to high numbers of triggers generated by short period urban seismic stations.

In this paper, we discuss a methodology based on deep learning to create an AI model that can discriminate between noises and events. We curated a dataset from the Raspberry Shake network that contains a labeled list of events and noises from different sources in urban settings. We created a Deep Neural Network based on AlexNet architecture and trained it in our curated dataset. Our AI model achieves high accuracy in distinguishing events from noise.

A Convolutional-Neural-Network-Based Damage Detection Method and Its Application to a Shake Table Test of an 18-Story Steel Frame Building Structure

WANG, L., Saiama University, Saitama, Japan, o.r.984@ms.saita-u.ac.jp; DANG, J., Saitama University, Saitama, Japan, dangji@mail.saitama-u.ac.jp; WANG, X., Tokyo University of Science, Noda, Japan, wangxin@rs.tus.ac.jp

Rapid structural damage detection of buildings based on measurement is indispensable information for the decision making of reinforcement and retrofitting of structures after earthquakes. In this case, not the damage existing of the whole building, but the damage of individual members of the structure should be recognized. For steel frame building structures, beam-end fractures and buckling of columns cause the degradation of story stiffness, which will lead to the collapse or tilt of the whole structure. It is difficult to recognize this kind of local damage using conventional building damage detection methods such as the identification of response characteristics and the wave propagation methods. However, these damages can be recognized directly from the ripples of the waveforms which are generated by the shock due to the fractures. Recently, with the development of technology of image classification and objects detection, the Convolutional Neural Networks (CNNs) have been proved as one of the effective methods for feature extraction from 2D image data. In order to train an effective damage recognition machine, a large amount of training data is necessary. Because the seismic response data accompanied with structural damage is very rare, in this study, a classifier for detecting beam end fracture of steel frame structures from acceleration waveforms using CNN model was built. And a robust classifier for damaged data and undamaged data was developed. The CNN model was trained using a great number of acceleration waveforms which were generated by numerical simulations. Finally, the proposed method was applied to the shake-table-test data of a specimen of an 18-story high-rise steel frame building to verify the feasibility to recognize the beam end fractures from acceleration waveforms directly.

Science Gateways and Computational Tools for Improving Earthquake Research

Oral Session · Wednesday · 4:15 PM · 24 April · Elliott Bay

Session Chairs: Andrea Donnellan, Lisa Grant Ludwig, Philip J. Maechling.

Science Gateways for Enhancing Earthquake Science

PIERCE, M., Indiana University, Indiana, USA, marpierc@iu.edu

Science gateways are Web interfaces and middleware that both simplify access to supercomputers and expand the capabilities of their users through graphical user interfaces. Since initially conceived two decades ago, science gateways have matured into production services used daily by many scientists. For example, science gateway users of XSEDE supercomputers consistently outnumber regular command line users.

We believe there is a need and an opportunity to dramatically increase the use of gateways and related cyberinfrastructure in earthquake science. This can be done in three related ways: by simplifying access to popular modeling and simulating tools, by providing better mechanisms for interacting with data products such as InSAR and GPS data, and by enabling novel applications of machine learning technologies that are outside the expertise of many geoscientists to geophysical data sets.

In this talk we introduce general science gateway concepts, provide an overview of the NASA-funded GeoGateway project, and describe how GeoGateway will evolve as we align it with the Apache Airavata framework for science gateways. We are developing GeoGateway as a means for geoscientists to access, integrate, and share multiple data sets, including InSAR, GPS, seismicity, and optical data. GeoGateway provides more than access to data sets: by coupling data to modeling and simulation codes, it enables users to easily incorporate data into their computational experiments.

It is important to develop GeoGateway's capabilities within a general framework in order that we can take advantage of features already available from other science gateways. At the same time, GeoGateway has unique or forward-looking capabilities compared to many gateways, so innovations made by GeoGateway can be contributed back to open source science gateway frameworks. We thus describe the synergies between GeoGateway and the Apache Airavata framework for building science gateways, and how Apache Airavata can be used to build other science gateways.

OpenTopography, a Science Gateway to High Resolution Topography for Earthquake Research

CROSBY, C. J., UNAVCO, Colorado, USA, crosby@unavco.org; ARROWSMITH, R., Arizona State University, Arizona, USA, ramon.arrowsmith@asu.edu; SCOTT, C., Arizona State University, Arizona, USA, cpscott1@asu.edu; NANDIGAM, V., San Diego Supercomputer Center, University of California, San Diego, California, USA, viswanat@ucsd.edu

High-resolution topography is a powerful observational tool for studying the Earth's surface, vegetation, and urban landscape. These sub-meter resolution data, collected with lidar and photogrammetry, have been especially transformative for earthquake research. Thanks to more than fifteen years of investment in lidar data of active fault systems, we now have extensive coverage of the San Andreas plate boundary, faults in the Basin and Range, faults in New Zealand, and multi-temporal coverage for several recent earthquakes (*e.g.*, 2016 Kumamoto and Kaikoura).

OpenTopography is an NSF-funded science gateway that facilitates open access to point cloud and raster topographic data, processing tools to generate and visualize derivative products, high performance computational resources, and education and training. With more than 1.1 trillion points online, OpenTopography is the official host of numerous community lidar datasets collected primarily for earthquake research. These include early examples such as the B4 and EarthScope datasets, as well as more recent data covering the Wasatch fault and the Walker fault system.

With increasing multi-temporal data coverage, especially after earthquakes, we are developing web-based on demand topographic differencing. Differencing of topographic datasets can detect surface change from a variety of tectonic and geomorphic processes including earthquakes, volcanic eruptions, flooding events, and landslides. We are implementing two types of topographic differencing: (1) Vertical differencing is the subtraction of rasters derived from lidar point cloud data. Error estimates of change can be derived from survey accuracies and propagated through the analysis. (2) 3D differencing is performed with a windowed implementation of the Iterative Closest Point algorithm. This calculates the best rigid deformation (translation and rotation) to align windows of point cloud topography and provides a complete 3D displacement.

Enhancing Seismology and Earthquake Engineering Research Through the DesignSafe Cyberinfrastructure

RATHJE, E., University of Texas at Austin, Texas, USA, e.rathje@mail.utexas.edu; ARDUINO, P., University of Washington, Washington, USA, parduino@u.washington.edu; BRANDENBERG, S. J., University of California, Los Angeles, California, USA, sjbrandenberg@ucla.edu; LOWES, L., University of Washington, Washington, USA, lowes@u.washington.edu; MOSQUEDA, G., University of California, San Diego, California, USA, gmosqueda@eng.ucsd.edu; PADGETT, J., Rice University, Texas, USA, jp7@rice.edu

The DesignSafe cyberinfrastructure (www.designsafe-ci.org) is part of the NSF-funded Natural Hazard Engineering Research Infrastructure (NHERI) and provides cloud-based tools for use in natural hazards research. The DesignSafe Data Depot provides private and public disk space to support research collaboration and data publishing, while the DesignSafe Discovery Workspace provides cloud-based tools for simulation, data analytics, and visualization; as well as access to high performance computing (HPC). This presentation will describe specific DesignSafe functionalities that serve the seismology and earthquake engineering communities, such as the SCEC Broadband Platform Ground Motion Portal and the OpenSees finite element software available on the Stampede2 supercomputer. Additionally, examples of the use of DesignSafe in earthquake research will be presented, such as the use of Jupyter notebooks to develop elecontric reports that allows researchers to interrogate data interactively within the portal and the publication of reconnaissance data using the DesignSafe Reconnaissance Portal and HazMapper tool.

Seamless Access to Data From Multiple Data Centers Through Federation

TRABANT, C., Incorporated Research Institutions for Seismology, Washington, USA, chad@iris.washington.edu; VAN FOSSEN, M., Incorporated Research Institutions for Seismology, Washington, USA, mick@iris.washington.edu; CASEY, R., Incorporated Research Institutions for Seismology, Washington, USA, rob@iris.washington.edu; CLARK, A., Incorporated Research Institutions for Seismology, Washington, USA, adam@iris.washington.edu; FALCO, N., Incorporated Research Institutions for Seismology, Washington, USA, nick@iris.washington.edu; AHERN, T., Incorporated Research Institutions for Seismology, Washington, USA, tim@iris.washington.edu; CARTER, J., Incorporated Research Institutions for Seismology, Washington, USA, jerry@iris.washington.edu

The IRIS Data Management Center (DMC) is the largest public repository of passive- and active-source seismic data in the world with over 1/2 petabyte archived and growing. Approximately that same volume of seismic data, from different stations, is publicly available from other data centers distributed around the globe. Until recently, the discovery and collection of data across centers required researchers to contact each center individually, often using different mechanisms. In 2013, the International Federation of Digital Seismograph Networks (FDSN[1]) adopted a web service specification for access to data in standard formats. In the years following, multiple data centers have implemented these interfaces. Leveraging this uniformity, we have created the IRIS Federator to integrate federated data discovery and access into our tools. The public interface to the Federator is the irisws-fedcatalog[2] web service, which provides the capability to search for time series data across multiple data centers. We initially integrated federated data access into our FetchData3 and MATLAB[3] tools and the community maintained ObsPy4 Python framework. We have more recently integrated federated access into Wilber[5], a web application for selecting and downloading data event-oriented data, the Metadata Aggregator[6], a web application for browsing metadata and GMap[7], a station mapping service. Ultimately, these efforts will make more data more discoverable, accessible, and usable for all researchers.

[1]International Federation of Digital Seismograph Networks: http://www.fdsn.org/

[2]IRIS Federator, irisws-fedcatalog web service: https://service.iris.edu/irisws/fedcatalog/1/

[3]IRIS web service tools: https://service.iris.edu/clients/

[4]ObsPy, Python framework for seismological data: http://www.obspy.org/

[5]Wilber, event-oriented data access: https://ds.iris.edu/wilber3

[6]Metadata aggregator: https://ds.iris.edu/mda/

[7]Station mapping service: http://ds.iris.edu/gmap/

Computational Tools to Support Large-Scale CyberShake PSHA Simulations

CALLAGHAN, S., University of Southern California, California, USA, scottcal@usc.edu; MAECHLING, P. J., University of Southern California, California, USA, maechlin@usc.edu; GOULET, C. A., University of Southern

California, California, USA, cgoulet@usc.edu; MILNER, K. R., University of Southern California, California, USA, kmilner@usc.edu; SU, M., University of Southern California, California, USA, mei@uscedu.onmicrosoft.com; VAHI, K., USC Information Sciences Institute, California, USA, vahi@isi.edu; DEELMAN, E., USC Information Sciences Institute, California, USA, deelman@isi.edu; GRAVES, R. W., U.S. Geological Survey, California, USA, rwgraves@usgs.gov; OLSEN, K. B., San Diego State University, California, USA, kbolsen@sdsu.edu; CUI, Y., San Diego State University, California, USA, yfcui@sdsc.edu; JORDAN, T. H., University of Southern California, California, USA, tjordan@usc.edu

The Southern California Earthquake Center (SCEC) has developed CyberShake, a software platform to perform physics-based probabilistic seismic hazard analysis (PSHA) using 3D deterministic wave propagation simulations. The CyberShake computational method requires the simulation of a volume of Strain Green Tensors using AWP-ODC-SGT, a parallel GPU code, and hundreds of thousands of serial CPU seismic reciprocity calculations to synthesize seismograms for all relevant events for a single site of interest.

Since a typical CyberShake hazard model includes PSHA results for hundreds of locations, performing a CyberShake regional study typically requires hundreds of terabytes of storage and tens of millions of core-hours on large systems. These studies are supported by a scientific workflow software stack, including Pegasus-WMS, HTCondor, and the Globus Toolkit, which enables automated remote job submission, data management, and fault tolerance.

Recently, SCEC conducted CyberShake Study 18.8, producing a physics-based PSHA hazard model for a large Northern California region that includes the San Francisco Bay Area. PSHA calculations up to 1 Hz for 869 locations in Central and Northern California were performed using the NCSA Blue Waters, OLCF Titan, and USC HPC supercomputers. We will present our software framework and workflow infrastructure which supported CyberShake Study 18.8. We will discuss features required for concurrent execution on multiple distributed systems, including dynamic assignment of workflows to systems, site-specific approaches for remote job submission, and monitoring tools. We will show how this integrated platform enables high throughput and supports the calculation of large-scale physics-based PSHA models in a reasonable makespan.

Photonic and Non-Inertial Seismology

Oral Session · Wednesday · 8:30 AM · 24 April · Grand Crescent

Session Chairs: Nathaniel J. Lindsey, Patrick Paitz, Paul Bodin, Jamie Steidl, Eileen Martin, Zefeng Li.

Optical Measurements of Temperature and Strain of New Zealand's Alpine Fault

BRODERICK, N. G. R., University of Auckland, Auckland, New Zealand, n.broderick@auckland.ac.nz; LOVEDAY, J., University of Auckland, Auckland, New Zealand, j.loveday@auckland.ac.nz; VAN WIJK, K., University of Auckland, Auckland, New Zealand, k.vanwijk@auckland.ac.nz; TOWNEND, J., Victoria University of Wellington, Wellington, New Zealand, john.townend@vuw.ac.nz; SUTHERLAND, R., Victoria University of Wellington, Wellington, New Zealand, rupert.sutherland@vuw.ac.nz

The Alpine Fault of southern New Zealand is a major plate boundary fault that produces large earthquakes approximately every 300 years and last ruptured in 1717AD. There is thus considerable interest in studying this fault for both scientific and practical reasons. In 2013 a program began to drill into the Alpine Fault at Whataroa in NZ where the fault is relatively shallow (about 1000 metres below the surface) and this was completed in 2014. As part of this project a fibre optical cable was cemented to the side of the borehole where it remains allowing passive monitoring of the fault. We will also present in this talk our initial measurements of the temperature profile down the borehole and how it correlates with the subsurface geological features. Repeated temperature measurements over time will allow us to see how the fault changes in response to seismic activities elsewhere. In addition we have performed an active seismic survey near the borehole and can compare the strain measurements taken using the fibre to those from more traditional acoustic sensors. Finally we will discuss our designs for making a suitable sensing head that is compact, solar powered, and highly reliable. Such a sensor head would find widespread applications not only in geophysical monitoring but also structural health monitoring etc.

Fiber Optic Sensing of Local and Regional Earthquakes

MELLORS, R. J., Lawrence Livermore National Laboratory, California, USA, mellors1@llnl.gov; GOK, R., Lawrence Livermore National Laboratory, California, USA, gok1@llnl.gov; MESSERLY, M., Lawrence Livermore National Laboratory, California, USA, messerly2@llnl.gov; PAX, P., Lawrence Livermore National Laboratory, California, USA, pax2@llnl.gov; YU, C., Lawrence Livermore National Laboratory, California, USA, gok1@llnl.gov; MART, C., Lawrence Livermore National Laboratory, California, USA, mart1@llnl.gov; MORENCY, C., Lawrence Livermore National Laboratory, California, USA, morency1@llnl.gov; SHERMAN, C., Lawrence Livermore National Laboratory, California, USA, sherman27@llnl.gov; WANG, H., University of Wisconsin–Madison, Wisconsin, USA, hfwang@wisc.edu

Fiber optic distributed acoustic sensors (DAS) are becoming a widely used tool for seismic sensing for both active and passive measurements. DAS sensors possess several advantages such as low-cost high spatial resolution and wide bandwidth response, but also includes disadvantages such as one component of measurement and a higher noise floor. Here we explore the components of the typical system response (interrogator, fiber/cable, and coupling) and the expected response along with an assessment of the potential for future improvements. Validation of the estimated response is ongoing using a custom interrogator and a fiber testbed. We then apply this understanding to measurements of local and regional events including full waveform modelling and earthquake parameters inferred from coda measurements using data from fiber sensors. We focus on a magnitude 4.3 (21 March 2016 at 07:37) earthquake recorded at a distance of 150 km by a multi-orientation (zig-zag) surface fiber deployment at Brady geothermal area that was co-located with a geophone array, allowing comparison of measurements between geophones and fiber recordings. Synthetic seismograms generated using a known moment tensor matched both the three-component geophones and, when converted to linear strain, the fiber data. Coda wave technique, which allow estimation of source parameters such as magnitude, were also consistent between the fiber and the geophone array. Coda waves are scattered waves and therefore are not as sensitive to fiber orientation. Finally, we speculate on possible key science advances that might be enabled by this new technology.

A Velocity-Based Earthquake Detection System Using Downhole DAS Arrays – Examples From SAFOD

LELLOUCH, A., Stanford University, California, USA, ariellel@stanford.edu; YUAN, S., Stanford University, California, USA, yyuan@stanford.edu; SPICA, Z., Stanford University, California, USA, zackspica@gmail.com; BIONDI, B., Stanford University, California, USA, biondo@stanford.edu; ELLSWORTH, W., Stanford University, California, USA, wellsworth@stanford.edu

Distributed acoustic sensing (DAS) has emerged as a reliable and high-resolution seismic sensing technology for passive and active surveys. One promising application of DAS is the ability to incorporate high spatial resolution downhole arrays in earthquake monitoring. We analyze about 20 days of data, recorded using an OptaSense ODH 3.1 interrogator at the San Andreas Fault Observatory at Depth (SAFOD) during June-July 2017. Data were sampled at 1 m spacing and a gauge length of 10 m in a tubed downhole fiber cemented between casing strings between 10 and 800 m depth. As a first step, we utilize near-vertical incidence earthquakes, traveling parallel to the vertical array, to estimate P- and S- velocities. We compare the estimated P-wave model to those derived from a surface refraction survey and a conventional vertical seismic profiling (VSP) survey. We also obtained a P-wave model using the ambient field with just one day worth of data. The continuous nature of the DAS array allows us to accurately retrieve a high-resolution P-velocity model and extract an S-velocity model that couldn't be estimated from the VSP data. Earthquakes recorded by the downhole DAS array display a depth-dependent moveout that is affected by the velocity structure at the location of the array as well as the angle of incidence at which wave-fronts cross the DAS fiber. We implement a moveout-based detection algorithm using previously estimated velocities. It is a pick-free, waveform-based, fast, simple to code, and fully automatic method. The technique scans a range of acceptable incidence angles, yielding the estimated incidence angle as a by-product. We apply the method to 20 days of recorded passive data, aiming at detecting both P and S phases. P and S detection results are combined and compared to the USGS catalog. We find that using a single, uniaxial downhole DAS system, we are able to detect above 70% of cataloged events within a radius of 15km as well as one weak uncatalogued event. These encouraging results set the path for downhole DAS monitoring of earthquakes.

Distributed Acoustic Sensing (DAS) for Continuous Monitoring of Near-Surface Properties Using Coda Wave Interferometry

RODRÍGUEZ TRIBALDOS, V., Lawrence Berkeley National Laboratory, California, USA, vrodrigueztribaldos@lbl.gov; DOU, S., Feasible Inc., California, USA, shan@feasible.io; LINDSEY, N. J., Lawrence Berkeley National Laboratory, California, USA, natelindsey@berkeley.edu; ULRICH, C., Lawrence Berkeley National Laboratory, California, USA, culrich@lbl.

gov; ROBERTSON, M., Lawrence Berkeley National Laboratory, California, USA, mcrobertson@lbl.gov; FREIFELD, B. M., Lawrence Berkeley National Laboratory, California, USA, bmfreifeld@lbl.gov; DALEY, T. M., Lawrence Berkeley National Laboratory, California, USA, tmdaley@lbl.gov; MONGA, I., Lawrence Berkeley National Laboratory, California, USA, imonga@es.net; TRACY, C., Lawrence Berkeley National Laboratory, California, USA, ctracy@es.net; AJO-FRANKLIN, J. B., Lawrence Berkeley National Laboratory, California, USA, jbajo-franklin@lbl.gov

Distributed Acoustic Sensing (DAS) re-purposes telecommunication optical fibers as multichannel seismic arrays. This rapidly developing technology enables acquisition of seismic data for long periods of time across long distances (10's of km) at unprecedented spatial (~1 m) and temporal resolutions, defining it as an ideal tool for monitoring variations in near-surface seismic properties.

Measuring changes in relative seismic velocity (dv/v) in the subsurface using ambient seismic noise interferometry is increasingly being used in environmental and geohazard monitoring. Here, we follow this approach and explore the utilization of DAS-based seismic observations for tracking temporal changes in dv/v through the analysis of coda waves in ambient noise recordings. The continuous recording of ambient seismic noise at frequencies from mHz to kHz at very high spatial density provided by DAS enables a thorough investigation of hypothesized spatial and temporal variations in seismic velocities and how they relate to changes in subsurface properties. We calculate cross-correlation function estimates between inline DAS sensors for consecutive time periods and apply coda wave analysis techniques to estimate traveltime shifts between waveforms. Issues related to the repeatability of DAS observations and the significance/interpretability of measured changes for monitoring near-surface properties will be addressed. This approach is applied to a variety of monitoring DAS datasets recorded over several months using both built-for-purpose fiber-optic installations and so-called 'dark fiber' networks, *i.e.* fiber-optic lines installed for telecommunication purposes but not currently utilized for data transmission (unlit). Applications range from detection of water-level fluctuations to permafrost thaw. Our observations will shed light into the potential for using DAS-based seismic networks as a tool for continuous monitoring of environmental and critical processes at a regional scale.

Experimental Assessment of Rocking and Torsion in Civil Engineering Structures Using 3C and 6C Sensors

GUÉGUEN, P., ISTerre, Université Grenoble Alpes/CNRS/IFSTTAR, Grenoble, France, philippe.gueguen@univ-grenoble-alpes.fr; GUATTARI, F., iXblue, Saint-Germain-en-Laye, France, frederic.guattari@ixblue.com; LAUDAT, T., iXblue, Saint-Germain-en-Laye, France, theo.laudat@ixblue.com

In this abstract, an experience is presented related to the rotations observed in the City-Hall building in Grenoble (France), a 12-story reinforced concrete building. This building is permanently monitored since 10 years, with 3 components accelerometers located at the bottom and the top. Modal decomposition including soil-structure interaction was done using ambient vibration and dozen earthquakes recordings and compared with iXblue 6C rotational sensor data, temporarily installed at the top then at the bottom. Dynamic response of structures to a seismic loading produce rotational forces that may generate considerable stresses. These rotational forces are essentially related (1) to the rotational deformation around the two horizontal axes (rocking) and resulting from soil-structure interactions considering the structure as rigid body; (2) the rotation around the vertical axis (torsion) essentially when the center of mass (*i.e.*, where the inertia seismic forces apply) is shifted from the center of stiffness (*i.e.*, where the elastic forces apply). Simplified models including rotations of the soil-structure interaction are based on the modal decomposition. In this case, each component of the motion is assumed to be independent of the others. Thus, in the structures, only translation sensors are generally installed and the rotation components are evaluated via the spatial derivatives of the horizontal and vertical components. For example the torsion is usually calculated as the relative difference between two horizontal sensors placed at the same floor and the rocking between two vertical sensors placed at the foundation level. However, combinations of translations and rotations exist which can only be evaluated with the measurement of the 6 motion components (3 translations and 3 rotations). In this study, an extensive comparison between the direct measurement of rotation and the spatial derivative rotation is done, validating the classical soil-structure interaction models used in civil engineering.

New Approaches to Geophysical Research Using Dense Mixed Sensor and Broadband Seismology Arrays

Oral Session · Wednesday · 10:45 AM · 24 April · Grand Crescent

Session Chairs: Tim Parker, Ninfa Bennington, Bruce Townsend.

Lessons From Two Years of Multi-Sensor Structural Monitoring at the UC San Diego Geisel Library

GOLDBERG, D. E., Scripps Institution of Oceanography, University of California, San Diego, California, USA, degoldberg@ucsd.edu; GOLRIZ, D., Scripps Institution of Oceanography, University of California, San Diego, California, USA, dgolriz@ucsd.edu; BOCK, Y., Scripps Institution of Oceanography, University of California, San Diego, California, USA, ybock@ucsd.edu; LO, E., University of California, San Diego, California, USA, eklo@eng.ucsd.edu; DE VIVO, L., University of California, San Diego, California, USA, ldevivo@eng.ucsd.edu; KUESTER, F., University of California, San Diego, California, USA, fkuester@ucsd.edu; WANG, X., University of California, San Diego, California, USA, xiw002@eng.ucsd.edu; HUTCHINSON, T., University of California, San Diego, California, USA, tahutchinson@eng.ucsd.edu; MAHER, R., KDM Meridian, California, USA, rmaher@kdmmeridian.com

We describe a multi-sensor approach to structural monitoring in development at the University of California San Diego (UCSD) Geisel Library. Our goal is to supplement visual inspections by the university's Planning, Design and Construction group to assess structural health, especially for rapid response following an extreme weather, seismic, or other hazard event. The library is instrumented with collocated Global Navigation Satellite Systems (GNSS) instruments and Micro-Electro-Mechanical Systems (MEMS) accelerometers. These data are streamed in real-time to the Scripps Orbit and Permanent Array Center for analysis. We investigate the frequency response of the healthy building and any changes over time. Once-yearly surveys using ground-based Light Detection and Ranging (LiDAR) and Unmanned Aerial Vehicles (UAVs) for high-resolution digital imaging are used to create a 3-D digital surrogate of the structure, which is tied to the precisely known locations of the rooftop GNSS instruments. The UAV is also equipped with a high-rate precision GNSS instrument, such that the precisely known UAV flight-path can be used as an additional constraint for UAV imagery alignment. Repeat surveys following natural hazards will provide estimates of any permanent changes to the structure. In the absence of a major event during our study period, we supplement our analysis with seismic tests at the Natural Hazards Engineering Research Infrastructure at UCSD Large High Performance Outdoor Shake Table. We installed GNSS and MEMS accelerometers on cold-formed steel structures subjected to dynamic seismic and monotonic pull tests, and conducted UAV photogrammetry during testing. We present lessons from two years of data collection at the Geisel Library and from seismic tests at the Shake Table that can be applied to our longer term monitoring strategies. We describe real-time monitoring capabilities that can be applied to earthquake and tsunami early warning and rapid response.

Clarifying the Distribution of Magmatic Fluids Within the Yellowstone Volcanic System: A Magnetotelluric and Seismic Study

BENNINGTON, N. L., University of Wisconsin–Madison, Wisconsin, USA, ninfa@geology.wisc.edu; SCHULTZ, A., Oregon State University, Oregon, USA, adam.schultz@oregonstate.edu; BOWLES-MARTINEZ, E., Oregon State University, Oregon, USA, bowlesme@oregonstate.edu; THURBER, C. H., University of Wisconsin–Madison, Wisconsin, USA, cthurber@wisc.edu; FARRELL, J., University of Utah, Utah, USA, jamie.farrell@utah.edu; LIN, F., University of Utah, Utah, USA, fanchi.lin@utah.edu

Many geophysical studies of the Yellowstone volcanic system have been carried out in order to assess the volcanic hazard that the region may represent. Such studies aim to address questions concerning the origin and location of magmatic fluids at lower crustal depths; how magmatic fluids migrate through and are stored within the crust; and the composition of stored magma. To this end, we are currently engaged in a multi-disciplinary, magntotelluric (MT) and seismic, study of the Yellowstone volcanic system. In summer 2017, we collected densely spaced wideband MT data throughout the Yellowstone area. As part of the EarthScope Magnetotelluric Transportable Array, widely space long period MT data were previously collected throughout the region. We use these wideband and long period MT data to invert for the 3D resistivity structure of the Yellowstone volcanic system from upper crustal through upper mantle depths. Concurrently, we are carrying out a seismic velocity study of the region where the P- and S-wave crustal velocity structure are solved for via joint inversion of surface and body-wave data. Since the inverted resistivity and seismic velocity models have spatially coincident model spaces, we can interpret the region in a joint geophysical parameter space. MT and seismic data are sensitive to different properties of the subsurface. Thus, interpretation of spatially coincident electrical resistivity and seismic velocity models allows us to more robustly constrain the structure and composition of the Yellowstone volcanic system in order to better understand the volcanic hazard it represents.

New High Resolution Very Low Powered Broadband Digitizer System, Pegasus

TOWNSEND, B., Nanometrics Inc., New Mexico, USA, brucetownsend@nanometrics.ca; MOORES, A., Nanometrics Inc., Kanata, Canada, andrewmoores@nanometrics.ca; PELYK, N., Nanometrics Inc., Kanata, Canada, nickpelyk@nanometrics.ca; PARKER, T., Nanometrics Inc., New Mexico, USA, timbobparker@gmail.com

The seismic research community has been looking for solutions and equipment for temporary array studies in broadband and mixed sensor deployments including Large-N science. Nanometrics is addressing this need with the introduction of the Pegasus digital recorder and supporting ecosystem which is designed to provide high resolution recording in temporary networks and remote environments. Data is recovered science ready and the Pegasus is compatible with not only broadband sensors, but with geophones and various other types of instrumentation.

The exceptionally low power consumption of the Pegasus digital recorder (<200mW) significantly reduces battery requirements, overall station size is less than 1.25 liters in volume, it is lightweight at less than.5kg and is IP68 rated for immersion. The enclosure is robust for autonomous operations in all terrestrial environments enabling efficient deployment of more stations for a longer period of time. Installation and servicing is simplified with applications and features making data harvesting fast, verified and reliable while field station operational review is completed quickly and with certainty. Stand-alone power is less than <200mW for three channels and a power cycled GNSS timing system. Coupled with the Nanometrics Trillium directly buriable broadband sensors the lowest possible total station power is less than 0.4W. A fourth high resolution channel can be used for complimentary geophysical sensors, such as infrasound, tilt meter or absolute pressure sensor. The Pegasus digitizer will work with other conventional analog out seismic sensors, such as geophones and accelerometers and has standard community data storage formats that are essentially archive ready leveraging the research community archive services. Data is complete and ready-to-process, with MiniSEED waveforms, StationXML metadata compliant to FDSN standards and comprehensive project audit information. For really remote operational awareness and logistical planning there is a very low power SOH(state of health) of heath telemetry option.

Aftershock Monitoring with a Heterogeneous Seismic Network

PEARSON, K. M., University of Maryland, Maryland, USA, karen.melinda@gmail.com; LEKIC, V., University of Maryland, Maryland, USA, ved@umd.edu; PRATT, T. L., U.S. Geological Survey, Virginia, USA, tpratt@usgs.gov; ROMAN, D. C., Carnegie Institution for Science, District of Columbia, USA, droman@carnegiescience.edu; WAGNER, L. S., Carnegie Institution for Science, District of Columbia, USA, lwagner@carnegiescience.edu; KIM, W., Lamont-Doherty Earth Observatory, New York, USA, wykim@ldeo.columbia.edu

The Mw 4.2 Dover, DE, earthquake in 2017 represented an opportunity to evaluate seismicity in a passive margin setting, motivating a rapid deployment of instruments in order to record aftershocks. Within 24 hours of the main shock, personnel from the Lamont-Doherty Earth Observatory, the Department of Terrestrial Magnetism of the Carnegie Institution for Science, the University of Maryland, Lehigh University, and the USGS mobilized to install a mix of instruments in the epicentral area. The deployment included 10 Fairfield Nodal ZLand three-component 5-Hz geophones, which operated on self-contained batteries for 37-40 days, as well as four Nanometrics Trillium 120 Compact posthole broadband seismometers, which used solar power and ran for 42 days until removal.

Using template-matching, we detect several dozen aftershocks, all with magnitudes ≤ 1.3, and locate a subset using a 1D model developed by modeling waveforms of the M4.2 main shock at regional broadband stations down to a 5-second period. We discuss the aftershock productivity and locations in the context of East Coast seismicity. We observe that a single broadband station detects more aftershocks than all 10 nodal stations combined, due to relatively high noise levels on the nodals, even though the frequency range of interest (4-40 Hz) is optimal for the 5-Hz geophone. We compare the signal power during the detection window for nodal and broadband data and relate that to estimated local magnitude of detected aftershocks. Finally, we analyze the relative performance of the three-component nodal geophones and the compact broadband seismometers, and discuss the associated tradeoffs when designing aftershock-monitoring deployments.

Calibrating the 2016 IRIS Community Wavefields Experiment Nodal Sensors for Amplitude Statics and Orientation Errors

BOLARINWA, O. J., University of Memphis, Tennessee, USA, jblrinwa@memphis.edu; LANGSTON, C. A., University of Memphis, Tennessee, USA, clangstn@memphis.edu

Gradiometry is an array analysis technique that is complementary to the traditional phased array method. Unlike the phased array that requires several signal cycles to accurately compute wave attributes, gradiometry uses a fraction of a signal cycle to compute wave attributes. This quality dictates the compactness of the gradiometer; which makes it deployable in areas inaccessible to large aperture arrays. However, differences in instrument response, digitizer gains, local site conditions and instrument orientation errors can introduce significant errors while computing wave attributes from gradiometer records. Therefore, it is necessary to correct the gradiometer element records for amplitude and instrument orientation variations due to the stated errors. The array calibration method employed in this study is based on the premise that a common wavefield should be recorded over a small-aperture array using teleseismic observation. Teleseismic P and S waves recorded in the course of the 2016 IRIS community-planned experiment in northern Oklahoma were used to estimate amplitude correction factors (ACFs) and orientation correction factors (OCFs) for the gradiometer sensors and two other gradiometer-sized subarrays' sensors. These subarrays were embedded in the 13-km aperture nodal array that was also fielded during the 2016 IRIS experiment. In situ estimates of ACFs for the gradiometer vary by 2.3% (coefficient of variation) for the vertical channels and, typically, variability is less than 6% for the horizontal channels. Gradiometer elements' OCFs generally dispersed by 8º. For the two subarrays, the vertical component ACFs usually vary up to 3.1%, while their lateral components' ACFs largely spread up to 4.9%. OCFs for the subarrays generally vary by 9º. Work is currently going on to calibrate the entire nodal sensors of the experimental arrays. The outcome of this study shows that small-aperture arrays can be calibrated for amplitude statics and instrument orientation errors so that the resulting dataset can be used for high precision gradiometry computations.

Evolving Best Practices for Station Buildout in EEW and New Permanent Networks

Oral Session · Wednesday · 2:15 PM · 24 April · Grand Crescent

Session Chairs: Fabia Terra, Mouse Reusch, Tim Parker, Geoffrey Bainbridge.

Network Expansion Challenges in Alaska

DALTON, S. M., Alaska Earthquake Center, Alaska, USA, sdalton4@alaska.edu

The Alaska Earthquake Center is expanding its real-time monitoring network of 150 stations by adding 43 stations first installed as part of the USArray project. Expansion regions were chosen to improve the speed and accuracy of earthquake reporting in southeast Alaska, and to lay a foundation for earthquake early warning in the state's populous and seismically hazardous south-central region. Within those regions, existing USArray stations were chosen based on location and accessibility, data quality, and telemetry method. We will present a summary of our operation and maintenance strategy as it relates to each of these categories and highlight challenges we have encountered that may be relevant to other network operators planning expansions.

Oregon's Multi-Hazard Monitoring Network: Recent Growth and Future Directions

TOOMEY, D., University of Oregon, Oregon, USA, drt@uoregon.edu; O'DRISCOLL, L. J., University of Oregon, Oregon, USA, lelando@uoregon.edu; WALSH, L. K., University of Oregon, Oregon, USA, lwalsh@uoregon.edu; MEYER, S., University of Oregon, Oregon, USA, smeyer11@uoregon.edu

The Oregon Hazards Lab uses science, technology, and education to detect, monitor, and mitigate multi-hazards. We are partners in the following projects: (1) the Pacific Northwest Seismic Network (PNSN), a cooperative operated by the University of Washington, the University of Oregon, and USGS; (2) ShakeAlert, the Earthquake Early Warning system developed by the USGS and its partner institutions; and (3) AlertWildfire, a consortium of three universi-

ties— The University of Nevada, Reno, University of California San Diego, and the University of Oregon— providing access to state-of-the-art Pan-Tilt-Zoom fire cameras and tools to help firefighters and first responders. Since 2014, the University of Oregon has worked closely with stakeholders, partner agencies, and policy makers to significantly grow a seismic monitoring network footprint. In 2015 Oregon contributed $1M to the buildout of PNSN and ShakeAlert. In 2018 Governor Kate Brown and State Resilience Officer Mike Harryman delivered a policy agenda entitled *Resiliency 2025: Improving Our Readiness for the Cascadia Earthquake and Tsunami*, wherein they focused on 6 key strategies. One strategy is that Oregon implement a statewide early warning system by 2023 that ties multi-hazard events— earthquakes, wildland fires, landslides, and flooding events— into one alerting and monitoring system. On the basis of her policy agenda, Governor Brown's recommended budget includes $12M to implement an early warning system by 2023. Building on these successes, the Oregon Hazards Lab was created in 2018. The PNSN is about halfway complete with the ShakeAlert sensor network and O-HAZ has a nascent presence of AlertWildfire stations. Robust telemetry will mutually serve both programs, and serve as a platform for the future growth of OHAZ. We will discuss the genesis of Oregon's multi-hazard monitoring network, challenges faced, and collaborations made along the way, as well as future plans for expansion and growth.

Expanding the Berkeley Digital Seismic Network for Earthquake Early Warning (EEW): Operations, Installation and Upgrades to Seismic Monitoring

TERRA, F., University of California, Berkeley Seismology Lab, California, USA, terra@berkeley.edu; HELLWEG, M., University of California, Berkeley Seismology Lab, California, USA, hellweg@berkeley.edu; MERRITT, J. M., University of California, Berkeley Seismology Lab, California, USA, jmerritt@berkeley.edu; ALLEN, R. M., Berkeley Seismological Laboratory, California, USA, rallen@berkeley.edu; FERRY, D., CalOES Earthquake and Tsunami Hazards Program, California, USA, dana.ferry@caloes.ca.gov; ARBA, R., CalOES Earthquake and Tsunami Hazards Program, California, USA, ryan.arba@caloes.ca.gov

With funding from CalOES and the USGS, University of California Berkeley Seismology Lab (BSL) is expanding the Berkeley Digital Seismic Network (BDSN) between 2015 and 2021, with funding currently committed to increase from 50 stations in 2015 to 98 stations in 2019. Additional support is in the process of being allocated to the BSL to install 45 or more stations by Spring 2021.

The rapid increase in the number of permanent co-located broadband and strong motion sites in the BDSN requires updates to our existing Network Operations, including: 1 written permits for all new and existing stations; 2 environmental permits for all new stations and upgrades; 3 improvements to techniques for evaluating existing instrumentation and QA/QC of seismic equipment being installed; 4 developing guidelines and configurations for equipment new to the BSL, including understanding firmware and working with the manufacturer to ensure its compliance with our needs; 5 station acceptance of installation quality and latency analysis for EEW ready stations; and 6 bringing in and QC-ing data for analysis and EEW from network partners such as CGS, DWR and UNR. Each of these factors presents different risks to scheduling and budgeting. Timing for steps 1 and 3 has been the most challenging.

BSL was contracted to install 43 new stations in two years using CalOES and USGS funds. The biggest impediments in preparing to install stations are scouting sites and obtaining permits. In coordinated efforts with the USGS and CalOES, BSL is participating in efforts to get bulk permits from USFS, State Parks, CalTrans, CalFire, and UCOP. "Streamlining" the permit process has brought many challenges. For example, BSL identified 19 sites on UC properties for new or upgraded stations. Although the various parties involved were very cooperative, many lawyers participated in the process to finalize a permit agreement including environmental requirements (CEQA/NEPA).

BSL is making good progress but deadlines, troubleshooting and budget creep are the largest stumbling blocks in the BSL's build out efforts.

Optimizing Borehole Station and Array Performance, Enabled by the Trillium Slim Borehole 120 Seismometer

BAINBRIDGE, G., Nanometrics Inc., Kanata, Canada, geoffreybainbridge@nanometrics.ca; PARKER, T., Nanometrics Inc., New Mexico, USA, timparker@nanometrics.ca; TOWNSEND, B., Nanometrics Inc., Ottawa, Canada, brucetownsend@nanometrics.ca

Downhole installation offers the potential for best seismic performance but also greater uncertainties compared to a near-surface direct bury or vault installation. This talk surveys some typical pitfalls, solutions, and future directions for cased borehole stations based on Nanometrics' experience.

A heuristic model is presented of the installation as a series of material interfaces where each presents a potential source of mechanical noise and affects the system transfer function. The single most important factor is the location of the seismometer relative to the interface of loose soil to solid rock. There are also a series of connections from the seismometer to a holelock or sand, to the casing, to cement, then to soil or rock, and also up to the wellhead via the cables and casing. Each of these interfaces can affect performance, which we illustrate with data and recommendation of best practices.

We also present Nanometrics' new borehole instrument: the Trillium Slim Borehole 120 seismometer, a 4.1 inch (104 mm) diameter instrument with Trillium 120QA/PH class performance having significantly improved SWaP (size, weight and power). It is designed for smaller holes down to 4.5" or 115 mm diameter, in shallow or deep deployment, using a simple passive holelock or sand installation. The small diameter permits deployment in existing small boreholes, and facilitates construction of new lower cost boreholes, minimizing disturbance of the surrounding rock and improving instrument coupling.

High performance and simpler logistics makes the Trillium Slim Borehole well suited for many applications, including new higher-density arrays for full waveform analysis and detection of earthquake gravity signals. In conclusion we present a proposed array design for optimal measurement of earthquake gravity signals on a regional scale.

Testing the Readiness of Strong Motion Sensors for Earthquake Early Warning

MASSIN, F., Swiss Seismological Service, ETH Zurich, Zurich, Switzerland, fred.massin@gmail.com; CLINTON, J., Swiss Seismological Service, Zurich, Switzerland, jclinton@sed.ethz.ch; RACINE, R., Swiss Seismological Service, Zurich, Switzerland, racine@sed.ethz.ch; ROSSI, Y., Institute of Geodesy and Photogrammetry, Zurich, Switzerland, rossiy@student.ethz.ch

Today many sensors are marketed as being ready for earthquake early warning (EEW) applications. EEW aims to provide very rapid estimates of event parameters or expected ground motions, spanning wide ranges of source dimension, in advance of the strong shaking. EEW systems based on seismic data can have significant differences in their approach, but in general if a seismic sensor is appropriate for EEW, it should meet a number of key features. It should be capable of resolving the strongest ground motions on-scale, have an appropriate (and linear) dynamic range and broadband frequency response to ensure that small and moderate events can be distinguished from great events, have accurate timing, and crucially be capable to provide reliable low latency data streams. It should also be robust enough to operate for multiple years in the typical vault conditions defined by the local conditions. EEW systems can be significantly improved by enhancing the network density, so there is a balance between sensor quality and cost. We have tested the suitability of 9 different strong motion sensors for EEW, ranging from very high quality though more expensive sensors, to the most reasonably priced sensors currently on the market. Our goal is to identify appropriate sensors for deployment in prototype EEW systems across Central America that are based on EEW algorithms embedded in SeisComP3. Thus, the latency for all sensors is measured via SeedLink streaming protocol. In this presentation we present the performance of the sensors we have tested with focus on parameters critical to EEW in Central America.

Advances in Ocean Floor Seismology

Oral Session · Wednesday · 4:15 PM · 24 April · Grand Crescent

Session Chairs: Charlotte A. Rowe, Susan M. Bilek, Michael Begnaud.

Millihertz Ground Motion at the Seafloor Excited by Large Regional Earthquakes

ITO, Y., Disaster Prevention Research Institute, Kyoto University, Uji, Japan, ito.yoshihiro.4w@kyoto-u.ac.jp; WEBB, S., Lamont-Doherty Earth Observatory, New York, USA, scw@ldeo.columbia.edu; KANEKO, Y., GNS Science, Lower Hutt, New Zealand, y.kaneko@gns.cri.nz; WALLACE, L. M., GNS Science, Lower Hutt, New Zealand, l.wallace@gns.cri.nz; HINO, R., Tohoku University, Sendai, Japan, hino@m.tohoku.ac.jp

The effects of sedimentary basins on strong ground motion have been recognized through the amplification and excitation of long-duration coda. Most studies evaluating these effects using seismograms have been land-based. Ocean bottom seismometers have recently been deployed in several subduction zones, that commonly use high-sensitivity and/or broadband sensors in the ocean bottom networks, which makes it difficult to measure large or strong ground motion without saturating the recorded seismograms. Herein, we analyze the ground motion retrieved from ocean bottom pressure gauges (OBPGs) as strong-motion seismometers, and discuss the effects of shallow submarine structures on the amplification and excitation of coda waves, particularly the Hikurangi Trough accretionary wedges.

The dynamic pressure changes (caused by strong motion) on the OBPGs can be converted to ground motion acceleration, based on the ground motion frequency and the water depth of a given OBPG. The water depth can be expressed in terms of the fundamental acoustic resonant frequency, which depends on the velocity of the ocean acoustic wave and the water depth above the OBPG. When the ground motion frequency is sufficiently low compared to the acoustic resonant frequency, the vertical acceleration of the ground motion at the seafloor can be estimated from the dynamic pressure change observed on the OBPG.

We investigated the ocean bottom seismograms of both M7.8 Kaikoura and M7.1 Te Araroa earthquakes from ocean bottom pressure recorders. Our results show that anomalous long-period waves, dominating in the range of 0.005–0.05 Hz, occurred near the coastline. However, the long-period waves have not been observed at onshore stations. This suggests that infragravity, or ocean surface gravity waves, might have been generated by the ground motion at shallow water depths, near the coastline.

Teleseisms and Microseism Generation Observed by an Ocean-Bottom Distributed Acoustic Sensing Array Offshore Belgium

WILLIAMS, E. F., California Institute of Technology, California, USA, efwillia@gps.caltech.edu; FERNANDEZ RUIZ, M. R., University of Alcala de Henares, Madrid, Spain, rosario.fernandezr@uah.es; FIDALGO MARTINS, H., University of Alcala de Henares, Madrid, Spain, h.fidalgo@uah.es; ZHAN, Z., California Institute of Technology, California, USA, zwzhan@gps.caltech.edu; GONZALEZ HERRAEZ, M., University of Alcala de Henares, Madrid, Spain, miguel.gonzalezh@uah.es; VANTHILLO, R., Marlinks, Leuven, Belgium, roel.vanthillo@marlinks.com; MAGALHAES, R., University of Alcala de Henares, Madrid, Spain, regina.teixeira@uah.es

In just the last five years, distributed acoustic sensing (DAS) technology, which converts an optical fiber into a dense array of linear strainmeters, has emerged as a promising technology for earthquake seismology applications. Here, we demonstrate that DAS arrays repurposing pre-existing fibers laid in ocean-bottom telecommunication cables represent a valuable tool for marine seismology, with real-time data telemetry, unlimited deployment duration, and relatively low cost per sensor compared to current ocean-bottom seismometers. In August 2018, we occupied 42 km of fiber in a submarine cable offshore Belgium with a chirped DAS system, recording at 10 Hz with 4192 channels and 10 m spacing. Transforming the raw strain records into the frequency-wavenumber domain, we utilize phase information to identify and separate energy from seismic waves and ocean waves. Below 0.1 Hz, we successfully recover S-wave phases from the M8.2 2018-08-19 Fiji deep earthquake, which show moderate to high waveform fidelity when compared with a nearby broadband station. We observe ocean surface gravity waves propagating both land-ward and sea-ward across the array with a dominant period of 5.5 s. Further, we observe Scholte waves with a dominant period of 2.75 s and phase velocity around 500 m/s, which we determine are generated in-situ based on the symmetry of their directional spectrum. We discuss the implications of our observations for physical models of secondary microseism generation.

Seismo-Tectonic Monitoring of Endeavour: Recent and Future Expansion of Ocean Networks Canada's NEPTUNE Observatory on the Juan de Fuca Ridge

FARRUGIA, J. J., University of Victoria, Victoria, Canada, jfarrugia@uvic.ca; HEESEMANN, M., University of Victoria, Victoria, Canada, mhessema@uvic.ca; WILCOCK, W. S. D., University of Washington, Washington, USA, wilcock@uw.edu; BAILLARD, C., University of Washington, Washington, USA, baillard@uw.edu; MIHALY, S. F., University of Victoria, Victoria, Canada, smihaly@uvic.ca; SCHERWATH, M., University of Victoria, Victoria, Canada, mscherwa@uvic.ca

Ocean Networks Canada's (ONC) NEPTUNE observatory provides real-time access to sensors on the northern segment of the Juan de Fuca Ridge (Endeavour). In 2010, an initial suite of disparate instruments (cameras, a short-period seismometer, and vent monitoring instruments) was installed at the Main Endeavour vent field, which was further fortified by the installation of four extension cables— connecting the Western Ridge Flank, Northern Circulation Moorings, Mothra Vent Field, and Southern Circulation moorings— in 2016. This past summer, vent monitoring systems and five seismic sensors were installed in the area.

We will present an overview of the data that are available in near real-time from Endeavour and future plans for additional experiments, including measurements of seafloor compliance. We will focus on initial results from our improved seismic network, which is critical to the understanding of geological processes that create oceanic crust, such as plate boundary extension, subsurface magma movements, and hydrothermal heat extraction. Moreover, we will demonstrate the efficacy of a small-scale three-sensor seismometer array (Güralp Maris) that is designed to detect and monitor small cracking events in the upper few hundred meters of crust that may be related to hydrothermal flow and chemical reactions in the Main Endeavour Vent Field.

Ambient Noise Analysis Near Hikurangi Margin, New Zealand Using an Amphibious Array

SHEEHAN, A. F., University of Colorado Boulder, Colorado, USA, anne.sheehan@colorado.edu; WANG, H., University of Colorado Boulder, Colorado, USA, hongda.wang@colorado.edu

We apply ambient noise analysis to data from the Hikurangi Ocean Bottom Investigation of Tremor and Slow Slip (HOBITSS) experiment and 32 New Zealand national seismic network (GeoNet) seismic stations to infer the seismic wave speed structure of the Hikurangi Margin and East Cape, New Zealand, regions. During the 2014-2015 HOBITSS experiment 15 ocean bottom seismometers (OBS) were deployed on the Hikurangi portion of the subduction zone off North Island New Zealand. We apply standard ambient noise data processing methods to the continuous vertical component data, including cutting daily records, calculating cross-correlation between station pairs, and stacking daily cross-correlations to obtain the Rayleigh wave Green's function estimates. Removal of tilt and compliance noise from the OBS vertical components using the horizontal components and pressure records produced little to no improvement in this study because of the limited bandwidth of the surface wave signal. We apply frequency-time analysis (FTAN) to the stacked cross-correlations to measure Rayleigh wave group speeds. We obtain reasonable measurements for periods of 5 to 12 seconds for most of the FTAN diagrams. Asymmetry on the positive and negative lags of the cross-correlation from both the waveform and signal to noise ratio (SNR) of the FTAN results is observed for many station pairs, likely due to the distribution of noise sources. The Rayleigh wave dispersion measurements are used to invert for group velocity maps at periods from 5 to 12 seconds using a straight ray theoretic tomography method. The group velocity maps correlate with regional features mostly as expected, most notably low seismic wave speeds in the ocean and higher wave speeds on the continent, with the highest group velocities beneath the Ruakumara range of the East Cape. We invert for 1-D velocity structures at selected points, obtaining constraints on sediment and upper crustal shear velocity structure of the Hikurangi accretionary prism, as well as coastal and continental northeast North Island, New Zealand.

Güralp Aquarius, The Future of Ocean Seismology

ALLARDICE, S., Güralp Systems LTD, Reading, United Kingdom, sallardice@guralp.com; HILL, P., Güralp Systems LTD, Reading, United Kingdom, phill@guralp.com

With 70% of the Earth covered in water, there is a significant gap in the seismic data catalogue which offshore datasets could refine and compliment current surface research. Güralp Systems have understood this and have been developing broadband Ocean Bottom Seismometers (OBS) systems for over 25 years.

Güralp have deployed systems in a range of ocean environments, from the Japan Trench to the North Sea, including passive and active seismic surveys, ambient noise recording, real-time reservoir monitoring and ocean bottom observatories. These applications can be achieved with Güralp's cabled and autonomous OBS family.

We have taken our knowledge and success, and invested into developing the next generation of autonomous OBS, the Aquarius family. The Aquarius family allows researchers to download raw seismic data via acoustic communications with zero cables to shore or other infrastructure during any period of the deployment. This capability allows the scientist to visit the deployment location multiple times to download data from events of interest and continue with their research whilst the system is still deployed at depth without disturbing the unit providing unparalleled flexibility.

The seismic community are highly motivated to perform transportable array style projects on land. Now Güralp can support the community with Aquarius; easily accessible, portable, off the shelf systems for similar array ocean based seismological research ventures.

The Aquarius family bridges the gap between real-time and offline ocean bottom systems and continues the trend of Güralp supporting the research community and supplying innovative OBS designs to meet operational requirements.

U.S. Geological Survey National Seismic Hazard Model Components

Oral Session · Wednesday · 8:30 AM · 24 April · Pike

Session Chairs: Peter M. Powers, Allison M. Shumway, Mark D. Petersen, Sanaz Rezaeian, Richard W. Briggs, Robert C. Witter, Charles S. Mueller.

2018 Update of the U.S. National Seismic Hazard Model

PETERSEN, M. D., U.S. Geological Survey, Colorado, USA, mpetersen@usgs.gov; SHUMWAY, A. M., U.S. Geological Survey, Colorado, USA, ashumway@usgs.gov; POWERS, P., U.S. Geological Survey, Colorado, USA, pmpowers@usgs.gov; MUELLER, C. S., U.S. Geological Survey, Colorado, USA, cmueller@usgs.gov; MOSCHETTI, M. P., U.S. Geological Survey, Colorado, USA, mmoschetti@usgs.gov; FRANKEL, A., U.S. Geological Survey, Washington, USA, afrankel@usgs.gov; REZAEIAN, S., U.S. Geological Survey, Colorado, USA, srezaeian@usgs.gov; MCNAMARA, D. E., U.S. Geological Survey, Colorado, USA, mcnamara@usgs.gov; HOOVER, S. M., U.S. Geological Survey, Colorado, USA, shoover@usgs.gov; LUCO, N., U.S. Geological Survey, Colorado, USA, nluco@usgs.gov; BOYD, O. S., U.S. Geological Survey, Colorado, USA, olboyd@usgs.gov; RUKSTALES, K., U.S. Geological Survey, Colorado, USA, rukstales@usgs.gov; JAISWAL, K., U.S. Geological Survey, Colorado, USA, kjaiswal@usgs.gov; THOMPSON, E. M., U.S. Geological Survey, Colorado, USA, emthompson@usgs.gov; CLAYTON, B., U.S. Geological Survey, Colorado, USA, bclayton@usgs.gov; FIELD, E. H., U.S. Geological Survey, Colorado, USA, field@usgs.gov; ZENG, Y., U.S. Geological Survey, Colorado, USA, zeng@usgs.gov

During 2017-2018, the National Seismic Hazard Model was updated by incorporating (1) new median ground motion models, new estimates of their epistemic uncertainties and aleatory variabilities, and new soil amplification factors for the central and eastern U.S., (2) amplification of long-period ground motions in deep sedimentary basins in the Los Angeles, San Francisco, Seattle, and Salt Lake City areas, (3) an updated seismicity catalog, which includes new earthquakes that occurred between 2012 and 2017, and (4) improved computer code and implementation details. Results show significantly increased ground shaking in many (but not all) locations across the central and eastern U.S., including the four urban areas (listed above) that overlie deep sedimentary basins in the western U.S. These maps are being considered by the Building Seismic Safety Council for inclusion in upcoming building codes. Due to population growth, more people live and work in areas of high or moderate seismic hazard than ever before, leading to higher risk of undesirable consequences from future ground shaking.

Additional Period and Site Class Maps for the 2018 USGS National Seismic Hazard Model

SHUMWAY, A. M., U.S. Geological Survey, Colorado, USA, ashumway@usgs.gov; REZAEIAN, S., U.S. Geological Survey, Colorado, USA, srezaeian@usgs.gov; POWERS, P., U.S. Geological Survey, Colorado, USA, pmpowers@usgs.gov; PETERSEN, M. D., U.S. Geological Survey, Colorado, USA, mpetersen@usgs.gov

The updated 2018 National Seismic Hazard Model (NSHM) includes new ground motion models (GMMs) and soil amplification factors for the central and eastern U.S. (CEUS) and the incorporation of basin depths from local seismic velocity models in the western U.S. (WUS). These additions allow us, for the first time, to calculate seismic hazard for an expanded set of spectral periods (0.01s to 10s) and site classes (V_{S30} = 2,000 m/s to 150 m/s) for the conterminous U.S., as well as account for amplification of long-period ground motions in deep sedimentary basins in the Los Angeles, San Francisco Bay, Salt Lake City, and Seattle regions. The availability of the new soil amplification factors in the CEUS has also allowed us to produce a variable V_{S30} map for the conterminous U.S. In order to calculate hazard for these additional periods and site classes we updated our GMM criteria to state that GMMs need to be valid for the range of spectral periods and site classes in which we calculate hazard. In addition, the WUS subduction GMMs were modified to be able to use basin depths from the local seismic velocity models. The additional period and site class maps for the 2018 NSHM will be compared to the maps for the 2014 NSHM, and differences will be discussed. The maps will be submitted to the Building Seismic Safety Council for consideration in the development of the next-generation of seismic design value maps.

Evaluation of Ground Motion Models for USGS Seismic Hazard Forecasts: NGA-Subduction

MCNAMARA, D. E., U.S. Geological Survey, Colorado, USA, mcnamara@usgs.gov; WOLIN, E., U.S. Geological Survey, Colorado, USA, ewolin@usgs.gov; PETERSEN, M. D., U.S. Geological Survey, Colorado, USA, mpetersen@usgs.gov; SHUMWAY, A. M., U.S. Geological Survey, Colorado, USA, ashumway@usgs.gov; POWERS, P., U.S. Geological Survey, Colorado, USA, ppowers@usgs.gov; MOSCHETTI, M. P., U.S. Geological Survey, Colorado, USA, mmoschetti@usgs.gov

The selection and weighting of GMMs introduces a significant source of uncertainty in probabilistic seismic hazard analysis (PSHA). The November 30, 2018 M7 Alaska earthquake sequence provides an excellent independent dataset of instrumental ground motion observations that we use to evaluate ground motion model (GMM) performance. In this study, we evaluate recently released NGA-Subduction GMMs, to inform logic-tree weights for future updates of the United States Geological Survey (USGS) National seismic hazard model project (NSHMP) seismic forecasts.

GMMs are selected and weighted based on analysis of total residuals and the log likelihood probabilistic scoring method (LLH; Scherbaum *et al.*, 2004; 2009). The LLH method compares the mean and total standard deviation where the total standard deviation is determined from the individual standard deviations in the distribution of the intra- (within) and inter- (between) event residuals. We apply the LLH scoring method to a database of instrumental ground motions from recent earthquakes Mw 4-7 associated with the 2018 Alaska aftershock sequence available from the USGS real-time ShakeMaps. The recent ShakeMap data provides independent ground motion observations for PGA and PSA at 3.0, 1.0, and 0.3s allowing us to evaluate the predictive power GMMs implemented in the new USGS NSHMP-haz software system. The LLH and residual results provide information for selecting and weighting GMMs for the 2019 update of the Alaska seismic hazard model.

Uncertainties in Probabilistic Seismic Hazard Analysis for a Poisson Earthquake Occurrence Model

ZENG, Y., U.S. Geological Survey, Colorado, USA, zeng@usgs.gov; PETERSEN, M. D., U.S. Geological Survey, Colorado, USA, mpetersen@usgs.gov

We revisit the theory of probabilistic seismic hazard analysis (PHSA) and solve for the standard errors of the rate and probability of exceedance. We show that the PSHA defined by the probability of one or more ground motion exceedances over a time period is equivalent to the mean probability of exceedance for a Poisson earthquake occurrence model. We apply a California seismic hazard model to evaluate the standard errors of the rate and probability of exceedances. We find that the range of values between the lower and upper limits are very high for the following cases: (1) rate/probability of exceedance for fixed ground motion and (2) ground motions with a fixed probability of exceedance. These uncertainties for probability/rate of exceedance and ground motions are both correlated with the relative earthquakes rate uncertainties on faults across the region. For example, at a fixed 2% in 50-year PGA probability of exceedance, the uncertainties in probability caused by the Poisson rate calculation are highest over less active faults and lower over the San Andreas Fault (SAF). Overall the standard error of the probability of exceedances are often higher than the mean and can span a factor of 2 to 10. On the other hand, the uncertainties in probability of exceedance for fixed ground motions is highest over the SAF and lower near the less active faults. The results also show that the average ground motion uncertainties across the state are about ±70%. In general, the uncertainties in the rate/probability of exceedance are much higher than many people have assessed in previous analyses and are comparable in size to the uncertainties in ground motions, often a factor of two or more. The results suggest that in places where seismic hazards are low, the risk could be higher or vice versa because of the high uncertainties.

Impacts on Catastrophe Loss Modeling from Multi-Segment and Multiple Fault Ruptures in UCERF3

LEE, Y., ImageCat, Inc., California, USA, yjl@imagecatinc.com; GRAF, W., ImageCat, Inc., California, USA, wpg@imagecatinc.com

Version 3 of the Uniform California Earthquake Rupture Forecast (UCERF3) is part of the current National Seismic Hazard Mapping Project model (Petersen, *et al.*, 2014) and has been adapted for modeling financial losses from earthquakes. UCERF3 relaxes fault segmentation, allowing multi-segment and multi-fault ruptures, with lengths up to 1200 km on the San Andreas Fault. In catastrophe loss modeling, fault rupture length determines the area affected by shaking and drives the correlation of losses for geographically-distributed sets of properties. Longer ruptures produce more severe consequences. Recently, Schwartz (2018)

examined surface ruptures observed worldwide from shallow crustal earthquakes since the mid-1800s and found that only a few ruptures have been longer than 300 km and none has exceeded 500 km. This suggests it may be more realistic to constrain rupture lengths for future earthquakes. In this study, we examine the impact of the UCERF3 ruptures with long rupture lengths on probabilistic losses, using a published residential inventory (Reinsurance Association of America, 2018) with more than 180,000 locations throughout California. We examine impacts from long UCERF3 ruptures on Average Annual Loss (AAL) and other loss parameters such as the Return Period Loss (RPL) as well as the Tail Conditional Expectation (TCE) at return periods of 100-, 250-, 500- and 1,000-years. Our results show that these long ruptures, even though rare, have significant impacts on probabilistic loss estimates. The impact increases as the loss return period of interest becomes longer. At the 250-year return period, about 30% of the expected loss contribution comes from ruptures with lengths greater than 500 km; at 1,000-year return period, the expected loss contribution reaches nearly 50%, even though such ruptures have not been observed from past shallow crustal earthquakes. Due to the impact the UCERF3 model on public policy and the financial industry, critical examination of the limits of potential rupture lengths is warranted in the future model update.

Updating the Seismic Source Model for a New USGS Earthquake Hazard Map of Alaska

HAEUSSLER, P. J., U.S. Geological Survey, Alaska, USA, pheuslr@usgs.gov; BENDER, A. M., U.S. Geological Survey, Alaska, USA, abender@usgs.gov; WITTER, R. C., U.S. Geological Survey, Alaska, USA, rwitter@usgs.gov; BROTHERS, D. S., U.S. Geological Survey, California, USA, dbrothers@usgs.gov; LIBERTY, L. M., Boise State University, Idaho, USA, lliberty@boisestate.edu

We are focused on updating the seismic source model for Alaska as a primary input for the next revision of the USGS National Seismic Hazard Model. The last USGS probabilistic seismic hazard map for Alaska dates to 2007, and there are significant improvements to our understanding of active faults across the state. We build on the 2013 Alaska Quaternary fault and fold database (Koehler, 2013) by updating it with recent findings. Significant updates include: 1) Changes in megathrust earthquake recurrence rates along most of the length of the subduction zone inferred from recent paleoseismology. 2) Inclusion of large intraslab earthquakes, prompted by recent damaging M7.0 to M7.9 events. 3) Refined long-term slip rates on megathrust seafloor splay faults in the southern Prince William Sound region and near Kodiak Island derived from seismic reflection and thermochronology studies. 4) A slip rate of ~5 cm/yr on the Queen Charlotte-Fairweather fault system inferred from offshore mapping. Moreover, a search for and failure to identify active fault traces to the east implies that virtually all of the plate boundary motion occurs on this fault alone. 5) Refinement of interior Alaska tectonic models clarify the relationships between the Denali fault, Totschunda fault, and thrust faults on both the north and south sides of the Alaska Range. 6) Recognition that Holocene activity on the Castle Mountain fault is predominantly thrust faulting, not strike-slip. 7) New details of contractional structures in the Chugach-St. Elias orogen. 8) The potential for large earthquakes in the eastern Brooks Range associated with the westward extrusion of crust revealed by the 2018 M6.4 Kaktovik earthquake. Significant remaining unknowns include the rate and magnitude of large earthquakes in the western Aleutians, and probably lower magnitude events in the vast region spanning western and northwestern Alaska.

Deformation in the August 2018 Mw 6.4 Kaktovik (North Slope), Alaska Earthquake

ROLLINS, C., Michigan State University, Michigan, USA, rollin32@msu.edu; MEYER, F., Geophysical Institute, University of Alaska Fairbanks, Alaska, USA, fjmeyer@alaska.edu; XUE, X., Michigan State University, Michigan, USA, xuexuemi@msu.edu; HOLTKAMP, S. G., Alaska Earthquake Center, Alaska, USA, sgholtkamp@alaska.edu; FREYMUELLER, J. T., Michigan State University, Michigan, USA, freymuel@msu.edu

On August 12, 2018, a M=6.4 earthquake ruptured a roughly ESE-WNW-striking fault in the Sadlerochit Mountains on Alaska's North Slope, ~90 km southwest of the nearest settlement of Kaktovik. The earthquake caused no injuries or damage due to its remote location, but it was the largest ever recorded on the North Slope and demonstrated that moderate to large earthquakes can and do occur in this corner of Alaska despite its distance from the effective Pacific-North American plate boundary (*e.g.* the Alaska-Aleutian subduction zone and Denali Fault) and comparatively low strain rate. Although no GPS stations were close enough to the earthquake to record substantial coseismic displacements, the earthquake's location in sparsely vegetated terrain meant that the Sentinel-1 satellite provided excellent InSAR coverage of the coseismic displacement field (perhaps uncommon for Alaska earthquakes) on both ascending and descending tracks. These data suggested that the earthquake occurred on or near the Sadlerochit Mountains Fault, which runs west to east through the middle of this local mountain range. We invert the ascending and descending data (after applying adaptive downsampling) for coseismic displacements on a best-fit fault plane. The best-fitting fault plane appears to be slightly nonplanar and the InSAR data suggest mostly right-lateral slip with a slight normal component, consistent with the USGS focal mechanism. The geodetic moment is equivalent to Mw=6.4, consistent with the seismological estimate. Comparison of the InSAR pattern with aftershock locations suggests that 3D structure may substantially affect seismic travel times in this part of Alaska, making the Transportable Array and the coverage it provides all the more valuable in this region.

An Integrated Geodetic Tectonic Model for Alaska

ELLIOTT, J., Purdue University, Indiana, USA, julieelliott@purdue.edu; FREYMUELLER, J. T., Michigan State University, Michigan, USA, freymuel@msu.edu

Over the past two decades, the number of GPS-constrained tectonic studies in Alaska has greatly increased. While these studies improved our understanding of some of the processes at work, they have largely focused on smaller, regional networks of GPS sites. This has lead to a patchwork of models across Alaska that are not fully compatible with each other, limiting geologic interpretations and assessments of larger scale seismic hazards. Based on data from the Plate Boundary Observatory network and several other GPS networks throughout Alaska and western Canada, we present an updated GPS velocity field. We use this improved data set to constrain an integrated tectonic block model that sheds light on regional tectonics and provides more robust estimates of motion along faults and their potential seismic hazard.

Our integrated model reveals a wide and heterogeneous plate boundary zone, with deformation distinct from that of stable North America extending to the Arctic Ocean and the Bering Sea. Most of the relative plate motion is accommodated along major fault systems such as the Alaska-Aleutian subduction zone, the Fairweather-Queen Charlotte transform system and the St. Elias fold-and-thrust belt, but the new model differs from previous estimates in important ways. In particular, our model suggests that locked or partially locked sections of the Alaska subduction zone may extend as far north and east as the eastern Alaska Range. The GPS data indicate that several margin parallel crustal slivers exist in the upper plate directly inboard from the trench. Our model also suggests that ~10 mm/yr of strain is localized along a proposed Totschunda-Fairweather Connecter fault, which transfers motion from the Fairweather system to the Denali system. Our results suggest that western and northern Alaska are comprised of several blocks, leading to small but significant amounts of motion across the western Denali fault, the Kaltag fault, and the Kobuk fault.

Updated GK17 Ground Motion Prediction Equation for Shallow Crustal Continental Earthquakes and Use of Proper Terminology

GRAIZER, V., U.S. Nuclear Regulatory Commission, Maryland, USA, graizer@comcast.net

The Pacific Earthquake Engineering ResearchCenter's Next Generation Attenuation Phase 2ground motion database developed from shallow crustal earthquakes in active tectonic regions was used to develop a ground motion prediction equation (GMPE) for the median horizontal components of peak ground acceleration, and 5% damped elastic pseudo-absolute acceleration response spectral ordinates. The GK17 (Graizer, 2018) model has a number of significant improvements relative to the previous GK15 (Graizer and Kalkan, 2016) model including improved magnitude scaling for M≤5.5, a bilinear attenuation slope reflecting attenuation of shear and surface waves, a refined shallow site response V_{S30}, a sediment thickness correction through the $Z_{2.5}$ term, style-of-fault corrections and a different approach in the estimation of apparent anelastic attenuation of response spectral accelerations (SA). The new GMPE is applicable for earthquakes with 4.0≤M≤8.5, at rupture distances of $0 \le R_{rup} \le 400$ km, at sites having V_{S30} in the range of 150 to 1500 m/s, for spectral periods of 0.01–10 s, and sediment thickness $Z_{2.5} \le 10$ km.

Using appropriate terminology and clarifying the meanings of such termsis critical in the GMPE development. For seismologists the term "spectra" means the Fourier, and for engineers – it refers to the response spectra (RS). Another example of confusion may be the definition of anelastic attenuation. In seismology, it refers to intrinsic and scattering attenuation of seismic energy, while in engineering seismology, when applied to GMPEs it is the apparent anelastic attenuation of the RS. The estimates of apparent attenuation factor demonstrate a difference between classical seismological $Q(f)$ and the SA Q_{SA}(f) quality factors. Yet, another example is the basin effect. In seismology, it refers to trapped seismic waves in a basin which tends to significantly amplify ground motions. In GMPE development, however, this effect is not as pronounced, because it is usually interpreted to be a sediment thickness adjustment not yet covered by an average V_{S30} correction.

Alaska Megathrust Source Characterization for Tsunami Hazard

THIO, H., AECOM, California, USA, hong.kie.thio@aecom.com

The Alaska subduction zone is the most significant source of tsunami hazard for Alaska, Hawai'i and most of California. Due to the inaccessibility of large swaths of the Aleutians through most of the year, relatively little is known about the history of large megathrust events, especially west of Kodiak. Building an event recurrence model for probabilistic seismic and tsunami hazard analysis is therefore quite challenging and inevitably includes a large epistemic uncertainty. For tsunami hazard, the challenge is even greater since details in the maximum extent and distribution of megathrust events will have a sizeable impact on the final hazard results.

For the update of the California tsunami hazard maps as well as the new ASCE 7-16 chapter on tsunami loads and effects, we adopted a simple recurrence model that consists of single and multi-segment ruptures based on the Jacobs and Nishenko model. These were largely constrained by paleoseismic data, recent event history and a general model of subduction zone tectonics.

Since that effort was concluded, the USGS Powell Center has funded a Working Group "Tsunami Source Standardization for Hazards Mitigation in the United States" tasked with the development of models those sources that contribute to the tsunami hazard in the United States. One of the first workshops was entirely devoted to the Alaska subduction zone and benefited from the expertise of a wide array of scientists from different disciplines including seismology, geodesy, geology and coastal engineering. Although this model is being developed for tsunami hazard analysis, it should also be easily adaptable for use in the next generation of seismic hazard model for Alaska.

In this presentation, we will discuss the evolution of the earlier USGS source model through the ASCE 7-16 model to the comprehensive Powell Center model and discuss the major differences, both in approach, constraints, uncertainties and potential impact on tsunami hazard studies.

Better Earthquake Forecasts

Oral Session · Wednesday · 2:15 PM · 24 April · Pike

Session Chairs: Andrew J. Michael, Camilla Cattania, David D. Jackson, Sara K. McBride, Warner Marzocchi, Maximilian J. Werner.

Improving Physics-Based Earthquake Forecasts for the 2016-2017 Central Italy Earthquake Sequence

MANCINI, S., University of Bristol, Bristol, United Kingdom, simone.mancini@bristol.ac.uk; SEGOU, M., British Geological Survey, Edinburgh, United Kingdom, msegou@bgs.ac.uk; WERNER, M. J., University of Bristol, Bristol, United Kingdom, max.werner@bristol.ac.uk; CATTANIA, C., Stanford University, California, USA, camcat@stanford.edu

After a devastating earthquake, the ensuing cascade of aftershocks can be even more destructive than the mainshock. Operational earthquake forecasting seeks to provide reliable real-time information about the time-dependence of seismic hazard. Two forecasting approaches are commonly used: statistical short-term clustering models, such as ETAS, that employ empirical laws to predict aftershock patterns and physics-based models (CRS) that combine the stress transfer hypothesis with the Dieterich's rate-and-state friction law.

Here we assess the effect of model choices at real-time conditions and quantify the influence of input data quality on the predictive skills of CRS forecasts during the 2016-17 Central Italy sequence with 7 M ≥ 5.4 events that occurred within less than 5 months. We develop 7 physics-based models with progressively increasing level of refinement as part of a pseudo-prospective experiment with 1-year time horizon. The preliminary CRS forecasts include data available few minutes after each M ≥ 5.4 event and feature synthetic source models with empirically determined fault length and fault constitutive parameters from literature. The sophisticated CRS models gradually incorporate optimized rate-state parameters, spatially heterogeneous receiver faults, best available slip models, and M3+ secondary triggering effects.

We evaluate model performance using CSEP metrics over different time horizons and compare against a benchmark ETAS model. We find that revised catalog data and a realistic representation of crustal heterogeneity boost CRS models' performance. The more complex and data-wealthy CRS forecasts reach probability gains per earthquake higher by 3 orders of magnitude when compared against preliminary models. The results confirm that CRS models are as informative as ETAS only when secondary triggering effects are combined with realistic slip models, spatially heterogeneous receiver planes and optimized fault constitutive parameters. Our results support and extend other recent retrospective experiments on the predictive power of CRS forecasts.

Aftershock Decay in Space and Time in Regions with Induced Seismicity in Oklahoma

ROSSON, Z., University of Oklahoma, Oklahoma, USA, zachrosson@ou.edu; WALTER, J., Oklahoma Geological Survey, Oklahoma, USA, jwalter@ou.edu; GOEBEL, T. H. W., University of California, Santa Cruz, California, USA, tgoebel@ucsc.edu; CHEN, X., University of Oklahoma, Oklahoma, USA, xiaowei.chen@ou.edu

The current paradigm for estimating long-term seismic hazard in a region includes removing dependent earthquakes that occur after a mainshock, otherwise known as aftershocks, from an earthquake catalog to identify the underlying background Poissonian-like seismicity rate. In Oklahoma, attempts to quantify the seismic hazard are complicated by the 200-fold increase in the seismicity rate in the last decade, where 901 earthquakes of M3.0 and greater occurred in 2015 against a pre-2009 historical seismicity rate of just a few M3.0 and greater earthquakes per year. Thus, it is unclear how one would assess the current seismic hazard in Oklahoma with conventional methods for declustering. To examine the usefulness of declustered catalogs of Oklahoma seismicity in hazard modeling, one must first scrutinize the parameters used in the declustering procedures. In this study, we work under the conceptual framework of identifying aftershocks using fixed space-time windows which are scaled by mainshock magnitude. We then use techniques from statistical seismology to examine how aftershocks decay in space and time, and compile data-driven distance-time cutoffs which can be used as parameters for fixed-window declustering of Oklahoma seismicity. Our approach also allows us to observe that the decay of aftershocks in space is more rapid in Oklahoma than in Southern California, while the decay of aftershocks in time is indistinguishable between the two regions. Since inadequately parameterized aftershock identification windows can ultimately under- or over-estimate the regional seismic hazard, our results speak to the necessity of well-founded declustering parameters for seismic hazard assessment, especially in regions of induced seismicity.

A Forecast of Peak Ground Motion Due to Aftershocks Based on the Extreme-Value Analysis of Seismograms

SAWAZAKI, K., National Research Institute for Earth Science and Disaster Resilience, Tsukuba, Japan, sawa@bosai.go.jp

Aftershock forecasting is one of the most required information after a large earthquake, especially at an early stage. However, earthquake detection becomes very difficult at this stage because many wave packets from aftershocks overlap in seismograms, which unable automatic identification of P- or S-phases at many stations. For this reason, both quality and quantity of earthquake catalog deteriorate, and eventually aftershock forecasting becomes unavailable at the early stage.

We propose a method that will overcome this situation. Instead of using an earthquake catalog, we directly analyze continuous seismograms to forecast frequency of occurrence of large peak ground motion by aftershocks. we calculate maximum amplitude within each unit time interval (*e.g.*, 1 minute) for a continuous seismogram. We propose a nonstationary extreme-value distribution for the maximum amplitudes by considering the generalized Pareto distribution and the Omori-Utsu type temporal decay. By optimizing three parameters that control this distribution, we evaluate current aftershock activity and forecast peak ground motion in near future at each station. Unlike earthquake catalog, this method is not suffered from deterioration of the data at the early stage. In addition, this method can provide forecast of peak ground motion rather than magnitude, which should be more desired information for public use.

We apply the proposed method to the 2016 Kumamoto earthquake sequence in Japan (M_W 7.3 for the mainshock). We find only three hours-long records can provide acceptable forecasting performance at most stations that experienced strong ground motion by the mainshock. Of note, our forecast performs well not only at stations near the mainshock source but also at relatively distant area, where many large events were triggered after the mainshock.

A Stress-Similarity Aftershock Forecast Model

HARDEBECK, J., U.S. Geological Survey, California, USA, jhardebeck@usgs.gov

Statistical models of earthquake clustering have performed well in prospective forecast tests, despite containing no physical mechanisms for the observed clustering. Including physics-based model components may improve the accuracy of the statistical forecasts. In particular, static stress changes have been shown to correlate with aftershock occurrence, and in some cases the addition of static Coulomb stress changes can improve upon purely statistical forecasts (*e.g.* Cattania *et al.*, SRL 2018; Segou et al, JGR 2013; Bach and Hainzl, JGR 2012) but this has not been uniformly successful (*e.g.* Woessner *et al.*, JGR 2011). I test a different approach to the inclusion of static stress changes, based on the observation that aftershocks tend to occur in locations where the static stress change is similar to the background stress. An example of this is the onshore normal faulting regions that were activated by the M9 Tohoku earthquake because of the extensional stress changes (Yoshida *et al.*, PAGEOPH 2018). For four M≥6.7 Southern California mainshocks, I show that aftershocks are significantly more likely than preshocks to occur in regions where the static stress change tensor and the background stress tensor are more similar, as measured by the tensor dot product. I use this observation to develop a stress-similarity spatial kernel for the ETAS model, which depends on both distance from the mainshock fault plane and the similarity of the static stress change and the background stress. For the Southern California M≥6.7 mainshocks, the improvement in the likelihood of the best-fitting ETAS parameters usually justifies the additional model parameters. The largest improvement over an ETAS model with a radially-uniform spatial kernel is early in the aftershock sequence, and diminishes as more secondary triggering occurs. Pseudo-prospective tests will be performed to determine if the stress-similarity model can outperform a standard ETAS model in CSEP-style tests.

Aftershock Forecasts Following the M7.0 Anchorage, Alaska Earthquake

MCBRIDE, S. K., U.S. Geological Survey, Washington, USA, drsaramcb@gmail.com; HARDEBECK, J., U.S. Geological Survey, California, USA, jhardebeck@usgs.gov; MICHAEL, A. J., U.S. Geological Survey, California, USA, amichael@usgs.gov; PAGE, M., U.S. Geological Survey, California, USA, mpage@usgs.gov; VAN DER ELST, N., U.S. Geological Survey, California, USA, nvanderelst@usgs.gov; MARTINEZ, E. M., U.S. Geological Survey, Colorado, USA, emartinez@usgs.gov

The 2018 M7.0 Anchorage earthquake generated several "firsts." It was the first large urban earthquake with intense shaking to strike the United States since the M6.7 Northridge earthquake in 1994. The 2018 earthquake also saw the release of several new USGS communication products: 2PAGER, which provides quick estimates of a variety of earthquake impacts; a new ground failure product that estimates the likely extent of landslides and liquefaction; and an aftershock forecast. This paper focuses on the development of the aftershock forecast, and on how it was communicated by the media and received by users.

The aftershock forecast, part of the field of Operational Earthquake Forecasts (OEF), builds on developments in forecasting that initiated with publication of the Reasenberg and Jones model in 1988. Challenges in this field include the refinement of forecasts using various algorithms and models, and the communication of such forecasts to a variety of people with different educational backgrounds and informational needs. Our challenge was to develop a template that can be released within the first two hours of a +M5.0 earthquake in most regions of the U.S., with format and contents that make it easy to understand, useful to a variety of audiences, easy to update, and still technically robust enough for use by scientists and engineers.

Our study focuses on the development of an aftershock forecast template, which we did using results from social science research combined with experiences from scientists who have communicated such forecasts operationally overseas. We also explore early insights from media and social media about how the information was communicated and how it was used by various groups of people. Finally, we explore proposed improvements to the USGS aftershock forecast, including visualizations and tables.

A Geodesy- and Seismicity-Based Local Earthquake Likelihood Model for Central Los Angeles

ROLLINS, C., Michigan State University, Michigan, USA, rollin32@msu.edu; AVOUAC, J., California Institute of Technology, California, USA, avouac@gps.caltech.edu

We estimate long-term-average earthquake likelihoods by magnitude in central Los Angeles using a recently developed model of interseismic strain accumulation and the 1932-2017 SCEDC seismic catalog. We assume that on the long-term average, 1) mainshocks obey a log-linear magnitude-frequency distribution (MFD) up to a maximum magnitude and follow a Poisson recurrence process, 2) aftershocks obey a log-linear MFD and "Bath's law" (largest aftershock 1.2 magnitude units below the mainshock), and 3) these mainshocks and aftershocks (and aseismic slip) collectively release seismic moment at a rate balancing the geodetic interseismic loading. We develop a method to use these constraints and the seismic catalog to probabilistically estimate the long-term MFD of earthquakes. The method generates a comprehensive suite of long-term MFDs obeying these assumptions, assesses how likely a long-term system obeying each MFD would be to produce earthquakes with an MFD like that of the 86-year SCEDC catalog over an 86-year period, and use these likelihoods to build the probability density functions of M_{max}, the *b*-value of the MFD, and earthquake rates at any magnitude. We estimate M_{max}=6.8 +1.05/-0.4 (every ~300 years) or M_{max}=7.05 +0.95/-0.4 assuming a truncated or tapered Gutenberg-Richter MFD, respectively. Our results imply that, for example, the (median) likelihood of a Mw≥6.5 mainshock in central LA is 0.2% in one year, 2.0% in 10 years, and 18% in 100 years. The effective "non-declustered" b-value of the best long-term models is 0.9-1. The actual parameter *b*in this method is essentially the "declustered" b-value as it governs the MFD of mainshocks; it is close to published estimates for the declustered b-value in California (~0.8-0.9). We find that if this *b* is instead modeled as governing a single MFD for all earthquakes (no mainshock-aftershock distinction) as the "non-declustered" *b*-value, M_{max} changes by only 0.1 and the long-term model is virtually unchanged.

San Andreas Rupture Gates?

JACKSON, D. D., University of California, Los Angeles, California, USA, djackson@g.ucla.edu

Many earthquake hazard models employ fault-based source models, often stated in the form of stochastic event sets. Testing source models against actual earthquakes requires "association", whereby each finite rupture can be matched with a hypothetical one with a preassigned rate or probability. In the old days, big earthquakes were assumed by some to occur in ruptures of prescribed fault segments or combinations thereof, with probabilities assigned for each combination. Segment boundaries played an important role in stopping rupture with a reasonably high probability. Now we recognize the need to assign uncertainties to segment geometry, or even abandon segmentation entirely. An alternative for linear strike slip faults is to identify polygonal sections with finite width and length, assigning "conditional stopping probabilities" (CSPs) describing the probability that rupture would end within a polygon if it gets in. Those with relatively high stopping probabilities are then referred to as "gates" or "sticky wickets." This approach can be used for arbitrarily many gates: just a few, as in polygons about the segments in the 1988, 1990, 1995 etc. reports of the Working Group on California Earthquake Probabilities (WGCEP), or thousands, as in the Uniform California Earthquake Rupture Forecasts (UCERF) of 2013 and later. A rupture can then be described by two sections, one at each of its ends, and a likelihood can be calculated by which sections stop or don't stop the rupture. An advantage of the approach is that it focuses on the resistance of the fault elements rather than the epicenters and size distribution of the earthquakes. Smaller events can help test the forecast model because each rupture has two end points. Another advantage is that simulated ruptures in a stochastic event set can be used to estimate the stopping probabilities and participation rates of the polygonal sections. In this presentation I'll show how the method applies in the WGCEP and UCERF forecasts mentioned above.

Characterizing the Spatial Uncertainty of Coseismic Slip for Past and Future Cascadia Subduction Zone Full-Margin Events

PAIGE, J. L., University of Washington, Washington, USA, paigejo@gmail.com; GUTTORP, P., University of Washington, Washington, USA, peter@stat.washington.edu; SCHMIDT, D. A., University of Washington, Washington, USA, dasc@uw.edu

Although numerous studies have been conducted along the US west coast to estimate the coseismic subsidence of past Cascadia subduction zone (CSZ) events, some estimates that are not based on state-of-the-art microfossil analyses are sometimes regarded as too noisy to use to fit any earthquake source model. This severely limits the amount of data that can be used for model fitting. Additionally, some earthquake source models attempt to characterize the full uncertainty in their predictions by using a handful of prespecified earthquakes rather than building a statistical model yielding an entire distribution of different possible outcomes. We attempt to overcome these obstacles by building a spatial statistical CSZ earthquake source model. Since spatial statistical models use spatial smoothing to produce robust estimates even in the presence of noisy observations, we are able to fit the model using both micro- and macrofossil based paleoseismic subsidence estimates. Additionally, we incorporate a set of locking rate estimates based on three decades of GPS data to provide information on coseismic slip spatial correlation range. We use this model to estimate the coseismic slips of the 1700 event as well as to cautiously make predictions about future full-margin CSZ events.

Implications of Temporal Clustering and Long-Term Fault Memory for Earthquake Forecasting

SALDITCH, L., Northwestern University, Illinois, USA, leah.salditch@gmail.com; STEIN, S., Northwestern University, Illinois, USA, s-stein@northwestern.edu; SPENCER, B., Northwestern University, Illinois, USA, bspencer@northwestern.edu; BROOKS, E. M., Northwestern University, Illinois, USA, eddie@earth.northwestern.edu

A major challenge for earthquake forecasts is that geologic records often show large earthquakes occurring in temporal clusters separated by periods of quiescence. If we are in the cluster, a large earthquake may happen soon. If we are between clusters, a great earthquake is less likely soon. Clusters are observed in paleoseismic records in a variety of tectonic settings, from subduction zones to intraplate regions. While clusters, sometimes known as supercycles, could be artifacts of the limits of the paleoseismic record, they appear in enough records that they warrant the attention of forecasters. The existence of clusters is problematic for long-term forecasts because it implies that the system is not stationary, and therefore traditional probability models do not apply. The cause of these clusters is unclear, and the traditional earthquake cycle model does not explain them. We are exploring an alternative model for the occurrence of large earthquakes, Long Term Fault Memory (LTFM). In LTFM, the probability of an earthquake grows with time at a steady rate, simulating steady strain accumulation. The probability drops after an earthquake, but does not necessarily reset to zero as in the traditional earthquake cycle model, simulating a partial strain release. This allows the fault's history over multiple cycles to influence the future probability of an earthquake. We use LTFM to simulate paleoseismic records from subduction zones, transform faults, and intraplate regions, including a particularly long record from the Cadell fault in intraplate Australia, exploring the similarities and differences between these regions. In some portions of the simulated earthquake history, events can appear quasi-periodic, while at other times, the events can appear more Poissonian. Hence a given paleoseismic or instrumental record may not reflect the long-term seismicity of a fault, which has important implications for hazard assessment.

Can Earthquake Clustering Explain the Paleo-Event Hiatus in California?

PAGE, M., U.S. Geological Survey, California, USA, pagem@caltech.edu; VAN DER ELST, N., U.S. Geological Survey, California, USA, nvanderelst@usgs.gov; FIELD, E. H., U.S. Geological Survey, Colorado, USA, field@usgs.gov; MILNER, K. R., University of Southern California, California, USA, kmilner@usc.edu

There has been a notable absence of large earthquakes in the last century in California, particularly on the highest slip-rate faults. This lull was noted by Jackson (2014), who argued that the observed data precluded Poissonian or log-normal earthquake occurrence, provided that earthquake times between distant sites were not correlated. We analyze the statistical significance of the hiatus given that earthquake times between sites may in fact be correlated by elastic rebound and aftershock-driven clustering effects. We look at three models, the UCERF3-TD model, which includes elastic rebound effects; the UCERF3-ETAS model, which includes both elastic rebound and aftershock clustering; and a critical ETAS model that includes aftershock clustering with a "long reach" in both space and time. The critical ETAS model has the highest probability of an extended hiatus affecting all paleoseismic sites, with a 6% chance of 1 or fewer paleo-events in a given century. Thus, we find that earthquake clustering does make the paleo-event hiatus more likely to occur; so, one explanation for the observed paleo-hiatus in California is that large events on the major faults, taken together, are clustered in time.

Earthquake Ground Motions and Structural Response in Subduction Zones: A Focus on Cascadia

Oral Session · Wednesday · 8:30 AM · 24 April · Pine

Session Chairs: Erin Wirth, Marine A. Denolle, Nasser A. Marafi, Valerie Sahakian.

Downdip Extension of Large Intraslab Earthquakes and Its Engineering Implications

JI, C., University of California, Santa Barbara, California, USA, ji@geol.ucsb.edu; ARCHULETA, R. J., University of California, Santa Barbara, California, USA, ralph.archuleta@ucsb.edu; HAO, J., IGGCAS, Beijing, China, haojl@mail.iggcas.ac.cn

Previous studies suggested a global correlation between the 600°-700°isothermal depth and the bottom of seismogeneic zone of the oceanic lithosphere (*e.g.*, Craig *et al.*, 2014). If the large intermediate depth and deep focus earthquakes occur along the existing faults before the subduction (*e.g.*, Jiao *et al.*, 2000), the maximum downdip extension of these events is limited. Here, we first test this hypothesis using the 2017 Mw 8.2 Mexico earthquake, the largest intraslab earthquake with close-fault modern observations. The downdip extensions inferred from published slip models varies from 30 km (Okuwaki and Yagi, 2017) to about 60 km (Melger et a., 2018). We constrain its slip history with local strong motion and high rate GPS waveforms, as well as body and surface waves in teleseismic distances. In particular, 3D Green's functions are used to model the earth response. The uncertainty of rupture downdip extensions will be specially investigated using a subject-oriented finite fault inversion approach. We illustrate the engineering implications of this hypothesis by simulating intraslab earthquakes for the Japan Trench and for Cascadia using a 1D velocity and attenuation model representative of each structure. We test the scenarios with moment magnitude M 6.2, 6.8, 7.4 and 8.0, and use a combination of 1) the temperature related brittle deformation limitation of the oceanic plate, 2) expected dip angle of outer-rise events, and 3) the plate unbending mechanism to place the limits on the maximum width of rupture. Using the inferred maximum width, we found magnitude saturation of PGA and PGV for intraslab earthquakes in Cascadia but no evident magnitude saturation for the Japan case. We interpret this magnitude saturation as the result of their difference in the pre-assigned maximum downdip extension of the scenario slip models. Finally, using the same approach, we estimate the expected saturation magnitude for several subduction zones.

Rupture Model of a Hikurangi Mw 8.6 Megathrust Earthquake for Strong Motion Simulations

SOMERVILLE, P., AECOM, California, USA, paul.somerville@aecom.com; BAYLESS, J., AECOM, California, USA, jeff.bayless@aecom.com; PITARKA, A., Lawrence Livermore National Laboratory, California, USA, pitarka1@llnl.gov; SKARLATOUDIS, A., AECOM, California, USA, andreas.skarlatoudis@aecom.com

For the purpose of strong ground motion simulations, we have developed a multi-segment M8.6 rupture model of a Hikurangi (North Island of New Zealand) megathrust event, including unilateral rupture with propagation towards the northeast, in accordance with Schellart and Rawlinson (2012). We used the Graves and Pitarka hybrid Irikura method (Pitarka *et al.*, 2018; GP-IM) for developing the source model. This method combines the Irikura and Miyake (2011) asperity-based kinematic rupture generator with the Graves and Pitarka (2015) rupture generation methods for stochastic spatial variability and background slip in shallow crustal earthquakes. We adapted these for use with subduction earthquakes using the Skarlatoudis *et al.* (2016) scaling for the corner wavenumbers in the along strike and down-dip directions for great interface subduction earthquakes. We also modified the perturbations to the rupture times for large earthquakes to make them smoother, and modified the parameters that control the average rupture speed and rise time. Relationships between seismic moment, rupture area, asperity area, and stress parameters were based on work by Murotani *et al.* (2008), Tajima et al (2013) and Miyake (2018). The maximum slip over the rupture planes was found to be approximately 14 m, and the average slip is approximately 3.5 m. Both of these values are broadly consistent with the scaling relations developed by Tajima *et al.* (2013) and Skarlatoudis *et al.* (2016). We are now performing simulations to assess the importance of slip randomness, asperity number and location, and hypocenter location in influencing the simulated ground motions.

Using Noise Correlation to Improve the Seismic Velocity Model of the Seattle Basin and 3D Simulations of Large Earthquakes

FRANKEL, A., U.S. Geological Survey, Washington, USA, afrankel@usgs.gov; BODIN, P., University of Washington, Washington, USA, bodin@uw.edu

Cross correlation waveforms of seismic noise in the Seattle basin were analyzed to determine the group velocities of surface waves and improve the velocity model used in 3D simulations of earthquakes. Twenty broadband seismometers were deployed for about three weeks by personnel from the U.S. Geological Survey and the Pacific Northwest Seismic Network of the University of Washington. The instruments were arranged in three dense arrays separated by about 5 km, with minimum intra-array station spacing of about 0.5 km. We found good correlations of seismic noise between the arrays at periods of 2 to 10 s using only 9 days of noise recordings. Usable noise correlations up to 2 Hz were determined for sites separated by 0.5-1.0 km. The cross correlation waveforms were typically larger for the transverse component of motion, indicating better correlation than the radial and vertical components. We used the cross correlation waveforms to determine Love wave group velocities at 0.5-10 s for paths within the Seattle basin and paths crossing the southern edge of the basin. We compared these observed group velocities in the basin to those calculated using a flat-layered velocity model approximated from the 3D velocity model of the Seattle basin derived by Stephenson *et al.*, 2017. The noise correlation results indicate that the shear-wave velocity (V_s) increases rapidly with depth in the top 0.3 km of the glacial sediments and then is relatively constant down to about 1 km depth, the base of the sediments. V_s values in the basin at depths of 1-5 km were found to be about 10-15% lower than in the model. We evaluate the effects of these differences in V_s on synthetic seismograms derived from 3D simulations of the M6.8 Nisqually earthquake and M9 Cascadia earthquakes.

Topographic Response to Ground Motion From Modeled Seattle Fault Earthquakes

STONE, I., University of Washington, Washington, USA, ipstone@uw.edu; VIDALE, J. E., University of Southern California, California, USA, seismoguy@mac.com

Topography significantly amplifies earthquake ground motion under special conditions, but is rarely considered during seismic hazard analysis. In this project, we attempt to model the response of surface topography to scenario Seattle Fault earthquakes using 3D spectral element method modeling. A topographic surface and mesh with 30-meter resolution allow us to model site response in and around the city of Seattle up to 3Hz. Using 3D velocity and attenuation models cognizant of local basin structure and shallow geology, we simulate scenario Seattle Fault earthquakes and compare the results with and without topography. We demonstrate that shaking is primarily affected on topographic highs and slopes, where we see locally amplified ground motion. Cliff faces in particular show a consistently elevated and localized pattern of amplification. Topographic effects at a given site are highly dependent on topography shape, ground motion frequency and source location. Our findings could have significant implications regarding landslide hazard and hill-slope engineering in the city.

Nonlinear Broadband Simulations of M9 Megathrust Earthquakes in the Cascadia Subduction Zone

ROTEN, D., San Diego State University, California, USA, droten@sdsu.edu; OLSEN, K. B., San Diego State University, California, USA, kbolsen@sdsu.edu; TAKEDATSU, R., San Diego State University, California, USA, rtakedatsu@sdsu.edu; WANG, N., San Diego State University, California, USA, naw021@ucsd.edu

We predict broadband (BB) ground motions in the Pacific Northwest urban areas during large earthquakes on the Cascadia megathrust using a hybrid approach which combines deterministic low-frequency (f < 1 Hz) signals obtained by 3-D wave propagation simulations with stochastic synthetics and 1-D simulations of nonlinear sites response. Velocities and densities in our computational mesh are derived by extending the regional Cascadia Community Velocity model (V1.6, Stephenson *et al.*, 2017) to 150 km depth and embedding a more detailed model of shallow velocities (Molnar *et al.* 2011) in the Georgia basin. In the near surface part, we used a recent empirical correlation between geomorphic terrain classes and measurement-based V_{S30} values for the Pacific Northwest (Ahdi *et al.*, 2017) to define a geotechnical layer. Wave propagation simulations were carried out with the discontinuous mesh finite difference code AWP-GPU-DM. Our 3-D simulations use a spatial discretization of 66 2/3 m in the shallow crust, with a minimum shear-wave velocity of 350 m/s and a maximum frequency of 1 Hz. The grid spacing was increased to 200 m at depths between 5 and 30 km, and increased again to 600 m at depths of 30 km or more. The ensemble of kinematic source realizations contains 8 M9.0, two M8.8 and one M9.2 scenarios, each consisting of a background slip distribution with superimposed high stress-drop subevents (Frankel, 2016) to mimic observations made during previous megathrust earthquakes (2011 M9 Tohoku and 2010 M8.8 Maule). An updated version of the San Diego State University broadband generation module, which includes frequency-dependent spatial correlation for risk analysis purposes, was used to compute BB synthetics. Site response simulations carried out using Noah1D show that nonlinear effects would not be significant for glacial deposits in Seattle or Vancouver, but potentially important for deep Quaternary deposits in the Fraser River delta. We obtain favorable comparisons between spectral accelerations for BB synthetics, the BC Hydro GMPE, and the M9 Tohoku event.

An Overview of the NGA-Subduction Research Program

BOZORGNIA, Y., University of California, Los Angeles, California, USA, yousef.bozorgnia@ucla.edu; ABRAHAMSON, N., University of California, Berkeley, California, USA, abrahamson@berkeley.edu; AHDI, S. K., University of California, Los Angeles, California, USA, sahdi@ucla.edu; ANCHETA, T. D., Risk Management Solutions, Oregon, USA, timothydancheta@gmail.com; ARCHULETA, R. J., University of California, Santa Barbara, California, USA, ralph@eri.ucsb.edu; ATKINSON, G. M., Western University, London, Canada, gmatkinson@aol.com; BOORE, D. M., U.S. Geological Survey, California, USA, dboore@yahoo.com; CAMPBELL, K. W., CoreLogic, Inc., California, USA, kcampbell@corelogic.com; CHIOU, B. S. J., Caltrans, California, USA, brian_chiou@dot.ca.gov; CONTRERAS, V., University of California, Los Angeles, California, USA, vcontreras@ucla.edu; DARRAGH, R. B., Pacific Engineering and Analysis, California, USA, bbalindavis@gmail.com; GREGOR, N., Gregor Consulting, California, USA, nick@ngregor.com; IDRISS, I., University of California, Davis, California, USA, imidriss@aol.com; JI, C., University of California, Santa Barbara, California, USA, ji@geol.ucsb.edu; KAMAI, R., Ben-Gurion University, Negev, Israel, rkamai@bgu.ac.il; KISHIDA, T., Khalifa University, Abu Dhabi, United Arab Emirates, kishidapple@gmail.com; KUEHN, N. M., University of California, Los Angeles, California, USA, kuehn@g.ucla.edu; MAGISTRALE, H., FM Global, Massachusetts, USA, harold.magistrale@fmglobal.com; MAZZONI, S., University of California, Los Angeles, California, USA, silviamazzoni@yahoo.com; PARKER, G. A., University of California, Los Angeles, California, USA, graceaparker@gmail.com; SI, H., University of Tokyo, Tokyo, Japan, shj@eri.u-tokyo.ac.jp; SILVA, W., Pacific Engineering and Analysis, California, USA, pacificengineering@juno.com; STEWART, J. P., University of California, Los Angeles, California, USA, jstewart@seas.ucla.edu; WALLING, M., GeoEngineers, Inc., Washington, USA, mwalling@geoengineers.com; WOODDELL, K. E., Pacific Gas and Electric Company, California, USA, katie.wooddell@gmail.com; YOUNGS, R. R., John Wood Group PLC, California, USA, bob.youngs@amec.com

This presentation provides an overview of the NGA-Sub, a large multidisciplinary community-based research program to develop a comprehensive ground-motion database and multiple ground-motion models (GMMs) for subduction events. In the NGA-Sub project, we developed a database of ground motions recorded in worldwide subduction events. The database includes the processed recordings and supporting source, path, and site metadata from Japan, Taiwan, the US Pacific Northwest, Alaska, Latin America (including Mexico, Peru and Chile), and New Zealand. The NGA-Sub database includes subduction events with moment magnitudes ranging from 4 to 9.1. The subduction events are classified as interface, intraslab, or outer-rise events. The NGA-Sub ground-motion database has over 213,000 component records. This is by far the largest ground motion database that we have ever developed in any NGA project. Pseudo-spectral acceleration as well as Fourier amplitude spectra for frequencies from 0.1 to 100 Hz have been included in the database. In NGA-Sub, using the empirical ground-motion database, five teams developed subduction GMMs. Following the tradition of previous NGA projects, the GMM modeling teams as well as database developers have had continuous technical interactions which resulted in much higher quality of the final products than each researcher could achieved individually.

NGA-Subduction Database

AHDI, S. K., University of California, Los Angeles, California, USA, seanahdi@gmail.com; ANCHETA, T. D., Risk Management Solutions, Oregon, USA, timothydancheta@gmail.com; BOZORGNIA, Y., University of California, Los Angeles, California, USA, yousef.bozorgnia@ucla.edu; CHIOU, B. S. J., Caltrans, California, USA, brian_chiou@comcast.net; CONTRERAS, V., University of California, Los Angeles, California, USA, vcontreras@ucla.edu; DARRAGH, R. B., Pacific Engineering and Analysis, California, USA, bbalindavis@gmail.com; KISHIDA, T., Khalifa University, Abu Dabi, United Arab Emirates, kishidapple@gmail.com; KUEHN, N. M., University of California, Los Angeles, California, USA, kuehn@ucla.edu; KWOK, A. O., National Taiwan University, Taipei, Taiwan, annieolkwok@engineering.ucla.edu; LIN, P., Sinotech Engineering Consultants, Inc, Taipei, Taiwan, person@sinotech.org.tw; YOUNGS, R. R., AMEC E&I, California, USA, bob.youngs@amec.com; STEWART, J. P., University of California, Los Angeles, California, USA, jstewart@seas.ucla.edu

The NGA-Subduction database is a collection of data from magnitude 4 to 9 earthquakes from global subduction zones including Japan, Taiwan, Mexico, Central and South America, Cascadia, and Alaska. The database includes information from more than 71,000 three-component recordings, many of which are from digital accelerograms. Maximum PGA and PGV are > 2.0 g and 90 cm/sec, respectively.

NGA-Subduction uses a relational database structure, consisting of a series of metadata and data tables that communicate via primary and foreign keys. The most critical tables are those related to source, site, and recordings. Advantages of relational databases include efficiency in data entry and access, and expandability.

The source table contains moment tensor information, classifications of events as interface, intraslab, or outer rise, and finite fault parameters describing planar representations of the ruptured fault surface. Finite-fault models are adapted from literature via trimming protocols for about 80 events. Simulation procedures, enhanced from prior work, were implemented to develop rupture distances for the remaining events. Rupture distances in the database range from 14 km to > 1000 km.

The site table contains average velocity V_{S30} for all sites, and basin depth parameters where available (Japan, Taiwan, Pacific Northwest). A significant effort was undertaken to compile seismic velocity profiles for use in defining V_{S30} at station locations and elsewhere in the study regions. This data was also used to derive a series of regional models for prediction of V_{S30} given local geology and other morphological parameters. V_{S30} was assigned from data where available, and from such models otherwise. Both aleatory uncertainty in V_{S30} and epistemic uncertainty in the natural log mean of V_{S30} are provided.

The relational database outputs flatfiles used in model development. Flatfiles are specific to different intensity measures, including pseudo-spectral acceleration for alternate damping values, Fourier amplitude spectra, and significant durations.

Cascadia-Specific NGA-Subduction Ground Motion Models for Interface and Intraslab Events with Regionalized Site Response

PARKER, G. A., University of California, Los Angeles, California, USA, parker@seas.ucla.edu; STEWART, J. P., University of California, Los Angeles, California, USA, jstewart@seas.ucla.edu; HASSANI, B., BC Hydro, Burnaby, Canada, behzad.hassani@bchydro.com; ATKINSON, G. M., Western University, London, Canada, gatkins6@uwo.ca; BOORE, D. M., Geophysicist, California, USA, dboore@yahoo.com

The Next Generation Attenuation – Subduction Project is a multi-year, multidisciplinary research project that is compiling processed ground motion recordings and the associated metadata from subduction zone events and developing a suite of semi-empirical ground motion models. Earthquake data came from Alaska, the Aleutian Islands, and the Cascadia subduction zone in the Pacific Northwest region of the United States, British Columbia, Mexico, Chile, Peru, Ecuador, Japan, Taiwan, and New Zealand. Some terms of the ground-motion prediction equations were regionalized due to observed differences between subduction zones including the intercept, anelastic attenuation, magnitude-scaling breakpoint, V_{S30}-scaling, and basin terms. We describe the process by which our model was developed, including these regional adjustments for source, path, and site effects. More specifically, this presentation emphasizes regional features of the ground motions in the Cascadia region for both interface and intraslab events. This includes an investigation of regional V_{S30}-scaling, and basin effects specific to the Seattle, Tacoma, Everett, Tualatin and Portland basins (Ahdi *et al.* 2019). We also make comparisons to the global NGA-Subduction models, and validate the regional model against ground motions from empirical events recorded in Cascadia, and broadband simulations for the region.

A Partially Non-Ergodic NGA Subduction Ground Motion Prediction Equation and Its Application to Cascadia

KUEHN, N. M., University of California, Los Angeles, California, USA, kuehn@ucla.edu; BOZORGNIA, Y., University of California, Los Angeles, California, USA, yousef.bozorgnia@ucla.edu; CAMPBELL, K. W., CoreLogic, Inc., California, USA, kcampbell@corelogic.com; GREGOR, N., Consultant, California, USA, nick@ngregor.com

We present a new NGA subduction ground-motion model (GMM), based on the 2018 PEER NGA-SUB global database. About 16,500 records from 247 events are used to estimate the model parameters for both subduction interface and intraslab events. The model takes into account regional differences in the constant, anelastic attenuation and linear site scaling. Seven regions were considered: Alaska, Cascadia, Central America and Mexico, Japan, New Zealand, South America, and Taiwan. The regional adjustment terms are modeled as regional random effects, which assumes that the regional coefficients are samples from a global coefficient distribution. The model includes a bilinear magnitude scaling, where the magnitude break point depends on the age/geometry of the subduction zone and whether the events are on the interface or within the slab. The model parameters are estimated via Bayesian inference, using Markov Chain Monte Carlo sampling. The Bayesian approach allows us to include prior information and assess uncertainty in a probabilistic way. Epistemic uncertainty associated with the model parameters and median predictions are taken into account via the posterior distribution of coefficients. To account for outliers due to low quality data, the parameters are estimated via robust regression.

For Cascadia, the available data are very limited, with only 624 records from 12 earthquakes, with no reliable data from interface events. The largest Cascadia earthquake in the data set is the Nisqually (M6.8) event. This leads to large epistemic uncertainties associated with the regional coefficients for Cascadia, which translate into large epistemic uncertainties for median predictions. The ground-motions from the Cascadia events are on average very low compared to the other regions, however, the two larger events in Cascadia have ground motions that are closer to the global average. We discuss strategies of how to adjust the model predictions for Cascadia to take these observations into account.

Subregional Attenuation of Ground Motion Amplitudes for Japan Megathrust Earthquakes

CAMPBELL, K. W., CoreLogic, Inc., Oregon, USA, ken.w.campbell@comcast.net

As part of the NGA-Sub project, I am developing a ground motion model (GMM) for Japan megathrust earthquakes for PGA, PGV, and pseudo-absolute spectral accelerations with periods ranging from 0.01-10 s (GMIMs). During this development, I discovered that there are tectonic regions within Japan that exhibit significantly different attenuation properties, making it difficult to develop a single generic GMM that accurately predicts GMIMs within these regions. Regional differences are greatest for short-period GMIMs. The regions are defined by travel paths that are (1) offshore, (2) onshore but within the subduction forearc, and (3) onshore but within the subduction backarc. Discrepancies in GMIM amplitudes within these three regions can be reduced significantly if different anelastic attenuation coefficients are defined for each zone. I propose that the relatively low attenuation observed at coastal sites for events whose down-dip rupture extent is offshore is due to travel paths that are primarily within the slab. Once propagation of ground motion is onshore within the forearc region, these travel paths all contain a component that includes propagation upwards through a deepening continental crust, thus increasing the observed attenuation. Travel paths primarily within the backarc region are subject to additional attenuation as a result of traversing the volcanic line and propagating within higher-attenuating continental crust with relatively deep slab depths. Although these complex wave-propagation characteristics can be incorporated into the GMM, the use of such a GMM requires that the proportion of the travel path between the source and site within each of these regions be estimated and incorporated into a probabilistic seismic hazard analysis (PSHA). Since this might not be feasible, an alternative GMM is being developed that does not require these partitioned distances but with the penalty of larger within-event aleatory variability.

Comparison of NGA-Sub Developed Ground Motion Models for Subduction Earthquakes

GREGOR, N., Consultant, California, USA, nick@ngregor.com; ABRAHAMSON, N., University of California, Berkeley, California, USA, abrahamson@berkeley.edu; AL ATIK, L., Consultant, California, USA, linda.alatik@gmail.com; ATKINSON, G. M., Western University, London, Canada, gmatkinson@aol.com; BOORE, D. M., Geophysicist, California, USA, dboore@yahoo.com; BOZORGNIA, Y., University of California, Los Angeles, California, USA, yousef.bozorgnia@ucla.edu; CAMPBELL, K. W., CoreLogic, Inc., California, USA, kcampbell@corelogic.com; CHIOU, B. S. J., California Department of Transportation, California, USA, brian.chiou@dot.ca.gov; GULERCE, Z., Middle East Technical University, Ankara, Turkey, zyilmaz@metu.edu.tr; HASSANI, B., BC Hydro, Burnaby, Canada, behzad.hassani@bchydro.com; KISHIDA, T., Khalifa University, Abu Dhabi, United Arab Emirates, kishidapple@gmail.com; KUEHN, N. M., University of California, Los Angeles, California, USA, kuehn@g.ucla.edu; MIDORIKAWA, S., Tokyo Institute of Technology, Tokyo, Japan, smidorik@enveng.titech.ac.jp; MAZZONI, S., University of California, Los Angeles, California, USA, mazzoni@berkeley.edu; PARKER, G. A., University of California, Los Angeles, California, USA, graceaparker@gmail.com; SI, H., Seismological Research Institute Inc., Tokyo, Japan, shj@seismo-r.com; STEWART, J. P., University of California, Los Angeles, California, USA, jstewart@seas.ucla.edu; YOUNGS, R. R., John Wood Group PLC, California, USA, bob.youngs@woodplc.com

The Next Generation Attenuation for Subduction Earthquakes (NGA-Sub) research program is the latest research initiative in the NGA series to develop a database and ground-motion models (GMMs) for events in various tectonic settings. Given the large empirical database of interface and intraslab earthquake recordings from different global subduction zone regions, multiple ground motion models have been generated as part of this community based approach. During the development process, comparisons between these interim models are analyzed and used along with the numerous technical discussions for the refinement of the models.

Multiple GMMs have been developed based on the database. A summary will be provided of the different parameterizations of these multiple models and as well the regionalization contained within each model. Comparisons of median ground motion plots (*e.g.*, attenuation curves and spectra) will be presented along with the associated uncertainty models. As part of this comparison, these new models will also be compared to previous GMMs including the recent BC Hydro update model. A focus will be placed on the expected controlling subduction zone earthquakes for sites located in the Pacific Northwest and British Columbia region for these comparisons. Additionally, comparison will also be provided for the global version of these GMMs.

Development of Basin Depths and VS30-Depth Centering Models for the Pacific Northwest

AHDI, S. K., University of California, Los Angeles, California, USA, seanahdi@gmail.com; ANCHETA, T. D., Risk Management Solutions, California, USA, tim.ancheta@rms.com; STEWART, J. P., University of California, Los Angeles, California, USA, jstewart@seas.ucla.edu

Basin depth terms in ground motion models (GMMs) are the vertical distances from the ground surface to a particular shear-wave velocity (V_S) horizon. These depths provide a first-order representation of basin geometry. Common basin depth terms are $z_{1.0}$ and $z_{2.5}$, which are depths to the V_S= 1.0 and 2.5 km/s horizons, respectively.

To some extent, the effects on ground motion of 3D site amplification in basins are reflected in site terms within GMMs that are conditioned on parameters other than depth (*i.e.*, time-averaged velocity in the upper 30 m, V_{S30}). As a result, it is desirable to center basin amplification models in GMMs (*i.e.* predict no amplification) for the case of an average depth conditional on V_{S30}. This requires the use of V_{S30}-depth correlation relationships, such as those developed for Japan and California in NGA-West2. Basin amplification or de-amplification in such models is then predicted for depths larger or smaller, respectively, than the centered value.

For Cascadia, we focus on the $z_{2.5}$ depth parameter, which has more physical meaning than $z_{1.0}$ for this region. We assign $z_{2.5}$ values for Pacific Northwest basins using the USGS 3D velocity model for locations of V_{S30} measurements and strong motion recording stations. Preliminary results indicate that overall there is no particular V_{S30}-$z_{2.5}$ relationship across the entire PNW, but there are strong differences in depths within specific basin structures. The Seattle basin has the largest depths; the Portland and Tualatin basins have consistent distribution of depths between about 1.5–2.0 km; and the Everett basin is much shallower than the Seattle basin. The reliability of these depths is based on the accuracy of the 3D velocity model, but it is important to represent these differences among basins for NGA-Subduction GMM development for Cascadia.

We provide mean relationships for $z_{2.5}$ conditional on certain basin structural characteristics and V_{S30}. These models are being used in some of the NGA-Subduction GMMs to develop basin-related site amplification models.

Implementation of Basin Effects in Seismic Hazard of the Greater Seattle Region

WALLING, M., GeoEngineers, Inc., California, USA, lytmelanie@yahoo.com; PUANGNAK, H., GeoEngineers, Inc., Washington, USA, hpuangnak@geoengineers.com; ABRAHAMSON, N., University of California, Berkeley, Washington, USA, abrahamson@berkeley.edu

We present a methodology for incorporating basin effects into a seismic hazard assessment for a site located in Seattle. In the Seattle region, there are three major source-types that contribute to the seismic hazard: interface and intraslab subduction events and crustal events. The basin effects are dependent on the source-type. The basin amplification factors (AFs) from the Cascadia interface sources use the University of Washington M9 simulations; intraslab sources use empirical site-specific AFs from the Nisqually earthquake; and crustal sources use basin factors derived for an analogous region.

We show how to incorporate site-specific basin effects from the intraslab and interface sources using the single-station sigma approach as compared to the fully-ergodic approach used in current practice. With the single-station sigma approach, the incorporation of site-specific site-effects provides a more accurate ground-motion estimate than an ergodic model. Consequently, there is a reduction in the aleatory variability as compared to the ergodic model; however, there is epistemic uncertainty in the estimation of the basin AFs which leads to additional branches on the ground motion characterization logic tree. Published values of the reduction of the ergodic standard deviation due to including site-specific terms range between 9 and 16 percent. Use of the single-station sigma approach in practice is not new. Major seismic hazard studies, both in the US and outside the US, have implemented the single-station sigma approach. By using site-specific basin AFs from recorded intraslab events and from the M9 interface simulations into the hazard analysis, we are providing a more informed ground-motion estimate at our site and consequently expect less variability in the ground motion than what would be predicted using the ergodic ground-motion model. As examples, we show a comparison of the uniform hazard spectra for the current approach used in Seattle and the single-station sigma approach for several locations in the Seattle region, both inside and outside of the basin.

Earthquake Source-Dependent Amplification of Ground Motions in the Puget Lowland Sedimentary Basins

WIRTH, E., U.S. Geological Survey, Washington, USA, ewirth@usgs.gov; VIDALE, J. E., University of Southern California, California, USA, seismoguy@mac.com; FRANKEL, A., U.S. Geological Survey, Washington, USA, afrankel@usgs.gov; PRATT, T. L., U.S. Geological Survey, Virginia, USA, tpratt@usgs.gov; MARAFI, N. A., University of Washington, Washington, USA, marafi@uw.edu; THOMPSON, M., University of Washington, Washington, USA, usherm42@uw.edu; STEPHENSON, W. J., U.S. Geological Survey, Colorado, USA, wstephens@usgs.gov

In the Puget Lowland, deep sedimentary basins amplify long-period ground shaking due to earthquakes, increasing the seismic hazard for cities located there. We perform 3-D numerical simulations of point-source earthquakes at many locations throughout the Puget Lowland. We examine the dependence of ground motion amplification in the Seattle and Tacoma basins on earthquake source azimuth and depth, as well as focal mechanism. For periods of 1-10 s, we find that the pattern of ground motion amplification is spatially heterogeneous and varies with the source-to-site azimuth. For close-in earthquakes around the Puget Lowland, the greatest basin amplification occurs towards the far side of the basin. Ground motions from shallow crustal earthquakes experience roughly twice as much amplification compared to the more vertically-incident waves from deeper intraslab earthquakes. Far-field earthquakes on the megathrust generate a different spatial pattern of basin amplification, with the greatest ground motion amplification occurring on the near side of the basin, likely due to differences in path effects or incidence angle. Overall, we demonstrate that the source dependence of basin amplification is an important factor for seismic hazard assessment, both in the Seattle and Tacoma basins, and by analogy, for deep sedimentary basins worldwide.

Effects of Simulated Magnitude 9 Earthquake Motions on Reinforced Concrete Wall Structures in the Pacific Northwest

MARAFI, N. A., University of Washington, Washington, USA, marafi@uw.edu; BERMAN, J., University of Washington, Washington, USA, jwberman@uw.edu; EBERHARD, M., University of Washington, Washington, USA, eberhard@uw.edu

The Cascadia Subduction Zone (CSZ) can produce long-duration, large-magnitude earthquakes, whose ground motions will be modified by the deep sedimentary basins, which underlie several cities in the Pacific Northwest (*e.g.*, Portland, Seattle, and Vancouver, BC). The effects of these basins on the ground motion duration and frequency content are poorly understood because no recordings are available for large-magnitude earthquakes in this region.

To compensate for this paucity of recordings, researchers from the United States Geological Survey and the University of Washington generated ground motions for numerous scenarios of an M9 event. The simulations were generated using deterministic, finite-difference (T>1s) and stochastic (T<1s) approaches. This seminar will present the impacts of 30 motions simulated in Seattle for 32 archetypical, reinforced-concrete-core-wall structures (4- to 40-stories).

The frequency dependent basin amplification increases the spectral accelerations at periods corresponding to tall structures and results in damaging spectral shapes. The duration of the M9 motions are long, but the basins have little effect on the significant duration of the motions. Tall buildings designed to enhanced building code requirements have collapse probabilities similar to that expected for a 2475-year motion, but the return period of an M9 earthquake is only about 500 years. Tall buildings designed to meet the minimum building code requirements were much more likely to collapse. A newly developed ground-motion intensity measure (effective spectral acceleration) explains these results and made it possible to evaluate the likely regional impacts of these motions.

Modeling and Understanding of High-Frequency Ground Motion

Oral Session · Wednesday · 4:15 PM · 24 April · Pine
Session Chairs: Marco Pilz, Ashly Cabas, Olga Ktenidou.

Decomposing Source and Path Terms in High-Frequency Ground Motion Data

BALTAY, A. S., U.S. Geological Survey, California, USA, abaltay@usgs.gov; HANKS, T. C., U.S. Geological Survey, Earthquake Science Center, California, USA, thanks@usgs.gov

Earthquake source effects are notoriously difficult to separate from those of path and site attenuation, both for earthquake source seismologists and researchers in the ground-motion engineering community. Yet correctly modeling the source properties can aid in accurately understanding attenuation trends and patterns. The positive relationship between earthquake stress drop and ground-motion event terms (*i.e.*, residuals between ground-motion prediction equations and high frequency data) is taken as a certainty, given that events with larger Brune stress drops generate more high-frequency energy and thus more ground motion.

However, this connection is contingent on those ground-motion event terms truly representing the earthquake source, thus being unbiased with distance or attenuation. We consider several cases in which event and attenuation effects are difficult to resolve. Specifically, we study high-frequency ground-motion data, PGA and PGV which should have a clear relationship to stress drop to demonstrate that seismological understanding can aid our interpretation. Furthermore, assuming anelastic attenuation has a small effect at close distances, we only consider close-in records with Rrup<20km to avoid contamination from path attenuation; we then model the remaining path attenuation, *i.e.*, Q, and site effect, such as kappa. For example, in the case of the 2014 M6.0 South Napa, California earthquake, the high-frequency ground-motion residuals show a strong dependence on distance, strongly biasing the event term and incorrectly mapping a specific regional attenuation effect into the source term. This is one situation when the event term from high-frequency ground-motion prediction equation residuals is clearly not equal to the earthquake stress drop and suggests how both event terms and regional attenuation should be estimated to be more indicative of physical behavior. Ground-motion models that correctly reflect the source and attenuation properties can thus be correctly extrapolated into different magnitude or distance ranges, or new geological regions.

Investigations on the Kappa Parameter Using Empirical and Numerical Approaches and Application for Site-Specific Ground Motion Assessment

GELIS, C., Institut de Radioprotection et de Sûreté Nucléaire, Fontenay-aux-Roses, France, celine.gelis@irsn.fr; BONILLA, L., Universite Paris Est, Marne-la-Vallée, France, fabian.bonilla@ifsttar.fr; CALVET, M., IRAP-OMP, Toulouse, France, marie.calvet@irap.omp.eu; COLVEZ, M., Centrale Supelec, Saclay, France, martin.colvez@centralesupelec.fr; GATTI, F., Centrale Supelec, Saclay, France, filippo.gatti@centralesupelec.fr; LAURENDEAU, A., IRSN, Fontenay-aux-roses, France, aurore.laurendeau-manpower@irsn.fr; LOPEZ-CABALLERO, F., Centrale Supelec, Saclay, France, fernando.lopez-caballero@centralesupelec.fr; MARGERIN, L., IRAP-OMP, Toulouse, France, ludovic.margerin@irap.omp.eu; MAYOR, J., EDF, Saclay, France, jessie.mayor@edf.fr; PROVOST, L., IRSN, Fontenay-aux-Roses, France, ludmila.provost@irsn.fr; BEUCLER, E., Université Nantes, Nantes, France, eric.beucler@univ-nantes.fr; BONNIN, M., Université Nantes, Nantes, France, mickael.bonnin@univ-nantes.fr; COURBOULEX, F., Géoazur, Sophia Antipolis, France, courboulex@geoazur.unice.fr; FROMENT, B., IRSN, Fontenay aux roses, France, berenice.froment@irsn.fr; GUÉGUEN, P., Universite Grenoble Alpes, Grenoble, France, philippe.gueguen@univ-grenoble-alpes.fr; MOCQUET, A., Université Nantes, Nantes, France, antoine.mocquet@univ-nantes.fr; MONFRET, T., Géoazur, Sophia Antipolis, France, tony.monfret@geoazur.unice.fr; TCHAWE, F. N., Universite Paris Est, Universite Paris Est, France, flomin.tchawenziaha@univ-paris-est.fr

Anderson and Hough (1984) defined the Kappa parameter κ as frequency-independent attenuation of the S-wave at high-frequency. Based on observations, they decomposed κ in local (κ_0) and regional attenuation (κ_R), respectively. In the last years, this parameter has become important in engineering seismology, in particular to take into account local site conditions in ground motion prediction studies. However, the link between κ and attenuation, traditionally represented in seismology by the 1/Q factor and composed of intrinsic $1/Q_i$ and scattering $1/Q_{sc}$ regimes, is still under study. In this project funded by the French strong-motion network (RESIF-RAP), we propose empirical and numerical approaches to improve the understanding of the link between κ and Q and we explore the influence of the uncertainties related to κ in a site-specific study.

We present results on both κ and $1/Q_i$ results at stations located in areas of small-to-moderate seismic activity in mainland France. Secondly, we look at the dependency of κ to $1/Q_i$ and $1/Q_{sc}$ through numerical simulations of 2D and 3D wave propagation. Wave scattering is generated by random velocity perturbations in the propagation medium. To do so, we model point sources at depth and study the waves recorded at the free surface. At last, a host-to-target exercise is carried out in the Nice area, southeast of France, where we compute site-specific response spectra using different GMPEs and compare to the ones obtained from recorded earthquake data.

Modeling Anelastic Effects Within the Near Surface

MOROZOV, I., University of Saskatchewan, Saskatoon, Canada, igor.morozov@usask.ca

In order to understand seismic site responses and wave propagation at various frequencies and scales, it is important to model them by using the same physical laws and consistent physical properties. In most current models, the elastic properties of the medium are generally well understood, but anelastic effects are only described by empirical parameters such as the damping ratio (ksi) spectral decay (kappa), or coda quality Q_c. In this paper, I discuss the medium properties and equations needed for *ab initio* modeling of these empirical parameters. Unfortunately, current models (including most seismic modeling codes) describe medium anelasticity also by empirical concepts such as the dynamic moduli, quality factor (Q) and the phenomenon of "material memory." Although these concepts work in material-science applications in which no spatial gradients are considered, they are insufficient for seismic waves and lead to overly complex but inaccurate or incorrect integro-differential equations for the medium.

As an alternative approach, a rigorous and physically-consistent description of Earth's media can be obtained by extending Biot's poroelasticity. Two general observations follow from realizing this analogy with poroelasticity. First, pore-fluid flow friction is indeed the dominant anelastic mechanism in many near-surface, sedimentary, hydrothermal, and partial-melt environments. Second, poroelasticity shows that in blocky or layered media, the attenuation is often dominated not by the "dynamic moduli" or Q-factors of the blocks but by boundary conditions between these blocks, such as allowed or prevented pore flows. These boundary conditions are poorly known but can be highly variable. Consequently, the popular "intrinsic" and "scattering" components of attenuation may in fact be impossible to consistently define and separate. Nevertheless, direct modeling by using the extended Biot's model can be used to model all types of seismic phenomena, as illustrated here by modeling laboratory experiments and wave transmission and reflections in layered media.

Capturing Regional Variations of Hard-Rock Attenuation in Europe

PILZ, M., GFZ German Research Centre for Geosciences, Potsdam, Germany, pilz@gfz-potsdam.de; COTTON, F., GFZ German Research Centre for Geosciences, University of Potsdam, Potsdam, Germany, fcotton@gfz-potsdam.de; ZACCARELLI, R., GFZ German Research Centre for Geosciences, Potsdam, Germany, rizac@gfz-potsdam.de

A proper assessment of seismic reference site conditions has important applications as they represent the basis on which ground motions and amplifications are generally computed. Besides accounting for the average S wave velocity over the upper 30 m (vS30), the parameterization of high-frequency ground motions beyond source-corner frequency has received significant attention in last few decades. κ, an empirical parameter introduced by Anderson and Hough (1984), is often used to represent the spectral decay of the acceleration spectrum at high frequencies. Definitions of reference site conditions are mostly based on indirect large-scale crustal velocity inversions while site effects for hard-rock sites are typically computed using analytical models for the effect of κ0, the site-specific component of κ at zero epicentral distance. Following Mayor *et al.* (2018), we propose an alternative procedure for capturing the reference κ0 on regional scales by linking the well-known high-frequency attenuation parameter κ and the properties of coda waves. Using near-distance records of more than 10,000 crustal earthquakes at more than 1300 sites, we observe that κ0 from coda waves seems to be independent of the soil type but correlated with the hard-rock κ0, showing significant regional variations across Europe. The values range between 0.004 s for northern Europe and 0.020 s for the southern and south-eastern parts. On the other hand, measuring κ (and correspondingly κ0) on the S wave window (as classically proposed), the results are strongly affected by transmitted (reflected, refracted and scattered) waves included in the analysed window. This effect is more pronounced for soft soil sites. In this way, κ0 of coda waves can serve as a proxy for the regional hard-rock κ0 at the reference sites.

Attenuation Estimation With Uncertainty for Seismic Noise Interferometry: Application to a Dense 3C Array in Groningen, Netherlands

LIU, X., Stanford University, California, USA, liuxin@stanford.edu; BEROZA, G. C., Stanford University, California, USA, beroza@stanford.edu; NAKATA, N., Massachusetts Institute of Technology, Massachusetts, USA, nnakata@mit.edu; SPICA, Z., Stanford University, California, USA, zspica@stanford.edu

Seismic wave attenuation information is important for shallow subsurface structure characterization because it is related to fracture, temperature, composition and fluid content. It is also important for efforts to predict strong ground motion We use a method based on noise cross-correlations of linear triplet of stations (*Liu et al.*, 2015) to compute the relative amplitude decay between different paths with respect to frequency. The focusing/defocusing effect for the ambient noise should be common for the co-linear triplet of stations under the assumption of a remote noise source. We further assume constant Q over each narrow frequency band considered. Combined with uncertainty quantification for the stacked noise cross-correlation (*Liu and Beroza,* 2019), we estimate Q from these relative amplitude measurements and propagate the amplitude uncertainty to the uncertainty of Q value through linear least-square estimation. We apply this method to the Loppersum dense 3C array in Groningen, Netherlands. The Loppersum array features 415 stations at ~250 m station spacing. We treat each station as a virtual source, and construct amplitude maps with uncertainties for both the fundamental and first higher Rayleigh wave modes. We remove errant amplitude measurements using a combination of statistical stability over time and spatial coherency. Stacking the results from different virtual sources yields an averaged attenuation map for each narrow frequency band. We convert the attenuation maps at different frequencies to attenuation with depth and construct a 3D attenuation model for the shallow crust from these results.

Characterizing Faults, Folds, Earthquakes and Related Hazards in the Pacific Northwest

Oral Session · Wednesday · 8:30 AM · 24 April · Puget Sound
Session Chairs: Scott E. K. Bennett, Ashley R. Streig, Colin Amos, Megan Anderson.

A Kinematic Model for Late Cenozoic Fault Motion Within the Greater Cascadia Subduction System

MCCRORY, P. A., U.S. Geological Survey, California, USA, pmccrory@usgs.gov; WILSON, D. S., University of California, Santa Barbara, California, USA, dwilson@geol.ucsb.edu

Relatively low fault slip rates complicate efforts to characterize seismic hazards associated with the diffuse subduction boundary between North America and offshore oceanic plates in the Pacific Northwest (PNW) region. A kinematic forward model that encompasses a broader region, and incorporates seismologic and geodetic as well as geologic and paleomagnetic constraints, offers a tool for constraining fault rupture chronologies within a framework of relative motion between the Juan de Fuca, Pacific, and North American plates during late Cenozoic time.

Our kinematic model tracks motions as a system of rigid microplates, bounded by significant mapped faults or zones of distributed deformation. The model extends eastward to the rigid craton in Montana and Wyoming, and southward to the Sierra Nevada block of California to provide important checks on its internal consistency. The model reproduces observed geodetic velocities [McCaffrey *et al.*, 2013, *JGR*] for 6–0 Ma, with generally slightly faster motion for 12–6 Ma. Constraints for the older deformation history are based on paleomagnetic rotations within the Columbia River Basalt Group, and geologic age dating of fault offsets. Since 17 Ma, our model includes 50 km of N-S shortening along 120°W in the Yakima fold and thrust belt, substantial NW-SE right-lateral strike slip distributed among faults in the Washington Cascade Range, ~90 km of shortening on thrusts of Puget Lowland along 123°W, and substantial oroclinal bending of the Crescent Formation basement surrounding the Olympic Peninsula. The large shortening modeled in western Washington suggests that many faults and deformation zones should be considered seismically active.

Our quantitative reconstruction provides an integrated framework with which to investigate the motions of various PNW forearc and backarc blocks during late Cenozoic time. By explicitly defining major known fault blocks and their Euler poles, the framework offers a preliminary platform for constructing a UCERF3 type model to characterize seismic risk and seismic hazard in the PNW region.

Evidence for a Quaternary-Active Fault Network in the Forearc of Southwestern British Columbia

MORELL, K., University of California, Santa Barbara, California, USA, kmorell@ucsb.edu; REGALLA, C., Boston University, Massachusetts, USA, cregalla@bu.edu; BENNETT, S. E. K., U.S. Geological Survey, California, USA, sekbennett@usgs.gov; LEONARD, L. J., University of Victoria, Victoria, Canada, lleonard@uvic.ca; AMOS, C., Western Washington University, Washington, USA, amosc2@wwu.edu; LYNCH, E., Boston University, Massachusetts, USA, emlynch2@bu.edu; HARRICHHAUSEN, N., University of California, Santa Barbara, California, USA, nharrichhausen@ucsb.edu; GRAHAM, A., University of Victoria, Victoria, Canada, audreychristinagraham@gmail.com

The seismic hazard posed by potentially active faults in the forearc crust of the northern Cascadia subduction zone has proven difficult to constrain because of relatively low rates of seismicity, recent glacial activity, and thick vegetation. Here we present results from lidar topography, structural-geomorphic mapping, and paleoseismic trenching that reveal evidence for a Quaternary-active fault network in southwestern British Columbia on southern Vancouver Island. Three paleoseismic trenches across the Leech River Fault indicate that this terrane-bounding structure has hosted at least three surface-rupturing earthquakes in the last ~9 kyr, with a Holocene slip rate of ≥0.2–0.3 mm/year, and is therefore capable of producing large (Mw > 6) earthquakes. Recent structural and geomorphic mapping on newly acquired lidar, and high-resolution topographic surveys along the San Juan and Beaufort Range Faults, two other prominent faults on southern Vancouver Island, indicate that these structures may have also hosted large-magnitude late Quaternary earthquakes. Both faults exhibit faulted channel networks developed in late Quaternary colluvial or alluvial units, with displacements on the order of ~2-6 m. These observations collectively argue for latest Quaternary activity along structures previously considered inactive since the Paleogene, and highlight the need for new seismic hazard assessments pertinent to residents of southwestern British Columbia and northwestern Washington State.

Near-Surface Geophysical, Geological and Geodetic Constraints on the Seismic Hazard of the Leech River Fault in the Northern Cascadia Forearc

LEONARD, L. J., University of Victoria, Victoria, Canada, lleonard@uvic.ca; GRAHAM, A., University of Victoria, Victoria, Canada, audreychristinagraham@gmail.com; MORELL, K., University of California, Santa Barbara, California, USA, kmorell@ucsb.edu; REGALLA, C., Boston University, Massachusetts, USA, cregalla@bu.edu; HARRICHHAUSEN, N., University of California, Santa Barbara, California, USA, nharrichhausen@gmail.com; ELLIOTT, J., Purdue University, Indiana, USA, julieelliott@purdue.edu; JIANG, Y., Natural Resources Canada, Sidney, Canada, yan.jiang@canada.ca; AMOS, C., Western Washington University, Washington, USA, colin.amos@wwu.edu; LYNCH, E., Boston University, Massachusetts, USA, emlynch2@bu.edu

The Leech River fault zone on southern Vancouver Island, British Columbia, which initially formed as a terrane-bounding fault during the Eocene accretion of the Crescent-Siletz terrane, has recently been identified as a Holocene-active structure that has produced at least three surface-rupturing earthquakes within the last 9 kyr. The proximity of the Leech River and adjacent faults to populated areas in SW British Columbia and NW Washington necessitates an updated assessment of their seismic (and tsunami) hazard. This requires characterization of potential rupture area, sense and magnitude of slip, and earthquake recurrence. Here we contribute constraints from several methods. Identification of brittle fault segments cutting bedrock and Quaternary deposits has been enabled by lidar and field mapping, along with imaging of the shallow subsurface via electrical resistivity tomography and ground penetrating radar, confirming disturbance along near-vertical zones underlying topographic lineaments. Paleoseismic trenching across some of these lineaments has yielded preliminary estimates of fault slip. Establishment of a new Global Navigation Satellite System network across SE Vancouver Island with an average inter-station spacing of ~4 km will provide additional constraints on the character and rate of slip on the Leech River and adjacent active faults. This network comprises 4 existing continuous stations and 21 campaign sites, 6 of which were previously surveyed in the 1990s and 15 were first occupied in August 2018. Repeated surveys are planned once every 1-2 years, to determine relative crustal motions across the study area, providing constraints on slip rates and on the extent of fault locking. Several years of data collection will be required in order to reduce the influence of megathrust processes (particularly Episodic Tremor and Slip events) on the relative site velocities and enable determination of strain accumulation on the crustal faults.

An Earthquake Nest in Cascadia

MERRILL, R., University of British Columbia, Vancouver, Canada, rmerrill@eoas.ubc.ca; BOSTOCK, M. G., University of British Columbia, Vancouver, Canada, bostock@eos.ubc.ca

A cluster of temporally persistent seismicity ($M_L < 3.2$) at > 60 kilometres depth below the Georgia Strait in southern British Columbia is investigated using data for the period 1985 to 2018. This isolated concentration of intermediate-depth intraslab earthquakes appears to be unique in Cascadia and meets the criteria of an earthquake nest. 129 relocated hypocenters elucidate two northwestward dipping structures likely within the subducting Juan de Fuca mantle within a ~30x10x14 km 3 volume. Focal mechanisms for 15 well recorded events represent a mixture of strike-slip and reverse faulting, and a stress regime approximating down-dip tension and plate-normal compression, consistent with previous stress inversions of regional intraplate seismicity. Dehydration embrittlement of antigorite is suspected as the primary agent of seismogenesis and is supported on several grounds. Converted seismic phases inferred to originate at the Juan de Fuca slab interface are observed at several seismic receivers and are consistent with a local slab depth of ~45 km, significantly shallower than recent JdF plate models. The source region displays an azimuthally variable V_P/V_S ratio that is best explained by a highly anisotropic source volume resulting from preferred orientation of minerals and/or organized fluid filled porosity. Finally, the nest is located within the extrapolated bounds of a propagator wake within the Juan de Fuca plate.

Seismic Risk Assessment for British Columbia, Accessible Via Web Portal

BIRD, A. L., Geological Survey of Canada, Sidney, Canada, alison.bird@canada.ca; JOURNEAY, J., Geological Survey of Canada, Vancouver, Canada, murray.journeay@canada.ca; HASTINGS, N., Geological Survey of Canada, Vancouver, Canada, nicky.hastings@canada.ca; CASSIDY, J. F., Geological Survey of Canada, Sidney, Canada, john.cassidy@canada.ca; WAGNER, C., Geological Survey of Canada, Sidney, Canada, carol.wagner@canada.ca

Natural Resources Canada (NRCan) has employed Global Earthquake Model's (GEM) *OpenQuake* engine to undertake a national-scale earthquake risk assessment, which began with a provincially-focussed evaluation of British Columbia (BC), the most seismically hazardous region of the country. The assessment includes an implementation of the probabilistic seismic hazard model derived for the most recent National Building Code of Canada, and the development of deterministic seismic hazard models representing a range of potentially damaging earthquake scenarios along BC's coastline and some interior regions. Anticipated ground motions were combined with vulnerability data, including site conditions, buildings and infrastructure, and population.

Given that comprehensive assessments are invaluable for effective emergency planning, focussed risk mitigation measures, and disaster management, the results will be available via a web portal. The portal will be demonstrated though a selection of deterministic scenarios, including a megathrust earthquake of M~9.0 along the Cascadia Subduction Zone, a M~7.1 crustal earthquake adjacent to the City of Victoria's waterfront, a M~7.0 off Haida Gwaii, and a deep M~6.8 beneath the Strait of Georgia just west of the City of Vancouver. This work is supporting Canada's efforts toward meeting the recommendations within the Sendai Framework developed by the United Nations Office for Disaster Risk Reduction.

Mapping Coda Q Across Western Canada: From an Active Subduction Zone to a Stable Craton

FARAHBOD, A., Consultant, Vancouver, Canada, mansour_farahbod@yahoo.com; CASSIDY, J. F., Natural Resources Canada, Victoria, Canada, john.cassidy@canada.ca

In this study we investigate the spatial variation in coda-wave attenuation (QC) across western Canada, covering a wide range of tectonic settings – from a seismically active subduction zone in the west, through a volcanic belt, to the stable craton of North America – a region of slow lithospheric deformation in the east. Our dataset is made up of more than 2500 earthquakes recorded at 85 Canadian seismic stations across the region. We employ the single back scattering approximation with a range of ellipse parameter (a2) from 20 km to 100 km. We find a very clear attenuation pattern across the study area. The lowest Q0 (Q at 1 HZ) values (*e.g.*, Q0 of 39, a2=33 km) are in the vicinity of Nazko Cone in the Anahim volcanic Belt (AVB), the highest Q0 values (*e.g.*, Q0 of 165, a2=90 km) are on the stable craton, and intermediate values of Q0 are determined across the Cascadia subduction zone. Our results showing low Q0 throughout the AVB provides additional support for an interpretation of magma injection into the lower crust during the 2007 Nazko earthquake swarm, fracturing of the crust, and resulting high seismic attenuation. Also, low Q0 estimates in the Horn River basin and Montney Basin can be partially attributed to Hydraulic fracture related seismicity. Within the subduction zone, Q0 is lowest closest to the active faults off the coast and in the vicinity of the only known large crustal earthquakes (1918, M~7 and 1946, M~7.3) on Vancouver Island, and Q0 increases moving inland. The highest Q0 values we determine are in the regions of slow lithospheric deformation.

Slip and Strain Accumulation Along the Sadie Creek Fault, Northern Olympic Mountains, WA

DUCKWORTH, W. C., Western Washington University, Washington, USA, duckwow@wwu.edu; AMOS, C., Western Washington University, Washington, USA, colin.amos@wwu.edu; SCHERMER, E. R., Western Washington University, Washington, USA, liz.schermer@wwu.edu; LOVELESS, J. P., Smith College, Massachusetts, USA, jloveles@smith.edu; RITTENOUR, T. M., Utah State University, Utah, USA, tammy.rittenour@usu.edu; PEREZ, Y. E., Western Washington University, Washington, USA, ysabel.e.perez@gmail.com

Upper-plate faulting in the Olympic Peninsula of Washington State reflects the interaction of crustal blocks within the Cascadia forearc, as well as poorly constrained contributions from various earthquake cycle processes along the Cascadia subduction zone (CSZ), including interseismic coupling, megathrust earthquakes, and aseismic slow slip events. In this study we utilize high resolution airborne lidar, optically stimulated luminescence (OSL) dating, ^{14}C dating, and field mapping of deformed surficial deposits and landforms to reconstruct fault slip rates since Late Pleistocene deglaciation on the recently discovered active Sadie Creek fault (SCF), located north of the Olympic Mountains. Our mapping shows the SCF is a ~14 km-long NW striking, subvertical, dextral fault with a subordinate dip slip component that connects with the longer Lake Creek Boundary Creek fault (LCBCF) beneath Lake Crescent. Field and lidar measurements of 48 scarp profiles and 11 laterally offset stream channels indicate cumulative slip on Late Pleistocene and younger surfaces varies along strike with vertical slip ranging from 1-6 m (average of 3.5 m) and cumulative dextral slip ranging from 6-26 m (average of 14.8 m). Recent work on the adjacent LCBCF presented a slightly higher range of cumulative dextral slip (11-28 m) and lower range of cumulative vertical slip (1-2m) suggesting that slip on the SCF may be more oblique than on the LCBCF. Preliminary ^{14}C ages of deposits within offset stream channels suggest a slip rate of 1-2 mm/yr on the SCF since deglaciation (~13-15ka) and will be refined with pending OSL and ^{14}C dates of other offset deposits. We will compare millennial slip rates to a geodetically-constrained boundary element method model which estimates the stress on the SCF and LCBCF as a result of different shorter-term (decadal) earthquake cycle processes on the CSZ. Taken together, our results will provide insight into how strain from the CSZ persists over multiple timescales on upper plate faults.

Connectivity of Holocene Fault Network Between the Southern Olympic Mountains and the Puget Lowland

BENNETT, S. E. K., U.S. Geological Survey, California, USA, sekbennett@usgs.gov; SCHARER, K., U.S. Geological Survey, California, USA, kscharer@usgs.gov; DELANO, J., U.S. Geological Survey, Colorado, USA, jdelano@usgs.gov

The extent and connectivity of crustal faults in the forearc of the Cascadia subduction zone is poorly understood due to limited paleoseismic and lidar data and surface processes such as recent glaciation, dense vegetation, and rapid erosion that obscure the geomorphic record. Documenting the extent and rupture histories of forearc faults and understanding how earthquake-related stress changes affect nearby structures, however, are crucial to characterizing seismic hazards in the region. Fault studies in western Washington have helped identify and map a Holocene-active, sub-vertical fault network that trends ENE from north of Grays Harbor (Canyon River fault-CRF) and along the southeast flank of the Olympic Mountains (Frigid Creek fault-FCF and Saddle Mountain fault zone-SMFZ), and trends eastward into the Puget Lowland along the south-dipping Seattle fault zone (SFZ). Geomorphic mapping indicates the CRF may be up to 60 km-long and recent trench results on the western CRF indicate it has displaced Holocene fluvial deposits during one or two left-lateral oblique earthquakes. New OxCal age modeling of these radiocarbon data constrains the most recent earthquake on the western CRF to ~4500 cal. yr BP. We integrate this mid-Holocene earthquake with timing information for younger (mid- to late-Holocene), left-lateral earthquakes farther east within this fault network (central CRF, FCF, SMFZ) and the youngest and easternmost earthquake on the adjacent north-vergent SFZ. Per-event vertical deformation on these faults ranges from ~2–8 m, suggesting significant modification to the static stress field. We use Coulomb stress-transfer modeling to evaluate how different ruptures may interact, particularly where paleoseismic data are insufficient to discriminate between or correlate events with large, overlapping uncertainties. These results further support a model that the Canyon River, Frigid Creek, Saddle Mountain, and Seattle faults comprise a kinematically-linked, ~150 km-long fault network that actively accommodates N-S shortening above the Cascadia subduction zone.

Shallow Offshore Deformation in the Seattle Fault Zone: Insights From High Resolution Seismic Reflection Imagery

MOORE, G. L., University of Washington, Washington, USA, ginevra@uw.edu; ROLAND, E., University of Washington, Washington, USA, eroland@uw.edu; BENNETT, S. E. K., U.S. Geological Survey, California, USA, sekbennett@usgs.gov; WATT, J., U.S. Geological Survey, California, USA, jwatt@usgs.gov; KLUESNER, J., U.S. Geological Survey, California, USA, jkluesner@usgs.gov; BROTHERS, D. S., U.S. Geological Survey, California, USA, dbrothers@usgs.gov

The Seattle fault zone (SFZ) is an east-west striking, north-vergent thrust fault system that is located beneath the greater Seattle area. In A.D. 900-930, a M 7.0-7.5 earthquake ruptured a blind, south dipping thrust fault in the SFZ, resulting in surface folding that produced up to 8 meters of land level changes, a local tsunami, and probable concurrent surface rupture on north dipping back-thrusts in the SFZ hanging wall. Over the last few decades, kilometer-scale geophysical datasets, lidar topography, and paleoseismology studies have been used to constrain the onshore SFZ geometry, and to develop several regional structural models to explain the connectivity and kinematics of the SFZ at depth. However, current models lack information from offshore studies of the shallow subsurface.

In 2017, a high-resolution seismic reflection dataset of the SFZ was acquired in the Puget Sound and Lake Washington, consisting of multichannel reflection profiles from boomer and sparker sources with collocated chirp imagery. Here, we present interpretations of this new multi-resolution seismic dataset that resolve lithologic discontinuities in the upper 300 meters of the subsurface. We integrate our offshore seismic interpretations with a geomorphic analysis of both new and existing bathymetric datasets, along with published observations of shoreline elevation changes associated with the A.D. 900-930 event. Through these efforts we find: 1) evidence that onshore scarps continue in offshore seismic sections, 2) shallow deformation features that coincide with the near-surface locations of previously identified crustal-scale structures, and 3) expressions of folding and vertical displacement of inferred Quaternary and Oligocene deposits, providing a strategy to assess the amplitude and relative timing of deformation on these structures.

The Gales Creek Fault – Active Northward Migration of an Oregon Forearc Sliver

WELLS, R. E., Portland State University, Oregon, USA, rwells@pdx.edu; BLAKELY, R. J., U.S. Geological Survey, California, USA, blakely@usgs.gov; REDWINE, J., U.S. Bureau of Reclamation, Colorado, USA, jredwine@usbr.gov; BEMIS, S., Virginia Tech, Virginia, USA, sbemis@vt.edu

New geologic mapping, geophysical surveys, and paleoseismic trenching show the Gales Creek fault (GCF) west of Portland to be part of an active, right lateral fault system that accommodates northward motion and uplift of the Oregon Coast Range. Aeromagnetic and geologic mapping of the GCF document about 12 km of dextral offset of an anticline in Eocene Siletz River Volcanics basement (Siletzia) since about 35 Ma, and about 6 km of right lateral separation of tilted flows of the Columbia River Basalt Group at Newberg, Oregon, since 15 Ma (~0.4 mm/yr, average long-term rate). Vertical offset across the GCF is at least 5 km based on depth to Siletzia basement under the Tualatin basin from a recent inversion of gravity data. Crustal models based on gravity and magnetic anomalies suggest a shallow popup structure along the fault and Siletzia basaltic basement on both sides. Five km west of the city of Forest Grove, the fault consists of two, subparallel, NW-striking strands, spaced ~3 km apart. Seismic-reflection data suggest the eastern Gales Creek strand may link southward to the E-W-striking Beaverton fault in the Tualatin basin. The Beaverton fault, in turn, links eastward to the right lateral Canby fault, thus forming a 30 km-wide compressive stepover that uplifts the Chehalem Mountains. Aeromagnetic data indicate the western strand links southward to the Mount Angel fault, the apparent source of the 1993 M 5.7 Scotts Mills earthquake. Recent deformation is indicated by LiDAR data which reveal 6 major (up to 1.5 km) right-lateral stream offsets, scarps, and other youthful geomorphic features for 60 km along the trace of the GCF north of Newberg, Oregon. Near Yamhill, Oregon, paleoseismic trenches document Eocene bedrock thrust over 250 ka surficial deposits along a splay of the fault system. Multiple late Pleistocene and Holocene earthquakes have been documented by the Bureau of Reclamation on the GCF south and west of Forest Grove, Oregon. This is the first direct geologic evidence in Oregon of large scale, northward motion of the Coast Range.

Crustal Deformation Near the Mendocino Triple Junction Inferred From GPS-Derived Strain Rate Maps

NUYEN, C., University of Washington, Washington, USA, cnuyen@uw.edu; SCHMIDT, D. A., University of Washington, Washington, USA, dasc@uw.edu; CROWELL, B. W., University of Washington, Washington, USA, crowellb@uw.edu

Crustal deformation in southernmost Cascadia represents the confluence of transpressive and convergent tectonics around the Mendocino Triple Junction (MTJ), which defines the intersection of the North American, Gorda, and Pacific plates. The transition between these major systems is achieved in part by faulting and deformation along the North American plate boundary, as well as large-scale rotation of the crust in southern Cascadia. However, the spatiotemporal history of deformation around the MTJ is poorly resolved due to previously sparse instrument coverage. Fortunately, GPS instrumentation in this area has increased significantly over the past decade, providing improved resolution on long enough time series to discern and refine steady strain rates. This work uses GPS data to investigate horizontal strain rates in southern Cascadia. To achieve this, we generate regional strain rate maps from horizontal GPS time series data collected over the past decade. We use multiple methods to clean the time series, including applying a monthly moving average, removing offsets from earthquakes and common mode signals, and employing a seasonal decomposition technique. We examine strain rate maps spanning from 2007-2017 to explore the heterogeneity of strain and correlation with quaternary fault zones around the MTJ. Our results indicate that strain rates change across the MTJ from north to south, with compressional signals to the north and extensional signals to the south. We observe high maximum shear strain rates broadly across the San Andreas fault system, indicating that strain is distributed across multiple major fault strands. Lastly, we observe a band of high maximum shear strain rates north of the MTJ around the vicinity of the Mad River fault zone. We examine the interseismic slip rates in this region to gain insight into the seismic hazards associated with these faults.

Geodetic and Geologic Observations Along the Southern Cascadia Subduction Zone: Implications for Strain Accumulation in the North America Plate – the Lahsāséte Fault

PATTON, J. R., Humboldt State University, California, USA, jrp2@humboldt.edu; LEROY, T. H., Pacific Watershed Associates, California, USA, toml@pacificwatershed.com; WILLIAMS, T. B., Cascadia GeoSciences, California, USA, todd.brian.williams@gmail.com; HEMPHILL-HALEY, M., Humboldt State University, California, USA, mark.hemphill-haley@humboldt.edu; MCPHERSON, R. C., Humboldt State University, California, USA, robert.mcpherson@humboldt.edu

Geodetic evidence for tectonic deformation in northern California associated with the overlapping Cascadia megathrust and northern San Andreas fault informs us of a direct impact upon local sea level rise and seismic hazard.

We analyse 3 independent geodetic data sets (tide gage, benchmark survey, GPS) to document 20^{th} to 21^{st} century rates of vertical land motion (VLM) along coastal northern California. VLM rates, corrected for glacial isostatic adjustment, range from about -5 mm/yr in southern Humboldt Bay to +2 mm/yr near Crescent City in the north. An East-West trending variation in VLM is primarily due to Cascadia subduction zone plate tectonics

We associate a second order heterogeneous North-South trend in VLM to crustal fault related strain. Discrete changes in VLM rates are localized to 5 known (and 2 previously unknown) Quaternary active crustal [MHH1] [JRP2] faults. We use these offsets to derive vertical separation and slip rates for these faults.

The faults we calculate vertical separation rates for include the newly described Lahsāséte fault 1.2-1.9 mm/yr, Table Bluff fault 3 mm/yr, Little Salmon fault 1.9-2.1 mm/yr, a newly described Eureka fault 1.3-1.6 mm/yr, Fickle Hill fault 1.3-1.6 mm/y, Trinidad fault 1.2-2.4 mm/yr, and Big Lagoon – Bald Mountain fault system 0.6-1.2 mm/yr.

The geodetic location of the Lahsāséte fault led to our discovery of a south facing topographic scarp crossing Quaternary fluvial terraces along the Eel River at Shively, CA with increasing scarp heights on progressively older terraces.

Using regional incision rates we estimate the terrace ages based on relative elevation. We use LiDAR measured scarp heights to derive a mean late Quaternary slip rate of about 0.35 mm/yr.

The Lahsāséte fault may be the southernmost expression of the south vergent imbricate thrust system related to the onshore portion of the Cascadia subduction zone. Alternatively, this structure may be evidence that the Russ fault may be a south vergent thrust fault, placing younger Yager Terrane stratigraphically above Franciscan Fm.

Quaternary Faults and Folds of the Northern Sacramento Valley: Accommodating Transpressional Strain in the Northern Sierra and Southern Cascadia Transition Zone

ANGSTER, S., U.S. Geological Survey, Washington, USA, sangster@usgs.gov; WESNOUSKY, S. G., University of Nevada Reno, Nevada, USA, wesnousky@unr.edu; FIGUEIRDO, P., University of Cincinatti, Ohio, USA, paulamfigueiredo@gmail.com; OWEN, L. A., University of Cincinatti, Ohio, USA, owenls@ucmail.uc.edu; SAWYER, T., Piedmont Geosciences, Nevada, USA, tom.sawyer.piedmont@gmail.com

The northern Sacramento Valley is located at the transition between the Sierra Nevada and Cascadia tectonic provinces where geodesy and seismology show crustal deformation is characterized by northwest oriented transpressional shear. The location and rate of individual structures taking up the deformation remains unconstrained. We map geologic structure in the subsurface and at the surface, construct fluvial terrace profiles, and date deformed Quaternary landforms in the northern Sacramento Valley to assess the evidence, style, and rate of Quaternary deformation for a series of previously identified northeast trending faults and folds within the zone of deformation including: 1) the Red Bluff fault, 2) the Inks Creek fold system, 3) the Battle Creek fault zone, and 4) the Bear Creek fault. Geophysical datasets, including a magnetic anomaly map and vintage 2-D seismic reflection profiles, suggest the Red Bluff and Bear Creek faults are deep-seated north-dipping reverse faults that displace and fold shallow strata above, while the Battle Creek is a long-lived south-dipping inverted Cretaceous normal fault. Topographic surface profiles extracted from a 10-meter DEM show each fault and fold to generally display north-side-up displacement and warp early to mid-

Quaternary deposits. Longitudinal fluvial terrace profiles constructed from lidar along the Sacramento River show that deformed late Pleistocene fluvial terraces are associated with windgaps and abandoned channel features where the river traverses the Inks Creek fold system and Red Bluff fault. The sum of the observations provide evidence for late Quaternary contractional strain accommodation within the northern Sacramento Valley; however, evidence of lateral motion remains less apparent within the geomorphology. These faults mark the southern-most extent of the northern Sierra and southern Cascadia transition zone. Pending radiocarbon and optically stimulated luminescence analysis of samples collected from the deformed fluvial terraces will help constrain long-term rates of deformation.

A Kinematic Model of Offshore Strike-Slip Faults in the Cascadia Accretionary Prism

SCHMIDT, D. A., University of Washington, Washington, USA, dasc@uw.edu

The Juan de Fuca oceanic plate subducts obliquely relative to the trench offshore Oregon and Washington at a rate of ~4 cm/yr relative to North America. At the same time, the Oregon and SW Washington forearc translate northward as part of regional rotation. The net motion between the downgoing plate and the forearc is largely convergent, but a small component of obliquity remains. Unlike other subduction systems were slip partitioning is observed, there is no evidence of partitioning along large trench-parallel strike-slip faults in the terrestrial forearc of Cascadia. Therefore, trench-parallel deformation must be accommodated on oblique structures in the offshore prism and forearc. Bathymetric and seismic reflection surveys have identified up to nine vertical faults that cut obliquely across the accretionary prism. These left-lateral structures, which extend from the deformation front to the edge of the continental shelf and may continue into the forearc, are believed to accommodate the trench-parallel deformation. However, little is known about these faults. In this work, I reevaluate these offshore structures given new kinematic constraints from plate motions and forearc rotation. A three-dimensional elastic model of the Cascadian forearc and prism is constructed in Poly3D with a realistic geometry. The appropriate kinematic boundary conditions are applied such that forearc motion agrees with terrestrial GPS velocities, as well as updated estimates of Juan de Fuca plate motion. Stress-free boundary conditions are assigned to these shallow strike-slip faults to infer long-term slip rates that are consistent with regional driving forces. The model predicts slip rates to be 3-6 mm/yr, which is slightly smaller than what has been inferred from geological constraints. This model can also be used to estimate how oblique convergence is partitioned between strike-slip faults, forearc rotation, and slip obliquity on the megathrust across the margin.

Does Subslab Buoyancy Govern Segmentation of Cascadia's Forearc Topography?

BODMER, M., University of Oregon, Oregon, USA, mbodmer@uoregon.edu; TOOMEY, D., University of Oregon, Oregon, USA, drt@uoregon.edu; ROERING, J. J., University of Oregon, Oregon, USA, jroering@uoregon.edu; KARLSTROM, L., University of Oregon, Oregon, USA, leif@uoregon.edu

Cascadia's forearc topography varies systematically along-strike with the high-standing Olympic and Klamath mountains separated by the relatively low-standing Oregon Coast range. This topographic variability reflects long-term patterns of surface uplift and erosion, however, the underlying drivers of uplift and the mechanisms supporting present day topography are unclear. Here, we synthesize results from seismic imaging, observations of vertical deformation, and characteristics of the megathrust interface to infer that buoyancy in the subslab asthenosphere influences the development and stability of Cascadia forearc topography. Northern and southern segments of Cascadia are characterized by rapid short- and long-term uplift rates, rapid erosion rates, shallower slab dip angles, and increased plate locking compared to the central segment. Similarly, tomographic images of the subslab asthenosphere show segmented low-velocity anomalies beneath northern and southern Cascadia. These low-velocity anomalies reflect localized upwellings and regions of excess buoyancy due to partial melt and possibly elevated temperatures. We propose that buoyant regions influence the integrated shear force at the megathrust by either shallowing slab dip or increasing strength of the megathrust. Either or both scenarios will locally increase the integrated shear force in the seismogenic zone, which has implications for long-term topographic development and the force balance sustaining high elevations. Because interseismic uplift, long-term uplift and erosion, and topography exhibit similar increases north and south, we infer that unrecovered interseismic strain leads to long-term deformation. Using inferred values for slab dip and plate coupling we predict first-order variations in Cascadia forearc topography. Our analysis suggests that lateral support for topography in Cascadia may be due to variations in the net shear force at the megathrust interface. Variations in subslab buoyancy may be critical to explaining forearc highs in this and other subduction systems.

Offshore Subduction Zone Structure and Seismicity Along Pacific Northwest: From the Gorda Plate to the Queen Charlotte Fault

Oral Session · Wednesday · 4:15 PM · 24 April · Puget Sound

Session Chairs: Pascal Audet, Mladen Nedimovic, Emily Roland, Shuoshuo Han, Suzanne Carbotte.

Constraints on Juan De Fuca Plate Hydration From Controlled-Source Wide-Angle Seismic Studies

CANALES, J., Woods Hole Oceanographic Institution, Massachusetts, USA, jpcanales@whoi.edu; BOULAHANIS, B., Lamont-Doherty Earth Observatory, New York, USA, bridgitb@ldeo.columbia.edu; CARBOTTE, S. M., Lamont-Doherty Earth Observatory, New York, USA, carbotte@ldeo.columbia.edu; NEDIMOVIĆ, M., Dalhousie University, Halifax, Canada, mladen@dal.ca

Quantifying hydration of oceanic lithosphere entering subduction zones is critical for understanding the range of subduction phenomena governed by dehydration of down-going slabs. Yet a comprehensive quantification of water content of incoming plate for any segment of the global subduction system is lacking, and how water is stored and distributed at depth within incoming plates, and how this hydration state is linked to various subduction zone processes, is debated. Here we use controlled-source wide-angle seismic reflection/refraction data collected in 2012 across the Juan de Fuca plate and along the central Cascadia margin seaward from the deformation front to estimate both pore and structurally bound water content and their distribution from the overlying sediments to the upper mantle of the Juan de Fuca plate entering the central Cascadia subduction zone. We find that the Juan de Fuca lower crust and mantle are drier than at any other subducting plate, with most of the water stored in the sediments and upper crust. Variable but limited bend faulting along the margin limits slab access to water, and a warm thermal structure resulting from a thick sediment cover and young plate age prevents significant serpentinization of the mantle. The dryness of the lower crust and mantle indicates that fluids that facilitate episodic tremor and slip must be sourced from the subducted upper crust, and that decompression rather than hydrous melting may dominate arc magmatism in central Cascadia. Additionally, dry subducted lower crust and mantle can explain the low levels of intermediate-depth seismicity in the Juan de Fuca slab beneath this portion of the Cascadia margin.

The Evolution of the Hydration State of the Juan De Fuca Plate From Ridge to Trench Offshore Washington State

BOULAHANIS, B., Lamont-Doherty Earth Observatory, New York, USA, bridgitb@ldeo.columbia.edu; CANALES, J., Woods Hole Oceanographic Institution, Massachusetts, USA, jpcanales@whoi.edu; CARBOTTE, S. M., Lamont-Doherty Earth Observatory, New York, USA, carbotte@ldeo.columbia.edu; CARTON, H., Institut de Physique Du Globe de Paris, Paris, France, carton@ipgp.fr; HAN, S., University of Texas Institute for Geophysics, Texas, USA, han@ig.utexas.edu; NEDIMOVIĆ, M., Dalhousie University, Halifax, Canada, mladen@dal.ca

Characterizing the evolution, hydration state, and extent of faulting on the Juan de Fuca (JdF) plate is an essential component of understanding the structure and convergent tectonics of Cascadia subduction zone. We present results from a 2D tomography study of the JdF plate from east of the ridge axis to the Cascadia subduction zone offshore Washington. We compare our results with a transect across the southern JdF plate from Axial Volcano to offshore Oregon (Horning *et al.*, 2016), facilitating a regional assessment of the velocity structure in the crust and shallow mantle. Velocity models are compared to predicted velocities for crustal and upper mantle lithologies at temperatures estimated from a plate-cooling model and used to provide constraints on water contents in these layers. Co-location of velocity models with multi-channel seismic reflection images (Han *et al.*, 2016), allows for comparison of the relationship between velocities and crustal structure.

Results show upper crustal velocities consistently less than predicted, indicating a fractured and hydrated upper crust. Lower crust and uppermost mantle velocities are similar to predicted values for all plate ages, suggesting a lack of significant lower crust and upper mantle fracturing or hydration. The Washington Transect shows a modest decrease in velocities approaching the deformation front, where crustal faults are few and confined to the upper crust, indicating little fracturing and hydration due to subduction bend faulting, in contrast to observations on the Oregon Transect. Washington and Oregon Transects show distinct crustal structure and velocity regimes at comparable plate ages: increased crustal velocities at 6-8 Ma, decreased velocities coincident with a zone of rough basement topography at 4-6 Ma, and higher velocities and smooth basement crust at 1-4 Ma. Distribution of crustal types across JdF plate suggests differing potential for hydration within the plate inherited from ridge processes.

Three-Dimensional Variations of the Slab Geometry Correlate With Earthquake Distributions at the Cascadia Subduction System

GAO, H., University of Massachusetts Amherst, Massachusetts, USA, haiyinggao@geo.umass.edu

Significant along-strike variations of seismicity are observed at subduction zones, which are strongly influenced by physical properties of the plate interface and rheology of the crust and mantle lithosphere. However, the role of the oceanic side of the plate boundary on seismicity is poorly understood due to the lack of offshore instrumentations. Here tomographic results of the Cascadia subduction system, resolved with full-wave ambient noise simulation and inversion by integrating dense offshore and onshore seismic datasets, show significant variations of the oceanic lithosphere along strike and down dip from spreading centers to subduction. In central Cascadia, where seismicity is sparse, the slab is imaged as a large-scale low-velocity feature near the trench, which is attributed to a highly hydrated and strained oceanic lithosphere underlain by a layer of melts or fluids. The strong correlation suggests that the properties of the incoming oceanic plate play a significant role on seismicity.

Plate Deformation at Cascadia's Northern Terminus

BOSTOCK, M. G., University of British Columbia, Vancouver, Canada, bostock@eos.ubc.ca; SAVARD, G., University of Calgary, Calgary, Canada, gen.svrd@gmail.com; HUTCHINSON, J., University of Victoria, Victoria, Canada, hutchij@uvic.ca; KAO, H., Geological Survey of Canada, Sidney, Canada, honn.kao@canada.ca; CHRISTENSEN, N. I., University of British Columbia, Vancouver, Canada, nchriste@wisc.edu

The Juan de Fuca (JDF) plate system, a vestige of the former Farallon plate, is breaking apart as a result of resistance to subduction. At its northern end, the Explorer plate moves independently of the JDF plate along the Nootka Fault Zone (NFZ) which forms an unstable triple junction with the JDF ridge and the Sovanco Fracture Zone. We examine the evolution of the NFZ from ocean basin to Vancouver Island using double difference tomography and earthquake relocation. Two independent inversions were undertaken: one focused on seismicity and structure along the NFZ near the deformation front using OBS recordings from the SeaJade1 experiment, and a second landward study employing permanent CNSN stations and data from portable POLARIS and SeaJade2 experiments. A margin-perpendicular seismicity profile extending landward from the offshore NFZ reveals a strong bend in the subducting lithosphere, comparable to but shorter wavelength (50 vs 150 km) than a similar structure at Cascadia's southern terminus by the Mendocino triple junction. The NFZ near the deformation front exhibits low-magnitude seismicity that extends well into oceanic mantle with low Vp/Vs (<1.7) values. This anomaly, continuous across both velocity models, extends to the NE below Vancouver Island with a more northerly trajectory than a linear subsurface extrapolation of the NFZ through the seismicity concentration off Nootka Island. We propose a model for the landward evolution of the NFZ that includes an increasingly oblique and extended zone of mechanically compromised oceanic plate that lies between seismicity concentrations at Nootka Island and Brooks Peninsula. This model is supported by independent constraints on the NW limit of the JDF plate afforded by LFEs and receiver functions. Accordingly, the Nootka Island and Brooks peninsula seismicity concentrations are ascribed to stress concentrations on either side of the NFZ associated with deformation at the edges of more competent JDF and Explorer plates.

Cross-Correlation Beamforming for Simultaneous Event Detection and Location in Conjunction With Logistic Regression for Event Discrimination

MOSHER, S. G., University of Ottawa, Ottawa, Canada, stephenmosher@gmail.com; AUDET, P., University of Ottawa, Ottawa, Canada, paudet.uottawa@gmail.com

Seismic event detection, location, and characterization (DLC) problems are fundamental problems in seismology, given that to study subsequent seismological questions, one or more of these elements needs to have been addressed first. Thus, improving DLC algorithms has been a major research focus in seismology over the past several decades. Recently, earthquake DLC algorithms involving the use of machine learning have been shown in many cases to be particularly effective tools at DLC related tasks, often surpassing methods from the previous generation.

In this study we combine cross-correlation beamforming, which allows us to simultaneously detect and locate seismic events, with logistic regression, a supervised machine learning algorithm that allows us to discriminate between different types of events such as earthquakes and tremors. A significant advantage to combining these methods is that the results of cross-correlation beamforming can be directly used to generate meaningful features for logistic regression. We apply this combined methodology to data recorded by networks of seismometers located along the Cascadia subduction zone. Using several high quality earthquake and tremor catalogs available for this region, we assess the robustness of our detections and locations, as well as our ability to automatically distinguish different event types from one another. In addition to the features generated by the cross-correlation beamforming results, we further explore those features that allow our algorithm to discriminate between different seismic events.

Advances in Intraplate Earthquake Geology

Oral Session · Wednesday · 8:30 AM · 24 April · Vashon
Session Chairs: Christopher B. DuRoss, Mark Zellman, Stephen Angster.

What Controls the Maximum Magnitude of Continental Normal Faulting Earthquakes?

NEELY, J. S., Northwestern University, Illinois, USA, james@earth.northwestern.edu; STEIN, S., Northwestern University, Illinois, USA, s-stein@northwestern.edu

Effective seismic hazard estimation requires assuming a potential earthquake's maximum magnitude (Mmax). Tectonic setting and faulting geometry play a key role in influencing an earthquake's potential size. In shallow (< 40 km), continental environments, the largest normal faulting earthquakes are approximately one magnitude unit smaller than strike-slip and reverse faulting earthquakes. The mechanisms causing this magnitude discrepancy, however, are unresolved. In this study, we examine why the largest normal fault earthquakes are smaller than other types of earthquakes in similar shallow continental environments.

A review of the Global Centroid Moment Tensor (GCMT) catalog for continental earthquakes reveals that normal fault earthquakes have an Mmax of M_w 7.1 whereas the largest strike-slip and thrust fault earthquakes reach ~M_w 8. The GCMT catalog indicates remarkable similarity in normal fault earthquake Mmax in a variety of extensional environments. Using simulated earthquake histories, generated with input parameters from the GCMT catalog's earthquake statistics, we find that that the lack of large normal fault earthquakes in the GCMT catalog is not likely due to the catalog's short length. These results suggest that differences in Mmax may reflect physical differences in faulting mechanics.

Since larger earthquakes generally have longer ruptures, fault length may be limiting Mmax. However, a review of global fault catalogs indicates that there are several normal faults in active extensional environments that are long enough to host M_w 7.5+ earthquakes. These results suggest that the observed Mmax differences may lie in the physics of the rupture process itself. We examine key earthquake parameters including moment tensor principal axes orientations and stress drops to explore why continental normal fault earthquakes have a smaller Mmax.

Towards Time-Dependent Modelling of Episodic Earthquake Occurrence on Intraplate Faults

GRIFFIN, J. D., University of Otago, Dunedin, New Zealand, jonathan.griffin@postgrad.otago.ac.nz; STIRLING, M. W., University of Otago, Dunedin, New Zealand, mark.stirling@otago.ac.nz; WANG, T., University of Otago, Dunedin, New Zealand, ting.wang@otago.ac.nz; CLARK, D., Geoscience Australia, Canberra, Australia, dan.clark@ga.gov.au

Increasing volumes of paleoseismological evidence suggest that the occurrence of large earthquakes on many, if not most, faults in low seismicity regions clusters in time. Faults appear to have a few large earthquakes within a relatively short period of time followed by long periods of quiescence. This contrasts with the assumption that earthquakes are Poisson distributed in time that typically underpins probabilistic seismic hazard assessment. Therefore a key challenge for hazard assessment for intraplate regions lies in describing the underlying temporal distribution of earthquake occurrence on such faults. In this study, relationships between clustering behaviour and the long-term deformation rate are explored using a global compilation of paleoseismic data from low-seismicity regions. Preliminary results suggest that clustering scales with the long-term deformation rate, such that faults with slower long-term slip rates have longer quiescent periods. The timing of the most recent earthquake gives information on the current state of the fault (active, quiescent or transitional) and can be used to make time-dependent estimates of the present day probability of a fault rupturing. However, predictive models are challenged by the limitations of paleoseismic records in intraplate regions. This includes uncertainty in resolving individual earthquakes in the record and dating uncertainties, which in turn contribute to uncertain and/or conflicting interpretations of the event chronology. In our present work we are using a Bayesian framework to test alternative time-dependent and independent distributions for earthquake inter-event times, with full consideration of the uncertainty inherent to paleoseismic chronologies.

Postglacial Paleoseismicity of the Teton Normal Fault Recorded by Lake Sediments in Grand Teton National Park, WY

LARSEN, D. J., Department of Geology, Occidental College, California, USA, dlarsen@oxy.edu; CRUMP, S. E., Geological Sciences and Institute of Arctic and Alpine Research, University of Colorado at Boulder, Colorado, USA, sarah.crump@colorado.edu; BLUMM, A., Department of Geology, Occidental College, California, USA, blumm@oxy.edu

Records of past earthquake occurrence are important for developing accurate seismic hazard assessments and for understanding temporal changes in fault behavior. However, in many tectonically active environments, few reliable geologic archives exist, and the majority of paleoseismic records rely on trench excavations, which can be incomplete, discontinuous, and/or limited by dating uncertainties. The Teton fault, which cuts across Grand Teton National Park (GTNP), WY, has been identified by the USGS as one of the most hazardous faults in the western US. Past movement along this 70-km normal fault has created the iconic landscape of the Tetons, one of the youngest and most tectonically active mountain ranges in the Rockies. High seismicity in the surrounding region is associated with intraplate extension and modern activity of the nearby Yellowstone hotspot, but the Teton fault itself has been curiously quiescent during historic time, and little is known about its paleoseismic history. Here, we present a continuous 14,000-year reconstruction of past earthquake events at GTNP based on sediments preserved in prominent, glacially-excavated lake basins positioned directly along the Teton fault trace. Beginning immediately after deglaciation ~14 ka and until ~7.5 ka, a series of at least 7 major fault ruptures resulted in diagnostic turbidite deposits in the lakes at regular intervals of ~1000 years, followed by a period of prolonged inactivity. These observations are consistent with existing trench data and model simulations that suggest accelerated fault slip rates followed deglaciation of the Teton-Yellowstone region, as well as with geodetic monitoring data that indicate the Teton fault may be locked by ongoing Yellowstone hotspot dynamics. This presentation will place emphasis on lake sedimentary signatures of past seismic activity, methods of integrating geophysical tools with lake sediment core data, and the temporal relationship between regional deglaciation and fault activity.

Paleoseismic History and Slip Rate of the Teton Fault at the Buffalo Bowl Site

DUROSS, C. B., U.S. Geological Survey, Colorado, USA, cduross@usgs.gov; GOLD, R. D., U.S. Geological Survey, Colorado, USA, rgold@usgs.gov; BRIGGS, R. W., U.S. Geological Survey, Colorado, USA, rbriggs@usgs.gov; DELANO, J., U.S. Geological Survey, Colorado, USA, jdelano@usgs.gov; OSTENAA, D., Ostenaa Geologic, Colorado, USA, deano3geo@gmail.com; ZELLMAN, M., BGC Engineering, Colorado, USA, mzellman@bgcengineering.ca; CHOLEWINSKI, N., Lettis Consultants International, California, USA, nycw006@gmail.com; WITTKE, S., Wyoming Geological Survey, Wyoming, USA, seth.wittke@wyo.gov; MAHAN, S., U.S. Geological Survey, Colorado, USA, smahan@usgs.gov

The Teton normal fault spans the base of the Teton Range in northwestern Wyoming, within the northeastern Basin and Range Province. Despite geomorphic evidence of postglacial (latest Pleistocene to Holocene) surface ruptures, the paleoseismic history and slip rate of the fault remain only broadly constrained, contributing epistemic uncertainty to regional seismic hazard assessments. For example, previous work suggests that the fault's latest Pleistocene to early Holocene postglacial slip rate (~2 mm/yr) significantly exceeds a Holocene rate (~0.5 – 0.7 mm/yr) calculated using two paleoseismic ruptures. To address open questions about prehistoric rupture timing, recurrence, and fault slip rate, we excavated a trench on the southernmost part of the fault. The Buffalo Bowl site records ~6.3 m of displacement in early Holocene (~10.5-ka) alluvial-fan sediments, yielding the longest and most complete Teton fault paleoseismic record. We interpret three Holocene surface-faulting earthquakes (BB3 to BB1) based on three packages of scarp-derived colluvium that postdate the alluvial-fan units. Bayesian models of radiocarbon (n=29) and luminescence (n=17) ages constrain the timing of earthquakes to ~5 – 10 ka and provide the basis for inter-event recurrence estimates of ~1.7 – 2.9 kyr and a mean recurrence of ~2.3 kyr. The Buffalo Bowl record confirms a previously documented mid-Holocene (~5 ka) most recent rupture of the southern Teton fault and provides evidence for an additional early Holocene earthquake. Earthquakes BB3 – BB1 yield a Holocene closed-interval vertical slip rate of ~0.9 mm/yr, which is similar to a latest Pleistocene to mid-Holocene rate of ~1.1 mm/yr and latest Pleistocene to early Holocene rate of ~1.3 mm/yr that integrate the displacement of a deglacial surface at Granite Canyon (4 km north). Our results corroborate a late Holocene period of tectonic quiescence on the southern Teton fault, but do not support a significant slip rate change in the early Holocene.

Paleoseismic Investigation of the Levan and Fayette Segments of the Wasatch Fault Zone, Central Utah

MCDONALD, G. N., Utah Geological Survey, Utah, USA, gregmcdonald@utah.gov; HISCOCK, A. I., Utah Geological Survey, Utah, USA, adamhiscock@utah.gov; HYLLAND, M. D., Utah Geological Survey, Utah, USA, mikehylland@utah.gov; KLEBER, E., Utah Geological Survey, Utah, USA, ekleber@utah.gov

The east margin of the Basin and Range extensional province is defined by the Wasatch fault zone (WFZ), whose central segments have been trenched for decades. The Levan segment (LS) and Fayette segment (FS) in central Utah are the southern segments of the WFZ and have little paleoseismic data available. Presence of evaporites at depth and a large discrepancy between regional geologic and geodetic rates could implicate salt tectonics as a contributor to displacement on the LS and FS. The Utah Geological Survey in cooperation with the U.S. Geological Survey excavated paleoseismic trenches on the LS and FS to determine Holocene earthquake timing and investigate if any fault displacement may be attributed to salt tectonics. A trench on the LS across a 3-m high scarp showed evidence for 1 – 2 Holocene surface-faulting earthquake(s). A trench on the FS across a 1-m high scarp revealed evidence for a single post-Lake Bonneville surface-faulting earthquake. The LS trench showed ~2.6-m of vertical offset and a complex 4.4-m wide zone of tilted, overturned and sheared blocks of alluvial-fan strata suggesting strike slip and horizontal extension. A soil covered by scarp colluvium on the hanging wall provides evidence for the surface-faulting earthquake that created the deformation zone. Scarp-derived colluvium overlying soil developed on older colluvial wedge suggests a second, smaller displacement event. Well-defined stratigraphic and fault relationships exposed in the trench across the FS scarp indicate a single surface-faulting earthquake with ~1 m of vertical displacement. Preliminary dating results for the FS trench site indicate it ruptured at 5.4 ± 0.1 ka (2s). A single Holocene surface-faulting earthquake on the FS is consistent with an expected lower slip rate and longer recurrence interval at the southern end of the WFZ. The deformation exposed in both trenches is consistent with discrete, rapid, meter-scale displacements and indicative of seismogenic earthquakes.

Late Quaternary Slip Rates and Holocene Paleoearthquakes of the Eastern Yumu Shan Fault, Northeast Tibet: Implications for Kinematic Mechanism and Seismic Hazard

REN, J., Institute of Crustal Dynamics, China Earthquake Administration, Beijing, China, renjunjie@gmail.com; XU, X., Institute of Crustal Dynamics, China Earthquake Administration, Beijing, China, xiweixu@vip.sina.com; ZHANG, S., Institute of Crustal Dynamics, China Earthquake Administration, Beijing, China, zhangshimin@263.net; ZHAO, J., Institute of Crustal Dynamics, China Earthquake Administration, Beijing, China, zhjx1014@sina.com; DING, R., Institute of Crustal Dynamics, China Earthquake Administration, Beijing, China, reiding@hotmail.com

The Yumu Shan (YMS) fault zone locates at the front of northeastward expansion of the Tibetan Plateau, where it is characterized by actively growing fault-related folds and northeast-vergent thrusts or buried faults, accompanying with strong earthquakes. The YMS fault zone is expressed by arc-shaped fault line and can be divided into two segments: the northern and eastern YMS faults. Numerous studies indicated that the northern YMS fault is marked by left-lateral strike-slip with a reverse component and has two paleoearthquakes in the Holocene. But the studies on the eastern YMS fault were conducted in the nineties of the 20th century, and the limitation of dating and survey techniques led to a big uncertainty in fault slip rates and paleoseismological results. In addition, the kinematic mechanism of the arc-shaped YMS fault zone remains unknown. In this study, combined with the interpretation of high-resolution satellite imagery, real-time kinematic (RTK) GPS survey, optically stimulated luminescence (OSL) and Accelerator Mass Spectrometry (AMS) radiocarbon dating of deformed landforms and trenching, we study slip rates and paleoseismology along the eastern YMS fault. Our results show that its Late Quaternary vertical and horizontal slip rate is ~0.3-0.4 mm/yr and ~1.1±0.1 mm/yr, respectively. At its northwest tip, the fault becomes dominantly reverse with a vertical rate of ~0.4 mm/yr. Trenching studies indicate that two events rupture the eastern YMS fault occurring at 7.37-5.24 ka and 5.17-4.01 ka, respectively. The eastern YMS fault may behave synchronously or interact with the northern YMS fault. We propose that the arcuate structure under the perpendicular compression to the arch apex can explain the kinematic mechanism of the arch-shaped YMS fault zone.

Recent Paleoseismic and Tectonic Geomorphic Studies of the Meers Fault, Oklahoma Reveal Longer Rupture Lengths and More Surface Deforming Earthquakes in the Last 6,000 Years

STREIG, A. R., Portland State University, Oregon, USA, ashleystreig@gmail.com; BENNETT, S. E. K., U.S. Geological Survey, California, USA, sekbennett@usgs.gov; HORNSBY, K. T., Portland State University, Oregon, USA, kristoferhornsby@gmail.com; CHANG, J. C., U.S. Geological Survey, Hawaii Volcano Observatory, Hawaii, USA, jchang@usgs.gov; MAHAN, S., U.S. Geological Survey, Colorado, USA, smahan@usgs.gov

Characterizing the frequency of large earthquakes and rupture behavior (single versus multi-section rupture) for intraplate faults is critical to improve seismic hazard models for the Central and Eastern United States region. Earthquake frequency, co-seismic displacement, rupture area and length data are fundamental inputs for estimates of maximum earthquake magnitude and seismic hazard assessment. The Meers fault in southwestern Oklahoma has been identified as the only Quaternary-active fault in the state (included in USGS seismic hazard maps), but remains poorly understood in terms of earthquake recurrence, rupture length, and rupture area. New high-resolution topography from lidar and balloon-based photography data coupled with new paleoseismic trenching studies reveal that the Holocene fault trace continues at least 6 km farther to the northwest than previously mapped. We document monoclinal fold deformation of Holocene deposits along the northwest fault trace and brittle deformation (surface rupture) along the central fault section. Style of surface deformation appears to be directly linked to bedrock type. Earlier studies of the fault indicate at least two surface deforming earthquakes in the last 2,900 years (Crone and Luza, 1990). New paleoseismic results from the Meers fault identify at least four surface deforming earthquakes in the last ~6,000 years and at least two different fault rupture lengths. These new observations have important implications for multi-mode strain release through surface fault rupture in this intraplate setting and will help refine future seismic hazard models and maps.

High-Resolution Seismic Reflection Imaging of the Low-Angle Panamint Valley Normal Fault System, Eastern California

GOLD, R. D., U.S. Geological Survey, Colorado, USA, rgold@usgs.gov; STEPHENSON, W. J., U.S. Geological Survey, Colorado, USA, wstephens@usgs.gov; KIRBY, E., Oregon State University, Oregon, USA, eric.kirby@geo.oregonstate.edu; WOOLERY, E. W., University of Kentucky, Kentucky, USA, ewoolery@uky.edu; BRIGGS, R. W., U.S. Geological Survey, Colorado, USA, rbriggs@usgs.gov; DUROSS, C. B., U.S. Geological Survey, Colorado, USA, cduross@usgs.gov; DELANO, J., U.S. Geological Survey, Colorado, USA, jdelano@usgs.gov; ODUM, J., U.S. Geological Survey, Colorado, USA, odum@usgs.gov; LEEDS, A., U.S. Geological Survey, Colorado, USA, aleeds@usgs.go; PARIS, D., U.S. Geological Survey, New Mexico, USA, dparis@usgs.gov; SETHANANT, I., Oregon State University, Oregon, USA, sethanai@oregonstate.edu; VON DASSOW, W., Oregon State University, Oregon, USA, vondassw@oregonstate.edu

A fundamental question in seismic hazard analysis is whether <30°-dipping low-angle normal faults (LANFs) slip seismogenically. In comparison to more steeply dipping (50-60°) normal faults, LANFs have the potential to produce stronger shaking given increased potential rupture area in the seismogenic crust and increased proximity to manmade structures built on the hanging wall. The western margin of the Panamint Range in eastern California is defined by an exhumed, archetype LANF. In addition, high-angle normal faults displace mid-to-late Quaternary alluvial fans near the range front. To observe shallow (<1 km depth), crosscutting relationships between the low- and high-angle normal faults along the range front, we acquired two high-resolution P-wave seismic reflection profiles. The northern 4.7-km profile crosses the 2-km-wide Wildrose Graben and the southern 1.1-km profile extends onto the Panamint Valley playa, ~7.5 km S of Ballarat, CA. We used a minivib trailer-mounted vibrator source, which swept through 20 to 180 Hz with 5 m source and receiver spacings. The profile across the Wildrose Graben reveals a robust, low-angle reflector that likely represents the LANF separating Plio-Pleistocene alluvial fan conglomerate and pre-Cambrian meta-sedimentary deposits. High-angle faults interpreted in the seismic profile correspond to fault scarps on Quaternary alluvial fan surfaces. Preliminary interpretation of the reflection data suggests that the high-angle faults displace the LANF within the Wildrose Graben. Similarly, the profile south of Ballarat reveals a low-angle reflector, which also appears displaced by high-angle faults. These preliminary results suggest that near the Panamint range front, the high-angle faults are the dominant late Quaternary structures. We speculate that, at least at shallow (<1 km) depths, the LANF is not seismogenically active today.

Paleoseismic Investigation of the Freds Mountain Fault and the Western Lemmon Valley Fault Zone, North Valleys-Reno, Nevada

DEE, S., Nevada Bureau of Mines and Geology, University of Nevada Reno, Nevada, USA, sdee@unr.edu; RAMELLI, A. R., Nevada Bureau of Mines and Geology, University of Nevada Reno, Nevada, USA, ramelli@unr.edu; KOEHLER, R. D., Nevada Bureau of Mines and Geology, University of Nevada Reno, Nevada, USA, rkoehler@unr.edu; MAHAN, S., U.S. Geological Survey, Colorado, USA, smahan@usgs.gov; DE MASI, C., University of Nevada Reno, Nevada Bureau of Mines and Geology, Nevada, USA, connidemasi@nevada.unr.edu

A series of fault-bounded basins north of Reno, NV, collectively known as the North Valleys, form an important structural linkage between some of the most active faults in the Basin and Range: the Carson Range fault system to the south; and dextral faults of the northern Walker Lane to the north. To improve characterization of the seismic hazard posed by the faults this study used new lidar data to remap faults in Lemmon and Antelope Valleys and paleoseismic trenching to determine the earthquake history and slip-rate of the Freds Mountain fault (FMF).

On the west side of Lemmon Valley a trench was excavated across a prominent scarp on a mapped, range-front fault. The trench exposed lacustrine sediments and no evidence for faulting. It was determined that the scarp is a wave cut shoreline formed by a Pleistocene lake in Lemmon Valley. Identification of the shoreline suggests that the highstand of Lake Lemmon reached the basin outlet elevation and spilled into the topographically lower Lake Lahontan in the latest Pleistocene. Recognition of the larger lake extent and the existence of fault parallel shorelines facilitated new mapping of the Western Lemmon Valley fault zone (WLVFZ), including removal of some previously mapped fault traces. New vertical separation measurements on WLVFZ fault scarps in nearby late Pleistocene fan deposits range from 5.6-6.7 m, yielding slip-rate estimates of 0.05-0.6 mm/yr. These fault scarps cross the lake highstand elevation with sharp morphology suggesting post-highstand deformation, weighting the higher slip-rate estimates.

To the north in Antelope Valley a second trench was excavated across a scarp on the FMF. The trench exposed faulted alluvial-fan deposits, evidence for 4 surface rupturing earthquakes, and yielded an average total vertical displacement estimate of 9.6 m. Age estimates of the paleo-earthquakes and displaced stratigraphy are pending OSL and radiocarbon analyses. New lidar-based mapping of the FMF suggests significant along-strike variability in slip-rate indicating the fault may have a segmented rupture history.

Geometry and Geomorphic Expression of Strike-Slip Faulting in the Central Walker Lane

PIERCE, I. K. D., University of Nevada Reno, Nevada, USA, ian@nevada.unr.edu; WESNOUSKY, S. G., University of Nevada Reno, Nevada, USA, wesnousky@unr.edu; OWEN, L. A., University of Cincinnatti, Ohio, USA, owenls@ucmail.uc.edu

Fault morphology and patterns revealed by high-resolution topography and imagery are indicative of dextral shear in the Carson, Smith, Mason, and Walker Lake basins. The shear is expressed either along discrete strike-slip faults, complex zones of numerous short faults, or obliquely on portions of previously mapped range-front normal faults. Each of these zones is optimally oriented for the accommodation of geodetically observed northwest-directed dextral shear. Dextral slip rates on these faults remain unconstrained by quantitative geologic methods, though geodetic block modeled rates for each of these fault zones range from ~0.5-1.5 mm/yr, which seems reasonable based on their geomorphic expressions. Together the fault zones comprise a left-stepping en-echelon pattern that accommodates northwest-directed dextral faulting, extending from south of Hawthorne, NV to Sierraville, CA, and aligns with the previously documented strike-slip Fish Lake Valley and Mohawk Valley faults, to the southeast and northwest respectively. It is suggested that the series of faults may ultimately coalesce into a ~500-km-long through-going strike-slip fault connecting the entire Walker Lane. Where the Antelope, Smith, and Mason valley rangefront faults exhibit primarily normal displacement, vertical slip rates based on cosmogenic ages of faulted alluvial fans are reported. Quaternary deposits are mapped in each of these basins at a scale of 1:12,000. The distribution of scarp heights along the Antelope and Smith valley range-bounding faults are plotted to estimate the magnitude of displacement and recurrence intervals of the most recent and penultimate surface rupturing earthquakes, resulting in ~4-6 ka return times of ~M7 events, similar to that reported by previous trenching studies.

Frontiers in Earthquake Geology: Bright Futures and Brick Walls

Oral Session · Wednesday · 2:15 PM · 24 April · Vashon
Session Chairs: Lydia Staisch, Brian L. Sherrod, Stuart Nishenko, H. Gary Greene.

Earthquake and Tsunami Hazards in the Inland Sea of the San Juan Archipelago, Salish Sea of Washington State

GREENE, H., Moss Landing Marine Laboratories, California, USA, greene@mlml.calstate.edu; BARRIE, J., Geological Survey of Canada, Sidney, Canada, vaughn.barrie@canada.ca; TODD, B. J., Geological Survey of Canada, Dartmouth, Canada, brian.todd@canada.ca; NISHENKO, S., Pacific Gas and Electric Company, California, USA, spn3@pge.com

Extensive seismic-reflection profiling and bathymetric fault mapping in the inland sea of the San Juan Archipelago has enabled the mapping of local earthquake and tsunami hazards in the region. This inland sea comprises the central part of the Salish Sea and is part of the upper tectonic plate associated with the Cascadia subduction complex. The region is composed of subducted, accreted, and transported blocks of rocks that have been heavily glaciated, forming deep fiord channels, and sounds. The Archipelago is bounded by two E-W trending active strike-slip fault zones, the Devils Mountain Fault Zone in the south and the newly mapped Skipjack Island Fault zone in the north, both of which extend for over 55 km where mapped offshore but may have a total length of over 125 km if connected to onland faults. Similar fault zones to the south (*e.g.*, Seattle, Tacoma fault zones) have produced M_w 6.5-7.5 earthquakes in the last 15 ka.

The Skipjack Island Fault Zone is especially significant as it crosses between the islands of the Archipelago and is near potentially unstable seafloor features. The close proximity of the fault zone to Orcas Island, composed of fractured Mesozoic basement rocks with a steep (locally near vertical) and high (732 m) NE facing side, could trigger rockfalls, which would produce impact tsunamis that could inundate the low-lying coastal areas of islands and the mainland of the US and Canada to the N and NE. In addition, the distal southern edge of the Fraser River Delta of Canada lies just north of the Skipjack Island Fault Zone. A moderate to large magnitude earthquake could mobilize mass wasting of deltaic sediment, thus producing a tsunami directed toward the islands of the San Juan Archipelago and low coastal areas of mainland US.

Recurrence of Large Upper Plate Earthquakes in the Puget Lowland

SHERROD, B. L., U.S. Geological Survey, Washington, USA, bsherrod@usgs.gov; STYRON, R. H., Earth Analysis, California, USA, richard.h.styron@gmail.com; ANGSTER, S., U.S. Geological Survey, Washington, USA, sangster@usgs.gov

Paleoseismic studies documented 27 paleoearthquakes from observations of postglacial deformation at 63 sites on 13 shallow fault zones in the northern Cascadia fore arc. These fault zones were created by northward fore arc block migration manifested as a series of bedrock uplifts and intervening structural basins in the Salish lowland between the 49^{th} parallel and Olympia, WA to the south, bounded on the east and west by the Cascade Mountains and Olympic Mountains. Estimates of paleoearthquake magnitude range from M~6.5 and M~7.5. For each paleoearthquake, we use published ages to calculate earthquake-timing probability density functions (PDFs); for some events broad PDFs reflect earthquakes constrained by only minimum or maximum limiting ages.

The earthquake record starts shortly after glacier retreat, which began ~16ka. Earthquakes prior to the mid-Holocene were apparently scarce, with only a handful of older earthquakes identified throughout the lowland. The paleoseismic record picks up in earnest ~4000 yrs BP, with 21 of the 27 paleoearthquakes on faults throughout the Salish lowland. A cluster of earthquakes started about 2500 yrs BP and lasted until about 900 yrs BP on faults located in the central and northern lowland.

A Monte Carlo approach was used to calculate the recurrence intervals and rates for earthquakes on individual fault zones as well as on the regional fault network as a whole. Thousands of samples were drawn from each earthquake age PDF, and these were sorted (following stratigraphic ordering where possible) and differenced, yielding distributions for inter-event times that reflect the uncertainty in the radiocarbon ages. For the Puget Lowland as a whole, the post-glacial mean recurrence interval is ~400 years, with a median of ~175 years and a mode of ~20 years (temporally proximal earthquakes are generally not on the same fault). These results are suggestive of earthquake clustering, and that a large earthquake may be followed soon after by additional large earthquakes on regional faults.

Mw 7.8 2016 Kaikoura, New Zealand Earthquake: Hundalee Fault Paleoseismology

STIRLING, M. W., University of Otago, Port Chalmers, New Zealand, mark.stirling@otago.ac.nz; BARRELL, D. J. A., GMA Science, Dunedin, New Zealand, d.barrell@gns.cri.nz; WILLIAMS, J. N., Cardiff University, Cardiff, United Kingdom, williamsj132@cardiff.ac.uk; SAUER, K. M., University of Otago, Dunedin, New Zealand, sauerkatrina@gmail.com; VAN DEN BERG, E. J., University of Otago, Dunedin, New Zealand, ella.vandenberg@postgrad.otago.ac.nz

The Hundalee Fault was one of the 20+ faults that ruptured during the 2016 Kaikoura earthquake. It was previously mapped as a major bedrock fault of approximately 30 km in length, and with a late Cenozoic throw of over 1 km. About 23 km of the fault ruptured during the Kaikoura earthquake, and ruptures were diffuse and distributed along and away from the main bedrock fault. The 2016 ruptures showed reverse-dextral motion on east-northeast-striking strands of the fault, and reverse-sinistral on north-northeast striking strands, consistent with the regional principal strain axes. Our surface rupture mapping identified several locations where scarps were present prior to the 2016 earthquake. The most prospective site identified for trenching was an approximately 2 m high pre-existing scarp at Okarahia Stream that experienced reactivation in 2016. This involved about 0.5 m of reverse-sinistral motion. This scarp was trenched in early 2018, revealing approximately 2 m reverse separation of lensoidal-bedded alluvial gravel and silt across a fault plane with a 30 degree dip. The deformation comprised discrete offset as well as broad folding, but it is unclear how much of the folding was produced by the 2016 rupture. Only about 0.5 m of the reverse separation can be attributed to the 2016 event, based on the displacement of near-surface units. There is no evidence of more than one pre-2016 event in the trench exposure. Radiocarbon dating of detrital charcoal from the middle of the faulted sediment package yielded ages of 3550±83 and 3499±68 calendar years BP. These provide maximum ages for the penultimate earthquake on the Hundalee Fault, an earthquake that produced more surface rupture deformation at this site than occurred in the 2016 event.

A Multi-Fault Model Estimation From Tsunami Data: An Application to the 2018 M7.9 Kodiak Earthquake

HOSSEN, M., Cooperative Institute for Research in Environmental Sciences, The University of Colorado, Colorado, USA, md.hossen@colorado.edu; SHEEHAN, A. F., Cooperative Institute for Research in Environmental Sciences, The University of Colorado, Colorado, USA, anne.sheehan@colorado.edu; SATAKE, K., The University of Tokyo, Tokyo, Japan, satake@eri.u-tokyo.ac.jp

A multi-fault model of a complex event, the January 23, 2018 M7.9 offshore Kodiak earthquake, is estimated from tsunami data by utilizing a Green's function based time reverse imaging (GFTRI) with an adjoint sensitivity (AS) method. The adjoint approach has been used in numerical weather prediction to find the optimal locations for adaptive observations, and has recently been adapted for tsunami studies. The GFTRI method requires Green's functions (GF) from each source patch obtained by dividing a source region into a regular grid of point sources. GFs are computed using an initial unit source model whose amplitude is concentrated near the grid point. The AS method has been successfully applied to the 2009 Samoa earthquake tsunami (Hossen *et al.*, GRL, 2018).

In this study, we applied the AS method with GFTRI to invert for the source of the January 23, 2018 Kodiak earthquake using tsunami waveforms from DART and tide gauge stations. The M7.9 earthquake occurred 300 km southeast of Kodiak Island, Alaska, on the incoming Pacific plate in the outer rise region of the Alaska-Aleutian subduction zone. The global Centroid Moment Tensor (GCMT) solution indicates faulting occurred on a steeply dipping fault striking either west-southwest (left lateral) or north-northwest (right lateral) while subsequent work (Ruppert *et al.*, GRL, 2018) reveals a more complex pattern of strike-slip faulting. Our results suggest that the rupture occurred on five fault planes oriented in both N-S and E-W fault direction. The result is based on the tsunami source inversion in which we estimated a sea surface displacement using tsunami data recorded by tide gauges and DART buoys located around the source. From the reconstructed sea surface displacement, we estimated the slip distribution on the fault planes chosen based on the fault-parameters suggested by GCMT solution but with different epicentral locations. We carried out a number of source inversions using different combinations of fault planes to find the multi-fault model that provides smallest residual error.

Slip Rates Are Dead. Long Live Slip Rates.

BRIGGS, R. W., U.S. Geological Survey, Colorado, USA, rbriggs@usgs.gov; GOLD, R. D., U.S. Geological Survey, Colorado, USA, rgold@usgs.gov

Fault slip rate is a fundamental parameter for earthquake rupture forecasts. However, the path from geologic slip rates to earthquake rates in seismic hazard models has many potential pitfalls that deserve close examination. It has long been recognized that magnitude-frequency relations/recurrence models for individual faults are highly uncertain and hard to test. But it is also increasingly clear that the theoretical relationship between fault slip rates and moment release rates (Brune, 1968) presents serious challenges at the temporal and spatial scales relevant for seismic hazard models. On- versus off-fault deformation, aseismic slip, and potential rapid variation in loading or release rates are only a few of the issues that complicate the conversion of slip rates to coseismic moment release. Detailed recurrence information from site-specific paleoseismic studies is usually considered the best way to augment and strengthen slip rate information, yet paleoseismic data are often highly uncertain themselves and can be very difficult to obtain.

Can we develop more useful hazard models with a different approach to collecting, reporting, and using geologic slip rates? We'd like to spark a discussion about how we collect and treat geologic slip rates by envisioning earthquakes as ruptures propagating along fault networks, rather than events 'caused' by faults with fixed, prescribed slip rates. From the fault-network hosted-rupture perspective, a few issues emerge. 1) *No slip rate, no problem?* The 3D character of the potentially active fault network is perhaps more important than modeling only faults with known slip rates; 2) *Slip rates are functions:* Characterizing slip rates as smooth functions that vary along network faults is key – how do we get there?; 3) *Honesty in reporting:* Slip rates should be reported as probability density functions that fully account for time and displacement history uncertainties; 4) *Recognize brick walls:* Where do we acknowledge the limitations of geologic slip rates and promote other approaches, like geodesy?

Slip-Rates, Obliquity Estimates and Plate Boundary Localization Along the Queen Charlotte Fault Based on Submarine Tectonic Geomorphology

BROTHERS, D. S., U.S. Geological Survey, California, USA, dbrothers@usgs.gov; MILLER, N., U.S. Geological Survey, Massachusetts, USA, ncmiller@usgs.gov; BARRIE, J., Natural Resources Canada, Sidney, Canada, vaughn.barrie@canada.ca; HAEUSSLER, P. J., U.S. Geological Survey, Alaska, USA, pheuslr@usgs.gov; GREENE, H., Moss Landing Marine Laboratories, California, USA, greene@mlml.calstate.edu; ZIELKE, O., King Abdullah University of Science and Technology, Thuwal, Saudi Arabia, olaf.zielke@kaust.edu.sa; ANDREWS, B., U.S. Geological Survey, Massachusetts, USA, bdandrews@usgs.gov; DARTNELL, P., U.S. Geological Survey, California, USA, pdartnell@usgs.gov

Seismic and geodetic monitoring of active fault systems does not typically extend beyond one seismic cycle, hence it is challenging to link the characteristics of individual earthquakes with long-term fault behavior. The Queen Charlotte Fault (QCF) is a dextral strike-slip fault that defines the North America-Pacific plate boundary for ~900 km offshore southeastern Alaska and western British Columbia. Although the QCF has generated seven M_w>7 earthquakes since 1900, its kinematics and long-term behavior have never been examined systematically due to an absence of marine geophysical imaging. We present new analysis of the tectonic geomorphology along the entire length of the QCF based on comprehensive multibeam bathymetry data acquired between 2010 and 2018. Along the northernmost ~315 km, the fault is a narrow, linear and continuous trace that is closely aligned with plate motion vectors. Its strike is increasingly oblique to plate motion moving south and secondary faults and folds along the continental slope become more prevalent, suggesting transpressional deformation increases. We present a catalog of 179 seabed features (*e.g.*, gullies, escarpments, ridges, and fan aprons) that have been offset horizontally by motion on the QCF since the late Pleistocene. Offset estimates are based on a quantitative reconstruction approach and range from 680–900 m. All of the features are relic, having formed rapidly during the final stages of deglaciation (17–13 ka) by high-energy outwash-derived sediment flows that crossed the QCF. Dated sediment cores and other proxies suggest these flows shut down abruptly, but the timing varied along strike, leading to variation in offset. The horizontal slip-rate estimates are consistently between 47–56 mm/yr over a distance of >680 km. Despite the apparent increase in transpression along the southern section of the fault, the average rate of convergence on this section may only be ~6 mm/yr. These results have implications for regional tectonic models, historical earthquake behavior, and tsunami generation along the QCF.

Expanding the Cascadia 1700 CE Paleogeodetic Database With Subsidence Estimates From Northern California and Washington

PADGETT, J. S., University of Rhode Island, Rhode Island, USA, jason_padgett@uri.edu; ENGELHART, S. E., University of Rhode Island, Rhode Island, USA, engelhart@uri.edu; SYPUS, M., University of Victoria, Victoria, Canada, matthewcrs@gmail.com; WANG, K., Geological Survey of Canada, Sidney, Canada, jklmwang@telus.net; HAWKES, A. D., University of North Carolina, North Carolina, USA, hawkesa@uncw.edu; CAHILL, N., Maynooth University, Kildare, Ireland, niamh.cahill@ucd.ie; WITTER, R. C., U.S. Geological Survey, Alaska, USA, rwitter@usgs.gov; NELSON, A. R., U.S. Geological Survey, Colorado, USA, anelson@usgs.gov; HONG, I., Rutgers University, New Jersey, USA, hong@marine.rutgers.edu; HORTON, B. P., Nanyang Technological University, Singapore, Singapore, bphorton@ntu.edu.sg; KELSEY, H. M., Humboldt State University, California, USA, hmk1@humboldt.edu

Quantitative relative sea-level reconstructions derived from foraminifera-based Bayesian transfer function analysis yield precise estimates of coseismic vertical deformation from the 1700 CE Cascadia Subduction Zone (CSZ) earthquake. These estimates inform hypothetical rupture scenarios used in seismic and tsunami hazard models. However, the current CSZ 1700 CE paleogeodetic database primarily consists of estimates from Oregon and comprises conspicuous spatial gaps in northern California and Washington. Therefore, strategically placed transfer function investigations within these geospatial gaps afford the opportunity to progress our understanding of Cascadia rupture and inform hazard characterization.

We examine stratigraphic sequences of CSZ 1700 CE earthquake subsidence (abrupt mud-over-peat contacts), from both northern California and Washington. We quantitatively reconstruct relative sea-level rise across stratigraphic contacts by applying a foraminiferal-based Bayesian transfer function to fossil foraminiferal assemblages. At northern Humboldt Bay, California, coseismic subsidence averaged across nine stratigraphic contacts of the 1700 CE earthquake is 0.58 m (±0.46 m). In southwestern Washington we analyzed 1700 CE earthquake contacts at seven sites; Copalis River, Ocean Shores, Chehalis River, Johns River, Smith Creek, Bone River, and Naselle River. At these sites, coseismic subsidence estimates ranged from 0.39 m (±0.37 m) at Johns River to 1.52 m (±0.51 m) at Smith Creek. Within error, subsidence estimates from northern California and Washington generally agree with a recent geophysical rupture model of the CSZ 1700 CE earthquake, which features heterogeneous fault slip distribution along strike. Our new subsidence data broadens the areal extent of the 1700 CE paleogeodetic database and increases the number of measurements by over a third, which will help improve our understanding of the seismogenic behavior of Cascadia megathrust.

Prehistoric, Headwater-Basin-Encompassing Debris-Avalanches, Northern California Coast Ranges: Temporal Association With Plate Boundary Earthquakes

KELSEY, H. M., Humboldt State University, California, USA, hmk1@humboldt.edu; SHERROD, B. L., U.S. Geological Survey, Washington, USA, bsherrod@usgs.gov; PADGETT, J. S., University of Rhode Island, Rhode Island, USA, jason_padgett@my.uri.edu; BROCHER, T., U.S. Geological Survey, California, USA, tmbrocher@gmail.com; ANGSTER, S., U.S. Geological Survey, Washington, USA, sangster@usgs.gov

What role do extreme events, climatic or seismic, play in the formation of high elevation landscapes in the northern California Coast Ranges? Exceptionally large (0.2-0.7 km^2) prehistoric debris avalanches in the northern California Coast ranges set landscape form, but the triggering mechanism is unclear. Within high-elevation (>1500 m) headwater regions underlain by competent rock types, the main slope process is periodic debris avalanching that occurs in morphologically distinct headwater bowls. Because the scars appear to be single aged based on the extent and character of revegetation, avalanche failures appear to have occurred all at once encompassing the entire headwater basin. Hence, the failures sculpt headwater basins. Although no headwater-basin failures have occurred historically, we map the location and extent of four pre-historic debris avalanches as indicated by headwater basin scars that are unvegetated or partially revegetated. These avalanches scour into bedrock, and revegetation of bedrock slopes is a slow process that proceeds over centuries. One unvegetated avalanche scar that encompasses a headwater basin failed in the interval CE 1871-1904, based on trees growing on a coherent slide block that recorded the trauma in their growth rings. Another partially revegetated debris-avalanche-headwater-basin scar can be dated using an alluvial fill sourced from the avalanche. The alluvial fill extends 1.5 km down channel from the avalanche source and buried riparian trees in growth position; ^{14}C age determinations indicate one of these trees was buried and killed within the interval CE 937-1071. Large headwater basin avalanches likely require extreme seismic or climatic events for slope destabilization. For the above two headwater-basin-encompassing debris avalanches for which we can constrain the time of failure to a defined time range, the time of failure— in both cases— overlaps with the time of a Cascadia plate boundary earthquake.

Bayesian Diatom-Based Estimates of Coastal Deformation During Megathrust Earthquakes at the Cascadia Subduction Zone

HONG, I., Rutgers University, New Jersey, USA, hong@marine.rutgers.edu; CAHILL, N., Maynooth University, Kildare, Ireland, niamh.cahill@mu.ie; ENGELHART, S. E., University of Rhode Island, Rhode Island, USA, engelhart@uri.edu; HAWKES, A. D., University of North Carolina, North Carolina, USA, hawkesa@uncw.edu; NELSON, A. R., U.S. Geological Survey, Colorado, USA, anelson@usgs.gov; PADGETT, J. S., University of Rhode Island, Rhode Island, USA, jason_padgett@my.uri.edu; HORTON, B. P., Nanyang Technical University, Singapore, Singapore, bphorton@ntu.edu.sg

Reconstructing the magnitude and frequency of megathrust earthquakes at Cascadia, as well as at other subduction zones, requires accurate measures of upper-plate deformation during great earthquakes. At Cascadia, coastal subsidence during successive earthquakes is commonly recorded by stratigraphic sequences of mud-over-peat contacts beneath tidal wetlands. The application of diatom-based transfer functions in relative sea-level reconstruction studies yields quantitative estimates of coseismic land-level change, but the estimates are limited by the high species diversity of tidal floras, the common absence of modern analogues for fossil assemblages, and the complex and variable species distributions in salt marsh and estuarine environments.

Using a newly developed diatom Bayesian transfer function (BTF) we quantitatively reconstruct coseismic coastal subsidence at Willapa Bay, WA. We address the problem of high species diversity and improve computational efficiency by employing a statistical pre-treatment, grouping species that indicate similar responses to elevation. The diatom BTF is used to calculate flexible species-response curves for the grouped taxons, capturing the complex relationships between species and elevation. The modern diatom training dataset (calibrations) consists of 60 samples from three tidal marshes in Willapa Bay with elevations tied to local tidal benchmarks. A 10-fold cross-validation provides an assessment of the predictive performance of the diatom BTF showing a strong relationship between observed and predicted elevations (mean absolute residual = 0.33 m) with a root-mean square error of prediction of 0.42 m. We apply the diatom BTF to fossil assemblages from a core along the Niawiakum River, Willapa Bay to estimate subsidence during four prehistoric earthquakes. Our new subsidence estimates will help constrain models of coseismic and interseismic deformation that are key to assessing the hazards from Cascadia's megathrust earthquakes.

Microfossil Measures of Subsidence During Past Plate-Boundary Earthquakes: Their Accuracy Revealed by a Sudden Tidal-Flooding Experiment in Cascadia

DURA, T., Virginia Tech, California, USA, tinadura@gmail.com; HORTON, B. P., Earth Observatory of Singapore and Asian School of the Environment, Singapore, Singapore, bphorton@ntu.edu.sg; MILKER, Y., University of Hamburg, Institute for Geology, Hamburg, Germany, yvonne.milker@uni-hamburg.de; WANG, K., Geological Survey of Canada, Sidney, Canada, kelin.wang@canada.ca; BRIDGELAND, W. T., Oregon Coast National Wildlife Refuge Complex, Oregon, USA, bill_bridgeland@fws.gov; BROPHY, L., Institute for Applied Ecology, Oregon, USA, brophyonline@gmail.com; EWALD, M., Institute for Applied Ecology, Oregon, USA, mewald@geomaticsresearch.com; KHAN, N., Earth Observatory of Singapore and Asian School of the Environment, Singapore, Singapore, nicoleskhan@gmail.com; ENGELHART, S. E., University of Rhode Island, Rhode Island, USA, engelhart@uri.edu; NELSON, A. R., U.S. Geological Survey, Geologic Hazards Science Center, Colorado, USA, anelson@usgs.gov; WITTER, R. C., U.S. Geological Survey, Alaska Science Center, Alaska, USA, rwitter@usgs.gov

Comparison of pre- and post-earthquake microfossil assemblages in intertidal sediment is the most widely applicable and accurate means to measure coseismic subsidence from past plate-boundary earthquakes at subduction zones. Quantitative methods typically state only the analytical uncertainty associated with predicted subsidence. However, uncertainty on subsidence estimates may not be well constrained because the response times of fossil taxa to coseismic relative sea-level (RSL) rise are unknown. We explored the response of diatoms and foraminifera to a sudden increase in tidal inundation following dike removal during restoration of a former salt marsh in southern Oregon. Tidal flooding following dike removal caused an increase in inundation equivalent to a RSL rise of ~1 m, as might occur by coseismic subsidence during Mw 8.1-8.8 earthquakes on this section of the Cascadia subduction zone, depending on the rupture length along strike. Less than two weeks after dike removal, diatoms colonized low marsh and tidal flats, showing that they can record seismically-induced subsidence soon after earthquakes. In contrast, it took at least 11 months for notable numbers of low-marsh foraminifera to colonize the restored marsh.

A comparison of diatom and foraminifera-based transfer functions—which use the empirical relationship between modern microfossil assemblages and elevation within the tidal frame to convert fossil assemblages into quantitative estimates of past RSL—reflects the delayed foraminifera response. This suggests that postseismic uplift or subsidence may cause foraminiferal-based transfer functions to underestimate or overestimate, respectively, coseismic subsidence if sedimentation rates post-earthquake exceed 1-2cm/yr given a typical fossil core/outcrop sampling resolution of 1cm. Our results suggest that different response times of diatoms and foraminifera may provide useful information on post-seismic vertical deformation in the months following past megathrust earthquakes.

Advances in Intraplate Earthquake Geology

Poster Session · Wednesday · 24 April · Fifth Avenue

Strike-Slip in Transtension: Complex Crustal Architecture of the Warm Springs Fault Zone, Northern Walker Lane, Nevada

BRIGGS, R. W., U.S. Geological Survey, Colorado, USA, rbriggs@usgs.gov; STEPHENSON, W. J., U.S. Geological Survey, Colorado, USA, wstephens@usgs.gov; MCBRIDE, J., Brigham Young University, Utah, USA, john_mcbride@byu.edu; ODUM, J., U.S. Geological Survey, Colorado, USA, odum@usgs.gov; REITMAN, N., University of Colorado Boulder, Colorado, USA, nadine.reitman@colorado.edu; GOLD, R. D., U.S. Geological Survey, Colorado, USA, rgold@usgs.gov

Faults in the transtensional northern Walker Lane accommodate 5-7 mm/year of dextral shear but summed Holocene geologic fault slip rates are lower than geodetically-measured strain accumulation rates at most latitudes. Distributed faulting and uncertain fault network connectivity complicate comparisons between geologic and geodetic data in the region. We use two newly acquired high-resolution seismic reflection profiles and a reprocessed deep crustal reflection COCORP profile to assess the subsurface geometry of the Holocene-active, right-lateral Warm Springs strike-slip fault zone near Reno, Nevada. Our multiscale observations extend to 12 km depth and suggest that the Warm Springs fault zone is far more complex at depth than implied by the distribution of post-Lahontan (<15.5 ka) surface scarps. The two ~4.5 km-long high-resolution profiles both image to a depth of ~2 km along fault-perpendicular lines and reveal moderately-dipping reflections and truncations that project to mapped surface scarps. The shallow lines are co-located with COCORP profile NV8 at ~40° N. Re-analysis of the COCORP data reveals previously unidentified coherent reflections to a depth of ~12 km. Truncations, juxtaposed regions of contrasting dip and/or reflectivity, and diffractions in the COCORP data define fault-bounded packages above a zone of moderately dipping, laterally continuous mid-crustal (4-12 km) reflections. From these profiles, the Warm Springs fault zone doesn't appear to be defined by a simple, sub-vertical fault zone extending through the entire seismogenic crust. Instead, the reflections are consistent with a zone of nested steep- and moderately-dipping faults that sole into a mid-crustal, moderately-dipping detachment. If this is the case, the common assumption that transtension is accommodated only by crustal-scale subvertical strike-slip faults in the northern Walker Lane may not be valid, with important consequences for seismic hazard models and models of fault mechanics.

Spatiotemporal Aftershock Analysis of the M5.8 Lincoln, Montana Event

SMITH, E. M., University of Montana, Montana, USA, ellenmsmith22@gmail.com

One of the most seismically active regions in the western United States far from any major plate boundary is the Intermountain Seismic Belt (ISB). On 6 July 2017, a M5.8 earthquake occurred 11 km southeast of Lincoln, Montana within the ISB. This was the largest earthquake to occur in the state of Montana since the 1959 M7.3 Hebgen Lake earthquake. Data from the University of Montana Seismic Network and the Montana Regional Seismic Network was used to investigate the aftershock sequences following the M5.8 Lincoln event. We have manually refined P- and S-wave arrival times, computed hypocenter locations and double-difference relocations, and generated focal mechanisms for hundreds of aftershocks in the year following the main shock. We are working to characterize the evolution of the aftershock sequence, identify unmapped faults, and analyze the local stress field. Based on preliminary results, focal mechanisms for aftershock events from August to October of 2018, when we had a dense deployment of temporary broadband stations, primarily represent left-lateral slip on a NNE-trending fault. The hypocenter locations align along a NNE-trending fault consistent with the fault plane for the main shock. A smaller percentage of the hypocenter locations align along two adjacent structures, one trending southwestward and one trending northeastward. Based on the alignment of the hypocenters and focal mechanisms, the Lincoln area appears to host a complex fault system that includes subparallel and perpendicular faults. The results can help to constrain estimates of seismic hazard and crustal stress conditions in Montana.

Quaternary Geologic Mapping and Paleoseismic Assessment of the Warm Springs Valley Fault, Washoe County, Nevada

CHUPIK, C. M., University of Nevada Reno, Nevada, USA, colin.chupik@nevada.unr.edu; KOEHLER, R. D., University of Nevada Reno, Nevada, USA, rkoehler@unr.edu

The northern Walker Lane, in western Nevada, is a region of distributed deformation that accommodates ~15% of the motion between the North American and Pacific plates along north-oriented normal faults and northwest-oriented strike slip faults including the Warm Springs Valley fault (WSVF). The WSVF extends ~70 km from the Warm Springs Valley to the Honey Lake basin. Previous studies on the northern section of the fault reveal a decreasing slip rate from 1.8-2.4 mm/yr in the late Pleistocene to 0.2 mm/yr in the Holocene; however, information on earthquake timing, recurrence and Holocene activity is poorly constrained. Here, we present preliminary results of Quaternary geologic mapping and a paleoseismic trench investigation on the WSVF. The goals of our study are to locate the distribution of active traces and characterize the faults earthquake history. Mapping observations indicate that the fault is characterized by (1) a single trace in Warm Springs Valley, (2) multiple parallel stepping and anastomosing fault strands, uphill and downhill facing scarps, push up mounds, and sag ponds between the Dogskin and Virginia mountains, and (3) a range front fault along the Fort Sage Mountains that steps to the east and cuts pluvial lake shorelines in the Honey Lake basin. A trench excavated across a 3 m downhill facing scarp on an alluvial surface revealed sandy alluvium on the footwall juxtaposed against red gravel and colluvial deposits on the hanging wall. A weakly developed soil with stage 1 carbonate filaments is cut at the fault and indicates the surface is latest Pleistocene in age. Based on stratigraphic relationships, we infer that at least two surface rupturing earthquakes have occurred along the WSVF since the latest Pleistocene, the timing of which will be evaluated with OSL and radiocarbon analyses. Evaluation of offset shorelines in Honey Lake basin is in progress and will provide a better constraint of the Holocene slip rate for the WSVF.

Paleoseismic Trench Investigation of the Petersen Mountain Fault, North Valleys-Reno, Nevada

DE MASI, C., University of Nevada Reno, Nevada, USA, connidemasi@nevada.unr.edu; KOEHLER, R. D., Nevada Bureau of Mines and Geology, University of Nevada Reno, Nevada, USA, rkoehler@unr.edu; DEE, S., Nevada Bureau of Mines and Geology, University of Nevada Reno, Nevada, USA, sdee@unr.edu; CHUPIK, C. M., University of Nevada Reno, Nevada, USA, colin.chupik@nevada.unr.edu; CASTILLO, C., Castillo Geophysical, Nevada, USA, chriscastillo101@gmail.com; KLEBER, E., Utah Geological Survey, Utah, USA, ekleber@utah.gov; KEEN-ZEBERT, A., Desert Research Institute, Nevada, USA, amanda.keen-zebert@dri.edu

The ~25-km-long Petersen Mountain fault (PMF) bounds the eastern side of Petersen Mountain north of Reno, NV within the northern Walker Lane. The fault is one of a series of north-striking faults that bound basins (known as the North Valleys) oriented oblique to major Walker Lane strike slip faults. The fault has been previously characterized as a late Quaternary normal fault (<130 ka), however information on its style and rate of deformation are poorly understood. Characterizing the PMF is important for assessing regional seismic hazards for the Reno metropolitan area.

Here we present preliminary results from a detailed paleoseismic trench excavated across a 3-m-high fault scarp along the eastern strand of the PMF. The site was selected by evaluation of lidar elevation and aerial photography data, and field mapping. The trench exposed thin alluvial-colluvial sediments overlying massive disintegrated granite sand. The fault trace is characterized by a wide shear zone that extends 10 m west from the main fault seen in the trench. Within the shear zone, faults and fractures dip eastward between 70° and 80°, and propagate through the granitic sand into the overlying soil. The footwall consists of disintegrated granitic sands overlain by debris flow alluvium and a thick argillic soil horizon. The hanging wall consists of a massive bouldery colluvium that fines upward into a weak soil, buried soils were not observed. The stratigraphic juxtapositions provide evidence for at least one earthquake that occurred after development of the footwall soil and suggest a component of lateral movement consistent with the presence of linear valleys, and subtle right offsets of alluvial channels south of the trench. Pending Optically Stimulated Luminescence (OSL) and radiocarbon dates will help constrain the ages of sedimentary units and provide constraints on the recency of faulting. We infer that pre-existing normal faults within the northern Walker Lane may be accommodating a component of shear in the contemporary stress field.

Evidence for Large Earthquakes About A.D. 0 and B.C. 1050 in the New Madrid Seismic Zone

TUTTLE, M. P., M. Tuttle and Associates, Maine, USA, mptuttle@earthlink.net; WOLF, L. W., Auburn University, Alabama, USA, wolflor@auburn.edu; STARR, M., Independent Cultural Resources, Mississippi, USA, maryevelynstarr@gmail.com; LAFFERTY, III, R. H., Lafferty & Hess Consultants, PLLC, Arkansas, USA, rhlafferty3@gmail.com; VILLAMOR, P., GNS Science, Lower Hutt, New Zealand, p.villamor@gns.cri.nz

A recent paleoliquefaction study in the New Madrid seismic zone has found evidence for a previously unrecognized large earthquake about A.D. 0 as well as supporting evidence for a previously proposed large earthquake about B.C. 1050. Liquefaction sites that predate the New Madrid paleoearthquakes of A.D. 1450 and A.D. 900 were identified by examining time series of satellite imagery for areas where Late Pleistocene fluvial deposits had been mapped. In addition, liquefaction sites in these areas were examined that occur in association with archaeological sites that predate the Mississippian cultural period (A.D. 800-1673). Two of these sites, Garner and Stiles, located in the southern portion of the seismic zone were selected for detailed archaeological, geophysical, and paleoseismological investigations. Trenches, sited and excavated based on archaeological and geophysical results, exposed sand blows and their feeder dikes and any associated cultural deposits. At the Garner site, earthquake-induced liquefaction features formed circa A.D. 0 ± 200 yr based on fragments of Synder Cluster projectile points/knives in the upper 0-10 cm of the soil buried by sand blows; radiocarbon dating of organic material in the upper 1.5 cm of the buried soil; and weathering characteristics of the sand blows and feeder dikes including the formation of manganese nodules. At the Stiles site, sand blows and feeder dikes formed circa B.C. 1010, probably during the B.C. 1050 ± 250 yr New Madrid event, based on radiocarbon dating of the upper 1 cm of the soil buried by the sand blow and supported by weathering characteristics of the liquefaction features including formation of soil lamellae. These findings contribute to the chronology of New Madrid earthquakes and suggest that recurrence times may have varied from about 500 to 1,100 years, that the chronology may not yet be complete prior to A.D. 800, and that the seismic zone has been in an active phase for the past 4,300 years.

Lidar-Based Evaluation of Faulting in the Northern Walker Lane, Upper Feather River Watershed, Plumas County, California

HITCHCOCK, C., InfraTerra, California, USA, chitchcock@infraterra.com; HOIRUP, D. F., California Department of Water Resources, California, USA, don.hoirup@water.ca.gov; KOZACI, O., InfraTerra, California, USA, okozaci@infraterra.com

To investigate Quaternary deformation across the northern Walker Lane, a zone of right-lateral shear between the Sierra Nevada and the Basin and Range in Plumas County, we analyzed high-resolution (10 points per square meter) airborne LiDAR data covering 1,008 square kilometers acquired for the California Department of Water Resources. Comparison of high-resolution topography developed from LiDAR data with regional geologic mapping documents the presence of geomorphic features coincident with previously mapped late Quaternary faults including the Indian Creek, Grizzly Valley, and Last Chance faults. In addition, mapped potentially tectonic-related features coincide with previously mapped bedrock faults and across areas of undifferentiated bedrock, providing information on possible locations of previously unrecognized late Quaternary faulting. Subsequent field mapping verified tectonically deformed geomorphic features including linear scarps in alluvial surfaces, elongated depressions aligned with adjacent linear escarpments, truncated bedrock spurs, closed depressions, linear swales, right-lateral deflections of creeks and river courses, and shutter ridges, as well as springs and linear seeps consistent with oblique strike-slip faulting. The discontinuous nature of many of the observed potential fault traces are consistent with incipient faulting undergoing simple shear deformation between the Honey Lake fault (HLF) in the east and Mohawk Valley fault (MWF) in the west. The NW-SE orientation of the MWF and HLF is consistent with regional geodetic plate boundary deformation measurements. The fragmented nature and orientation of the mapped faults is consistent with secondary faulting manifested as synthetic riedel shears and normal faults. This study complements on-going investigations by DWR to assess the impact of seismic hazards on State Water Project infrastructure.

Is the Antelope Flats Fault an Antithetic Rupture of the Teton Fault?

THACKRAY, G. D., Idaho State University, Idaho, USA, thacglen@isu.edu; DUROSS, C. B., U.S. Geological Survey, Colorado, USA, cduross@usgs.gov; ZELLMAN, M., BGC Engineering, Colorado, USA, mzellman@bgcengineering.ca; WITTKE, S., Wyoming Geological Survey, Wyoming, USA, seth.wittke@wyo.gov; GOLD, R. D., U.S. Geological Survey, Colorado, USA, rgold@usgs.gov; DELANO, J., U.S. Geological Survey, Colorado, USA, jdelano@usgs.

gov; JOBE, J. A. T., U.S. Geological Survey, Colorado, USA, jjobe@usgs.gov; HILLE, M., U.S. Geological Survey, Colorado, USA, madeline.hilledeb@gmail.com; GRASSO, K., Idaho State University, Idaho, USA, graskyla@isu.edu; MAHAN, S., U.S. Geological Survey, Colorado, USA, smahan@usgs.gov

The Antelope Flats fault is a west-dipping normal fault zone, antithetic to the central section of the Teton fault in eastern Jackson Hole Valley, Wyoming. Fault scarps along the Antelope Flats fault are ~1–2 m high––far smaller than those marking the Teton fault––and form a discontinuous, ~6-km-long zone in an undated glacial outwash fan associated with the earliest phase of Pinedale glaciation (Pd-1; ~21–18 ka). Although the prehistoric rupture history and displacement of the Antelope Flats fault remain unconstrained, we hypothesize that because of the limited total length and height of scarps along the fault, it only ruptures to the surface in association with large, surface-faulting earthquakes on the Teton fault, located 9-km to the west. To determine the paleoseismic history of the fault as well as its kinematic relation to the Teton fault, we hand-excavated two trenches about 100 m apart across a <2-m high, west-facing fault scarp. The trenches exposed coarse gravel and cobbles that we interpret as sourced from the latest Pleistocene glacial outwash. These latest Pleistocene sediments have been vertically displaced by a single steeply west-dipping zone of shearing and are overlain by a ≤0.6-m-thick deposit of scarp-derived colluvium in the hanging wall. These relations suggest that only a single postglacial surface rupture has occurred along the Antelope Flats fault. Pending radiocarbon (n=9) and luminescence (n=12) ages for the outwash and scarp colluvium will establish the first direct ages for the Pd-1 glacial outwash fan, constrain the timing of Antelope Flats fault rupture, and permit comparisons of paleoseismic records for the Teton and Antelope Flats faults.

Evolving Best Practices for Station Buildout in EEW and New Permanent Networks

Poster Session · Wednesday · 24 April · Fifth Avenue

Station Quality Monitoring for the Pacific Northwest Seismic Network and Shakealert

HUTKO, A., Pacific Northwest Seismic Network, Washington, USA, ahutko@uw.edu; REUSCH, M., Pacific Northwest Seismic Network, Washington, USA, topo@uw.edu; MARCZEWSKI, K., Pacific Northwest Seismic Network, Washington, USA, marczk@uw.edu; CONNOLLY, J., Pacific Northwest Seismic Network, Washington, USA, joncon@uw.edu; HARTOG, J. R., Pacific Northwest Seismic Network, Washington, USA, jrhartog@uw.edu; BODIN, P., Pacific Northwest Seismic Network, Washington, USA, bodin@uw.edu

The Pacific Northwest Seismic Network is responsible for monitoring seismic activity in Cascadia and is also part of the USGS ShakeAlert earthquake early warning system. Fulfilling our role effectively requires monitoring station state of health metrics, those related to waveform quality such as power spectral density estimates, and those specific to ShakeAlert. We currently monitor station quality in near-real time at all PNSN stations as well as all stations contributing to ShakeAlert. Using our large database of metrics spanning many months and in collaboration with the ShakeAlert regional coordinators, we have established acceptance criteria for adding new stations to the ShakeAlert system. These include measures of latency, data completeness and number of potential earthquake triggers among others. We are also mining our database as well as logfiles from Earthquake Point-source Integrated Code (EPIC), one of two algorithms used by ShakeAlert, to identify parameters that can be modified and additional waveform checks that can be added to reduce the number of false triggers while not negatively impacting EPIC's performance. To test out ideas, we run test instances of EPIC as well as replay past earthquakes to assess any suggested changes. Finally we are exploring ways to establish thresholds for various metrics to be used to grey/black-list problematic stations in ShakeAlert. These are assessed using a map-based tool of theoretical alert time. To better visualize and comprehend the mountain of information that we collect and generate, we have begun work on an API which will be able to digest any properly formatted JSON message sent to the API and thus can ingest metrics from databases, AQMS messages, other APIs, upload via wget, etc. The API will be web-serviceable that utilizes Tableau visualization tools.

Station Building Strategies Developed During Earthscope Transportable Array – A Retrospective

BUSBY, R., Incorporated Research Institutions for Seismology, District of Columbia, USA, busby@iris.edu; FRASSETTO, A. M., Incorporated Research Institutions for Seismology, District of Columbia, USA, andyf@iris.edu; ADERHOLD, K., Incorporated Research Institutions for Seismology, District of Columbia, USA, kasey@iris.edu; HAFNER, K., Incorporated Research Institutions for Seismology, Colorado, USA, hafner@iris.edu; WOODWARD, R. L., Incorporated Research Institutions for Seismology, District of Columbia, USA, woodward@iris.edu

Between 2004-2015, the Incorporated Research Institutions for Seismology (IRIS) built and operated the National Science Foundation sponsored EarthScope Transportable Array (TA), a network of ~400 seismographs that moved west to east across the conterminous ("Lower 48" or L48) United States to occupy ~1679 stations with an average deployment span of ~22 months at each location. The goal was to gather robust and uniformly spaced measurements of the seismic wavefield at a range of scales and bandwidths for use in the investigation of the geologic structure and geodynamics of the North American continent. To accomplish this, the TA was designed to meet a data performance metric of >85% uptime, minimize gaps in the recorded data, and produce seismic records with low noise to maximize both earthquake detection and seismic imaging techniques.

A detailed description of the approaches used by TA to create (and remove) stations at the rate of 20 per month for several years is available at: http://www.usarray.org/researchers/obs/transportable/l48_ta_report

Highlights from the report are presented in the context of efforts to construct EEW stations in the western US.

Noise Characteristics of Alaska Transportable Array Posthole Sensor Emplacements

FRASSETTO, A. M., Incorporated Research Institutions for Seismology, District of Columbia, USA, andyf@iris.edu; ADERHOLD, K., Incorporated Research Institutions for Seismology, District of Columbia, USA, kasey@iris.edu; BUSBY, R., Incorporated Research Institutions for Seismology, District of Columbia, USA, busby@iris.edu

IRIS currently operates 194 seismic stations across Alaska and northwestern Canada as part of the EarthScope Transportable Array (Alaska TA). Our stations are complemented by existing and upgraded stations from contributing networks to make the full 280-station network. The Alaska TA was completely deployed by the fall of 2017, and it will continue to operate through at least early 2020. These stations use Kinemetrics STS-5A and Nanometrics T-120 posthole broadband seismometers, emplaced at ~3 m depth in cased holes within fractured bedrock outcrops, permafrost, or soil. Utilizing a customized portable drilling system, this emplacement technique streamlined logistics for the challenging, remote conditions and optimized station design and performance. Posthole sensor emplacements were also made at 28 contributing stations that were upgraded by the IRIS team.

With the full network deployed for over a year now, we have the opportunity to assess in detail the noise performance of stations across the entire Alaska TA footprint. We use power spectral density measurements (McNamara and Boaz, 2004) calculated by the IRIS DMC MUSTANG metric service to characterize noise levels at each station. In general, the noise performance of the Alaska TA is excellent, with most stations running with lower median noise levels than Lower 48 TA vault emplacements at both long and short periods. The quietest stations approach the performance of high-quality, permanent Global Seismographic Network stations even on horizontal channels at long periods. Ambient background noise at Alaska TA stations displays a strong but expected regional and seasonal variation due to environmental factors, and we closely examine variations in performance based on difference in posthole casing type (PVC vs. steel) and substrate (soil vs. bedrock vs. permafrost). The low noise floor at many of these stations also allows us to observe the influence of geomagnetic activity on seismometers.

From Boutique to Wholesale Seismic Monitoring: Performance Evaluation Tools to Prepare a Traditional Regional Seismic Network for Earthquake Early Warning

BODIN, P., University of Washington, Washington, USA, bodin@uw.edu; CONNOLLY, J., University of Washington, Washington, USA, joncon@uw.edu; MARCZEWSKI, K., University of Washington, Washington, USA, marczk@uw.edu; HUTKO, A., Pacific Northwest Seismic Network, Washington, USA, ahutko@uw.edu

The ShakeAlert Earthquake Early Warning (SAEEW) system combines data from three Regional Seismic Networks (RSNs) to produce real-time shaking alerts for the US west coast. In Oregon and Washington states, the contributing RSN is the Pacific Northwest Seismic Network (PNSN). SAEEW has necessitated RSNs to evaluate metrics that challenge traditional RSN capabilities even to evaluate. The additional requirements include robust measures of station density, product latency (combining data telemetry and seismic propagation factors), and the distribution of stations with respect to specific hazards. Moreover, differences in hazard characteristics along the west coast combined with variations in

RSNs states of technical development may make it difficult to generate a synoptic SAEEW-wide performance assessment, although this is frequently requested for accounting and political purposes. These needs stretch the RSNs traditional station-by-station data quality assessment tools and favor an approach that produces simple views of the overall capability of the network to generate high-quality products. We present the results of a set of map-based python-implemented forward modeling studies to assess overall network performance of the entire ShakeAlert network on the west coast of the US. These include assessments of the density of seismic stations, the time to produce a warning, and the size of the zone surrounding the epicenter of an earthquake point source that would receive late warning. Our modeling permits us to easily assess where future instrumentation would have the greatest impact, what the impact would be of loss of data from stations, and how improving station performance would benefit the ShakeAlert performance (or not). Our models provide an abundance of detailed evaluations of expected product performance that we compare directly to the hazard and system performance standards. Overall, our models reveal that average station density, the depths of earthquakes, and data delivery latency are primary determinants for overall EEW system performance.

Station Service Statistics for Alaska Transportable Array: Suspected Causes and Potential Mitigation Approaches

ENDERS, M., Incorporated Research Institutions for Seismology, Alaska, USA, enders@iris.edu; BLOOMQUIST, D., Incorporated Research Institutions for Seismology, Alaska, USA, doug.bloomquist@iris.edu; ADERHOLD, K., Incorporated Research Institutions for Seismology, District of Columbia, USA, kasey.aderhold@iris.edu

The Alaska Transportable Array (Alaska TA) is a broadband seismic network made up of 280 new and existing stations that uniformly cover Alaska and north-west Canada. Over five field seasons, from 2013-2017, 194 new stations were installed as part of EarthScope's Alaska Transportable Array. Most of these new stations have a nearly identical design and installation methodology which ensured that the stations could be built, transported, and installed at the field location efficiently and predictably. The stations were installed over a vast area in a variety of environments from rain forests and swamps to mountains and arctic tundra. Operation and Maintenance (O&M) has been a critical phase of the project and has been ongoing since the first stations were installed in 2013. In late 2017 following the completion of installation,the project shifted primarily to O&M and will continue until the last of the Alaska TA stations are removed. This presentation focuses on O&M activities with an emphasis placed on network performance statistics, a review of the types of failures seen at Alaska TA stations, and how the design of the stations as well as the O&M activities have been modified to address common failure modes. Statistics on failures of station equipment (seismometers, digitizers, telemetry systems, etc.) will be presented along with failure rates due to extreme weather damage from wildlife. This analysis will inform plans for future improvements to further increase the reliability and resilience of the stations.

Shakealert: The Journey From Research to Implementation

STEELE, W. P., University of Washington, Washington, USA, wsteele@uw.edu; WALSH, L. K., University of Oregon, Oregon, USA, lwalsh@uoregon.edu

For over a decade Caltech and UC Berkeley have been working to develop an earthquake early warning system initially with California as the target region of interest. The USGS provided some early research dollars in 2006 and in 2012 a major grant from the Gordon and Betty Moore Foundation (GBMF) accelerated development of ShakeAlert (SA) System in Pacific Northwest Seismic Network, transitioning the program into a West Coast System. A great deal of work was accomplished bringing these research communities together to develop the joint system with direction and management from both University PIs and the USGS who was tasked with managing the newly developed SA system. Once a nascent system, ShakeAlert is rapidly growing it's user base. Built upon an exploration prototype system, ShakeAlert is now in an operational phase, concurrent with phase one of a public roll out.

ShakeAlert is changing the way we think about earthquake preparedness and challenging us to develop loss reduction technologies that can be triggered seconds before shaking arrives. Introducing SA to government agencies, utilities, businesses and the general public is a high priority and, until very recently, a largely unfunded effort. Development and management of early adopters, or pilot partners, of the SA system is needed to learn from successes and demonstrate the utility of the system. Last year, SA Communication, Education, and Outreach (CEO) efforts expanded integrating Emergency Managers and the State Geologic Surveys into the CEO program efforts. This talk will review the development of ShakeAlert CEO and Pilot Project development efforts and challenges we face to prepare our economy and communities to take full advantage of SA early warnings.

What Would You Do if You Received a ShakeAlert Earthquake Early Warning Right Now? The Strategy for Education, Training and Outreach in the Pacific Northwest

TERBUSH, B. R., Washington Emergency Management Division, Washington, USA, brian.terbush@mil.wa.gov

The West Coast ShakeAlert Earthquake Early Warning system is coming to the Pacific Northwest. Buildout of the network to an adequate station density, and ability to alert end users are rapidly progressing, and the system will be available for public rollout within the next couple of years. This is excellent news, and the network improvement efforts have been a huge success. Unfortunately, this progress alone does not paint a complete picture of the requirements for this life-saving technology. To illustrate this point, we ask a simple question: how would the public react right now, if they received an alert on their mobile devices, warning them to "Expect shaking soon. Protect yourself now."? Current public understanding of earthquake protective actions varies significantly between individuals and communities, based on their experience, culture, education, exposure, and a variety of other factors.

Washington State Emergency Management Division and the University of Washington worked with social scientists to develop a more complete understanding of how to implement a successful Earthquake Early Warning System. Information gathering included surveying and interviewing over 150 Emergency Managers, Public safety officials, and technology operators in Washington and Oregon. The results were used to develop a strategy for a fully-realized and successful earthquake early warning system. Success in this system is defined as: an alert being delivered – to both public and technical users – giving enough time for protective actions to be taken, resulting in all end-users taking protective actions, which decrease loss of life, and prevent economic loss. With this definition of success in mind, and stakeholder input, the strategy maps out the path of education, training, and outreach, which must be taken concurrently with station buildout. We share lessons learned through development of this strategy, and detail what has already been accomplished, what still needs to be done, and what you can do to help ensure this system's success in the Pacific Northwest.

Multi-Sensored Small Diameter Cased Borehole for EEW – Turn an EEW Station Into an Greater Capability Long Term Observatory and Monitoring Solution

PARKER, T., Nanometrics Inc., New Mexico, USA, timbobparker@gmail.com; BAINBRIDGE, G., Nanometrics Inc., Kanata, Canada, geoffreybainbridge@nanometrics.ca

As the requirements and science evolves for improved EEW, a more capable infrastructure would enable greater monitoring capabilities. We propose a deeper grouted casing when appropriately using borehole best practices to ensure improved coupling for lower noise high and low frequency recording. Casing emplacements should be a day operation for installation and a subset could be used for the densification of geodetic arrays with only slight modifications by using the wellhead as a monument supporting the antenna as has been demonstrated on some PBO borehole stations. Stations using a new slimline T120PH and dual sensor Cascadia in a single cased hole will add large dynamic range, resiliency and low noise recording that would enable prompt gravity wave observations along with higher sensitivity for local earthquake recording. Dry cased holes are the standard for long term geophysical observatories and a better investment when all the associated costs of operating EEW observatories are considered while recognizing that these networks are in their infancy in the evolution of hazard monitoring best practices.

The State of PNSN and Growth to Meet ShakeAlert Requirements

MEYER, S., University of Oregon, Oregon, USA, smeyer11@uoregon.edu; UW, P., University of Washington, Washington, USA, topo@uw.edu; UO, P., University of Oregon, Oregon, USA, drt@uoregon.edu

The Pacific Northwest Seismic Network (PNSN) is undertaking rapid growth to facilitate implementation of ShakeAlert in Oregon and Washington. Factors driving the build-out of the network include pace of growth and alignment with finite funding cycles, standards for low-latency data, telemetry diversity and topology, robustness of station design, and database management. While many of these factors are certainly not new to seismic network operations, the ShakeAlert requirements are driving revisiting of operational practices.

We will discuss the state of the PNSN, with emphasis on the ShakeAlert program. Description of station design as constrained by the variety of environmental conditions in the Pacific Northwest will be provided. Standardization of station components and data networking architecture will be discussed, with consideration of developing a sustainable network.

We continue to leverage regional resources that work towards a robust, resilient seismic network. Data transport via wireless communication networks in Oregon and Washington will be expanded to reach the last mile links to seismic stations. We partner with fiber networks and other internet service providers to link to our seismic network and to ensure redundancy in data transport. Large utility companies in the public and private sector help identify and host groups of new seismic stations. We value such partnerships to leverage and absorb best practices in operations, all with an eye on seismic network reliability and uptime.

Using Shakealert to Protect Water and Sewer Systems in the Pacific Northwest

STEELE, W. P., University of Washington, Washington, USA, wsteele@uw.edu; ERVIN, D., Varius, Inc., Washington, USA, dan.ervin@variusinc.com

Water and sewer districts are notoriously vulnerable to damage in strong shaking. Damage to these systems have resulted in public health emergencies, limited fire fighting capabilities, and burdened the response community with huge logistical problems to deliver fresh drinking water to affected populations and remove waste. Water and sewer districts have invested in hardened reservoirs, isolation valves, backup power, and other strategies to improve earthquake resilience. Earthquake early warning provides great opportunities to automatically trigger loss reduction additional actions before strong ground motion arrives.

RH2 Engineering and later spin-off company Varius Inc. have integrated ShakeAlert actuated valves, transfer switches and communication systems into the seismic resilience planning and construction projects for Water and Sewer Districts in the Pacific Northwest. Water and Sewer districts are uniquely suitable for implementation of automated loss reduction actions due to a high cost/benefit ratio for system modifications and a low cost of restoration of normal service in the case of false alerts. This talk will discuss the loss preventive actions that are being taken and the collaborative project development process that is helping dozens of utility districts reduce their vulnerability to earthquake losses. Lessons learned in developing these technologies will be applied to other sectors in 2019.

Towards Understanding the Effects of Atmospheric Pressure Variations on Long-Period Horizontal Seismic Data: A Case Study

ALEJANDRO, A. C. B., U.S. Geological Survey, Albuquerque Seismological Laboratory, New Mexico, USA, aalejandro@usgs.gov; RINGLER, A. T., U.S. Geological Survey, Albuquerque Seismological Laboratory, New Mexico, USA, aringler@usgs.gov; WILSON, D. C., U.S. Geological Survey, Albuquerque Seismological Laboratory, New Mexico, USA, dwilson@usgs.gov; ANTHONY, R. E., U.S. Geological Survey, Albuquerque Seismological Laboratory, New Mexico, USA, reanthony@usgs.gov; MOORE, S. V., U.S. Geological Survey, Albuquerque Seismological Laboratory, New Mexico, USA, svmoore@usgs.gov

Seismological studies utilizing long-period (>10 s period), horizontal-component seismic records are often limited by incoherent noise generated by seismometer tilt, induced by variations in atmospheric pressure. Several case studies have suggested methodologies for correcting these unwanted signals using collocated pressure records. However, it is unclear if these corrections are applicable to a variety of different geologic settings and installation types (*e.g.*, vault vs. posthole). To better understand how long-period, pressure-induced noise changes with time and emplacement, we examine the coherence of signals recorded on collocated seismometers and barometers at five different Global Seismographic Network (GSN) stations. We also examine three Streckeisen STS-2 broadband seismometers collocated with a barometer at the Albuquerque Seismological Laboratory (ASL).

We calculate the mean magnitude-squared coherence between seismic and pressure signals from collocated sensors to determine the relationship between them as a function of both frequency and time. In addition to these two varying parameters, coherence levels vary greatly even on collocated seismic instruments. This suggests that tilt-generated signals are highly sensitive to very local (<10 m) site effects, making it difficult to apply pressure corrections to horizontal component seismic data unless the effects of the pressure changes are greater than those from the local site. Additionally, the frequency dependence of the coherence suggests that some corrections may only be applicable over a limited range of frequencies. Using this information, we hope to be able to identify locations that are highly susceptible to pressure-induced horizontal noise, identify locations in a vault where tilt effects can be mitigated, and understand the optimal frequency bands for applying pressure corrections.

A Fault Hazard Based Expected Value Metric for Earthquake Early Warning Seismic Network Stations

BIASI, G., U.S. Geological Survey, California, USA, gbiasi@usgs.gov; STUBAILO, I., Southern California Seismic Network, California Institute of Technology, California, USA, istubailo@gmail.com; ALVAREZ, M., U.S. Geological Survey, California, USA, malvarez@usgs.gov

Funding agencies and network operators are interested in ways to measure the performance benefits from investments in new and existing seismic stations. Biasi and Alvarez (SSA Annual, 2018) showed that the contributions of individual stations and telemetry investments to EEW could be expressed in physically meaningful units using alert time improvement and area of coverage improvement. This work used the alert time calculator of Hotovec-Ellis *et al.* (SRL, 2017). A grid of hypothetical earthquake source points is assumed, and EEW alert times to some central point are then calculated. A candidate new station is added to the original station coverage, and alert times recalculated. The new station decreases time to alert in some area around it. The integral of time improvement over this area has units of km^2-seconds. The impact of station removal (say, due to a maintenance problem) is computed the same way except for the sign of the effect.

The time-area metric can say nothing about whether the station would actually contribute to EEW without some estimate of earthquake activity nearby. The seismic engineering metric of return time is here adapted to add the expected utilization component. The corresponding return time reflects how often the station is expected to contribute to EEW based on the fault hazard.

The approach is readily implemented in California using the fault model and earthquake rupture rates in the Uniform California Earthquake Rupture Forecast v.3 (Field *et al.*, 2014). The return time at a ground level of EEW significance (*e.g.*, peak ground acceleration (PGA) = 5 cm/s/s) is combined with the alert time-area metric to become an expected value in km^2-s/yr. Consistent with intuition, the expected value metric favors stations filling modest holes in a network near high slip rate faults and large holes beside low slip rate faults.

Scsn Advanced System Monitoring and Telemetry Planning Tools

STUBAILO, I., California Institute of Technology, California, USA, istubailo@gmail.com; ALVAREZ, M., U.S. Geological Survey, California, USA, malvarez@usgs.gov; BIASI, G., U.S. Geological Survey, California, USA, gbiasi@usgs.gov; BHADHA, R., California Institute of Technology, California, USA, rayo@gps.caltech.edu; WATKINS, M., California Institute of Technology, California, USA, watkins@gps.caltech.edu; BRUTON, C., California Institute of Technology, California, USA, cpbruton@caltech.edu; HAUKSSON, E., California Institute of Technology, California, USA, hauksson@caltech.edu; THOMAS, V., U.S. Geological Survey, California, USA, vthomas@usgs.gov

The USGS/Caltech Southern California Seismic Network (SCSN) is a modern digital ground motion seismic network. It develops and maintains Earthquake Early Warning (ShakeAlert) data collection and delivery systems in southern California as well as real-time ShakeAlert algorithms.

Here we present recent and ongoing innovations in telemetry, system monitoring, and data analysis that keep the network running efficiently and provide timely high-quality streaming data.

As part of the Earthquake Early Warning (EEW) System, additional stations are currently being installed across Southern California. Before the new stations are added to the pool of sites used for the EEW, they go through a rigorous automated acceptance procedure that covers seismic data analysis, triggering performance, presence of data gaps and glitches, gain evaluations and more.

For more than 350 seismic stations currently installed, we developed tools to automatically monitor the system state of health, data quality control, EPIC algorithm triggering, data transport latency, system security and up to date status, telemetry performance. One of our goals is also improving the telemetry and adding the redundancy for the data paths to maximize the data availability in case of a strong event or outage. We apply the advanced routing techniques to create secure VPN connections, send the second data stream to the Amazon cloud (AWS) for the event detection and ShakeMap generation.

We continue to improve the telemetry path diversity and minimize data transfer latency. As the state funding became available to support the EEW, we are looking to a possibility using the Californian Microwave Tower backbone. The MW network would allow us to reroute data stream from approximately 50 sites currently using cell modems.

New Approaches to Geophysical Research Using Dense Mixed Sensor and Broadband Seismology Arrays

Poster Session · Wednesday · 24 April · Fifth Avenue

Delineating the Near-Surface West Napa Fault in St. Helena, California Using Vp/Vs and Guided Waves

GOLDMAN, M. R., U.S. Geological Survey, California, USA, goldman@usgs.gov; CATCHINGS, R. D., U.S. Geological Survey, California, USA, catching@usgs.gov; CHAN, J. H., U.S. Geological Survey, California, USA, jchan@usgs.gov; PHILIBOSIAN, B., U.S. Geological Survey, California, USA, bphilibosian@usgs.gov; DELONG, S., U.S. Geological Survey, California, USA, sdelong@usgs.gov; SICKLER, R. R., U.S. Geological Survey, California, USA, rsickler@usgs.gov; CRILEY, C. J., U.S. Geological Survey, California, USA, ccriley@usgs.gov

We used Vp/Vs ratios and guided waves to locate the northern extension of the West Napa Fault in St. Helena, California. We acquired two high-resolution, P- and S-wave seismic profiles (Profiles 1 and 2) using multiple hammer hits to generate both P- and S-wave seismic energy along Profile 1 (215 m long) at 109 shot points, each spaced 2 m apart and co-located with the 109 geophones. We also generated additional P-wave energy along Profile 1 at every fifth geophone using a 227-kg accelerated weight drop (AWD). Profile 2 was a shorter (75 m), higher resolution (1 m shot and geophone spacing) profile located about 70 m northward and parallel to Profile 1. For both profiles, we recorded P-wave data using 40-Hz, vertical-component geophones and S-wave data using 4.5-Hz, single-component geophones. The resulting data sets allowed us to develop P- and S-wave refraction tomography and reflection models along the seismic profiles. From the P- and S-wave tomography models, we developed Vp/Vs and Poisson's ratio models that delineate the fault most clearly at about 15 m depth as areas of very high ratios. In addition, we generated guided waves within the fault zone 220 m north of Profile 1 and 150 m north of Profile 2 using the AWD source, and we recorded them with the S-wave geophones. We observed high-amplitude guided waves on both profiles in the vicinity of the fault trace, as shown by the tomography and Vp/Vs ratio models. Our data indicate that the West Napa Fault extends northward into the St. Helena area, but the fault may not extend to shallow (< 10 m) depths, as suggested by the trenching results of (Philibosian *et al.*, 2019).

Geophysical Studies of the Subsurface Structure of the Castle Mountain Fault System, Upper Cook Inlet, Alaska

ZIWU, F. D., The University of Texas at El Paso, Texas, USA, fdziwu@miners.utep.edu; DOSER, D. I., The University of Texas at El Paso, Texas, USA, doser@utep.edu; SCHINAGEL, S. M., Newfield Exploration, Texas, USA, smschinagel@gmail.com

The Castle Mountain fault system (CMFS) lies less than 50 km from Anchorage and represents an important seismic hazard to the Anchorage-Matanuska-Susitna Valley region. The character of seismicity varies along the CMFS. Although its western strand (west of 149.5 W) has produced 4 magnitude > 7 earthquakes within the past 2700 years, it has been seismically quiet over the past 40-50 years. In contrast, the eastern strand is associated with considerable seismicity including the Mw 5.7 1984 Sutton earthquake. We have used gravity and magnetic data, constrained with results of previous seismic reflection and seismic tomography studies, to model subsurface structure of the CMFS from 149 to 151 W. Our models are consistent with high angle reverse faulting (dip~80 degrees) along the CMFS. At the western and eastern ends of our study area the fault system appears to lie at the contact between Cretaceous igneous rock and late Mesozoic sedimentary rock, while in the middle region the fault system appears to have offset late Mesozoic sedimentary rock 1000-2000 m over early Tertiary sedimentary rocks. Comparison of our subsurface models to background seismicity suggest that both the bedrock geology and location of the southwestern edge of the Yakutat microplate influence the current seismic behavior of the CMFS.

Evolution of the IRIS Portable Facility: New Tools for Wavefield Imaging, Rapid Response and Magnetotellurics

SWEET, J. R., Incorporated Research Institutions for Seismology, New Mexico, USA, justin.sweet@iris.edu; ANDERSON, K., Incorporated Research Institutions for Seismology, New Mexico, USA, kent@iris.edu; FRASSETTO, A. M., Incorporated Research Institutions for Seismology, District of Columbia, USA, andyf@iris.edu; BEAUDOIN, B. C., Incorporated Research Institutions for Seismology, PASSCAL Instrument Center, New Mexico, USA, bruce@passcal.nmt.edu; BILEK, S., New Mexico Institute of Mining and Technology, New Mexico, USA, susan.bilek@nmt.edu; WOODWARD, R. L., Incorporated Research Institutions for Seismology, District of Columbia, USA, woodward@iris.edu

As IRIS embarks upon a new 5-year cooperative agreement with NSF titled the Seismological Facilities for the Advancement of Geosciences (SAGE), the PASSCAL portable facility will undergo several important changes to enhance the capabilities it provides to Principal Investigators (PIs) conducting portable deployments.

The most immediate change to the portable instrumentation pool will be the addition of hundreds of nodal-style sensors. These all-in-one systems combine the sensor, datalogger, GPS timing, and power in a small self-contained unit with the ability to record continuously for up to a month without battery replacement or recharge. In comparison to the aging Texan pool, these nodes represent a technological leap that will enable new kinds of portable deployments (*e.g.* rapid response, Large N, full-wavefield characterization) with significantly less logistical effort. IRIS/PASSCAL now has approximately 500 of these nodes available for community use, with plans to exceed 1,000 nodes within the next few years.

IRIS also plans to build a new pool of intermediate-period sensors that can record data with low noise and high fidelity from 10s of Hz to 10s of seconds. These intermediate-period sensors are smaller, cheaper, and easier to deploy than traditional broadband sensors in use today, making them ideal for source studies in remote or challenging areas. IRIS/PASSCAL is planning for this pool to grow over the next five to ten years to as many as 400 systems.

IRIS will enhance capabilities for investigators to respond to geo-hazards with a pool of nodal and intermediate period instruments that will be set aside for fast response work and may incorporate telemetry systems for monitoring.

Lastly, IRIS is planning to establish a new pool of magnetotelluric (MT) systems at the PASSCAL Instrument Center, leveraging PASSCAL expertise to facilitate new multidisciplinary geophysical investigations. This effort will provide centralized and maintained access to several dozen long period and, eventually, wideband MT systems to support PI-led campaigns.

Velocities and Upper Crustal Structure of the Hayward Fault Zone: Results From the 2016 East Bay Seismic Experiment

STRAYER, L. M., California State University, East Bay, California, USA, luther.strayer@csueastbay.edu; CATCHINGS, R. D., U.S. Geological Survey, California, USA, catching@usgs.gov; CHAN, J. H., U.S. Geological Survey, California, USA, jchan@usgs.gov; RICHARDSON, I. S., California State University, East Bay, California, USA, ian.richardson@csueastbay.edu; MCEVILLY, A. T., California State University, East Bay, California, USA, adrian.mcevilly@csueastbay.edu; GOLDMAN, M. R., U.S. Geological Survey, California, USA, goldman@usgs.gov; CRILEY, C. J., U.S. Geological Survey, California, USA, ccriley@usgs.gov; SICKLER, R. R., U.S. Geological Survey, California, USA, rsickler@usgs.gov

The 2016 East Bay Seismic Investigation (EBSI-16) was designed to examine the greater Hayward Fault Zone (HFZ) and the San Leandro Block (SLB) that defines the block'score near San Leandro, California. The EBSI-16 data allowus to examine the subsurface of the entire East Bay plain and a wide swath of the East Bay hills using a variety of seismic methods. We deployed vertical- and horizontal-component seismographs, spaced at 100 m intervals along a 15-km-long, ~55°-trending profile from the East Bay Shore to the eastern East Bay hills, centered on the active trace of the Hayward Fault (HF). Where the profile crossed known or suspected faults, we deployed closely-spaced (20-m) vertical-component seismographs to better locate these faults with multiple seismic methods. Seismic energy was generated by buried explosions (up to 45 kg) spaced at ~1-km intervals. From the data, we developed refraction tomography images of the HFZ to depths of 5–6 km for *Vp*and ~2 km for *Vs*. Our *Vp*images show that the San Leandro Block (SLB) is a low-velocity structure in the upper ~1 km, with nearly the same *Vp*as the adjacent Great Valley sediments to the east. Deeper (>1 km) *Vp*and *Vs*images show high velocities and significant basement topography within the SLB, west of the active trace of the HF, and beneath much of the East Bay plain. Shallow depth (<1 km) *Vp/Vs*and Poisson's ratio images imply several fault zones east of the active trace of the HF, which is consistent with known splay faults of the HFZ. At >1 km depth near the western end of our profile, we observe a *Vp/Vs*anomaly (~3.2) that far exceeds anomalies within the HFZ, including the active trace of the HF (~2.2). The westernmost *Vp/Vs*anomaly is near-vertical and is on-strike with the northward projection of the Silver Creek Fault, which trends through downtown San Jose and parts of the East Bay toward our seismic profile. The EBSI-16 data provide the best constraints on upper crustal *Vp*(1900 – 5750 m/s), *Vs*(700 – 3100 m/s), and structure of the HFZ to date.

High Resolution Imaging of the San Andreas Fault System in Baja California Using Triple-Difference Tomography

SHARE, P., Scripps Institution of Oceanography, University of California, San Diego, California, USA, pshare@ucsd.edu; CASTRO, R. R., Center for Scientific Research and Higher Education of Ensenada, Ensenada, Mexico, raul@cicese.mx; VIDAL, A., Center for Scientific Research and Higher Education of Ensenada, Ensenada, Mexico, vidalv@cicese.mx; MENDOZA, L., Center for Scientific Research and Higher Education of Ensenada, Ensenada, Mexico, lmendoza@cicese.mx; BEN-ZION, Y., University of Southern California, California, USA, benzion@usc.edu

Understanding transform plate boundary processes and the associated seismic hazard for society requires knowledge of the geometry and material properties along major faults comprising these boundaries. While high-resolution structural properties of the San Andreas Fault System (SAFS) in Southern California have been obtained through various geoscientific studies, corresponding information for the SAFS in northern Baja California is less clear. Deriving high-resolution velocity models for the southern portion of the SAFS in Baja California is important for understating properties and processes of the plate boundary. Toward this goal, we image the seismogenic crust in the area at high-resolution using arrival time tomography that incorporates both station-pair and event-pair double differences (triple-difference tomography). The study uses arrival time data of local earthquakes and stations from the Seismological Network of CICESE (*Centro de Investigación Científica y de Estudios Superiores de Ensenada, Baja California, México*) and southern stations of the Southern California Seismic Network. The addition of station-pair data allows for better absolute event locations and higher model resolution near the surface. In total, ~120,000 P-wave and ~75,000 S-wave arrivals recorded by >150 stations from >10,000 events (from 2007-2018) are incorporated in the tomographic inversion. Initial tomographic results with interpretations on the geometries and material properties of major faults in northern Baja California will be presented at the meeting.

Time-Dependent Earthquake Tomography in Southern California

HU, J., University of Science and Technology of China, Hefei, China, jhsa26@mail.ustc.edu.cn; SHARE, P., University of California, San Diego, California, USA, pshare@usc.edu; QIU, H., University of Southern California, California, USA, hongruiq@usc.edu; ZHANG, H., University of Science and Technology of China, Hefei, China, zhang11@ustc.edu.cn; BEN-ZION, Y., University of Southern California, California, USA, benzion@usc.edu

Temporal changes of seismic velocities have been determined through analysis of earthquake and ambient noise data in Southern California and other place, but there is limited understanding about the spatial distribution and amplitudes of these changes. In this study, we apply a new time-dependent earthquake tomography algorithm to monitor systematically 3-D velocity perturbations in the Southern California crust. The employed time-lapse double-difference tomography method utilizes differential times between two nearby earthquakes that occurred at different times. We use P picks of earthquake arrival times from 2000 to 2016 recorded at 285 stations in a region spanning longitudes 242o – 246o and latitudes 32o – 35o. The 16 year time span is separated into 98 intervals, each containing 1000 events, and velocity changes are monitored between successive time intervals. We first perform standard double-difference tomography at each time period to obtain a 3D P-wave velocity model using the CVM-H15.1 as the initial model. To analyze velocity changes between subsequent intervals, we use the inverted 3-D P-wave velocity model and associated relocated earthquakes of the earlier interval as initial model and event locations. Through trial and error, we find that horizontal grid size of 10 km and a depth grid setting of 0, 4, 7, 10, 13, 20, and 40 km lead to robust results. The obtained models include significant apparent velocity changes in the source region of the 2010 Mw 7.2 El Mayor – Cucapah earthquake, both before and after the event. We plan to incorporate differential times between station pairs in the time-lapse algorithm to increase the resolution of shallow structures. These and other updates will be presented in the meeting.

Installation and Performance of a Small Aperture Posthole Array at Albuquerque Seismological Laboratory

ANTHONY, R. E., U.S. Geological Survey, New Mexico, USA, reanthony@usgs.gov; RINGLER, A. T., U.S. Geological Survey, New Mexico, USA, aringler@usgs.gov; WILSON, D. C., U.S. Geological Survey, New Mexico, USA, dwilson@usgs.gov; RODD, R. L., KBRwyle, New Mexico, USA, rrodd@contractor.usgs.gov; MAHARREY, J. Z., KBRwyle, New Mexico, USA, jzmaharrey@contractor.usgs.gov

The ability to detect and characterize seismic events is fundamentally limited by background noise levels at seismic stations across a given network. Such noise arises from both self-noise of the sensors as well as from local (< 10 m) site effects related to both the installation methodology and geographical setting. As improvements in the noise floor of seismic instruments have been small and incremental over the past few decades, new techniques for sensor emplacement must be developed to drive continued improvement in event detection. We investigate the potential of using stacking and other array processing techniques across a 10-element, 500 m aperture array at the U.S. Geological Survey Albuquerque Seismological Laboratory (ASL) to reduce station noise levels and improve event characterization.

The array was formed by supplementing the primary and secondary borehole sensors at the Global Seismographic Network (GSN) station ANMO and the ASL underground reference vault sensor with seven additional posthole sensors. The sites for each array element were selected such that each 2.5 m, cased posthole would be installed within Precambrian granite, could be accessible to the IRIS Transportable Array Alaska drilling rig towed behind a truck, and would provide complete azimuthal coverage within the footprint of the ASL land lease. As these sites are located far away from power and network connections, each station is powered by a 220W solar system and data is telemetered in real-time using wireless bridges. Small aperture arrays constructed similarly to this at select stations across the GSN may have the ability to improve the monitoring capabilities of the network. Here, we report some initial observations from the array including examining local sources of seismic noise and how they may be influenced by local geographic effects such as buildings and topography.

Seismic Fault Exploration in Urban Fault Zones, Los Angeles, California

CATCHINGS, R. D., U.S. Geological Survey, California, USA, catching@usgs.gov; HERNANDEZ, J. L., California Geological Survey, California, USA, janis.hernandez@conservation.ca.gov; OLSON, B. P. E., California Geological Survey, California, USA, brian.olson@conservation.ca.gov; GOLDMAN, M. R., U.S. Geological Survey, California, USA, goldman@usgs.gov; CHAN, J. H., U.S. Geological Survey, California, USA, jchan@usgs.gov; SICKLER, R. R., U.S. Geological Survey, California, USA, rsickler@usgs.gov; CRILEY, C. J., U.S. Geological Survey, California, USA, ccriley@usgs.gov

The main traces of the Hollywood, Raymond, and Santa Monica faults in Los Angeles, California have been identified in several locations on the basis of geologic mapping, paleoseismic trenching, and boreholes, but there are also many locations where the main and auxiliary fault traces are not well determined. Locating fault traces is an important requirement of California's Alquist-Priolo Fault Zoning Act, which limits building on surface fault ruptures. To more precisely locate individual traces of the Hollywood fault, in June 2018, the US Geological Survey (USGS) and the California Geological Survey (CGS) jointly conducted a series of seismic imaging investigations using V_P and V_S tomography (including V_P/V_S ratio and Poisson's ratios), seismic reflection, surface-waves (MASW), and guided waves. Each of the seismic imaging methods identified an anomaly over a narrow zone (~20 m) identified as the main fault based on a series of borings. Using guided-wave peak ground velocities (PGV), we narrowed the location of the near-surface (upper few meters) fault trace to an ~2-m-wide zone, which was also consistent with the borings. The 2018 seismic study was one of several USGS-CGS collaborative seismic imaging studies that have successfully located fault traces along the Raymond, Hollywood, and Santa Monica faults in highly urbanized Los Angeles, and the USGS has also used these seismic methods along other major fault zones. We find that the guided-wave PGV method is effective in fault-trace mapping in both rural and urban areas and can be an excellent, less-expensive alternative to invasive exploratory methods, such as trenching and boring. However, the seismic methods do not provide critical slip information or dates, which can only be obtained from paleoseismic methods.

Photonic and Non-Inertial Seismology

Poster Session · Wednesday · 24 April · Fifth Avenue

Towards Multi-Observational Full-Waveform Inversion

PAITZ, P., ETH Zurich, Zürich, Switzerland, patrick.paitz@erdw.ethz.ch; SAGER, K., ETH Zurich, Zürich, Switzerland, korbinian.sager@erdw.ethz.ch; SCHMELZBACH, C., ETH Zurich, Zürich, Switzerland, cedric.schmelzbach@erdw.ethz.ch; DOETSCH, J., ETH Zurich, Zürich, Switzerland, joseph.doetsch@erdw.ethz.ch; CHALARI, A., Silixa Ltd, London, United Kingdom, athena.chalari@silixa.com; FICHTNER, A., ETH Zurich, Zürich, Switzerland, andreas.fichtner@erdw.ethz.ch

With the benefit of high spatial and temporal sampling even in remote and urban areas using existing fiber-optic infrastructure, Distributed Acoustic Sensing (DAS) has the potential to revolutionise seismological data acquisition on multiple scales across the Earth.

By combining (1) theoretical, (2) numerical and (3) experimental investigations, we want to underline the strengths and weaknesses of DAS and present a "roadmap for DAS in seismology", with the ultimate goal being a full waveform inversion workflow that can combine all observed quantities (*e.g.* strain, displacement and rotation) at once.

(1) In the theoretical part, we demonstrate that existing seismological applications need to be adapted to a variety of newly emerging observational quantities, using the example of ambient noise interferometry. Specifically, we investigate how seismic interferometry may be used with newly emerging DAS data. We extend the theory of seismic interferometry to a variety of observational quantities with the focus on strain and strain rate - such as obtained from DAS systems.

(2) Using 3D spectral-element simulations based on the high-performance wave propagation software Salvus we implement the new theoretical framework.

At this early stage, it serves to investigate the impact of heterogeneous ambient noise sources and different measurements on the simulated interferograms and their sensitivity to Earth structure.

(3) The third part consists of a series of DAS experiments from a tunnel system in the Grimsel Rock Laboratory in southern Switzerland. This is intended to assess the quality of DAS data in a broad range of frequencies, including earthquake recordings from regional to global scale, ambient noise recordings and a wide range of active seismic experiments.

While the goal of multi-observable full-waveform inversion is not within reach yet, first results are promising and underline the great potential and possible impact that the recent advances in instrumentation could have on seismology across all scales.

Distributed Fiber-Optic Sensing on Infrastructure Installations

KARRENBACH, M., OptaSense, California, USA, martinkarrenbach@att.net; COLE, S., OptaSense, California, USA, steve.cole@optasense.com; MINTO, C., OptaSense, Farnborough, United Kingdom, chris.minto@optasense.com; GODFREY, A., OptaSense, Farnborough, United Kingdom, alastair.godfrey@optasense.com

Distributed Fiber-optic Sensing interrogator units can utilize either already existing or temporarily deployed fiber-optic cables to sense ground motion or subsurface strain. To date the main applications for DAS have focused on oil and gas reservoir monitoring and pipeline integrity monitoring. In general, infrastructure has telecommunication grade fiber optic cables embedded for a variety of other primary purposes. These cables can be interrogated to obtain information about the surrounding or the subsurface medium. The coupling of the fiber to the medium is often highly variable, manifesting itself in spatially variable stain transduction onto the fiber. A strain tensor projection as part of the more complicated transfer function. However, the transfer function is typically highly consistent over time for a given spatial location. Such transduction models are focus of ongoing research in the community. We will be showing a variety of data examples where we observed small, regional or tele-seismic earthquakes, as well as fluid and wind flow patterns across an infrastructure embedded fiber onshore and offshore. DAS as a passive photonic sensing system has the advantage that power is needed only at the interrogator location, while the fiber providing the sensor locations can be placed in hostile environments and left on site indefinitely. In contrast to point sensors telemetering their data back to a central collection site, the large number of fiber-based sensors (thousands to tens of thousands on a single fiber) lend itself to multi-channel processing techniques which can be provided on site as part of the interrogation system. This fits the edge computing model, where compute intensive analysis is performed locally near-real-time with relevant data and results are collected centrally.

Quantitative Assessment of Earthquake Detection Capability of DAS, MEMS and Broadband Networks in Pasadena, CA

LI, Z., California Institute of Technology, California, USA, zefengli@gps.caltech.edu; ZHAN, Z., California Institute of Technology, California, USA, zwzhan@gps.caltech.edu; KOHLER, M. D., California Institute of Technology, California, USA, kohler@caltech.edu; HAUKSSON, E., California Institute of Technology, California, USA, hauksson@caltech.edu

Low-cost sensors have been increasingly used in the seismological community in recent years, thanks to advances in seismic instrumentation such as nodal sensors, distributed acoustic sensing (DAS), and microelectromechanical systems (MEMS). These new technologies provide unprecedented dense coverage in study areas, however at the expense of lower resolution on individual sensors. Therefore, it is important to quantitatively evaluate their detection capability and understand the advantages and limitations, especially when compared to current state-of-the-art broadband networks. Here, we systematically evaluate the earthquake detection capability of three different instruments, the Pasadena DAS array (optic fiber), Community Seismic Network (MEMS), and the Southern California Seismic Network stations (Broadband) in Pasadena. First, we quantify the visibility of cataloged local earthquakes on individual sensors and obtain the observation limits for the three instruments. Second, we evaluate the detectability of whole arrays by stacking the characteristic functions of these earthquakes and computing their stack significance level. Finally, we investigate the improvement on local earthquake location to demonstrate the benefit from a large number of sensors.

How Broadband is DAS? Two Empirical Evaluations of Instrument Response

LINDSEY, N. J., University of California, Berkeley, California, USA, natelindsey@berkeley.edu; RADEMACHER, H., University of California, Berkeley, California, USA, horst@berkeley.edu; DREGER, D. S., University of California, Berkeley, California, USA, ddreger@berkeley.edu; TITOV, A., Colorado School of Mines, Colorado, USA, alekseititov@mymail.mines.edu; AJO-FRANKLIN, J. B., Lawrence Berkeley National Laboratory, California, USA, jbajo-franklin@lbl.gov

Distributed Acoustic Sensing (DAS) is a novel form of array seismology that has been shown to resolve decameter-scale ground motions over tens of kilometers. DAS measures the optical phase change of laser pulses traveling inside of a fiber-optic cable, which can be related to the strain acting along a portion of the fiber. The combination of DAS and excess telecommunications infrastructure – so-called “dark fiber seismology” – can be used to address a diversity of earth science questions where access, security, field logistics, and cost have historically hindered seismic observation. However, DAS instrument response has not been disclosed with the commercial instruments and thus is poorly understood. Here we probe the instrument response of one instrument, the Silixa iDAS, in the field and lab. In the field experiment, an iDAS was connected to one single-mode fiber inside of an unused telecommunications fiber-optic cable. This experiment measured horizontal strains over 20-km at a 2-m channel spacing, and the volumetric flow rate of data was ~8 TB/week. A Guralp CMG-3T broadband inertial seismometer with a well-characterized instrument response function was installed near a portion of the fiber, presenting an opportunity to compare DAS ground motion estimates with a classic inertial seismometer. Using data from five different M>7 teleseismic earthquakes, we investigated instrument response in the 0.01 – 0.5 Hz frequency range. In a second experiment, we used a mechanical fiber cable stretcher in the laboratory to simulate strain with 0.01 - 0.1 Hz signal frequency, and measured this strain with the iDAS. We explain results in terms of the photonic measurement, azimuthal sensitivity to particle motion, and fiber-soil coupling.

High-Resolution Mapping and Monitoring of Shallow Shear-Wave Velocity in Urban Pasadena with Distributed Acoustic Sensing

WILLIAMS, E. F., California Institute of Technology, California, USA, efwillia@gps.caltech.edu; ZHAN, Z., California Institute of Technology, California, USA, zwzhan@gps.caltech.edu; KARRENBACH, M., OptaSense, California, USA, martin.karrenbach@optasense.com; COLE, S., OptaSense, California, USA, steve.cole@optasense.com; LAFLAME, L., OptaSense, California, USA, lisa.laflame@optasense.com

We excite resonance of Caltech’s Millikan Library between 0.8 and 5 Hz using a specialized shaker installed on the roof of the nine-story building and record monochromatic Rayleigh waves generated by the building along the Pasadena Array. Operating almost continuously since May 2018, the Pasadena Array utilizes distributed acoustic sensing (DAS) technology to convert a >25-km optical fiber, originally installed by the city of Pasadena for telecommunications use, into a dense array of >5000 linear strainmeters. Rayleigh wave velocity at each frequency is computed from observed phase lag between any pair of stations, and then inverted to form a continuous shear-wave velocity model throughout the city with lateral resolution between 1 and 10 m. We benchmark our model with velocities calculated at coarser resolution from ambient noise correlation functions. Throughout Pasadena, Vs30 varies as much as 40 percent across spatial scales of less than 10 m, suggesting that current stochastic models of near-surface elastic heterogeneity may significantly underestimate the intensity of fractal randomness at large wavenumbers. Because measurement uncertainty decreases with shaking duration at each frequency and the Millikan Library source is fully repeatable, we are capable of high-precision time-lapse monitoring of shallow velocity structure. With new DAS arrays being installed throughout Southern California in 2019, the methods we demonstrate are designed to be generalizable, permitting robust, non-invasive, low-cost estimation of shear-wave velocity on a block-by-block scale in urban areas and hence a revolution of scale in the accuracy of ground motion predictions.

Preliminary Analysis of Distributed Acoustic Sensing at the Kafadar Commons Geophysical Laboratory

TRAINOR, W. J., Colorado School of Mines, Colorado, USA, wtrainor@mines.edu; TITOV, A., Colorado School of Mines, Colorado, USA, alekseititov@mymail.mines.edu; LAFLAME, L., OptaSense, California, USA, lisa.laflame@optasense.com; SULLIVAN, B., Colorado School of Mines, Colorado, USA, chrsulli@mymail.mines.edu; HANNUM, C., Colorado School of Mines, Colorado, USA, channum@mymail.mines.edu; HUXEL, Z., Colorado School of Mines, Colorado, USA, zhuxel@mymail.mines.edu; BINDER, G., Colorado School of Mines, Colorado, USA, gabinder@mines.edu; COLE, S., OptaSense, California, USA, steve.cole@optasense.com; KARRENBACH, M., Optasense, California, USA, martin.karrenbach@optasense.com

The Kafadar Commons geophysical lab located centrally on the Colorado School of Mines campus was created to inspire and provide geophysics students with

known buried targets including UXO, archaeological walls, and a dipping concrete wall, among others. Additionally, about 1 km of fiber-optic cable was buried in an approximate rectangular shape of 30m by 90m. For the distributed acoustic sensing (DAS) recording we use an OptaSense ODH3.1 interrogator unit. Ambient recordings began approximately on November 27, 2018 and have continued through January 8, 2019, with some intermittent downtimes. During this time, a local earthquake sequence in Glenwood Springs (~100 miles west of the Mines campus) was recorded, and hammer-source seismic surveys with collocated geophones have been acquired.

We will present the DAS data processing, geometry assignment, and 3D visualizations of both the active and passive data collected thus far, and the feasibility of surface-wave analysis. Data processing includes bandpass filtering in several frequency ranges and despiking. Frequency-band data can be used to analyze different seismic events (from teleseismic to near-surface seismic reflection data). We use two approaches for geometry assignment. The first is the analysis of the recorded data from vehicular/pedestrian traffic, and localizing the rotation points of the cable. The second uses hammer tap-test recordings. Visualizations in 3D will provide an intuitive representation of how observed wavefields are traveling across the DAS array through time. We will also present preliminary results of using an outlier-detecting algorithm to identify these events automatically.

Small Giant Gyroscope: BlueSeis_1c, Ultimate but Affordable Ground Rotation Sensor

GUATTARI, F., iXblue, Saint-Germain-En-Laye, France, frederic.guattari@ixblue.com; LAUDAT, T., iXblue, Saint-Germain-En-Laye, France, theo.laudat@ixblue.com; DE TOLDI, E., iXblue, Saint-Germain-En-Laye, France, elliot.de-toldi@ixblue.com; JOLLY, O., iXblue, Saint-Germain-En-Laye, France, olivier.jolly@ixblue.com; LEFÈVRE, H., iXblue, Saint-Germain-En-Laye, France, herve.lefevre@ixblue.com

Rotational seismology starts in laboratory thanks to Giant Ring Laser Gyroscope (RLG), and then have been brought to the field thanks to portable sensor blueSeis_3A made of Fiber-Optic Gyroscope (FOG). However, all the applications where rotation measurements can bring a strong benefit are not addressed by these two available technologies. There is a gap to fill between ultimate precision reached by large, costly, and static RLG, and compact, portable 3C FOG.

iXblue has carried out an important development called 'GiantFOG' to study the limit of its design targeting ultimate performances, leading to sensors mockup up to metric scale. These developments first, help us to improve our knowledge to reach higher performances, and second, to better understand the need of potential users. It appears that in the large scope of applications in this middle-range of performance, the need to have 3-component is less important than the possibility to integrate the sensor inside complex system (vaccum, size limitation, porthole access, thermal stability).

Consequently, the product we designed in this middle range, named blueSeis_1C, is a single axe, where the electronic boards (3W) can be up to 3meters away from cold (<100 W) sensor head, and the sensor coil is not gigantic, even not large, but only 40cm diameter, with empty space at this center. Same electronic board will be able to accept up to 3 remote sensor axis, leading to a total power consumption of 3W for 1 axis and 6W for 3 axis. Typical self-noise of this sensor will be 4-times better than blueSeis_3A reaching 5nrad/s/sqrt(Hz).

The Science of Slow Earthquakes from Multi-Disciplinary Perspectives

Poster Session · Wednesday · 24 April · Grand Ballroom

Earthquake Swarms and Slow Slip on a Sliver Fault in the Mexican Subduction Zone

FASOLA, S., Miami University, Ohio, USA, fasolasl@miamioh.edu; BRUDZINSKI, M. R., Miami University, Ohio, USA, brudzimr@miamioh.edu; HOLTKAMP, S. G., University of Alaska Fairbanks, Alaska, USA, sgholtkamp@alaska.edu; GRAHAM, S. E., Boston College, Massachusetts, USA, shannon.graham@bc.edu; CABRAL-CANO, E., Universidad Nacional Autónoma de México, Mexico City, Mexico, ecabral@geofisica.unam.mx; SKOUMAL, R. J., U.S. Geological Survey, California, USA, rskoumal@usgs.gov

The Mexican Subduction Zone is an ideal location for studying subduction processes due to the short trench-to-coast distances that bring broad portions of the seismogenic and transition zones of the plate interface inland. Using a recently generated seismicity catalog from a local network in Oaxaca, we identified 20 swarms of earthquakes (M<5) from 2006-2012. Swarms outline what appears to be a steeply dipping structure in the overriding plate, indicative of an origin other than the plate interface. This steeply dipping structure corresponds to the northern boundary of the Xolapa terrane. In addition, we observed a new characteristic of slow slip events (SSEs) where they showed a shift from trenchward motion towards an along-strike direction at coastal GPS sites. A majority of the swarms were found to correspond in time to the along-strike shift. We propose that swarms and along-strike SSEs are occurring on a sliver fault that allows the oblique convergence to be partitioned into trench-perpendicular motion on the subduction interface and trench-parallel motion on the sliver fault. The low resistivity structure surrounding the sliver fault suggests that SSEs and swarms of earthquakes occur due to high pore fluid pressures in the fault zone. We propose that the sliver fault provides a natural pathway for buoyant fluids attempting to migrate upward after being released from the downgoing plate. Thus, sliver faults could be responsible for the downdip end of the seismogenic zone by creating drier conditions on the subduction interface trenchward of the sliver fault, fostering velocity weakening seismogenic behavior.

Seafloor Borehole Observation Network in the Nankai to Observe Slow Slip Events and Slow Earthquakes

ARAKI, E., Japan Agency for Marine-Earth Science and Technology, Yokosuka, Japan, araki@jamstec.go.jp; KIMURA, T., Japan Agency for Marine Earth Science and Technology, Yokosuka, Japan, kimurat@jamstec.go.jp; MACHIDA, Y., Japan Agency for Marine Earth Science and Technology, Yokosuka, Japan, ymachida@jamstec.go.jp; YOKOBIKI, T., Japan Agency for Marine Earth Science and Technology, Yokosuka, Japan, yokobikit@jamstec.go.jp; NISHIDA, S., Japan Agency for Marine Earth Science and Technology, Yokosuka, Japan, shuheinishida@jamstec.go.jp; KODAIRA, S., Japan Agency for Marine Earth Science and Technology, Yokohama, Japan, kodaira@jamstec.go.jp

Shallow part of the Nankai subducting plate interface is under the sea. Shore based observation is not sensitive to slow slip events there. Observation in IODP seafloor borehole has revealed existence of shallow slow slip events which repeats at relatively short time intervals (Araki *et al.*, 2017). GPS/A observation by Japan Coast Guard has also detected shallow slow slip event in 2017-2018 in other part of the Nankai Trough, which may be larger in magnitude and longer in slip duration than those observed by the borehole observation. Currently, distribution of areas of such slow slip events, duration and recurrence interval of larger slow slip are not clear. Interval of few times a year with GPS/A observation is infrequent to capture slow slip events. Borehole observation is much more sensitive than GPA/A, but currently distributed in dense linear array, and is not suitable to watch wide area. As we have already infrastructure, seafloor cabled observation network (DONET) that can distribute and connect new observatories in wide area, we are working to add borehole observatories which has enough sensitivity to observe slow slip events as expected from past observations. In addition to three working IODP deep borehole observatories (C0002, C0010, C0006), we plan to install a shallow hole observatory with a tiltmeter in 2019 to form SSE observation areal network in the east of the borehole array. The new borehole is shallower than 20m but expected to provide quiet enough observation environment to capture known magnitude SSEs. Another shallow hole observatory with similar configuration is planned near the area of the SSE observation by GPS/A in 2019-2020. Further deep borehole observatory installation is also considered, in which cost is reduced by simpler observation system with fiber-optic broadband strainmeter array and pore-fluid pressure sensor.

Numerical Modeling of Long- and Shallow Slow Slip Events Including Shallow Region in Hyuganada and Western Nankai, Japan

MATSUZAWA, T., National Research Institute for Earth Science and Disaster Resilience, Tsukuba, Japan, tkmatsu@bosai.go.jp; SHIBAZAKI, B., Building Research Institute, Tsukuba, Japan, bshiba@kenken.go.jp

Deep long-term slow slip events (SSEs) are newly found in the Hyuganada and western Nankai region in recent years (*e.g.*, Kobayashi, 2014; Ozawa. 2017). Shallow SSEs are also recently reported with low-frequency tremor and very low-frequency earthquakes (*e.g.*, Araki *et al.*, 2017; Nakano *et al.*, 2018). In our previous study, we have numerically reproduced recurring deep long- and short-term SSEs in the Shikoku region (Matsuzawa *et al.*, 2013), considering the actual distribution of slow earthquakes and configuration of subducting plate. We aim to reproduce deep long- and short-term SSEs and shallow SSEs in a single numerical model applying a similar approach in Matsuzawa *et al.* (2013).

We adopt a rate- and state-dependent friction law (RS-law) with cutoff velocities. We assume that (a-b) value in the RS-law is negative within the SSE region, and positive outside the region. Deep short-term SSE region is modeled based on the actual distribution of low frequency tremor. Deep long-term SSE region is assumed based on the geodetic observation. We also assumed low cut-off velocity at the depth shallower than 9 km to reproduce shallow SSEs. Low effective normal stress is assumed at the depth of SSEs. Temporal evolution of slip velocity is numerically simulated, introducing elastic response and realistic configuration of the plate interface.

In our simulation, shallow episodic SSEs off Ashizuri are reproduced. This suggests that the configuration of plate interface can characterize the occurrence of shallow SSEs. In terms of deep long-term SSEs in Hyuganada, a simple extension of the long-term SSE region in the Bungo Channel cannot reproduce the segments of observed SSEs. Narrowed long-term SSE region in the dip direction between Bungo and southern Hyuganada can reproduce the segments of SSEs. Our model comprehensively reproduces various SSEs, including newly found long-term SSEs which seem to occur commonly in the subduction zone of southwestern Japan. Moreover, when our model is simply applied to the Cascadia region, long-term SSEs are also predicted.

Quantitative Relationship Between Aseismic Slip Propagation Speed and Frictional Properties

ARIYOSHI, K., Japan Agency for Marine-Earth Science and Technology, Yokohama, Japan, ariyoshi@jamstec.go.jp; AMPUERO, J., Université Côte d'Azur, IRD, CNRS, Observatoire de la Côte d'Azur, Géoazur, France, ampuero@gps.caltech.edu; BÜRGMANN, R., University of California, Berkeley, California, USA, burgmann@seismo.berkeley.edu; MATSUZAWA, T., Research Center for Prediction of Earthquakes and Volcanic Eruptions, Graduate School of Science, Tohoku University, Sendai, Japan, toru.matsuzawa.c6@tohoku.ac.jp; HASEGAWA, A., Research Center for Prediction of Earthquakes and Volcanic Eruptions, Graduate School of Science, Tohoku University, Sendai, Japan, akira.hasegawa.d8@tohoku.ac.jp; HINO, R., Research Center for Prediction of Earthquakes and Volcanic Eruptions, Graduate School of Science, Tohoku University, Sendai, Japan, hino@m.tohoku.ac.jp; HORI, T., Japan Agency for Marine-Earth Science and Technology, Yokohama, Japan, horit@jamstec.go.jp

Recent observations show evidence of the propagation of slow slip transients, including postseismic slip as a slow earthquake family, and expanding aftershock areas. Here, we develop a new analytical relationship between the propagation speed of aseismic slip transients and frictional properties of the fault, modeled by a rate- and state-dependent friction law. The relationship explains the propagation speed of slow slip in 3-D numerical simulations to first order, except near the earth's surface. Based on this relationship, we identify systematic dependencies of slow slip propagation speed on effective normal stress σ and frictional properties (the coefficients a and a-b which quantify the instantaneous and the steady-state velocity-dependence of friction, respectively, and the characteristic slip distance d_c of fault state evolution). Lower values of the parameter $A = a\sigma$ cause faster propagation in areas where the passage of the postseismic slip front induces large shear stress changes $\Delta\tau$ compared to A. In areas where $\Delta\tau/A$ is small, slow-slip propagation speed is more sensitive to $(a\text{-}b)\sigma$. The propagation speed is inversely proportional to d_c. The relationship developed here should be useful to constrain the frictional properties of faults based on observed propagation speeds, independently of rock laboratory experiments, which can then be used in predictive numerical simulations of aseismic slip phenomena.

Long-Range Dependence in Low-Frequency Earthquakes Catalogs?

DUCELLIER, A., University of Washington, Washington, USA, ariane.ducellier.pro@gmail.com; CREAGER, K. C., University of Washington, Washington, USA, kcc@uw.edu

Long-range dependence is a phenomenon that may arise in the statistical analysis of time series data. It relates to the slow rate of decay of the statistical dependence between two points with increasing time interval between the points. Evidence of long-range dependence has been found in regional and global earthquake catalogs, and in catalogs of mining-induced seismicity. Low-frequency earthquakes (LFEs) are small magnitude earthquakes, with typical magnitude less than 2, and reduced amplitudes at frequencies greater than 10 Hz relative to ordinary small earthquakes. Their occurrence is often associated with tectonic tremor and slow slip events along the plate boundary in subduction zones and occasionally transform fault zones. They are usually grouped into families of events, with all the earthquakes of a given family originating from the same small patch on the plate interface, and recurring more or less episodically in a bursty manner. In this study, we analyze catalogs of LFEs from the Olympic Peninsula, Northern California, Mexico, and the San Andreas Fault. For each family of LFEs, we translate the catalog into a continuous time series defined by number of events per minute. The sample interval is 1 minute. Then, we compute the value of the fractional parameter d, which represents how fast the variance in the number of LFEs increases with the length of the time window considered. For most families of the catalogs studied, we find that $0 < d < 0.5$, which is characteristic of long-range dependence in the time series. The only exception is the San Andreas Fault catalog, where the LFE families show a wider range of behaviors, and where only some of the families exhibit evidence for long-range dependence. Long-range dependence may be explained by interactions among several asperities associated with the same LFE family. The statistical characterization of LFE occurrence could provide important constraints on future mechanical models of slow earthquake phenomena.

Variable Slow Slip Speeds at Sub-Daily Timescales: Constraints From High-Rate GPS Records

HALL, K., University of Washington, Washington, USA, hallka01@uw.edu; SCHMIDT, D. A., University of Washington, Washington, USA, dasc@uw.edu; HOUSTON, H., University of Southern California, California, USA, houstonh@usc.edu; CROWELL, B. W., Pacific Northwest Seismic Network, Washington, USA, crowellb@uw.edu

Episodic tremor and slow slip events (ETS) have been observed in many studies as a several-day-long transient on daily GPS positions with net horizontal offsets of ~5 mm. The tremor record is suggestive of sub-daily signals of discontinuous slip, which are not captured by daily solutions. For example, Hawthorne *et al.*, (2016) used strainmeters to show that rapid tremor reversals (RTRs) represent 10-20% of the slow slip moment. By studying sub-daily signals, we hope to observe discontinuous behavior in slow slip, suggested by the tremor record. We use Track, a high-rate GPS processing package within GAMIT (Herring *et al.*, 2010) to find 1 Hz solutions. We chose several GPS stations on the Olympic Peninsula from PANGA and PBO. These stations are located above the strongest tremor signals during the 2010 ETS event (8/18 - 8/19), based on tremor locations from the PNSN. We solve for the positions on the horizontal components relative to a reference station on stable North America. One of the challenges of using high-rate GPS is the increased noise, which is averaged out in daily positions. We process the raw positions by removing significant outliers (Bock *et al.*, 2000) and using sidereal filtering (Nikolaidis *et al.*, 2001) to remove any repeatable noise sources. Additionally, Langbein & Bock (2004) found that they could resolve 2 mm of offset by averaging 1 min of data, suggesting that further averaging might allow for the observation of smaller signals. We use forward modeling to determine what potential sub-daily signals from the tremor record, such as RTRs, would look like in a high-rate GPS record and whether that signal would be above the noise level. We attempt to observe sub-daily nuances of slow slip, such as accelerating and decelerating. These potential observations will help better characterize the source physics behind slow slip and tremor.

Stress Regime of the Nankai Trough Megathrust: A Stress Analysis Incorporating Geodetic and Seismic Fault Slip

NEWTON, T. J., University of Oregon, Oregon, USA, tjnewton.uni@gmail.com; LIN, J., University of Oregon, Oregon, USA, jiunting@uoregon.edu; THOMAS, A. M., University of Oregon, Oregon, USA, amt.seismo@gmail.com

The stress field in different tectonic regimes provides insight into the mechanics of faulting for the considered region. Crustal stress fields are routinely determined using inversion methods that solve for a stress tensor best describing the distribution of slip vectors from earthquake focal mechanisms. Slow fault slip is generally not represented in focal mechanism catalogs, and is therefore excluded from stress inversions. In the Nankai trough region of Japan, a substantial portion of fault slip along the subducting Philippine Sea plate is accommodated by geodetic episodes of slow fault slip with durations of days to years, or slow slip events (SSEs), so standard earthquake focal mechanism catalogs are not a comprehensive representation of local crustal deformation. We utilize focal mechanisms of deep short-term SSEs determined from inversions of GNSS data to include slow fault slip in an analysis of the stress regime of the Nankai trough megathrust. We invert SSE focal mechanisms in conjunction with a declustered standard focal mechanism catalog to estimate the best-fitting spatially variable stress field. Previous studies have revealed principal stress orientations in the Nankai trough that are misoriented for megathrust faulting. The area of apparent principal stress misorientation coincides with the location of SSEs. Our results suggest that crustal principal stress orientations of the Nankai trough are well oriented for megathrust faulting when slip due to SSEs is considered. Stress inversions assume that the input (focal mechanisms of fault slip) samples all sources of slip, therefore regional principal stress analyses of the subduction zone interface should include all substantial sources of megathrust slip. Our results emphasize the importance of including all major sources of slip in stress analyses, and suggest that the stress state of the Nankai Trough is less unique than previously thought, compared to other subduction zones.

High-Resolution Imaging of Slow Earthquake Source Processes Resulting From the Cholame Dense Array Experiment

THOMAS, A. M., University of Oregon, Oregon, USA, amt.seismo@gmail.com; INBAL, A., University of Tel Aviv, Tel Aviv, Israel, asafinbal@tauex.tau.

ac.il; BÜRGMANN, R., University of California, Berkeley, California, USA, burgmann@seismo.berkeley.edu

Despite over a decade of intense research, the processes governing Low Frequency Earthquakes (LFE), Non-Volcanic Tremor (NVT), and associated Slow-Slip Events (SSEs) remain enigmatic. Cholame, a densely instrumented segment of the San Andreas fault with one of the best LFE catalogs in the world, is a natural laboratory for studying slow-slip related processes. Cholame's LFEs occur in 10-100 second-long bursts separated by several hours or more, are largely non-coeval with long-duration NVT, and exhibit migration speeds of tens of km/hour evidenced by successive activation of LFE families along-strike. The latter implies that LFEs may be driven by an underlying slow-slip event. However, due to the limited sensitivity of geodetic monitoring systems, and because LFEs are sparsely distributed along strike, the relation between SSE and LFE activity in Cholame is not well understood. To study LFEs and NVTs we deployed three dense (25-30 sensors, ~500 m aperture) arrays of 3C 5Hz Nodal seismometers < 20 km away from the fault. The arrays captured an unusually large 5-day-long period of significantly increased LFE activity that included families from Cholame to Parkfield. Here we present preliminary results from array- and network-based cross-correlation analysis of these data. Array analysis will be used to image propagation of tremor/LFE producing activity along the fault, and analyze spatiotemporal amplitude and coherency variations. The cross-correlation results will provide a more comprehensive LFE catalog, thus enhancing our resolution of repeating LFE sequences in space and time. These two complementary approaches will allow us to better understand what fraction of coherent energy emanating from the fault (which we interpret as fault slip) is made up of discrete LFEs helping to better constrain the physical processes giving rise to slow-slip related phenomena and the architecture of deep fault zones.

Uncovering the Physical Controls of Slow Slip Events Using Machine Learning

MCLELLAN, M., University of Ottawa, Ottawa, Canada, morganemclellan@gmail.com

The discovery of slow-slip events (SSE) from GPS monitoring has drastically altered our understanding of how accumulated tectonic stress at subduction zones is released. Unlike regular "fast" earthquakes, stress during SSE is released over a period of days to months and is often associated with tectonic tremor. When the geodetic and seismic signals are correlated spatially and temporally, this is referred to as a single event of episodic tremor and slip (ETS). Slow slip events have not been observed along all subduction zones and are sometimes confined to specific segments along a given subduction zone. Several subduction zone characteristics (geometric, kinematic, and physical) have been proposed to explain the occurrence of SSE. Here we attempt to uncover the conditions that favor the nucleation of SSE using machine learning (ML) techniques. ML has the unique ability to uncover complex data patterns from known (*i.e.*, training) data. that can be used to predict outcomes in an untested dataset. This has the dual benefit of determining which subduction zone characteristics (or discriminant features in ML volcabulary) are correlated with SSE as well as predicting the probability of their occurrence in poorly monitored areas. Our approach is based on extracting subduction zone characteristics from geophysical data that are mapped globally. We examine features that characterize the incoming, subducting plate at the trench, including sediment thickness, plate age, plate roughness, plate deformation, and relative plate velocity. Global subduction zones are split into 50 km-wide trench-parallel segments. Each segment is assigned a scalar value corresponding with each characteristic, and a label corresponding to the occurrence of SSE along that segment. We apply various ML algorithms (Guassian Naïve Bayes, Random Forest, Logistic Regression, Support Vector Machine, K-Nearest Neighbour, and Linear Discriminant Analysis) to test the validity of these plate characteristics as predictors in the frinctional behaviour of a given plate segment.

Slow Slip and Potential Earthquake Triggering Near Guerrero, Mexico From Geodetic Remote Sensing

MAURER, J., Jet Propulsion Laboratory, California Institute of Technology, California, USA, maurer.jeremy@gmail.com; BEKAERT, D. P. S., Jet Propulsion Laboratory, California Institute of Technology, California, USA, david.bekaert@jpl.nasa.gov; GONZÁLEZ ORTEGA, J., Centro de Investigación Científica y de Educación Superior de Ensenada, Ensenada, Mexico, aglez@cicese.mx; GUALANDI, A., Jet Propulsion Laboratory, California Institute of Technology, California, USA, adriano.gualandi@jpl.nasa.gov; HUANG, M., University of Maryland, Maryland, USA, mhhuang@umd.edu; FATTAHI, H., Jet Propulsion Laboratory, California Institute of Technology, California, USA, heresh.fattahi@jpl.nasa.gov

Slow slip events (SSEs) are known to occur episodically along subduction zones, in areas known as "seismic gaps" that seldom produce large earthquakes. The Guerrero seismic gap in Mexico has seen several SSEs, the most recent having been observed in 2017-2018. These events can change the local stress field and could be responsible for triggering large earthquakes, and they provide an opportunity for studying mechanical conditions on subduction zone faults near areas of fast earthquake nucleation. The Sentinel-1 Interferometric Synthetic Aperture Radar (InSAR) mission provides geodetic deformation measurements with unprecedented coverage, having data acquisitions every 6-12 days at high spatial resolution, which allow for constraining the spatio-temporal evolution of slow events. We use data from the Sentinel-1 mission from two look geometries and regional Global Navigation Satellite System (GNSS) stations to generate a time-series of surface displacements, and apply novel techniques to disentangle the different tectonic components superimposed in the time-series. We estimate cumulative slip for the SSE and earthquakes and investigate the spatial temporal aspects of how deformation and slip evolve during the event. Finally, we investigate the impact of the SSE on the local stress field and discuss possible triggering relationships between SSEs and earthquakes on this part of the Mexico subduction zone.

Using Earthquake Focal Mechanisms to Investigate Slow Slip Driving Forces in the Northern Hikurangi

WARREN-SMITH, E., GNS Science, Lower Hutt, New Zealand, e.warren-smith@gns.cri.nz; FRY, B., GNS Science, Lower Hutt, New Zealand, b.fry@gns.cri.nz; WALLACE, L. M., GNS Science, Lower Hutt, New Zealand, l.wallace@gns.cri.nz

Understanding the processes that drive slow slip events (SSEs) may assist in improving our understanding of the physics of both slow and fast earthquakes. Recent work has shown that the stress ratio, R, retrieved by focal mechanism inversion systematically decreases prior to SSEs in New Zealand's northern Hikurangi subduction zone, and subsequently increases during the evolution of each SSE. These R fluctuations are proposed to represent slow, precursory increases and fast concurrent decreases in fluid pressure within overpressured subducting oceanic crust during the SSE cycle.

These observations represent an exciting opportunity to improve forecasts of SSE occurrence via monitoring of R changes. Thus far, this cyclic behaviour has only been observed over a short time-period (9 months, 4 SSE cycles) when ocean-bottom seismographs were deployed.

Here we present the results of a waveform cross-correlation study that aims to extend the catalogue in time and reduce the magnitude of completeness for focal mechanisms of northern Hikurangi seismicity. This enables improved temporal coverage and statistical analysis of stress tensor changes across multiple SSE cycles. By using well constrained focal mechanisms of events recorded on >30 OBS and land stations as templates, we automatically assign correlation-derived relative polarities (Shelly *et al.*, 2016) to waveforms and subsequently invert for focal mechanisms and R using many more earthquakes complete to a lower magnitude. This approach offers an important step towards accurate SSE forecasting and an improved understanding of the physical processes leading to slow rupture nucleation

Frontiers in Earthquake Geology: Bright Futures and Brick Walls

Poster Session · Wednesday · 24 April · Grand Ballroom

Dispersion of Alluvial Fan Scarp Ages and Epistemic Uncertainty of Cumulative Vertical Separation, Cucamonga Fault, Southern California

MCPHILLIPS, D., U.S. Geological Survey, California, USA, devin.mcphillips@gmail.com; SCHARER, K., U.S. Geological Survey, California, USA, kscharer@usgs.gov

Characterizing cumulative fault displacement is an essential component of geologic slip rate and seismic hazard assessment. However, cumulative fault displacement, measured as vertical separation, is over-dispersed along the strike of the Cucamonga Fault and perhaps other such thrust faults. This observation suggests that the measurement of geologic slip rates may be severely limited by epistemic uncertainty. One probable source of dispersion on the Cucamonga Fault is the range of alluvial fan fault scarp ages: we expect that the avulsing and/or braided channels of an active alluvial fan can yield a patchwork surface with some areas altered recently by erosion or deposition while other areas remain stable. If alluvial fan surfaces are abandoned gradually, rather than instantaneously, then late-stage fan modification could yield considerable dispersion of vertical separations by destroying scarps, even within one geological map unit with one nominal surface age. In order to better understand the role of scarp age variability, we measure 310 morphological ages of fault scarps by solving a linear diffusion equation.

Within single map units, ages grow younger with increasing distance from the mountain front, which is consistent with previous interpretations. Within one map unit, we calibrate a linear model relating morphological age to vertical separation at Day Canyon, Rancho Cucamonga, California. This model can explain at least half of the observed dispersion within the same map unit elsewhere along the Cucamonga Fault. Our results suggest that (1) scarp age variability is the source of a considerable fraction of epistemic uncertainty in cumulative thrust displacement and (2) this uncertainty may be resolved with accurate and precise geochronology, perhaps including a combination of radiometric and morphological ages.

10Be Exposure Age of the Third Terrace in Bingzhongluo Reach of Nujiang River

LV, Y., Institute of Crustal Dynamics, China Earthquake Administration, Beijing, China, tonyradish@gmail.com; REN, J., Institute of Crustal Dynamics, China Earthquake Administration, Beijing, China, renjunjie@gmail.com

Fluvial terraces are common in the Nujiang River valley, while the third level is widest and mostly distributed. Three granite boulders were taken as samples at the posterior margin of the third terrace of the Nujiang River at Bingzhongluo. The diameters of all boulders are large (>2m) and buried in soil layers. Sample NJ2-1 was collected from one large granite boulder on floodplain, which is used to estimate the inheritance. Sample BZL43 was chiseled about 1.5cm from the surface of a quartz vein, that insets a sandy slate of the third terrace at downstream about 2km. The ^{10}Be concentrations of BZL43 is highest of the four samples from the third terrace. Weathering processes have a greater impact on the exposure ages of boulder samples according to the relief, environmental features and ^{10}Be concentration. Assuming the erosion rate of sample BZL43 from the quartz vein as 0.05cm/ka, the erosion rate of granite boulders is represented graphically as 0.3cm/ka by the relationship among effective exposure age, exposure time and erosion rate. The exposure ages of the three granite boulders on the third terrace were obtained after the correction for erosion and ignoring inheritance. Combined with the corrected exposure age of sample BZL43, it is considered that the third terrace of Nujiang River at Bingzhongluo was developed during 150~203ka.

Stereopaired Morphometric Protection Index Red Relief Image Maps (Stereo MPI-RRIMs): Effective Visualization of High-Resolution Digital Elevation Models for Interpreting and Mapping Small Tectonic Geomorphic Features

KANEDA, H., Chiba University, Chiba, Japan, kaneda@faculty.chiba-u.jp; CHIBA, T., Asia Air Survey Co., Ltd., Kawasaki, Japan, ta.chiba@ajiko.co.jp

We propose stereopaired morphometric protection index red relief image maps (Stereo MPI-RRIMs) for effective visualization of high-resolution digital elevation models (DEMs) to interpret and map small tectonic geomorphic features along active faults. Stereo MPI-RRIMs resolve problems of an original red relief image map (RRIM) in active fault studies and allow simultaneous expression of all of the three basic topographic parameters of elevation, slope, and convexity and concavity with minimal degradation of original data quality. Although stereographic viewing may require some practice and/or supporting devices, this is a big advantage over the most often used DEM visualization of shaded relief maps and slope maps, both of which only represent one aspect of 3D morphology. We show that Stereo MPI-RRIMs vividly visualize various tectonic geomorphic features and even errors from DEM production processing, thereby maximizing the potential of the digital topographic data for active fault studies. We argue that those who use DEMs need to pay more attention to DEM visualization, and our proposed method, along with our simple calculation programs, would aid in more complete interpretation and mapping of small tectonic geomorphic features.

Slip Rate and Paleoseismic History of the Tianjingshan Fault, Northeast Tibet, China

PIERCE, I. K. D., Center for Neotectonic Studies, Nevada, USA, ian@nevada.unr.edu

The western and central segments of the Tianjingshan fault zone in conjunction with the more southerly Haiyuan fault accommodate sinistral deformation in the northeast Tibet Plateau. The Tianjingshan fault extends for ~240 km, and a portion of the fault produced a M7.5 earthquake in 1709. The Late Quaternary slip rate of the left-lateral Tianjingshan fault is constrained to 1.1 ± 0.2 mm/yr based on measurements of dated displaced landforms, offset measurements, and GPS data. Results from five trenches across the western Tianjingshan fault provide evidence of 6 ~M7.5 paleoseismic events with an average recurrence interval of ~5000 years.

Core Penetrometer Tests, Continuous Cores and Paleoseismic Trenching Combined to Infer a Mid-Holocene Slip Rate for the Imperial Fault, California

ROCKWELL, T. K., San Diego State University, California, USA, trockwell@sdsu.edu; KLINGER, Y., Institut de Physique Du Globe de Paris, Paris, France, klinger@ipgp.fr; JERRETT, A., AERA Energy LLC, California, USA, ajerrett5@gmail.com; WESSEL, K., Chevron North America Exploration and Production Company, Texas, USA, knwessel@gmail.com; SINGLETON, D. M., San Diego State University, California, USA, dsinglet@ucsd.edu; LEVY, Y., San Diego State University, California, USA, yulevy@ucsd.edu; ŠTĚPANČÍKOVÁ, P., Institute of Rock Structure and Mechanics, Czech Academy of Sciences, Prague, Czech Republic, petstep@centrum.cz; WECHSLER, N., University of Tel Aviv, Tel Aviv, Israel, neta.wechsler@gmail.com; OKUMURA, K., University of Hiroshima, Hiroshima, Japan, kojiok@hiroshima-u.ac.jp; STEMBERK, J., Institute of Rock Structure and Mechanics, Czech Academy of Sciences, Prague, Czech Republic, kuba.stemberk@gmail.com

We conducted a multi-disciplinary approach to study the paleoseismology on the Imperial fault along the section that ruptured during the Mw7 1940 earthquake. We investigated a small pull-apart basin in the Imperial Valley, located about 2 km north of the US/Mexico border. The Imperial fault is the main plate boundary fault between the North American and Pacific lithospheric plates and has been attributed with a slip rate up to 35-40 mm/yr. We excavated trenches across the fault to a depth of 4 m to expose the past 500 years of stratigraphy, and used cone-penetrometer (CPT) soundings and continuous coring to extend the record to the middle Holocene at 25 m depth.

Post-earthquake aerial photos show that the 1940 earthquake (event E1) produced 6 m of lateral slip through the sag depression, and >90 cm of subsidence within the sag. The penultimate earthquake (E2) in ca 1726 also produced ~1 m subsidence, whereas two other events (E3 and E4) produced only 0-6 cm of subsidence. We interpret these observations to imply that large 1940-type earthquakes activate the sag depression with about a meter of subsidence whereas smaller events, such as 1979, either do not reach as far south as the sag or produce only minor displacement.

Two cores and 26 CPTs were acquired across the sag that penetrated a succession of lake and deltaic deposits to ~25 m depth: the sediments west of the fault date to about 4500 years at the base of the core whereas in the sag itself, the sediments are about 2-2.2 ka at 25 m depth. Using a particularly distinctive CPT signature for the 2-2.2 ka lake deposit, the sag records ~17 m of vertical subsidence in the past 2.2 ka, with increasing subsidence with successively older lakes. If the ratio of lateral slip and subsidence has remained relatively constant, then these data imply that the Imperial fault carries most of the plate boundary slip across the international border.

Refining the Spatial and Temporal Signatures of Creep and Co-Seismic Slip Along the Southern San Andres Fault, Coachella Valley, California

BLANTON, C. M., San Diego State University, California, USA, chelseablanton8282@gmail.com; ROCKWELL, T. K., San Diego State University, California, USA, trockwell@sdsu.edu; GONTZ, A., San Diego State University, California, USA, agontz@sdsu.edu; KELLY, J. T., San Diego State University, University of California, San Diego, Scripps Institution of Oceanography, California, USA, jtkelly@sdsu.edu

The southern segment of the San Andreas fault (SAF) has historically been the subject of geologic and geodetic slip rate and creep studies. Our investigation expands this research by focusing on small-scale offsets, potentially related to creep since the last earthquake, in addition to larger offsets due to paleoearthquakes which ruptured the Coachella Valley section of the SAF. Previous studies have utilized Structure from Motion methodologies and achieved sub-meter to decimeter resolution (Javernick *et al.*, 2014, Westoby *et al.*, 2012, etc.), whereas this study has acquired sub-centimeter resolution, allowing for the examination of decimeter to meter scale offsets. We conducted UAS surveys using a DJI Phantom 4 Pro flown at altitudes of 25 to 60 m above ground level over eight sections of the fault. We acquired a swath measuring 4 km long and 75 to 150 m wide resulting in 488,000 m^2 of aerial imagery. Imagery was processed using Agisoft PhotoScan, producing Digital Surface Models (DSMs) and orthomosaics from base imagery with a maximum resolution of 7.7 mm/px. DSMs were further analyzed in ArcGIS to create hillshade models, contour maps, and slope maps. Geomorphic offsets were measured in the field using standard techniques and compared to measurements extracted from the GIS coverages in ArcGIS. Observed offsets range from 15 cm to 85 m and reflect creep and multiple rupture events. This section of the SAF last ruptured in 1726 ± 7 years CE (Rockwell *et al.*, 2018) and related studies have demonstrated a local creep rate of ~3 mm/yr (Lindsey *et al.*, 2014) at our sites. We expect that any offset less than about a meter should be related to creep. Currently, all offsets less than 1 m are being evaluated with Gaussian Distribution analysis for variations in creep rate along the fault and to differentiate creep from co-seismic slip. The ultimate goal is a refined model of Late Holocene slip-per-event for the southern SAF.

Evaluating the Reliability of Reported Deep Seismicity Beneath Long Beach by Back-Projection of Randomized Traces

YANG, L., Stanford University, California, USA, yanglei@stanford.edu; LIU, X., Stanford University, California, USA, liuxin@stanford.edu; BEROZA, G. C., Stanford University, California, USA, beroza@stanford.edu

Precise earthquake locations are important for monitoring the location and geometry of active faults, yet it is difficult to monitor earthquakes in urban settings due to high levels of cultural noise. The dense array deployments in 2011 and 2012 at Long Beach provide a unique opportunity in terms of spatial coverage and density for monitoring local seismicity in an urban setting. Applying a combination of downward continuation and back-projection to this dataset, Inbal *et al.* (2015; 2016) found widespread seismicity with depths greater than 20 km, which is much deeper than the conventionally determined seismogenic depth beneath the western Los Angeles. A later study by Li *et al.* (2018), however, found that most of the earthquakes have shallow origins compared with Inbal *et al.*'s results. We test the reliability of the deep imaged sources determined by Inbal *et al.* by randomizing the traces among different receivers and back-projecting the randomized data to the source locations to compare with Inbal *et al.*'s results. In addition, we experimented with enhancing the earthquake signals by exploring the newly developed DeepDenoiser algorithm based on deep learning of earthquake waveform and noise characteristics (Zhu *et al.*, 2018). Our results should inform the understanding of the reliability of the deep earthquake locations under the Long Beach array.

Structural Architecture of the Western Transverse Ranges and Potential for Large Earthquakes – Initial Results of 3D Trishear Forward Modeling

LEVY, Y., San Diego State University, California, USA, yulevy@ucsd.edu; ROCKWELL, T. K., San Diego State University, California, USA, trockwell@mail.sdsu.edu

The Western Transverse Ranges (WTR) is an active fold and thrust belt. Fold-and-thrust belts usually evolve over time, can involve large-scale faults and potentially accommodate large magnitude earthquakes. The thrust fronts of these structures typically form large fold structures in their hanging walls, and they tend to propagate forward (in sequence) over time to form new thrust fronts. The evidence for large thrust events in the area of Ventura and the existence of competing structural models led us to test new models that incorporate the full range of geological observations, and apply different methods than ones previously used in that region. We propose an imbricated Thrust-Ramp-Thrust architecture, which has propagated southward since the inception of shortening in the Pliocene. Based on the stratigraphic and topographic relief, the ages of structures, geometry of the folds and faults, and observed type of deformation (uplift and folding), we interpreted the nearly continuous, overturned Tertiary stratigraphy of the Santa Ynez Mountains as a large anticlinorium that formed as the first thrust front over the (mostly) blind San Cayetano fault, and that the thrust front propagated south with time to the Red Mountain and South Sulfur Mountain faults and eventually to the currently active, southward-verging Pitas Point-Ventura fault. We completed 7 cross-sections based on published geologic maps and subsurface data from the upper several kms and forwarded-modeled these in 2D with Trishear. The regional cross-sections have been linked in 3D by interpolation in MOVE and we now test our proposed model by using 3D Trishear forward modeling of the interpolated fault surfaces. The underlying inferred master fault has a surface area of about 6000 km^2, consistent with recently published observations of large coastal uplift that suggest earthquake magnitudes in the high M7s. While these are initial results, our intention is to compare in 3D the observed first order structures to the deformation produced in the model and then tune the model against geodetic data.

Combining Geologic and Geophysical Techniques to Study Fault Geometry Beneath a Major Coastal Metropolitan Area

SINGLETON, D. M., San Diego State University, Scripps Institution of Oceanography, California, USA, dsinglet@ucsd.edu; MALONEY, J. M., San Diego State University, California, USA, jmaloney@sdsu.edu; AGNEW, D. C., Scripps Institution of Oceanography, University of California, San Diego, California, USA, dagnew@ucsd.edu; ROCKWELL, T. K., San Diego State University, California, USA, trockwell@sdsu.edu; BROTHERS, D. S., U.S. Geological Survey, California, USA, dbrothers@usgs.gov; KLUESNER, J., U.S. Geological Survey, California, USA, jkluesner@usgs.gov; SLITER, R., U.S. Geological Survey, California, USA, rsliter@usgs.gov

The Newport-Inglewood-Rose Canyon (NIRC) fault zone is the easternmost fault in a system of strike-slip faults within the Inner Continental Borderlands (ICB), a region offshore of southern California that accommodates ~10-15% of the total North American - Pacific plate boundary slip. With both onshore and offshore segments, the Rose Canyon fault, the southern section of the NIRC fault zone, provides an ideal laboratory to combine geologic and geophysical techniques to constrain the behavior and character of a fault within the ICB. Recent paleoseismic work has shown the Rose Canyon fault to be more active than previously thought, with interpreted stratigraphic evidence indicating the occurrence of six surface rupturing earthquakes in the past 3,300 years and a recurrence interval of ~700 years. This recurrence interval is several hundred years shorter than previous estimates and raises questions regarding the slip rate and the slip per event for the Rose Canyon fault. With its location directly beneath the city of San Diego, geomorphic piercing points for slip rate estimates have been obscured and altered by urbanization. However, it is possible to resolve a slip rate for the Rose Canyon fault by using geodetic techniques. We present new results from a network of survey GPS sites constructed in 1998 (last surveyed in 2017) with monumentation designed to study low slip rate faults. Velocity from the network shows a signal that is towards the higher value of geologic estimates indicating that the Rose Canyon fault may be accommodating a higher portion of the slip budget in the ICB. Additionally, preliminary results of reprocessed legacy multichannel seismic data from San Diego Bay shows the presence of extensive faulting between the Rose Canyon and San Miguel-Vallecitos faults, which may offer a structural link through which slip is partitioned across the Baja Peninsula and into the ICB.

A Database and Working Group for Cascadia Earthquake Research: Synthesizing Existing Knowledge to Answer Outstanding Questions

WALTON, M. A. L., U.S. Geological Survey, California, USA, mwalton@usgs.gov; STAISCH, L., U.S. Geological Survey, California, USA, lstaisch@usgs.gov; GOMBERG, J., U.S. Geological Survey, Washington, USA, gomberg@usgs.gov; PERKINS, J., U.S. Geological Survey, California, USA, jperkins@usgs.gov; WATT, J., U.S. Geological Survey, California, USA, jwatt@usgs.gov; WITTER, R. C., U.S. Geological Survey, Alaska, USA, rwitter@usgs.gov

Understanding and forecasting the magnitude and risk of hazards associated with subduction zone earthquakes presents a compelling but complicated scientific problem because subduction zones straddle a multitude of physical systems. The Cascadia Subduction Zone is an example of a convergent plate boundary where large uncertainties remain about seismogenesis and great earthquakes (magnitude >8.0). Reducing these uncertainties requires addressing three fundamental questions: (1) To what extent does the earthquake-cycle model apply to Cascadia, and to great earthquake recurrence more broadly? (2) How do megathrust earthquakes rupture and radiate, and how does slip propagate? (3) How does the record of secondary coseismic geologic effects inform Cascadia Subduction Zone earthquake timing, magnitude, and hazards? To address these questions, we have enlisted a diverse range of researchers with expertise in tectonics, geophysics, crustal structures, landslides, sedimentology, paleoseismology, land-level changes, geodesy, mantle and crustal rheology, and earthquake rupture dynamics into a USGS Powell Center Working Group. The group will address the aforementioned questions during a series of three week-long meetings in 2019-2020. Our Working Group activities also include engaging with disaster management and risk communication experts to ensure that our focus remains on risk reduction, and so that our results most effectively meet community and stakeholder needs. As a part of this Powell Center project, we are also working to compile and integrate available geological and geophysical data in the Cascadia region into a publicly available geodatabase, which will include objective assessment of dataset uncertainties. Here, we introduce this database and highlight results of the first Powell Center meeting (March 2019) focused on the Cascadia earthquake cycle.

Paleoseismology of the Colton Site, Northern San Jacinto Fault, San Bernardino County, Southern California

KENDRICK, K., U.S. Geological Survey, California, USA, kendrick@usgs.gov; FUMAL, T., U.S. Geological Survey, California, USA, kendrick@usgs.gov

The Colton paleoseismic site is 5 km south of San Bernardino, along the Claremont segment of the San Jacinto Fault. Two parallel trenches oriented orthogonal to the fault strike exposed a 20m-wide, complex fault zone, including compressional uplift and folding juxtaposed with an extensional graben. This site shows edimentary deposits of interbedded peat, clay and sand. Radiocarbon dating of detrital charcoal, seeds and other plant parts contained in the peat layers shows that most of the units were deposited between approximately 4000 and

6000 ^{14}C yr BP, with a poorly-constrained younger section, dated near the top by two detrital charcoal samples at 1815±35 and 170±35 ^{14}C yr BP. We found evidence for at least six earthquakes in the older part of the stratigraphic section, including filled fissures, growth strata, upward fault terminations, and cross-cutting faults. The youngest part of the section, which is younger than 4500 y BP, is within the extensional graben and contains evidence for three additional, younger earthquakes. The uppermost detrital charcoal sample constrains the most recent two ruptures to have occurred since 170 ^{14}C yr BP. In the San Bernardino region, the fault system produced earthquakes in 1907 (M 5.8) and 1923 (M 6.2), although there were no reports of ground rupture for these events in the area [all magnitudes based on historical reports, after Toppozada, 2002]. The northern San Jacinto Fault system experienced earthquakes in 1899 (M 6.7) and 1918 (M 6.8), but the maximum damage in both of these was much farther to the SE, and no damage was reported in the area of the Colton paleoseismic site. A nearby paleoseismic site on the Claremont Fault, at Mystic Lake (Onderdonk *et al.*, 2013), located ~ 28 km to the SE, also has evidence suggesting an earthquake within the last ~150 yr BP, but this feature is instead attributed to subsidence, compaction, liquefaction or creep rather than co-seismic rupture. Here we present evidence for, and radiocarbon age constraints for each of the paleoearthquakes.

Characterizing Faults, Folds, Earthquakes and Related Hazards in the Pacific Northwest

Poster Session · Wednesday · 24 April · Grand Ballroom

Neotectonic Investigation of the Chehalis Basin, Southwestern Washington, USA

REEDY, T. J., Washington Geological Survey, Washington, USA, taborreedy@gmail.com; VON DASSOW, W., Washington Geological Survey, Washington, USA, wesley.vondassow@dnr.wa.gov; ANDERSON, M., Washington Geological Survey, Washington, USA, megan.anderson@dnr.wa.gov; LAU, T., Washington Geological Survey, Washington, USA, todd.lau@dnr.wa.gov; CAKIR, R., Independent Researcher, cakir.recep@gmail.com; STEELY, A., Washington Geological Survey, Washington, USA, alex.steely@dnr.wa.gov

The Chehalis Basin in southwest Washington was an active depocenter from the Oligocene through the Miocene, and has since been uplifted and incised to create the Doty Hills. Oblique subduction of the Juan de Fuca plate and rotation of the Oregon forearc are recognized as driving forces for uplift of the Doty Hills and the Cascadia margin, but what structures accommodate strain in the upper crust remain unclear. We undertake a multidisciplinary effort to understand uplift within this region and potential hazard posed by upper crustal faults like the Doty fault. Recent gravity anomaly maps show steep gradients co-located with mapped faults, suggesting kilometer scale total displacement. New detailed mapping confirms this interpretation and shows the Doty fault separating steeply dipping Miocene rocks in the footwall from the overlying Eocene Crescent Formation in the hangingwall. New kinematic data found on fracture surfaces near the fault suggest a lateral component to offset rather than pure dip-slip. Field and lidar observation along an approximately 40 km by 3 km swath which includes the Doty fault and surrounding structures did not reveal tectonic scarps. Shallow seismicity (<20 km) in the area of the Doty fault is sparse suggesting a locked fault or aseismic deformation since recording began by the Pacific Northwest Seismic Network. Without tectonic scarps and shallow seismicity, we intend to use reconnaissance scale mapping of marine terrace surfaces to the west and inland fluvial and glacial outwash terraces to the east in conjunction with forthcoming optically stimulated luminescence (OSL) and ^{10}Be cosmogenic surficial ages to test hypotheses for the timing of deformation.

Finite-Difference Wave Simulation of High-Frequency Seismic Waveforms in the Cascadia Subduction Zone

RATHNAYAKA, S., University of Massachusetts Amherst, Massachusetts, USA, srathnayakam@geo.umass.edu; GAO, H., University of Massachusetts Amherst, Massachusetts, USA, haiyinggao@geo.umass.edu

The goal of this study is to simulate high-frequency seismic waveforms recorded by ocean bottom seismometers within the Juan de Fuca plate, and ultimately to provide a high-resolution crustal-scale seismic velocity model. The first P-arrivals of air-gun shots from the active-source experiment MGL1211 provide high-quality crustal phase Pg or head wave Pn signals at a frequency range of 4-40 Hz. The signal-to-noise ratio of the first P-arrivals generally decreases with increasing source-to-receiver distance, from deep to shallow water, with increasing sediment thickness and decreasing air-gun shot spacing and time interval. We don't observe strong correlations between the data quality and the air-gun array depth. We simulate the wave propagation at a narrow frequency range of 4-6 Hz using the finite-difference method with a 3-D reference model generated based on the recent active-source work in Cascadia. We apply a ricker pulse with a half width of 0.3 s as the source-time function of the vertical force. Our preliminary tests show a good match of the first P-arrivals between the observed and synthetic data with less than 1-second phase delays and cross-correlation coefficients ≥ 0.7. Our next step of this study is to perform a joint inversion of high-frequency air-gun shot signals and short-period ambient noises within the Juan de Fuca plate. The tomographic results of a joint inversion will provide a tight constraint of the structure from the shallowest sedimentary layers down to tens of kilometers, filling the gap in the model resolution between active- and passive-source seismic tomographic images.

Seismic Source Characterization of Faults in the Portland and Tualatin Basins and a Paleoseismic Study of the Gales Creek Fault, OR

HORST, A. E., Portland State University, Oregon, USA, alisonhorst13@gmail.com; STREIG, A. R., Portland State University, Oregon, USA, streig@pdx.edu; WELLS, R. E., Portland State University, Oregon, USA, rwells@pdx.edu; GUILDERSON, T. P., Lawrence Livermore National Laboratory, California, USA, guilderson1@llnl.gov

Portland, OR lies within the tectonically active forearc of the Cascadia subduction zone. Several, potentially hazardous, northwest striking faults in and around the Portland Basin are classified as Quaternary active by the USGS, but little is known about their Holocene activity. Geologic and geodetic studies in the Pacific Northwest (PNW) document ongoing clockwise rotation of the region since 16 Ma. Current models for crustal deformation in the PNW suggest NW trending faults accommodate dextral shear inferred from increasing clockwise rotation rates west of Portland. We compiled structural information to improve the seismic source characterization of these faults, and using empirical scaling relationships for fault length and earthquake magnitude, we find that many of the faults in the region are capable of generating earthquakes of magnitude 6 to 7. The northwest trending Gales Creek fault (GCF) has strong surface expression, and geophysical evidence points to a fault of at least 50 km length. We excavated a paleoseismic trench at a site on the northern GCF characterized by a prominent break in slope, in the form of a side-hill bench, to document the style and timing of surface deforming earthquakes. We interpret two surface rupturing earthquakes from stratigraphic and structural relationships in the trench and radiocarbon samples from offset stratigraphy constrain these earthquakes to have occurred ~1,000 and ~7,200 calibrated years before present. The penultimate earthquake backtilted a buried soil into the hillslope creating accommodation space that was infilled by a colluvial deposit, and the most recent earthquake faulted and formed a fissure within the penultimate colluvial deposit. New earthquake timing from this northern site combined with existing data on the central GCF will better constrain the lateral extent of prehistoric surface rupturing earthquakes, and can be used to refine magnitude estimates for the GCF.

A Post-Glacial Record of Large, Strike-Slip Earthquakes on the Sadie Creek Fault, Northern Olympic Peninsula, WA

AMOS, C., Western Washington University, Washington, USA, colin.amos@wwu.edu; SCHERMER, E. R., Western Washington University, Washington, USA, liz.schermer@wwu.edu; ANGSTER, S., U.S. Geological Survey, Washington, USA, sangster@usgs.gov; DELANO, J., U.S. Geological Survey, Colorado, USA, jdelano@usgs.gov; DUCKWORTH, W. C., Western Washington University, Washington, USA, duckwow@wwu.edu; NELSON, A. R., U.S. Geological Survey, Colorado, USA, anelson@usgs.gov; SHERROD, B. L., U.S. Geological Survey, Washington, USA, bsherrod@usgs.gov

Active faulting in the northern Olympic Peninsula of Washington reflects ongoing shortening and dextral transpression of the Cascadia subduction zone forearc. The Sadie Creek fault (SCF), a recently discovered splay of the Lake Creek – Boundary Creek fault (LCBCF), extends for ~15 km WNW from the northwest shore of Lake Crescent, immediately south of the Strait of Juan de Fuca. The surface trace of the SCF, identified and mapped using airborne lidar, reveals abundant geomorphic offsets suggesting a history of repeated post-glacial earthquake surface ruptures dominated by dextral displacement along a steeply dipping fault zone. We excavated two trenches across the SCF to investigate the timing and extent of surface ruptures and to assess their relationship to earthquakes identified in trenches on the adjacent LCBCF. The SCF trenches, along the eastern and central portions of the fault, were sited in fault-bounded depressions where uphill-facing scarps locally pond N-NW-flowing drainages. Stratigraphy in these trenches reveals till and post-glacial outwash overlain in the down-dropped block by progressively buried, organic-rich, forest and wetland soils developed on scarp-derived colluvial wedges. Complex faulting, fracturing, and tilting of these deposits strongly suggests an overall dextral sense of displacement, combined with dip-slip separation similar in magnitude to the scarp height (~2-5

m), consistent with the fault geomorphology. From these observations we infer 3-5 earthquake surface ruptures along the SCF since retreat of the Juan de Fuca lobe of the Cordilleran. Preliminary radiocarbon dating of charcoal fragments in gouge cores extending beneath the trenches restrict these events to younger than ~13.5 ka. Additional dating of abundant charcoal and woody plant fragments will further constrain the timing of these earthquakes for comparison with Holocene records in nearby Lake Crescent and the LCBCF to the east.

Fault Investigation in Western Washington Using 2D Ambient Noise Tomography

HAYASHI, K., OYO Corporation, California, USA, khayashi@geometrics.com; CAKIR, R., Independent Researcher, cakir.recep@gmail.com

Geophysical investigations were carried out at Centralia, WA, to delineate geological structure associated with an major fault. The geophysical methods include seismic reflection, active and passive surface wave methods. This paper summarizes data acquisition and analysis of 2D passive surface wave data. Thirteen cableless seismic data acquisition units with vertical component 2 Hz geophones were used to record ambient noise data. Each unit includes a GPS clock so that all units can be synchronized over any distance without cables. Data acquisition mainly used a linear array with geophone spacing of approximately 100 m and four geophones were moved up forward every 45 min. along approximately 2500 m length lines. Two T-shaped arrays were also measured to confirm the omni directional propagation of ambient noise. Total data acquisition took 2 days. Recorded ambient noise data were processed using the common midpoint spatial autocorrelation method (CMP-SPAC) and clear dispersion curves were obtained at all CMP locations. Minimum frequency ranges from 0.4 to 0.7 Hz and maximum frequency ranges from 5 to 15 Hz depending on the CMP. Dispersion curves obtained from the linear array are generally consistent with those obtained from T-shaped arrays. Non-linear inversion was performed and 2D S-wave velocity (VS) models were obtained. The method penetrated to a depth of 1500 m and provided 2500 m cross sections along the survey line. The interpretation focused on identifying the change of bedrock depth associated with the fault. Resultant VS profiles are generally consistent with seismic reflection method and existing geological information.

Wedge Plasticity and Coupled Simulations of Dynamic Rupture and Tsunami in the Cascadia Subduction Zone

WILSON, A. L., San Diego State University, California, USA, andwilson88@gmail.com; MA, S., San Diego State University, California, USA, sma@sdsu.edu

In an elastic dislocation model, whether or not a subduction plate boundary fault breaks the trench has a significant effect on the seafloor deformation and resulting tsunami. However, this boundary condition at the trench plays an insignificant role when plastic deformation in the overriding wedge is considered. Several seismic profiles along the Cascadia subduction zone indicate that the subduction megathrust does not reach the trench. Coupled dynamic rupture and tsunami simulations for a buried fault in Cascadia incorporating realistic fault geometry, bathymetry, and velocity structure have been carried out in Lotto *et al.* (2018) assuming elastic dislocation. Here we extend that model by incorporating wedge plasticity, which we will show can be more efficient than slip on a buried fault in generating seafloor uplift and tsunami. In the Cascadia subduction zone, which contains large amounts of sediments in the overriding wedge, wedge plasticity may be a very important factor in tsunami generation.

Two Seattle Earthquakes: Evidence From the Duwamish Waterway

DAVIS, E. J., University of Washington, Washington, USA, edav@uw.edu

The Duwamish Waterway in the city of Seattle provides clues to the city's earthquake hazards. The industrialized banks of the waterway locally expose intertidal mud of the former Duwamish River estuary. These deposits contain evidence for two earthquakes in the centuries since the large Seattle Fault earthquake of 900–930. (All age ranges are in calibrated years CE at two standard deviations).

The evidence consists of intrusions and extrusions of andesitic sand within the mud. These sand bodies were likely produced by earthquake-induced liquefaction of the Mount Rainier lahar-runout deposits that underlie the mud. The earlier of the two inferred earthquakes is evidenced by a sand layer that extends discontinuously for at least 50 m. This layer consists of coalesced sand lenses up to 12 cm thick. The layer coincides with the upper limit of parallel, mostly vertical sand intrusions interpreted as evidence for lateral spreading. The implied earthquake likely dates to 1010–1150, as judged from radiocarbon ages of growth-position Triglochin maritima leaf bases that one of the sand lenses drapes. At least one later earthquake is evidenced by dikes in younger mud. One of these dikes approaches the stratigraphic level of T. maritima leaf bases from 1250–1290. Other dikes nearby were traced up to Bolboschoenus maritimus corms from 1470–1640. None of the injected or erupted sand bodies observed thus far reach the likely stratigraphic level of the 1700 Cascadia earthquake or the Puget Sound earthquakes of 1949, 1965, and 2001.

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Vertical Land Motion in Western Washington: Separating Cascadia Locking From Other Sources

NEWTON, T. J., University of Oregon, Oregon, USA, tjnewton.uni@gmail.com; WELDON, R. J., University of Oregon, Oregon, USA, ray@uoregon.edu; SCHMIDT, D. A., University of Washington, Washington, USA, dasc@uw.edu; MILLER, I. M., Washington Sea Grant, Washington, USA, immiller@uw.edu

To help forecast local relative sea level rise in coastal Washington, we have compiled a new vertical land motion (VLM) dataset for Western Washington that combines GPS, tide gauges, and differential leveling data. We find two dominant signals in the data that are most-evident in north-central Washington, an east-west gradient consistent with locking along the Cascadia subduction zone (CSZ), and a smaller magnitude north-south gradient that is apparent east of the region affected by subduction zone locking. The two gradients are superimposed in the coastal region, although VLM data are routinely used to inform subduction zone models that assume the data are absent of independent sources of motion. To assess the contribution of each component, we generate simple elastic dislocation models for CSZ locking with and without the north-south gradient by subtracting the observed gradient east of the Puget Sound from all of Washington, including the CSZ locking-dominated gradient in coastal Washington, west of the Cascades. We compare the predicted horizontal strain from each model to the observed horizontal strain, measured from horizontal GPS motion. Preliminary results show that the observed vertical and horizontal strain best fit our model with the north-south regional uplift gradient removed. Therefore we hypothesize that this gradient is superimposed on the coastal region, and likely unrelated to the CSZ. We suggest that the observed north-south gradient is GIA, however other possible mechanisms are possible, including a 3D viscoelastic response to past CSZ rupture, and local subsidence associated with the broader Puget Sound forearc basin region.

Leech River Fault Array

MULDER, T. L., Geological Survey of Canada, Sidney, Canada, taimi.mulder@canada.ca

The Leech River Fault is one of three major terrane bounding fault that runs through the southern tip of Vancouver Island, BC. The Survey Mountain Fault and San Juan Fault separate Wrangellia terrane to the north, from the Leech River schists to the south. The Leech River Fault separates the Eocene Metchosin basalts to the south from the Leech River schist to the north. It runs from Sombrio point on the western edge of Vancouver Island over seventy-five km eastward, through the waterfront of Victoria, BC, and presents a seismic hazard to the region. Recent studies suggest that the fault may have been active in the Quaternary, however it is unclear how much of a present day risk it presents. Previous studies have shown that seismic activity in the Victoria region lies within the large packages of terrain rocks, rather than on the pre-existing faults bounding them. To explore whether there is any small scale movement on the fault that may have not been recorded by the regional seismic network, ten instruments were deployed around the Victoria area to cover the eastern portion of the fault (approximately one-third the total fault length) and the subsurface expression of the fault, which dips to the northeast. This seismic array uses Geotech S-13 sensors with sample rate of 500 sps at a station spacing of 5-10 km to detect small, high-frequency events.

Offshore Subduction Zone Structure and Seismicity Along Pacific Northwest: From the Gorda Plate to the Queen Charlotte Fault

Poster Session · Wednesday · 24 April · Grand Ballroom

Seismic Imaging of the Gorda Slab Subduction Interface Near the Mendocino Triple Junction Using Converted Phases

GONG, J., MIT/WHOI Joint Program, Massachusetts, USA, gongjh@mit.edu; GUO, H., University of Science and Technology of China, Hefei, China, guohao.ustc007@gmail.com; MCGUIRE, J. J., U.S. Geological Survey, California, USA, jmcguire@whoi.edu

Geodetic observations show that the interseismic coupling of subduction interfaces can vary strongly in both the along strike and downdip directions. Identifying the structural and material properties responsible for these variations is often hindered by a lack of high-resolution imaging at seismogenic depths. We use seismic phases from local earthquakes in the downgoing plate (Ps or Sp) converted at the subduction interface of the Gorda plate to constrain its location and material properties. We use data from a dense onshore-offshore seismic array deployed during the Cascadia Initiative experiment near the Mendocino triple junction. The abundant seismicity generates coherent waveform sections at each station with clear Ps and Sp converted phases that are observed at both onshore and offshore stations.

In the shallow part of the subduction zone near the deformation front, Ps and Sp converted phases from the slab interface arrive at about 2.5 s after P or before S on horizontal or vertical components. Other velocity discontinuities are also observed within the overlaying sediments. Using the converted phase arrival times and a previously studied active source seismic line, we estimate the average Vp/Vs ratio in the overlaying sediment ranges from 2.3 to 3.0. Given these constraints, the converted phases imply that the slab interface in the vicinity of the deformation front is ~2-4 km shallower than the Slab 1.0 model.

For several onshore stations, Sp converted phases are observed. Their arrival times are nearly consistent with the slab 1.0 model. The amplitude and waveforms of the Sp phases at nearby stations can vary significantly, indicating strong along-dip and along-strike variations in material properties near the interface. Our dataset includes phases that convert at depths from 2-25 km and span significant transitions in interseismic coupling that will be utilized to explore the relationship between material properties and coupling.

Lithospheric Structure of the Juan De Fuca and Gorda Plates From Ambient Noise

WANG, H., University of Colorado Boulder, Colorado, USA, hongda.wang@colorado.edu; RITZWOLLER, M., University of Colorado Boulder, Colorado, USA, michael.ritzwoller@colorado.edu; ZHONG, S., University of Colorado Boulder, Colorado, USA, shijie.zhong@colorado.edu

We estimate Rayleigh wave empirical Green's functions (EGFs) by cross-correlating vertical component ambient noise data from the 4-year deployment of the Cascadia Initiative (CI) ocean bottom seismometers (OBSs). Tilt and compliance noise are removed from the vertical component records prior to cross-correlation. Daily cross-correlations are then stacked over the duration of each station's deployment. We invert for a 3-D shear wave velocity model of the crust and upper mantle using Bayesian Monte Carlo inversion applied to Rayleigh wave phase and group velocity maps which are estimated from the EGFs.

We perform and compare results from two different parameterizations of 3-D shear wave velocity structure for the sediments, crust and uppermost mantle that differ in the mantle. One is a seismic parameterization in which we use five cubic B-splines for the mantle shear wave speed to a depth of 100 km. The second is a thermal plate model parameterization in which we model the shear wave velocity in the oceanic upper mantle via a temperature model and convert it to shear wave speeds based on mantle composition and Q models. The thermal parameterization is based on temperature of the top of the mantle, mantle cooling age and the potential temperature of the underlying adiabatic mantle.

Given these 3-D models, we address the following questions: (1) How well do the dispersion measurements fit with these two parameterizations of mantle structure? (2) Does the thermal model fit the data from midocean ridge to continental shelf or for only part of the region? (3) Is there an age-dependent relationship for mantle shear wave velocity on the plates? Are the age-dependent relationships the same for different profiles on the same plate? Do the Juan de Fuca and Gorda plates have the same age-dependent relationship? (4) In the resulting models, is there information about partial melt in the mantle?

Décollement initiation at Cascadia Subduction Zone from Full-Waveform Inversion

HAN, S., University of Texas Institute for Geophysics, Texas, USA, han@ig.utexas.edu; ARNULF, A. F., University of Texas Institute for Geophysics, Texas, USA, aarnulf@ig.utexas.edu; CANALES, J., Woods Hole Oceanographic Institution, Massachusetts, USA, jpcanales@whoi.edu; CARBOTTE, S. M., Lamont-Doherty Earth Observatory, New York, USA, carbotte@ldeo.columbia.edu; NEDIMOVIĆ, M., Dalhousie University, Halifax, Canada, mladen@dal.ca

The plate-boundary décollement at subduction zones is expected to follow a mechanically weak stratigraphic horizon where low frictional strength material resides or high pore fluid pressure develops. The stratigraphic level at which the décollement forms directly controls the amount of sediments being subducted, thus affecting the amount of fluid entering the subduction zone and the plate interface properties. At Cascadia subduction zone where the incoming Juan de Fuca plate is covered by 3-4 km thick sediment, the stratigraphic level of décollement varies significantly along strike, resulting in minimum sediment subduction offshore Washington, yet a 1.4-1.7 km thick layer of under-consolidated sediments is being subducted offshore Central Oregon. To investigate the sediment properties associated with décollement initiation and the conditions that give rise to different décollement depths off Central Oregon and Washington, we conducted 2-D elastic full waveform inversion (FWI) of multichannel seismic (MCS) data and resolved the fine-scale velocity structure of the incoming sediments within 40 km seaward of the deformation front. Sediment velocity from pre-stack depth migration and oceanic crustal velocity derived from travel-time tomography of ocean bottom seismometer data were used to build the starting model. We inverted for the refracted and then the reflected energy in downward extrapolated MCS data. Our preliminary results from offshore Central Oregon show that a low-velocity zone initiates ~10 km seaward of the deformation front at the stratigraphic boundary between Astoria fan sediment and abyssal plain turbidites. This low velocity zone is likely associated with anomalous high porosity that developed in response to the horizontal compression from the wedge. Further landward, this horizon becomes the décollement where the frontal thrusts shoal. We will present a comparative study of the velocity structures offshore Oregon and Washington at the meeting.

Onshore/Offshore Shear-Wave Velocity Structure Along the West Coast of British Columbia from Surface-Wave Tomography

GOSSELIN, J., University of Ottawa, Ottawa, Canada, jeremy.gosselin@uottawa.ca; AUDET, P., University of Ottawa, Ottawa, Canada, pascal.audet@uottawa.ca; SCHAEFFER, A. J., Geological Survey of Canada, Sidney, Canada, aj.schaeffer@gmail.com

The west coast of British Columbia, Canada, consists of active tectonic boundaries including the northernmost extent of the Cascadia Subduction Zone (CSZ) as well as the Queen Charlotte Fault (QCF) zone. Off the coast of Vancouver Island, seismicity is associated with the Explorer and Juan de Fuca ridges, as well as with convergence in the CSZ, which has the potential for producing large (M9.0) megathrust earthquakes. Further north, the transpressive interaction between the Pacific plate and the North American plate results in significant seismicity along the west coast of Haida Gwaii, including both strike-slip and thrust events. This research investigates the onshore/offshore tectonic structure of the west coast of Canada (from southern Vancouver Island to northern Haida Gwaii) using surface-wave tomography. In this work, Rayleigh-wave dispersion is estimated from regional earthquakes recorded primarily on Canadian National Seismograph Network (CNSN) stations, supplemented by short-term station deployments from various sources (*e.g.*, POLARIS, IRIS-PASSCAL). Some of the CNSN stations have recorded decades of data, and several hundred events. We consider a new direct Bayesian (probabilistic) inversion method to estimate a posterior probability density (PPD) of parameters that describe a three-dimensional shear-wave velocity model for the region. The velocity structure and associated uncertainties are estimated from properties of the PPD. This work provides constraint on the variations in offshore tectonic structure along the west coast of Canada and may help explain the complex processes occurring in the region.

Pn Tomography of the Juan De Fuca and Gorda Plates: Constraints on Mantle Deformation and Hydration in Young Oceanic Lithosphere

VANDERBEEK, B. P., University of Oregon, Oregon, USA, brandon.p.vanderbeek@gmail.com; TOOMEY, D., University of Oregon, Oregon, USA, drt@uoregon.edu

Tomographic analysis of Pn arrival times—the guided P-wave propagating within the lithospheric mantle—is ideal for studying uppermost mantle structure. While plate-scale seismic images of Pn velocities are common beneath the continents, similar scale studies have not been possible within ocean basins due to the sparse distribution of seismic stations. The Cascadia Initiative (CI) dataset provides the first opportunity to image spatial variations in lithospheric structure from accretion to subduction across an entire oceanic plate. We measure 2,862 Pn arrivals from local earthquakes recorded by the CI array and the complimentary Blanco and Gorda arrays. We invert the measured arrival times for 3D variations in isotropic and anisotropic P-wave velocity and event hypocentral parameters. Despite surficial evidence of extensive active faulting, the velocity structure of the Gorda uppermost mantle is remarkably consistent with predictions from a conductive cooling model. Limited deformation at mantle depths is supported by seismic anisotropy measurements that show the fast-direction of P-wave propagation rotates in concert with the magnetic anomaly lineations. This rotation may be explained by local plate kinematics without internal deformation and hydration of the shallow mantle. In contrast to Gorda, the seismic velocity structure of the JdF plate does not exhibit a clear age dependence. Anomalously slow mantle velocities are found along the southern edge of the JdF plate and are spatially associated with the termini of pseudofaults. We attribute these velocity reductions to mantle alteration by seawater. Beneath the central JdF plate, P-wave speeds remain relatively constant (~7.7 km/s) out to ~4-5 Myr before abruptly increasing to ~7.9 km/s at older plate ages. Curiously, this transition occurs near the onset of asthenospheric downwelling inferred from teleseismic body wave tomography [Byrnes *et al.*, 2017] and attenuation [Eilon and Abers, 2017] suggesting that the underlying geometry of mantle flow may influence the physical properties of young oceanic lithosphere.

New Constraints on Mantle Shear Velocity Structure Offshore Cascadia From the Joint Analysis of Teleseismic Body and Rayleigh Wave Data

VANDERBEEK, B. P., University of Oregon, Oregon, USA, brandonv@uoregon.edu; FORSYTH, D. W., Brown University, Rhode Island, USA, donald_forsyth@brown.edu; TOOMEY, D., University of Oregon, Oregon, USA, drt@uoregon.edu

To better constrain mantle dynamics offshore Cascadia, we jointly analyze teleseismic body wave delay times and Rayleigh wave phase and amplitude observations for 3D shear velocity (Vs) structure. Rather than simultaneously invert both seismic datasets, we instead progress through an alternating series of inversions in which the body and Rayleigh wave data are independently inverted for Vs perturbations. At each step in the series, the starting model is taken as the solution from the previous step thus coupling the two datasets. Preliminary results demonstrate that this simple approach is effective in yielding solutions that fit both datasets while also highlighting the consistencies and inconsistencies between them. A notable feature required by both datasets is a sharp gradient in seismic velocity east of the Juan de Fuca (JdF) Ridge that cannot be attributed to conductive cooling alone (*e.g.* Bell *et al.*, 2016; Byrnes *et al.*, 2017). The body wave data illuminate a deeper (~200 km) low velocity region beneath the JdF Ridge than recovered by the Rayleigh wave data alone. In the upper 100-200 km of the mantle beneath the Gorda plate, northern and southern ends of the JdF Ridge, and near the shelf, we observe a negative correlation among sequential velocity corrections in later iterations required by the two datasets, indicating fundamental inconsistencies. These differences are small compared to the absolute velocity variations, but still are significant. We consider the role of seismic anisotropy and the contrasting sensitivities of these seismic phases to Earth structure as possible explanations for these discrepancies.

Northern Cascadia Subduction Zone Observatory

HEESEMANN, M., University of Victoria, Victoria, Canada, mheesema@uvic.ca; WANG, K., Geological Survey of Canada, Sidney, Canada, kelin.wang@canada.ca; DAVIS, E., Geological Survey of Canada, Sidney, Canada, earl.davis@canada.ca; CHADWELL, D. C., University of California, San Diego, California, USA, cchadwell@ucsd.edu; NISSEN, E., University of Victoria, Victoria, Canada, enissen@uvic.ca; JIANG, Y., Geological Survey of Canada, Sidney, Canada, yan.jiang@canada.ca

To accurately assess earthquake and tsunami hazards posed by the Cascadia Subduction Zone, it is critically important to know which area of the plate interface is locked and whether or not part of the energy is being released aseismically by slow creep on the fault. Deeper locking that extends further to the coast produces stronger shaking in population centers. Shallow locking, on the other hand, leads to bigger tsunamis. We will report on and discuss plans for a new amphibious Northern Cascadia Subduction Zone Observatory (NCSZO) that will leverage the existing NEPTUNE cabled seafloor observatory, which is operated by Ocean Networks Canada (ONC), and the onshore network of geodetic stations, which is operated by Natural Resources Canada (NRCan).

To create a NCSZO we plan to (1) add a network of seven GPS-Acoustic (GPS-A) sites offshore Vancouver Island, (2) establish a Deformation Front Observatory, and (3) improve the existing onshore geodetic network (see Figure below). The GPS-A stations will provide the undistrurbed motion of the Juan de Fuca (JdF) Plate (1), deformation of the JdF plate (2), deformation of the overriding plate (3-7) and a cabled laboratory to study the potential for continuous GPS-A measurements (6). The Deformation Front Observatory will be used to study transient slip events using seafloor pressure and tilt instruments and fluid flux meters.

The majority of the offshore instruments will be installed in summer 2019. The station layout shown on the map below is a first draft. Finial locations that maximize scientific return and optimize logistics are currently under discussion.

Earthquake Ground Motions and Structural Response in Subduction Zones: A Focus on Cascadia

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Feasibility of Uniformly Applicable Basin Amplification Models for the United States

SKARLATOUDIS, A., AECOM, California, USA, andreas.skarlatoudis@aecom.com; BAYLESS, J., AECOM, California, USA, jeff.bayless@aecom.com; SOMERVILLE, P., AECOM, California, USA, paul.somerville@aecom.com

We utilize an extended dataset of subduction and crustal events, recorded in different basins around the world to estimate empirical basin amplification factors. The analysis aims to resolve potential differences in basin amplification between different types of events (crustal and subduction) and investigate the possibility of creating a uniform basin amplification model that could be applied in seismic hazard studies. For the crustal event dataset, which includes recordings from Taiwan and Japan, we observed strongest trends in the residuals for 1, 7.5 and 10s. Weaker amplification was observed in the period range 2-5s. A comparison with the amplification function proposed for California in Boore *et al.* (2014) shows a similar increase in the amplification with increasing spectral period, but the magnitude of the amplification developed from our dataset is lower. Our initial analysis of basin response in Japan from subduction events (Skarlatoudis *et al.*, 2015) indicated basin amplifications comparable to those obtained in the Seattle region by Frankel *et al.* (2018). However, an updated analysis that we performed for the subduction event dataset resulted in amplifications close to 1 for the whole period range (1 to 10s). While the results we obtain should not be outright discounted, we believe that the basin amplification for subduction events should not be drastically different from the crustal events and should not disagree so strongly with other empirical models. Therefore, we consider our residual analysis as inconclusive for the subduction events. These results could be attributed to the specific dataset that was used in the analysis, which may not be adequate to resolve such trends. This result could also imply that grouping together recordings from basins around the world, with different properties and geometries, is not an effective procedure for developing average, empirically estimated, basin amplification factors. As a step forward, a larger database would allow a more robust statistical analysis and better constrain the contribution of path effects.

Predicting Ground Motion for Hypothetical Earthquakes in the Cascadia Region Using Virtual Earthquakes

MA, Z., Harvard University, Massachusetts, USA, zhitu_ma@brown.edu; DENOLLE, M. A., Harvard University, Massachusetts, USA, mdenolle@fas.harvard.edu

Predicting the ground motion levels of the next Cascadia earthquakes are critical to mitigating seismic hazard in the Pacific Northwest. Here, we use the continuous recordings of both on shore and off shore seismometers in the Pacific Northwest, including the ones from the Cascadia Initiative Experiment, toward predicting ground motions of M8-M9 earthquakes with kinematic source models and following Denolle *et al.* (2014). We first characterize the Green's function content from offshore to onshore paths, we then explore the possibility to extend the previous method to a higher frequency range (up to ~1 Hz) while keeping the relative amplitude information among stations robust. Finally we convolve the 3D Green's functions with kinematic source models to predict ground motions in the broad region of Oregon and Washington areas.

Proposed Break in Magnitude Scaling of Earthquake Ground Motion and Source Dimensions for Subduction Mega-Earthquakes

CAMPBELL, K. W., CoreLogic, Inc., Oregon, USA, ken.w.campbell@comcast.net

In this study, I estimate the breakpoint magnitude (Mb) at which subduction megathrust earthquakes are expected to exhibit a break in scaling of both source dimensions and magnitude scaling rate (MSR) of radiated seismic ground motion for 79 global subduction zones identified by GEM. Reduced scaling of rupture length, rupture area, and MSR with moment magnitude is proposed to occur for events with magnitudes greater than Mb. Breakpoint magnitude is estimated from seismogenic fault widths, empirical source scaling relations, and aspect ratios of physically unbounded earthquake ruptures and their uncertainty. The concept stems from the well-established observation that source scaling and MSR of shallow continental strike-slip earthquakes exhibit a scaling break at approximately a magnitude of 6.5 and maximum seismogenic fault width of 15 km. A similar scaling break for megathrust earthquakes is difficult to observe because of the relatively large subduction interface widths and the limited number of events with ruptures that exceed these widths. However, I observe that all of the his-

torical M > 8.7 mega-earthquakes in recent history have occurred on subduction zones for which the breakpoint magnitude is estimated to be approximately 8.5, consistent with the observed break in source scaling relations derived from these same subduction zones. Mean breakpoint magnitudes for selected global subduction zone interfaces are estimated to be 7.6 for Cascadia, 8.5 for Japan Trench, 7.5 for Nankai Trough, 8.2 for Hikurangi (North Island, New Zealand), 8.3 for Andaman, 8.0 for Sumatra, 7.6 for Java, 8.4-8.6 for South America, and 7.2-7.5 for Mexico-Central America. For all 79 subduction zones, the mean and median breakpoint magnitudes are 7.8 and 7.9, respectively, with standard deviations of 0.24. These mean and median global breakpoint magnitudes are consistent with the generic break in magnitude scaling defined in the updated (2018) BC Hydro subduction ground motion model.

Development of NGA-Sub Ground Motion Model of 5%-Damped Pseudo-Spectral Acceleration Based on Database for Subduction Earthquakes in Japan

SI, H., Seismological Research Institute Inc., Bunkyo-ku, Japan, shj@seismo-r.com; MIDORIKAWA, S., Tokyo Institute of Technology, Tokyo, Japan, smidorik21@gmail.com; KISHIDA, T., Khalifa University, Abu Dhabi, United Arab Emirates, kishidapple@gmail.com

We developed an empirical ground motion model (GMM) for subduction earthquakes in Japan. The model is based on the extensive and comprehensive subduction database in Japan by Pacific Engineering Research Center, and was developed for the RotD50 horizontal components of peak ground acceleration (PGA), peak ground velocity (PGV), and 5%-damped elastic pseudo-absolute acceleration response spectral ordinates (PSa) at the selected periods ranging from 0.01 to 10 sec. The model includes terms and predictor variables considering tectonic setting (*i.e.* interplate and intraslab), hypocenter depths, magnitude scaling, distance attenuation, and site responses. The magnitude scaling derived in this study is well constraint by the data observed during the large-magnitude interface events in Japan (*i.e.* 2003 Tokachi-Oki earthquake, 2011 Tohoku earthquake) for different periods. The developed GMPE covers subduction earthquakes occurred in Japan for magnitudes ranging from 5.5 to as large as 9.1 with distances less than 300 km from the source.

Generic Ground Motion Model for Subduction Earthquakes in Japan; Implication for Cascadia Subduction Zone

HASSANI, B., BC Hydro, Burnaby, Canada, behzad.hassani@bchydro.com; ATKINSON, G. M., Western University, London, Canada, gmatkinson@aol.com

We use the adjustable generic ground-motion model (GMM) of Hassani and Atkinson (2018) (HA18) to develop predictive relations for the amplitudes of shaking for subduction earthquakes in Japan. The database of the study is extracted from the recently developed Next Generation Attenuation for Subduction Earthquakes (NGA-Sub) database (Kishida *et al.*, 2017). The NGA-Sub database includes ground-motion data for interface, inslab, and crustal earthquakes from subduction regions around the world, with the Japanese database contributing more than 50% of the records. The HA18 model is based on the equivalent point source approach, allowing regional modifications to its key input variables such as geometrical spreading rate, anelastic attenuation, stress parameter, near surface attenuation parameter (kappa), and crustal amplification. The GMM of this study is developed in a way to account for inferred differences in the median stress parameters and geometric spreading for interface and inslab earthquakes, and for differing attenuation in forearc and backarc regions. The GMM is developed for peak ground acceleration, peak ground velocity, and 5% damped pseudospectral acceleration (PSA) at frequencies from 0.1 to 100 Hz, for rupture distances up to 1000 km. The reference ground condition is V_{S30} = 760 m/s (time-averaged shear-wave velocity in the top 30m); individual site terms relative to the model are derived for each station. In future work, the model will be adjusted for the Cascadia subduction zone to account for regional source, attenuation and site attributes that differ from those in Japan.

Characterizing Strong Shaking Hazard in Puget Sound Using Ambient Noise Seismology

TOGHRAMADJIAN, N., Harvard University, Massachusetts, USA, natasha_toghramadjian@g.harvard.edu; DENOLLE, M. A., Harvard University, Massachusetts, USA, mdenolle@fas.harvard.edu

Puget Sound contains several shallow sedimentary basins, comprised of unconsolidated deposits underlain by sedimentary rocks and set within hard crystalline bedrock. The basins underlie some of Washington's most populous cities, and the region is subject to high seismic hazard. To characterize the shaking hazard in Puget Sound, we aim to understand how the seismic wavefield propagates within the basins. We extract this information from the ambient seismic wavefield. Using a newly developed set of correlation codes written in Julia, we cross-correlate ambient noise from all available short-period and broadband stations in the Puget Sound area in the 2010-2018 window. We present examples of all 9 components of the correlation tensor in the period band of 1-10 seconds. We characterize surface and body waves to investigate seismic amplification in the basins, and compare these amplifications with the current velocity model. We show preliminary dispersion curve measurements to extract Love- and Rayleigh-wave modes.

Challenges and Consequences of Input Motion Selection for Subduction Zone Environments: Seattle, Washington

CHOWDHURY, I., North Carolina State University, North Carolina, USA, ichowdh@ncsu.edu; CABAS, A., North Carolina State University, North Carolina, USA, amcabasm@ncsu.edu; KAKLAMANOS, J., Merrimack College, Massachusetts, USA, kaklamanosj@merrimack.edu; KOTTKE, A. R., Pacific Gas and Electric Company, California, USA, arkk@pge.com; GREGOR, N., Consultant, California, USA, nick@ngregor.com

The selection of hazard-consistent ground motions is a critical step for many geotechnical and structural engineering analyses. Earthquake ground motions serve as the link between evaluations of seismic hazards and assessments of civil infrastructure performance. This study investigates the challenges associated with selecting and scaling motions representative of the site-specific seismic hazards in subduction zone environments, using Seattle, Washington, as an example. Like many locations in subduction zones, Seattle has seismic hazard contributions from both crustal events and subduction events (including interface and intraslab earthquakes). This diverse tectonic setting makes the selection of representative input motions a challenging task, as the mean magnitude and distance from the seismic hazard deaggregation are not physically consistent with any individual type of seismic source. Moreover, the paucity of available ground motion recordings in the U.S. corresponding to subduction events imposes yet another challenge for ground motion selection. In this study, we have used ground motions from subduction events included in the Japan KiK-net database. A site-specific seismic hazard analysis is conducted for Seattle, and target spectra are defined for different hazard levels and different periods of interest. Input motion sets representative of each seismic source identified are then selected from different databases. Geotechnical site response analyses are conducted to investigate the implications of selected motions, and significant soil nonlinearity is observed in Seattle for design level ground motions. The study site in Seattle consists of approximately 50 m of loose soil (artificial fill over young alluvial deposits), overlying a dense layer of glacial deposits. The results suggest that the selection approach for hazard-consistent ground motions may require explicit consideration of multiple design earthquake scenarios in subduction zone environments.

Trans-Boundary Earthquakes of the Himalayan Thrust Region and Their Bearing on Hazard Potential in Around Geographical Boundaries

SHARMA, B., National Center for Seismology, Ministry of Earth Sciences, New Delhi, India, babita.s@nic.in; MISHRA, O. P., National Centre for Seismology, Ministry of Earth Sciences, New Delhi, India, opmishra2010.saarc@gmail.com

2015 Nepal Earthquake (M_w 7.9) and 2009 Bhutan Earthquake (M_w 6.1) along with their prominent aftershocks have been studied to understand the degree of hazard potential in around border areas of India to Bhutan and Nepal. The ground motions of the 2015 Nepal Earthquake (M_w 7.9) showed a conspicuous process associated with non-linearity besides the proximity of the sites located on the sediments of Indo-Gangetic planes. We considered the detailed heterogeneity, medium of propagation, and rupture characteristics of the earthquakes to arrive at better explanation of trans-boundary earthquakes. We found that the horizontal components of all magnitudes ($M_w \geq 6.1$) show peak pseudo-velocity responses at periods of 0.4 s to 0.6 s. The large elastic pseudo-velocity responses range between 20 cm/s and 45 cm/s at 5 % critical damping using data of Nepal earthquake sequence recorded in the Indo-Gangetic planes whilst low values less than 10 cm/s for pseudo-velocity responses were found for 2009 Bhutan earthquake (M_w 6.1). A comparison of the observational data with Ground Motion Prediction Equation (GMPE) for Himalaya demonstrated a close similarity. The observed peak ground accelerations and peak ground velocities at the various sites are generally well described by the GMPEs for trans-boundary earthquakes of Himalaya. It is also revealed that the basin sediments of Indo-Gangetic planes and Brahamputra valley are strongly amplified by the long-period components of the ground motions of the main shocks and their prominent aftershocks used in the present study. We infer that our findings are important for estimating the seismic hazard potential of the trans-boundary region having no constraints on geographical boundaries in around source zones of two prominent earthquakes of 2009 Bhutan earthquake (M_w 6.1) and 2015 Nepal earthquake (M_w 7.9) which, can also be utilised in the engineering practices for better structural resiliency of the region.

New Earthquake Classification for the NGA-Subduction Project

WOODDELL, K. E., Pacific Gas and Electric Company, California, USA, katie.wooddell@gmail.com; ABRAHAMSON, N., University of California, Berkeley, California, USA, abrahamson@berkeley.edu; BOZORGNIA, Y., University of California, Los Angeles, California, USA, yousef.bozorgnia@ucla.edu; CAMPBELL, K. W., CoreLogic, Inc., California, USA, kcampbell@corelogic.com; STEWART, J. P., University of California, Los Angeles, California, USA, jstewart@seas.ucla.edu; CHIOU, B. S. J., California Department of Transportation, California, USA, brian.chiou@dot.ca.gov; YOUNGS, R. R., John Wood Group PLC, California, USA, bob.youngs@amec.com

The NGA-Subduction project evaluated two new Class 2 (C2) aftershock classification methods. Each method uses the time window from Gardner and Knopoff (1974) and distance windows of 10, 20, 40, and 80 kilometers are evaluated. The difference between the methods is in the distance metric that is used. One method uses a distance metric for C2 earthquakes based on the closest distance from the Class 1 (C1) rupture plane to the C2 hypocenter while the other method uses the closest distance from the C1 rupture plane to the C2 rupture plane. Ultimately, the choice of the distance window width is left to the expert judgment of each developer team. Using a distance window of 40 kilometers, ground motions for the C2 aftershocks are about ten percent lower than the ground motions for C1 events over all spectral period. We present Class 1 and Class 2 results for the NGA-subduction database and provide examples of how they are applied in the subduction GMPEs.

The Period-Dependent Effects on the Amplification of Observed Ground Motions Within the Seattle Basin

REKOSKE, J., U.S. Geological Survey, Colorado, USA, jrekoske@usgs.gov; MOSCHETTI, M. P., U.S. Geological Survey, Colorado, USA, mmoschetti@usgs.gov; THOMPSON, E. M., U.S. Geological Survey, California, USA, emthompson@usgs.gov

Previous studies have shown the Seattle basin's potential to amplify observed ground motions. We compile a database of ground motions from earthquakes in the Pacific Northwest and compute amplifications from all records relative to ground motion prediction equations (GMPEs) for Vs30=760 m/s site conditions. We compile a catalog for 159 earthquakes in the region with M ≥ 3.0 and four recent events (M ≥ 5.2) that occured SW of Vancouver Island, Canada. Each event is classified by tectonic regime (crustal, interface, intraslab, or undetermined) using the Slab 2.0 model. For each event, waveform data from stations located within 3.0 degrees from the epicenter are requested from IRIS. We develop an automated processing workflow (ShakeMap-Amp-Tools) that follows the standard procedures: baseline correction, removal of clipped waveforms, instrument response correction, removal of waveforms with invalid amplitudes, high-pass and low-pass filtering with dynamically-selected corner frequencies, and polynomial baseline correction. For each processed waveform, the pseudo-spectral accelerations (SA) are calculated at 9 different periods (0.1, 0.2, 0.3, 0.5, 1, 2, 3, 5, and 10 s) for combined horizontal-components (RotD50, RotD100) and for radial-, transverse-, and vertical-components. The observed RotD50 ground motions for crustal earthquakes are compared with predicted ground motions using an average of the NGA-West-2 GMPEs. Comparison with predicted ground motions helps identify issues in the database and provides a feedback for assessing station quality. We compute ground motion residuals from the final database, relative to average-predictions from the GMPE suite, and assess the spatial variations of the resulting amplifications. Initial analysis of these amplification factors indicates higher spatial variability among the shorter period amplifications, while longer periods show amplifications that correlate more closely with the basin structure.

Using Noise Correlation to Improve the 3D Seismic Velocity Model of the Seattle Basin

HUTKO, A., Pacific Northwest Seismic Network, Washington, USA, ahutko@uw.edu; REUSCH, M., Pacific Northwest Seismic Network, Washington, USA, topo@uw.edu; GIBBONS, D., Pacific Northwest Seismic Network, Washington, USA, dgibbons@uw.edu; BODIN, P., Pacific Northwest Seismic Network, Washington, USA, bodin@uw.edu

The Seattle sedimentary basin beneath Seattle is known to significantly amplify long period ground motions. The basin has been characterized by past seismic and other geophysical experiments. The goal of the Seattle Urban eXperiment (SUX) is to use ambient noise cross-correlation of broadband data recorded along receiver-receiver lines throughout the city to understand the basin structure in areas not previously studied and help guide larger experiments in the city scheduled later this year. Ambient noise cross-correlation can be used to extract Green's functions between two receivers since the cross-correlation functions are similar to surface waves excited by earthquakes. Analysis of the surface wave dispersion is used to generate a near-surface velocity model. Our experiment currently uses data recorded by six portable broadband stations as well as existing broadband stations sited in the city. Only a few weeks of data are needed for stable correlelegrams after which the stations are moved. As long as the portable instruments are not needed for other purposes, we plan on continuing to collect data throughout the Puget lowlands and will potentially target other structures such as the Tacoma basin.

Better Earthquake Forecasts

Poster Session · Wednesday · 24 April · Grand Ballroom

A New Application of Operational Aftershock Forecasting: Sequence Duration

MICHAEL, A. J., U.S. Geological Survey, California, USA, michael@usgs.gov; MCBRIDE, S. K., U.S. Geological Survey, California, USA, skmcbride@usgs.gov

U.S. federal funds for disaster relief are tied to a declaration of the incident that describes its boundaries in time and space. FEMA seeks information from federal agencies with expertise in each type of disaster in order to make well-founded and documented decisions. For wildfires and floods they rely on the U.S. Forest Service and the USGS, respectively. Past earthquake incident declarations have lasted from a day for the M9.2 1964 Great Alaska earthquake to 10 months for the M6.7 1994 Northridge earthquake but it is unclear how those limits were set. After the M7.0 2018 Anchorage earthquake FEMA requested information on the expected duration of the aftershock sequence. The temporal limits of an aftershock sequence can be hard to define and so this request was responded to with a forecast that includes uncertainty, using the Reasenberg and Jones (1989) model as updated by Page *et al.* (2016). Using two sets of parameters, determined as of December 14, 2018, USGS OFR-2018-1195 estimated that it will take between 2.5 to 30 years before the rate of aftershocks decays to the rate of earthquakes that were occurring in this area before the M7.0 mainshock. The large uncertainty is due to uncertainty in the decay parameter (p) between the generic model for that tectonic region (which fit the first 10-days of past sequences) and the sequence specific model for the first two weeks. The report also estimated the amount of time after the mainshock until the annual probability of M~5 and M~6 aftershocks decreases to 50, 25, 10, and 5%. For instance, the probability of one or more M~6 aftershocks in the following year decreases to 10% between 7 and 250 days after the mainshock. The same probability for M~5 earthquakes is reached between 500 and 7,000 days after the mainshock. The uncertainty in these estimates highlights the importance of the p-value for very long-term forecasts. Forecasting duration could help users understand the implications of aftershock sequences.

Towards Improved Uncertainty Quantification and Visualization for Aftershock Forecasts in the Pacific Northwest

SCHNEIDER, M., University of Washington, Washington, USA, maxs15@uw.edu; GUTTORP, P., University of Washington, Washington, USA, guttorp@uw.edu

Probabilistic aftershock forecasts based on seismicity models are crucial for earthquake risk reduction. However, forecasts have uncertainty stemming from several sources, which must be rigorously quantified to properly assess seismic risk. We build several models for on-shore seismicity in the Pacific Northwest (PNW) of North America, based on the Epidemic Type Aftershock Sequence (ETAS) method. ETAS is a parametric space-time point process model that describes background seismicity and aftershock clustering. We combine three earthquake catalogs for the PNW from 1970-2001, including data on measurement errors for reported magnitudes and locations for all earthquakes. We discuss the effects of estimating parameters differently across two- and three-dimensional space. Unlike other seismicity models, we propagate the known measurement errors through the model to obtain more realistic uncertainties on estimates of earthquake rate and its parameters. We use a simulation-based approach that isolates the effect of measurement error and model stochasticity on these model outputs. We present results showing spatial dynamics in estimated PNW earthquake rates and ETAS parameters. The effect of measurement error on model outcomes is more nuanced and also influenced by space and time. Implications for aftershock forecasting are discussed. We also introduce early work on the improved visualization of such model uncertainties. In an experiment, we evaluate the effectiveness of three competing visualizations of aftershock forecasts and their uncertainties. We provide the experimental design and first results of this evaluation.

A Comparison of Probabilistic Seismic Hazard Maps to Shakemap Footprints in Indonesia

POTHON, A., AXA Group Risk Management, ISTerre, Université de Grenoble-Alpes/Université de Savoie Mont Blanc/CNRS/IRD/IFSTTAR, Grenoble, France, adrien.pothon@univ-grenoble-alpes.fr; GUÉGUEN, P., ISTerre, Université de Grenoble-Alpes/Université de Savoie Mont Blanc/CNRS/IRD/IFSTTAR, Grenoble, France, philippe.gueguen@univ-grenoble-alpes.fr; BARD, P., ISTerre, Université de Grenoble-Alpes/Université de Savoie Mont Blanc/CNRS/IRD/IFSTTAR, Grenoble, France, pierre-yves.bard@univ-grenoble-alpes.fr; BUISINE, S., AXA Group Risk Management, Paris, France, sylvain.buisine@axa.com

This study provides the results of testing three probabilistic seismic hazard assessment (PSHA) PSHA maps: the Global Seismic Hazard Assessment Program (GSHAP; Giardini *et al.* 1999), the Global Assessment Report 2015 (GAR2015; International Strategy for Disaster Reduction 2013) and the Standar Nasional Indonesia (SNI2017; Irsyam *et al.* 2017). The observations are earthquakes occurred in Indonesia between May 1968 and May 2018 and modelled by the USGS Shakemap program. Despite they are not as accurate and complete as continuous recorded ground motions, the 959 collected Shakemap footprints cover 7,642,261 grid points, at 1km^2 resolution, when only 126 seismic stations are currently operating in Indonesia.

After verifying the representativeness of Shakemap footprints for the maximum historical peak ground acceleration (PGA) between May 1968 and May 2018, this data has been extracted from Shakemap footprints for 177,674 sites with rock conditions and 232 different mainshocks, according to a new process, developed in this study. Then, PSHA maps are tested by selecting randomly one site per mainshock to meet the condition for testing of independency between PGA observations. Furthermore, to ensure that a dataset made of 232 values is large enough for statistical analyses, a new relationship is introduced between the minimum number of observations needed, the return period of the PSHA map tested and the observation period length.

The three PSHA maps are finally tested for both the whole Indonesia and only the Western part of Indonesia. Results showed that the SNI2017 map is consistent with the last 50 years seismicity over the whole country, but overestimates it when focusing on Western Indonesia. At the opposite, the GSHAP and the GAR2015 PSHA maps fit the past seismicity on Western Indonesia, but underestimate it when considering the whole country. This study concludes that using Shakemap footprints for a large country, prone to earthquake risk in its entirety, enables to differentiate PSHA maps by using past seismicity for testing.

Earthquake and Tsunami Nowcasting and Forecasting Using Shannon Information Theory

RUNDLE, J. B., University of California, Davis, California, USA, jbrundle@ucdavis.edu; NANJO, K., University of Shizuoka, Shizuoka, Japan, nanjo@u-shizuoka-ken.ac.jp; TURCOTTE, D. L., University of California, Davis, California, USA, dlturcotte@ucdavis.edu; DONNELLAN, A., Jet Propulsion Laboratory, California Institute of Technology, California, USA, andrea@jpl.caltech.edu; CRUTCHFIELD, J., University of California, Davis, California, USA, crutchfield@ucdavis.edu

What is the information content of a sequence of earthquakes? In 1948 Claude Shannon described a method for understanding the quantity of information provided by a sequence of events derived from an alphabet of symbols. Shannon's statistical communication theory is now widely recognized as one of the fundamental discoveries of the 20th century, and is the foundation for modern computer technology.

We have begun to apply Shannon's methods in an attempt to extract the information content of earthquake events. Clearly, both nowcasting and forecasting are techniques that try to understand the information content of earthquake sequences and the implication for future earthquakes. We note that nowcasting refers to the estimation of the current uncertain state of a dynamical system, whereas forecasting is a calculation of probabilities of future state(s).

In this talk we describe a new method for nowcasting and forecasting that incorporates some of the results of statistical communication theory. We describe preliminary results for global catalogs and regional catalogs such as the Japanese islands, and discuss implications of future and ongoing research, particularly as it might apply to both great earthquakes and tsunamis.

We also adopted and further developed the earthquake nowcasting method to Japan. For southern Kanto, we used earthquakes since 1926 with depths shallower than 150 km and set M_L=6.0 and M_S = 4.2. The obtained result as of December 20, 2018 is EPS of 8%. This is interpreted as an indication that if a large (M6+) earthquake occurred on this date, the recurrence interval would be relatively short. Errors that arise from statistics-based estimation such as this must be considered so that we introduced the calculation of uncertainties to the earthquake nowcasting, using a bootstrap approach. Taking into account the contribution of these errors to the EPS calculations, we conclude that the earthquake nowcasting generates stable estimates of EPS for southern Kanto.

Bayesian Inference on the Magnitude of the Largest Expected Earthquake

SHCHERBAKOV, R., Western University, London, Canada, rshcherb@uwo.ca; ZHUANG, J., Institute of Statistical Mathematics, Tokyo, Japan, zhuangjc@ism.ac.jp; ZOELLER, G., University of Potsdam, Potsdam-Golm, Germany, zoeller@uni-potsdam.de; OGATA, Y., Institute of Statistical Mathematics, Tokyo, Japan, ogata@ism.ac.jp

Majority of earthquakes occur unexpectedly and can trigger subsequent sequences of events that can culminate in more powerful earthquakes. This self-exciting nature of seismicity generates complex clustering of earthquakes in space and in time. Therefore, the problem of constraining the magnitude of the largest expected earthquake during a future time interval is of critical importance in mitigating earthquake hazard. We address this problem by developing a methodology to compute the probabilities for such extreme earthquakes to be above certain magnitudes. We combine the Bayesian analysis with extreme value statistics to compute the Bayesian predictive distribution for the magnitude of the largest event to exceed a certain value in the near future. In the analysis, we assume that the earthquake occurrence rate can be modelled by the ETAS process, where each earthquake is capable of triggering subsequent events. To model the uncertainties of the model parameters, we employ the Markov Chain Monte Carlo method to sample the posterior distribution of the model parameters and use the generated chain of the parameters to simulate forward in time an ensemble of the ETAS processes. To illustrate our approach, we analyzed one recent prominent sequence, the 2016 Kumamoto, Japan, earthquake sequence, where we were able to compute the probabilities of having the largest expected events above certain magnitudes to occur during several stages of the sequence. As a main result of this work, we developed and tested an inference procedure to estimate the probabilities of having largest expected events during an earthquake sequence governed by the ETAS process. The suggested approach can be implemented in current or future operational earthquake forecasting schemes, where the constraints on the magnitudes of future large earthquakes are taken into account.

The Collaboratory for the Study of Earthquake Predictability Version 2 (CSEP2): Testing Forecasts That Generate Synthetic Earthquake Catalogs

SAVRAN, W., University of Southern California, California, USA, wsavran@usc.edu; MAECHLING, P. J., University of Southern California, California, USA, maechlin@usc.edu; WERNER, M. J., University of Bristol, Bristol, United Kingdom, max.werner@bristol.ac.uk; JACKSON, D. D., University of California, Los Angeles, California, USA, djackson@g.ucla.edu; SCHORLEMMER, D., GFZ German Research Centre for Geosciences, Potsdam, Germany, ds@gfz-potsdam.de; RHOADES, D., GNS Science, Wellington, New Zealand, d.rhoades@gns.cri.nz; MARZOCCHI, W., Istituto Nazionale di Geofisica e Vulcanologia, Naples, Italy, warner.marzocchi@ingv.it; YU, J., University of Southern California, California, USA, johnyu@usc.edu; JORDAN, T. H., University of Southern California, California, USA, tjordan@usc.edu

The Collaboratory for the Study of Earthquake Predictability (CSEP) supports an international effort to conduct and rigorously evaluate earthquake forecasting experiments. CSEP has concluded its first phase of testing (CSEP1) with recent results published in the June/July 2018 Special Issue of Seismological Research Letters. CSEP1 experiments evaluate forecasts expressed as expected rates in small space-magnitude bins that can be updated at regular intervals (*e.g.*, daily or yearly). This experiment design is simple and allows a wide range of models to participate. However, recently developed forecast models, including candidate models for authoritative Operational Earthquake Forecasting (OEF), can simulate thousands of synthetic seismicity catalogs (stochastic event sets), which express important dependency structures between triggered earthquakes. These forecasts eliminate the assumption that seismicity can be described by independent Poisson processes. As part of CSEP's second phase (CSEP2), we are redesigning CSEP's software system to support the testing of such model classes. Requirements include access to high-performance computing, distributed processing of forecasts and evaluations, and simplifying data management, as well as adhering to CSEP's principles of transparency and reproducibility within a controlled, open-source software environment. To begin the transition into CSEP2, we redesigned core CSEP1 evaluations to be consistent with forecasts that produce stochastic event sets; namely, the N-test, the M-test, and the S-test. We apply these tests as part of a retrospective experiment that initially focuses on evaluating UCERF3-ETAS within the California testing region. The new evaluations are available as part of an open-source Python package that will provide the community with the necessary tools to conduct regional forecasting experiments.

Numerical Simulation of Stress Evolution and Earthquake Sequence of the Sichuan-Yunnan Region, China

DONG, P., Institute of Seismology, China Earthquake Administration, Wuhan, China, dongpeiyu10@gmail.com

The Sichuan-Yunnan region is located in the southern section of the South-North seismic belt in China, behaves as lots of left-lateral strike –slip active fault system. Since 1900 , more than 30 earthquakes of M > 6.5 occurred sequentially in this region. How did the stresses evolve during the last more than 100 years, how did the earthquakes interact with each other? Can this knowledge help us to forecast the future seismic hazards? In this essay, we tried to simulate the evolution of the stress field and the earthquake sequence in the Sichuan-Yunnan region of China within the last 110 years with a 2-D finite element model.

In this study, we estimated a reasonable range of initial stress, and then based on Coulomb-Mohr criterion to regenerate the earthquake sequence, starting from the Daofu earthquake of 1904. We regenerated all of the 30 historical earthquakes, considering both the tectonic loading and interaction between the earthquakes. Ultimately we got a sketch of the present stress. Of course, a single model with certain initial stress is just one possible model. Consequently the potential seismic hazards distribution based on a single model is not convincing. We made test on tens of thousands of possible initial stress, all of them can produce the historical earthquakes occurred sequentially, and summarized all kinds of calculated probabilities of the future seismic activity. Although we cannot provide the exact state in the future, but we can narrow the estimate of regions where is in high probability of risk. Our primary results indicate that the Xianshuihe fault and adjacent area is one of such zones with higher risk than other regions in the future. We emphasized the importance of the initial stress field for the earthquake sequence, and provided a probabilistic assessment for future seismic hazards. This study may bring some new insights to estimate the initial stress, earthquake triggering, and the stress field evolution.

Effects of Low-Magnitude Earthquakes' Focal Mechanisms on the Evolution of Aftershock Sequences

TOWNEND, J., Victoria University of Wellington, Wellington, New Zealand, john.townend@vuw.ac.nz

Most studies of earthquake interaction via incremental stress transfer have focused on the effects of the largest events only. In aftershock sequences, these events typically constitute the mainshock alone, or the mainshock and the largest aftershocks. Some of the gross spatial and temporal features of aftershock sequences can be accounted for with this approach, but the role played by interactions between lower-magnitude events remains unclear. To date, comparatively little attention has been paid to aftershocks' focal mechanisms, which, in principle, enable incremental stress changes associated with lower-magnitude events to be computed and incorporated in stress transfer models. Here, we consider the interaction between one earthquake and the next in terms of the vector joining their hypocenters and represented in a coordinate system defined by the earlier event's focal mechanism. This approach enables us to describe the sequence of focal mechanisms with reference to a common coordinate system and to take into consideration the perturbations produced by all earthquakes large enough for a focal mechanism to be calculated. We investigate whether the faulting geometry of each aftershock contributes to the sequence's overall evolution, using complete and declustered examples.

Uncertainties on Fault Parameters and Seismotectonic Source Zones for Site-Specific PSHA in Southeastern France

DUVERGER, C., CEA, Bruyères-le-Châtel, France, clara.duverger.pro@gmail.com; VALLAGE, A., CEA, Bruyères-le-Châtel, France, amaury.vallage@cea.fr; BOLLINGER, L., CEA, Bruyères-le-Châtel, France, laurent.bollinger@cea.fr

The quantification of uncertainties is crucial to correctly assess a seismic hazard for safety purposes. Among other sources of uncertainties, the ones associated with the seismic sources are still considerable and are likely to remain high for many more years. Indeed, French instrumental and historical catalog durations are short compared to the return period of significant earthquakes and progress in resolving the French fault activity is limited due to low seismicity and deformation rates.

We present a site-specific PSHA study focused on Southeastern France, where debates are still open with divergent opinions and where strong efforts are devoted to the characterization of faults and seismic activity. We explore the variability of the computed hazard curves at different frequencies in order to depict the current diversity of seismotectonic zone models and fault models. We use the FCAT-17 catalog, which incorporates the instrumental catalog (SiHex) and the historical catalog (SisFrance) converted in Mw. We compare several source zone models to take into account different interpretations existing among specialists, especially the CEA zoning integrating recent neotectonic indices. We also investigate extreme plausible fault models based on information given in the French Active Fault Database (BDFA) including some geodetic data.

PSHA computation is performed using OpenQuake and implemented assuming three main hypotheses: (1) zoning with diffuse seismicity, (2) faulting with characteristic earthquakes and (3) faulting with seismicity following a Gutenberg-Richter law. Logic trees enable to take into account epistemic uncertainties on input source parameters and on suitable GMPEs for the French seismotectonic context. Sensitivity tests show that uncertainties on the fault parameters are the dominant factor controlling the variability of the seismic hazard level at various time scales, greater than epistemic uncertainties due to GMPEs and zonings. Finally, this study opens discussions towards alternative models of seismicity generation in intra-continental regions.

Revisiting Source Modeling in Complex Tectonic Environments for PSHA: A Taiwan Case Study

VELASQUEZ, J., Risk Management Solutions, California, USA, jessica.velasquez@rms.com; FITZENZ, D. D., Risk Management Solutions, California, USA, delphine.fitzenz@rms.com; PORTO, N. M., Risk Management Solutions, California, USA, natanya.porto@rms.com

All six Taiwan cities with populations of over one million people are located less than 10 km from at least one known, active seismogenic structure. The importance of characterizing the hazard associated with these structures is critical for understanding the risk in Taiwan, a country not unfamiliar with large, damaging earthquake. The complexity of the tectonics in this region make it well-suited for an investigation into the dynamics of how systems of faults and subduction interfaces may interact and accommodate plate motions. Here we build on and explore the recent Taiwan Earthquake Model Probabilistic Seismic Hazard Assessment study (TEM PSHA2015; Wang *et al.*, 2016). We show the variation in hazard that can result from the inclusion of sub- and multi-fault ruptures. The systems of crustal faults across Taiwan translate the motions between the two opposite-dipping subduction zones at either end of the island. We will therefore also explore how coupling assumptions affect the overall moment budget of the system. We present end member cases to showcase the hazard variability and show how these variations can translate into significant differences in risk.

Assessments of the Performance of the 2017 One-Year Seismic Hazard Forecast for the Central and Eastern United States via Simulated Earthquake Shaking Data

BROOKS, E. M., Northwestern University, Illinois, USA, eddie@earth.northwestern.edu; NEELY, J. S., Northwestern University, Illinois, USA, james@earth.northwestern.edu; STEIN, S., Northwestern University, Illinois, USA, s-stein@northwestern.edu; SPENCER, B., Northwestern University, Illinois, USA, bspencer@northwestern.edu; SALDITCH, L., Northwestern University, Illinois, USA, leah@earth.northwestern.edu; PETERSEN, M. D., U.S. Geological Survey, Colorado, USA, mpetersen@usgs.gov; MCNAMARA, D. E., U.S. Geological Survey, Colorado, USA, mcnamara@usgs.gov

As a result of wastewater injection from nonconventional oil and gas production, the central and eastern United States experienced a dramatic increase in seismicity. To better characterize the resulting hazard, the U.S. Geological Survey began producing one-year seismic hazard maps intended to capture both natural and induced seismicity as of 2016. In its first year, we found that the map performed very well, demonstrating both a good match between the observed and expected number of exceedances, and between observed and predicted shaking. We repeat this analysis for the 2017 map, using "Did You Feel It?" (DYFI) data to explore the map's performance in different regions of the country. We find that the 2017 model performed well, but not as well as the previous year's model. We explore the likelihood of observing the performance seen in 2017, by simulating earthquake shaking realizations using the assumptions of the 2017 hazard model, including a- and b-values, locations of induced earthquakes, and ground motion models. These simulations indicate a low likelihood of this decrease in performance happening by chance if the assumptions in the hazard model were appropriate. Hence, it is likely that the map's performance reflects a reduction in wastewater injection rates, possibly due to regulatory and economic pressures. Future maps could benefit from better modeling how seismic rates may change year-to-year and improved ground motion models.

Seismogenic Zones and their Influence on Seismic Hazard Assessments – Case Studies from the Caucasus

ONUR, T., OSC, Inc., Victoria, Canada, onur.osc@gmail.com; GOK, R., Lawrence Livermore National Laboratory, California, USA, gok1@llnl.gov; GODOLADZE, T., Ilia State University, Tbilisi, Georgia, tea_godoladze@iliauni.edu.ge; BUZALADZE, A., Ilia State University, Tbilisi, Georgia, albert.

buzaladze.1@iliauni.edu.ge; GUNIA, I., Ilia State University, Tbilisi, Georgia, irakli.gunia@iliauni.edu.ge

Seismogenic zones are delineated, based on all available information from tectonics, active faulting, geology, geodesy, and past seismic activity, for use in probabilistic seismic hazard assessments (PSHA). Often the delineation of seismic zones is dependent on availability of information and how the seismic hazard specialist interprets and makes a judgement based on the available information.

As these decisions may have a significant impact on the estimation of seismic hazard in a region, we explore the sensitivity of hazard results to the delineation of seismic source zones. We first examine the impact of using a single seismogenic zone model versus using multiple zone models in seismic hazard assessments. We then investigate how altering the source zone boundaries impact the earthquake recurrence characteristics of each zone. Of particular interest are the moderate to large earthquakes or occurrence of large number of small earthquakes near source zone boundaries, and assessment of accurate magnitudes and locations.

New Software for Computing Time Dependent Seismic Hazard During Aftershock Sequences Using the Opensha Platform

VAN DER ELST, N., U.S. Geological Survey, California, USA, nvanderelst@usgs.gov; MILNER, K. R., University of Southern California, California, USA, kmilner@usc.edu; PAGE, M., U.S. Geological Survey, California, USA, pagem@usgs.gov; FIELD, E. H., U.S. Geological Survey, California, USA, field@usgs.gov; MCBRIDE, S. K., U.S. Geological Survey, California, USA, skmcbride@usgs.gov

The chaos caused by a major earthquake does not end when the shaking stops. Search and rescue, damage assessment, and lifeline repairs all need to be carried out under the constant threat of damaging aftershocks. In some cases, aftershocks can be even more destructive than the initial event, as was the case in Christchurch, New Zealand . While it may never be possible to predict the exact time, place, and magnitude of an impending earthquake, it is nonetheless possible to make probabilistic assessments of aftershock hazard based on past regional sequences and the specifics of an ongoing sequence. Forecasts, and in particular forecast maps, can provide situational awareness, increase public resilience, and help decision makers to prioritize response and recovery operations. The public has increasingly come to expect such information, and information vacuums are likely to be filled by non-authoritative sources.

The USGS, with support of USAID-Office of U.S. Foreign Disaster Assistance, is developing several lines of aftershock forecasting products with the goal of providing rapid quantitative aftershock information to emergency responders, lifeline operators, and the general public. Here we introduce a software application designed to streamline the process of analyzing and forecasting aftershock sequences within a modified Epidemic-Type Aftershock Sequence framework. Forecasts are a Bayesian combination of a regionalized generic model and a specific model tuned to the ongoing sequence. The software uses the OpenSHA architecture to translate spatio-temporal rate forecasts into time-dependent probabilistic hazard estimates using standard ground-motion prediction equations. The software automatically generates graphical forecast summaries and hazard maps that supplement standard magnitude-probability tables. This poster will describe modifications to the ETAS model that allow for efficient and stable generation of aftershock forecasts, and discuss expected applications of the software.

The Current Unlikely Earthquake Hiatus at California's Transform Boundary Paleoseismic Sites

SCHARER, K., U.S. Geological Survey, California, USA, kscharer@usgs.gov; BIASI, G., U.S. Geological Survey, California, USA, gbiasi@usgs.gov

If the average interval between paleoearthquakes at 16 high-resolution paleoseismic sites along the major transform faults in California range from 100 to 220 years, what are the odds that none of these sites has experienced an earthquake in the last 100 years? A similar question was posed by Jackson (AGU, 2014) who found the odds were exceptionally low. We revisit the question using full earthquake age uncertainties and subsets of high-resolution sites that sample the five major transform fault sections in California: the Northern and Southern San Andreas Fault, San Jacinto Fault, Hayward Fault, and Elsinore Fault (Biasi and Scharer, SRL, accepted). A 100-year hiatus can be observed in the 1000-year record of sets of a few proximal sites. In contrast, if a single site from each of the five major fault sections is assumed to reflect the complete behavior of that strand, a 100-year period without a major earthquake is not predicted by common time-dependent (lognormal) or time-independent (Poisson) recurrence models. If known rupture behavior complexity (*e.g.*, partial section ruptures like 1812 and 1857) are included, the odds of the 100-year gap are further reduced. To examine the recurrence across all 16 sites, we remove possible double-counted ruptures and find time-independent probability of the current 100-year gap is of order 0.3%. We review published models of earthquake modulation due to post-seismic loading, viscous flow in the deep crust, and Coulomb stress transfer for potential explanations. We also invite discussion of earthquake recurrence for seismic hazard estimation, given that the current models seem, at least, incomplete.

U.S. Geological Survey National Seismic Hazard Model Components

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Coseismic Deformation of the 2018 Kaktovik Earthquakes Illuminate Active Tectonics in Alaska's Brooks Range

GAUDREAU, É., University of Victoria, Victoria, Canada, gaudreau@uvic.ca; NISSEN, E., University of Victoria, Victoria, Canada, enissen@uvic.ca; BERGMAN, E., Global Seismological Services, Colorado, USA, bergman@seismo.com

The M6.4 and M6.0 August 8th 2018 Kaktovik earthquakes occurred in the northeastern Brooks Range, ~80 km SW of Kaktovik, Alaska. Despite northern Alaska being seismically active, the tectonics of this area remain enigmatic due to its remote location. However, Sentinel-1 satellite radar imagery captured the coseismic ground deformation of the M6.4 event and the M6.0 aftershock, the largest-magnitude earthquakes ever recorded in the Brooks Range and North Slope, providing an opportunity to investigate regional tectonics. We use Sentinel-1 InSAR data and elastic modelling, calibrated main shock and aftershock relocations, and a seismic back-projection to characterize the fault geometry and rupture process of the Kaktovik earthquakes. Our InSAR models show that the rupture occurred on a roughly E-W right-lateral fault in the Sadlerochit Mountains, composed of two distinct south-dipping fault segments. The rupture initiated on the western sub-vertical pure right-lateral fault segment, and propagated onto the shallower-dipping (63°) oblique (dextral-normal) fault segment to the east. The rupture likely did not reach the surface, with slip concentrated between depths of 4 and 8 km. Notably, the location of the fault indicated by the InSAR data suggests the reactivation of a previously identified south-dipping Paleogene thrust fault east of the conjugate NNE-SSW left-lateral Canning Displacement Zone. The E-W right-lateral faults that ruptured in the Kaktovik earthquakes could accommodate NNE-oriented left-lateral shear by rotating about vertical axes through time, in a pattern similar to that observed in some other continental belts. The Kaktovik earthquakes thus demonstrate the potential for large-magnitude earthquakes in the Brooks Range and the presence of unknown active faults whose kinematics may be influenced by inherited geological structures.

Landslide and Megaturbidite Records Reveal a 2.5 Kyr History of Seismic Shaking in Skilak Lake, Alaska

PRAET, N., Ghent University, Gent, Belgium, nore.praet@ugent.be; VAN DAELE, M., Ghent University, Gent, Belgium, maarten.vandaele@ugent.be; MOERNAUT, J., University of Innsbruck, Innsbruck, Austria, jasper.moernaut@uibk.ac.at; MESTDAGH, T., Ghent University, Gent, Belgium, thomas.mestdagh@ugent.be; VANDORPE, T., Flanders Marine Institute, Oostende, Belgium, thomas.vandorpe@vliz.be; HAEUSSLER, P. J., U.S. Geological Survey, Alaska, USA, pheuslr@usgs.gov; DE BATIST, M., Ghent University, Gent, Belgium, marc.debatist@ugent.be

On 27 March 1964, a M_w 9.2 megathrust earthquake ruptured an 800-km-long segment of the Alaska-Aleutian Subduction Zone (in south-central Alaska). In order to better understand the recurrence pattern of such large earthquakes in that region, we studied the sediments of Skilak Lake, a proglacial lake located in the area affected by the 1964 earthquake, using a combination of high-resolution seismic stratigraphy (3.5 kHz), multibeam bathymetry (50 kHz) and sediment cores (~13-16 m). Seismic profiles and bathymetric maps reveal 23 lacustrine landslide deposits caused by the 1964 megathrust earthquake. We also identified a series of six older landslide events in the subsurface, which we infer to result from multiple, coeval slope failures, and can thus be attributed to past seismic shaking. Sediment cores in two sites show varved "background" sedimentation that is occasionally interrupted by megaturbidites and slump deposits. From this megaturbidite record we can infer five large mass-wasting events, which can also be observed in the upper part of the landslide record. In order to precisely date our paleoseismic records, we organized a student crowdsourcing project, in which continuously varved core sections were counted by multiple observers. Varve counts, combined with 10 ^{14}C ages, provide a high-resolution age framework for our 2.5 kyr-long paleoseismic record. As Skilak Lake lies in a position between a more fully locked part of the megathrust beneath Prince William Sound, and a more creeping part of the megathrust offshore the Kenai Peninsula, the results of this study may elucidate the extent of past ruptures, rupture pattern variability and interplate coupling.

Regionally Optimized Background Earthquake Rates from ETAS (ROBERE) for Probabilistic Seismic Hazard Assessment

LLENOS, A., U.S. Geological Survey, California, USA, allenos@usgs.gov; MICHAEL, A. J., U.S. Geological Survey, California, USA, ajmichael@usgs.gov

U.S. Geological Survey probabilistic seismic hazard assessments (PSHA) often use background earthquake rate estimates determined by spatially smoothing a single declustered earthquake catalog from which aftershocks have been removed using the method of Gardner and Knopoff (hereafter GK74; 1974). Declustering seeks to remove aftershocks and leave behind a suite of independent, or background, events that can be modeled as a Poisson process. We expect declustering to reduce the estimated earthquake rates because it removes earthquakes from the catalog, but this is not always the case. During development of the 2018 1-year PSHA model for the Central and Eastern United States (Petersen *et al.*, 2018), the total number of M≥3 earthquakes in Oklahoma and Kansas decreased from 2016 to 2017 but the number of events in the declustered catalog using GK74 rose. This can partially be explained by a number of spatially scattered events in western Oklahoma, but Petersen *et al.* also noted that GK74 may not work well in regions of induced seismicity. There are more general problems. GK74 and many declustering methods reduce the Gutenberg-Richter b-value. While declustering lowers the overall number of earthquakes, reducing the Gutenberg-Richter a-value, the estimated rate of large earthquakes can be higher after declustering due to the extrapolation to larger magnitudes using an artificially low b-value. We seek to improve these hazard assessments with a method for determining Regionally Optimized Background Earthquake Rates from ETAS (ROBERE). ROBERE produces a spatially-smoothed background earthquake rate model by applying existing spatial smoothing techniques to a suite of declustered catalogs, each of which was produced with the stochastic Epidemic Type Aftershock Sequence (ETAS) (Zhuang *et al.*, 2002) declustering method. This method optimizes parameters for the region being studied, includes parameter uncertainty, and has the advantage of preserving the original b-value.

Recent Trends in Seismicity Catalogs for the USGS National Seismic Hazard Model

MUELLER, C. S., U.S. Geological Survey, Colorado, USA, cmueller@usgs.gov; HOOVER, S. M., U.S. Geological Survey, Colorado, USA, shoover@usgs.gov

Seismicity catalogs and seismicity-based earthquake rate models for the conterminous United States were updated for the 2018 USGS National Seismic Hazard Model (NSHM). Since the previous NSHM update in 2014, new earthquakes in 2013–2017 were added, and parameters for some pre-2013 earthquakes were revised. Although the basic procedures for catalog construction and gridded-seismicity hazard modeling were unchanged, some details of the methodology such as regional moment magnitude estimation and catalog-completeness modeling were updated for 2018. There were significant rate changes where new earthquakes occurred in previously quiescent areas (for example, local increases in Delaware and southern Ohio) or where magnitudes were revised for some older earthquakes (local increases or decreases throughout the U.S.). Regional decreases in the intermountain west are attributed to a revised procedure for estimating moment magnitudes there. Induced earthquakes were included in special hazard studies in 2016, 2017, and 2018. Changes occurred in the Oklahoma–Kansas induced-seismicity belt, where an increase in activity in 2013–2014 was followed by a decrease in 2015–2017 (presumably reflecting efforts to mitigate earthquakes and trends in hydrocarbon production), and new earthquakes occurred westward of the established active zones. Interestingly, the recent overall decrease was not apparent in the declustered catalog; this paradoxical behavior in 2016 and 2017 may be related to the strong, but only short-term, declustering that followed three magnitude 5+ earthquakes in Oklahoma in 2016, and to limitations in our standard declustering methodology as applied to the Oklahoma-Kansas catalog. Changes will be illustrated with maps comparing results from the 2018 and 2014 NSHM.

A Comprehensive Offshore Quaternary Fault Database for California

PAPESH, A. G., U.S. Geological Survey, California, USA, apapesh@usgs.gov; WALTON, M. A. L., U.S. Geological Survey, California, USA, mwalton@usgs.gov; CONRAD, J. E., U.S. Geological Survey, California, USA, jconrad@usgs.gov; JOHNSON, S., U.S. Geological Survey, California, USA, sjohnson@usgs.gov; BROTHERS, D. S., U.S. Geological Survey, California, USA, dbrothers@usgs.gov; KLUESNER, J., U.S. Geological Survey, California, USA, jkluesner@usgs.gov

In the last decade, a number of new marine geophysical datasets collected by the U.S. Geological Survey (USGS), the Ocean Exploration Trust, and other organizations has led to substantially improved high-resolution mapping of the seafloor in areas including California's mainland State Waters and the southern California continental borderland. Data include comprehensive multibeam bathymetry, seismic-reflection, and marine magnetic data in numerous offshore areas. Most of these data have been processed, merged, and released by the USGS in maps, data releases, and journal publications in support of the California Seafloor Mapping Program and the U.S. West Coast and Alaska Marine Geohazards Project. Improved data coverage has allowed researchers to better map offshore faults in areas previously unmapped or covered only by low-resolution data. Additionally, subsurface imaging and seafloor sampling has led to better understanding of fault kinematics and recency of deformation, which are highly relevant for assessing California's seismic and coastal hazards. For example, inclusion of updated offshore faults resulted in a 37% increase in calculated seismic hazard for the San Diego area in a 2015 rupture forecast.

Here, we present a fault geodatabase with comprehensive metadata including accurate locations, geometries, ages, slip rates, and relevant published references. This represents a significant update to previous national and regional fault compilations, developed without the benefit of new high-resolution datasets. The geodatabase has been designed for easy ingestion by partners including the California Geological Survey and the USGS Quaternary Fault and Fold Database, and to be used to improve seismic hazards products, especially the USGS National Seismic Hazard Maps and the Uniform California Earthquake Rupture Forecast. Other stakeholders include the Southern California Earthquake Center and the academic and consulting communities. We plan to expand this effort in the near future to include work now in progress in other regions offshore of the Pacific Northwest and Alaska.

Coseismic Ground Failure and Impacts on the Built and Natural Environment

Poster Session · Wednesday · 24 April · Grand Ballroom

The New USGS Near-Real-Time Ground Failure Product and Its Performance for Recent Earthquakes

ALLSTADT, K. E., U.S. Geological Survey, Colorado, USA, kallstadt@usgs.gov; THOMPSON, E. M., U.S. Geological Survey, Colorado, USA, emthompson@usgs.gov; HEARNE, M., U.S. Geological Survey, Colorado, USA, mhearne@usgs.gov; WALD, D. J., U.S. Geological Survey, Colorado, USA, wald@usgs.gov; FEE, J. M., U.S. Geological Survey, Colorado, USA, jmfee@usgs.gov; MARTINEZ, E. M., U.S. Geological Survey, Colorado, USA, emartinez@usgs.gov; HUNTER, E., U.S. Geological Survey, Colorado, USA, ehunter@usgs.gov; BROWN, J. D., U.S. Geological Survey, Colorado, USA, jdbrown@usgs.gov

As of September 2018, a new USGS earthquake product called "Ground Failure" provides quantitative estimates of the severity and extent of earthquake-triggered landslide and liquefaction hazards in near-real-time to the public through the USGS webpages. The product provides a generalized summary of hazard and population exposure, communicated through alert levels and summary statistics, as well as interactive maps of the estimated spatial distribution. The product is intended to provide situational awareness of areas with higher probability of experiencing ground failure to officials, responders, and the public in the time window between the event and reconnaissance. Ground failure results were publicly available for three significant earthquakes in late 2018: Hokkaido, Japan (M6.6), Palu, Indonesia (M7.5), and Anchorage, Alaska (M7.0). Each of these earthquakes tested the product in different ways, revealing both strengths and weaknesses of the underlying models, product design, and communication effectiveness. Overall, we found that the alert levels, which span four logarithmic levels from green to red, were effective at communicating the general importance of ground failure for these events. However, their definitions are qualitative and are thus hard to test quantitatively. Both the Palu and Anchorage earthquakes triggered lateral spreads, flow-slides, cracking, and subsidence that were societally impactful but were not well-represented by either model. In addition, the liquefaction model tends to overestimate hazard for areas of weaker shaking while the resolution of the landslide model slope data (~250 m) is too coarse to effectively capture important smaller steep slopes such as coastal bluffs or road cuts. Beyond evaluating model performance, we also discuss how the product has been received by the scientific community, officials, the media, and the public. The feedback and lessons learned from the response to recent earthquakes will guide the path forward as we continue to improve and expand the USGS Ground Failure product.

Past and Future Coseismic Landslides Triggered by Seattle Fault Earthquakes

HERZIG, E., University of Washington, Washington, USA, eherzig@uw.edu; DUVALL, A., University of Washington, Washington, USA, aduvall@uw.edu

In this study, we consider coseismic landslides generated from earthquakes along the Seattle Fault, a thrust zone which stretches roughly east-west across the Puget lowland of Washington state. Steep topography, high precipitation, weak glacial deposits, and active crustal faults make Western Washington an ideal site to study the impacts of coseismic landslides. Though the nearby Cascadia subduction zone has the potential to cause large M9 earthquakes, recent work suggests that a smaller earthquake on the Seattle Fault may cause more landsliding in the Seattle area. To better understand the coseismic landslide hazards associated with Seattle Fault ruptures, we will assess the timing of past landslides using a calibrated roughness-age curve and we will make predictions about future coseismic landslides based on modeling of expected ground motions. An inventory of landslides mapped from LiDAR in the vicinity of the Seattle Fault will be dated using a roughness-based metric first calibrated on similar glacial sediments along the western flanks of the Cascades. Using these dates, we can estimate whether slides may overlap in time with the last known rupture on the Seattle Fault ~1100 ybp. To find the areas most susceptible to future coseismic landslides, we will model the expected ground motions for a Seattle Fault earthquake using the finite difference code SW4 and a recently updated crustal velocity model. This code allows us to consider both basin and topographic seismic amplification effects. Ultimately, these modeled ground motions can be used to create a landslide susceptibility map of the area. Together, dated coseismic landslide inventories and landslide susceptibility maps will provide a more complete picture of past and future landslides associated with Seattle Fault earthquakes.

The Next-Generation Liquefaction Database Project: Current Status and Future Goals

ZIMMARO, P., University of California, Los Angeles, California, USA, pzimmaro@ucla.edu; BRANDENBERG, S. J., University of California, Los Angeles, California, USA, sjbrandenberg@ucla.edu; BOZORGNIA, Y., University of California, Los Angeles, California, USA, yousef.bozorgnia@ucla.edu; STEWART, J. P., University of California, Los Angeles, California, USA, jstewart@seas.ucla.edu; KWAK, D., Hanyang University, Ansan, Gyeonggi-do, Korea, Republic of, dkwak@hanyang.ac.kr; CETIN, K., Middle East Technical University, Ankara, Turkey, ocetin@metu.edu.tr; FRANKE, K. W., Brigham Young University, Utah, USA, kevin_franke@byu.edu; MOSS, R. E. S., California Polytechnic State University, California, USA, rmoss@calpoly.edu; KRAMER, S. L., University of Washington, Washington, USA, kramer@uw.edu; STAMATAKOS, J., Southwest Research Institute, Texas, USA, jstamatakos@swri.org; JUCKETT, M., Southwest Research Institute, Texas, USA, mjuckett@swri.org

A community database of liquefaction case histories was developed as part of the Next-Generation Liquefaction (NGL) project. A case history must contain the following three objects: (1) a “site” consisting of characterization of soil conditions by means of field and laboratory tests, (2) an “event” consisting of earthquake source and ground motion characterizations, and (3) an “observation” of liquefaction effects, or lack thereof, induced at a site by a specific event. The NGL relational database was developed using the My Structured Query Language (MySQL) relational database management system. The NGL database schema (*i.e.* its organizational structure) and a meta-dictionary that contains information about each database entry are available along with the current incarnation of the database at http://www.nextgenerationliquefaction.org/. The NGL database is mirrored on a secure server hosted at the DesignSafe-CI cyber-infrastructure at the University of Texas at Austin, Texas Advanced Computing Center. Such mirroring also allows users to interact with the database in the cloud using Python scripts in Jupyter notebooks.

The NGL user interface includes visualization tools to analyze spatial distribution of ground motions, site investigations, and observations. It also provides plotting tools to visualize in-situ investigations, laboratory tests, and post-earthquake observations. Each case history in the database must be reviewed by at least two reviewers before becoming an NGL case history. Such quality-control process is overseen by the NGL database working group. Currently, the NGL database includes both legacy case histories (*i.e.*, used in existing liquefaction models) and new case histories generated by recent earthquakes. New data include case histories generated by the M9.1 Tohoku-Oki, 2011 earthquake in Japan, and the 2010-2011, Canterbury earthquake sequence in New Zealand. We anticipate that the NGL database will provide the natural hazard community with a robust basis for development of liquefaction susceptibility, triggering, and consequences models.

West Shore Lake Oroville Lineament Geologic Investigation, Northern California, Part 1 of 2

HOIRUP, D. F., California Department of Water Resources, California, USA, don.hoirup@water.ca.gov; KOZACI, O., InfraTerra, California, USA, okozaci@infraterra.com

The California Department of Water Resources (DWR) owns and operates the California State Water Project (SWP). The SWP comprises more than 700 miles of canals, pipelines, and tunnels as well as 34 storage facilities, 30 dams, 23 pumping plants, and 9 hydroelectric power generation plants all spanning two-thirds of the length of California. It supplies water to more than 26 million people throughout California. SWP water also irrigates about 750,000 acres of farmland, mainly in the San Joaquin Valley.

The flagship structure of the SWP is Oroville Dam, part of the Oroville-Thermalito Dam Complex. At 770 feet, Oroville Dam is the tallest dam in the United States and the most voluminous dam in California. Oroville Dam was constructed between 1961 and 1967. The reservoir filled for the first time in 1968. Power generation from Oroville Dam is regulated by the Federal Energy Regulatory Commission (FERC).

On August 1, 1975, the ML 5.7 Oroville earthquake occurred along the Cleveland Hill fault (CHF) damaging the town of Oroville, located a few miles downstream of Oroville Dam, and causing little to no damage to the dam. The Oroville earthquake resulted in previously unrecognized Quaternary fault activity along the foothills of the northern Sierra-Nevada.

In December 2014, Independent Consultants for FERC recommended that DWR inspect the northern projected trace of the CHF to determine whether the fault continues north passing less than one mile upstream of Oroville Dam.

In 2015, DWR began a phased geologic investigation of the northern projection of the CHF. Due to several years of drought, low reservoir water levels allowed opportunity to view shoreline areas typically submerged. Using LiDAR, supplemented with multi-beam survey data, DWR identified anomalous geomorphic features resembling active faults north of the mapped trace of the CHF along the West Shore of Lake Oroville (WSLO).

Liquefaction Loss Estimation for the United States

BAISE, L. G., Tufts University, Massachusetts, USA, laurie.baise@tufts.edu; RASHIDIAN, V., Tufts University, Massachusetts, USA, vahid.rashidian@tufts.edu

In recent years, the USGS and others have worked to develop predictive regional models for ground failure with a focus on landslides and liquefaction. The models provide probability estimates of ground failure given the shaking from an earthquake event. The current preferred models (*e.g.* Zhu *et al.*, 2017 for liquefaction) result in a probability estimate for the respective ground failure. The liquefaction probability is converted to a value that represents spatial extent as a percentage per pixel. Currently, the USGS includes the ground failure models as a product on the overview page for each earthquake on the USGS Earthquake Hazard Program website (as discussed by Wald *et al.*, 2018). This is an important first step in including ground failure as part of the regional assessment of earthquake hazard; however, there is not full integration into the loss estimation part of the USGS products. Therefore, in this research we develop the datasets on liquefaction loss and infrastructure which can be used to provide loss estimates due to liquefaction after an earthquake. Liquefaction loss occurs across a variety of infrastructure categories: single family dwellings, commercial buildings, lifeline infrastructure (pipelines, roads, bridges), ports, and airports. Due to the common occurrence of liquefaction near coastlines and in artificial fill, extensive loss due to liquefaction is often related to port and airport facilities. Therefore, the development of GIS datasets by state for the United States will inform loss estimates. We present a liquefaction loss database and loss for a variety of infrastructure and building types. As an example, we also present a GIS infrastructure dataset for California.

West Shore Lake Oroville Lineament Geologic Investigation, Northern California, Part 2 of 2

KOZACI, O., InfraTerra, California, USA, info@ozgurkozaci.com; HOIRUP, D. F., California Department of Water Resources, California, USA, don.hoirup@water.ca.gov; ZACHARIASEN, J., Sierra Geoscience, California, USA, judyzach@yahoo.com; BLOSZIES, C., Lettis Consultants International, California, USA, bloszies@lettisci.com; HITCHCOCK, C., InfraTerra, California, USA, chitchcock@infraterra.com; KOEHLER, R. D., University of Nevada Reno, Nevada, USA, rkoehler@unr.edu; LINDVALL, S., Lettis Consultants International, California, USA, lindvall@lettisci.com;

MCDONALD, E., Desert Research Institute, Nevada, USA, desertdirtdr@gmail.com; FEIGELSON, L., California Department of Water Resources, California, USA, leah.feigelson@water.ca.gov; ABRAMSON-WARD, H., Lettis Consultants International, California, USA, abramsonward@lettisci.com; HARTLEB, R., Lettis Consultants International, California, USA, hartleb@lettisci.com; HUEBNER, M., Lettis Consultants International, California, USA, huebner@lettisci.com

The ML5.7 1975 Oroville earthquake occurred seven years after construction of Oroville Dam, the tallest earth-fill embankment dam in the United States. The Oroville earthquake and aftershocks resulted in recognition of Quaternary activity along the Cleveland Hill fault (CHF), Swain Ravine fault zone (SRF), located west of the Foothills fault system, where the seismic hazard is relatively low based on moderate earthquake activity and small co-seismic displacements. For relicensing, lidar data was acquired to evaluate the possible northward extension of the CHF. An approximately 10 km-long, northsouth oriented zone of topographic lineaments were identified in the lidar along the West Shore of Lake Oroville (WSLO) north of Oroville Dam. The lineaments are coincident with the northern projection of the CHF and are expressed as scarps, benches, and saddles along the steep slopes of WSLO. In order to assess the origin of the lineaments, and determine whether or not the prominent lineament is related to recent fault activity that could pose a co-seismic surface rupture potential at Oroville Dam, our study integrated geomorphic mapping, field reconnaissance, and four trenches across the lineament. Detailed mapping documented a roughly north-south oriented bedrock fabric throughout the region associated with a series of parallel lineaments. Field reconnaissance and trench exposures revealed a robust correlation between strength of the Jurassic metavolcanic bedrock and localized erosion and slope failures. These surface processes exploit weaker zones within the bedrock, resulting in differential erosion and stepped topography. The stepped topography is accentuated by side-hill benches formed by colluvium that infills areas between resistant bedrock zones. The result is a youthful zone of topographic lineaments. Furthermore, a clay-rich saprolitic unit (~175 ka) was mapped in trench T3 that crosses the lineament in Bear Meadow. No faulting or deformation was observed in the saprolite; therefore, precluding an active fault consideration.

Estimating the Likelihood and Impact of Seismically Induced Landslides in Near Real-Time

NOWICKI JESSEE, A., Indiana University - Purdue University Indianapolis, Indiana, USA, manowick@iu.edu; HAMBURGER, M. W., Indiana University, Indiana, USA, hamburg@indiana.edu

We present a new, high-resolution, globally applicable statistical model for estimating the distribution and impact of earthquake-triggered landslides in near real-time. A previous version of the model has been adapted for use in the USGS Ground Failure product, which runs in near real-time for significant earthquakes around the globe. An important addition to previous models is testing the incorporation of high-resolution (1 arc-second, roughly 30m) data to improve detailed estimates of slope vulnerability. We use standardized estimates of ground shaking from the USGS ShakeMap tool, together with broadly available landslide susceptibility proxies, including topographic slope, surface geology, and high-resolution land cover data, to develop an empirical landslide probability model. We include observations from landslide-triggering earthquakes from a variety of tectonic and geomorphic settings for which we have obtained landslide inventories. We plan to test additional landslide susceptibility proxies, including high-resolution geologic, hydrologic, and climatic parameters. Using logistic regression, this database is used to build a predictive model that can estimate the probability of landsliding within minutes of an earthquake's occurrence. As ground shaking data become available, we can automatically generate maps of landslide probabilities. These landslide probability estimates can be combined with population density values and past landslide fatality counts to provide order-of-magnitude fatality loss estimates. We also apply this approach to scenario earthquakes to assess probabilities for future landslides in areas of known seismic risk, and calculate the effect of changing seismological parameters on the expected distribution of landsliding. These models can be used to rapidly provide regional estimates of the probability and distribution of seismically induced landslides, as well as their potential impact on the surrounding population. Future efforts can extend this work to estimate impact on infrastructure and economic losses as well.

An Open Repository of Earthquake-Triggered Ground-Failure Inventories

SCHMITT, R., U.S. Geological Survey, Colorado, USA, rschmitt@usgs.gov; ALLSTADT, K. E., U.S. Geological Survey, Colorado, USA, kallstadt@usgs.gov; GODT, J., U.S. Geological Survey, Colorado, USA, jgodt@usgs.gov; JIBSON, R. W., U.S. Geological Survey, Colorado, USA, jibson@usgs.gov; WALD, D. J., U.S. Geological Survey, Colorado, USA, waldjd@usgs.gov; KNUDSEN, K. L., U.S. Geological Survey, California, USA, kknudsen@usgs.gov; TANYAS, H., University of Twente, Enschede, Netherlands, h.tanyas@utwente.nl; THOMPSON, E. M., U.S. Geological Survey, Colorado, USA, emthompson@usgs.gov; VAN WESTEN, C., University of Twente, Enschede, Netherlands, c.j.vanwesten@utwente.nl; GORUM, T., Istanbul Technical University, Instanbul, Turkey, tgorum@gmail.com; NOWICKI JESSEE, A., Indiana University Bloomington, Indiana, USA, anowicki28@gmail.com; RATHJE, E., University of Texas at Austin, Texas, USA, e.rathje@mail.utexas.edu; BIEGEL, K., U.S. Geological Survey, Colorado, USA, kbiegel@usgs.gov; XU, C., Institute of Geology, China Earthquake Administration, Beijing, China, xuchong@ies.ac.cn; SATO, H., Nihon University, Tokyo, Japan, satou.hiroshi37@nihon-u.ac.jp; ZHU, J., AIR Worldwide, Massachusetts, USA, jingz.ce@gmail.com

Ground-failure inventories are often created after major earthquakes and are a key research tool that can be used to develop, train, and test hazard models. The development of robust, transportable, and predictive ground-failure models requires access to numerous inventories of ground-failures that span a broad range of terrains, shaking characteristics, and climates. We present an open access, centralized repository for earthquake-triggered ground-failure inventories in the form of a U.S. Geological Survey (USGS) ScienceBase repository with the goal of accelerating research progress. The ScienceBase repository hosts point and polygon inventories created by both USGS and non-USGS authors. The USGS also developed a separate ArcGIS Online web application that enhances the ScienceBase repository by allowing users to interactively explore the inventories available. Currently, the repository contains 49 inventories from 39 earthquake events. The repository is designed to allow more inventories to be added as they become available, making it possible for the collection of data to grow.

Explosion Seismology Applications

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Finite-Difference Algorithm for 3D Orthorhombic Elastic Wave Propagation

JENSEN, R. P., Sandia National Laboratories, New Mexico, USA, rpjense@sandia.gov; PRESTON, L., Sandia National Laboratories, New Mexico, USA, lpresto@sandia.gov

Many earth materials and minerals are seismically anisotropic; however, due to the weakness of anisotropy and for simplicity, the earth is often approximated as an isotropic medium. Specific circumstances, such as in shales, tectonic fabrics, or oriented fractures, for example, require the use of anisotropic simulations in order to accurately model the earth. An orthorhombic medium is characterized by three mutually orthogonal symmetry planes comprising a dense system of vertically-aligned microfractures superimposed on a finely-layered horizontal geology, which can be reduced to an elastic stress-strain constitutive relationship containing nine independent moduli comprising a set of nine, coupled, first-order, linear, inhomogeneous partial differential equations. A new massively parallel 3-D full seismic waveform simulation algorithm within the principle coordinate system of an orthorhombic material, which is a specific form of anisotropy common in layered, fractured media, has been developed.

This FD code is used to support the modeling component of the Source Physics Experiment (SPE), a series underground chemical explosions at the Nevada National Security Site. The data from the experiments are used to help determine event signatures that vary depending on geology, yield and depth of burial. An improved anisotropic model has been developed using observations from the SPE Phase I experiments and tomographic inversion. The velocity parameters obtained from the tomographic inversion are used in the FD code to simulate all six experiments of Phase I using a point moment source at the source depth. The observed data is then compared to the synthetic data. The observations are also inverted with simulated Green's Functions to obtain the source time functions.

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Physics-Based Simulations of Aftershock Productivity From Explosion and Earthquake Sources

KROLL, K., Lawrence Livermore National Laboratory, California, USA, kakroll5@gmail.com; PITARKA, A., Lawrence Livermore National Laboratory, California, USA, pitarka1@llnl.gov; FORD, S. R., Lawrence Livermore National Laboratory, California, USA, ford17@llnl.gov; WALTER, W. R., Lawrence Livermore National Laboratory, California, USA, walter5@llnl.gov; RICHARDS-DINGER, K. B., University of California, Riverside, California, USA, keithrd@ucr.edu

Previous observation-based studies suggest that the statistical properties and productivity of aftershocks triggered by explosions may be distinctly different compared to aftershocks triggered by equivalent magnitude earthquakes (Ryall and Savage, 1969; Jarpe *et al.,* 1994; Gross, 1996; Ford and Walter, 2010; Ford and Labak, 2016). Recent numerical experiments suggest that early aftershocks primarily occur during the passage of dynamic stress waves, which are at least an order of magnitude smaller following purely isotropic explosions than those generated by a double-couple earthquake (Kroll *et al.*, 2018). Kroll *et al.*, (2018) also showed that the location and kinematics of potential receiver faults (that host aftershocks) plays a significant role in aftershock generation. Receiver faults located in the direction where the first pulse of explosion generated Coulomb stress change is positive tend to generate robust aftershock sequences, whereas receiver faults in the opposite direction (where the first pulse of Coulomb stress change is negative) tend to remain seismically quiet. Here, we continue these numerical experiments to compare aftershocks productivity from explosions and earthquakes. While the occurrence of aftershocks depends on several factors, for this analysis, we focus our effort at understanding the effects of receiver fault location and kinematics. These experiments employ a 3D seismic wave propagation code, SW4, to compute the static and dynamic stresses that result from each source in a volume. Synthetic aftershocks are generated with the 3D physics-based earthquake simulator, RSQSim. The SW4 stress perturbations are projected onto each receiver fault which is loaded only with stochastically generated random pre-existing shear stress. Statistical properties of each synthetic aftershock sequence related to both source types are compared in terms of productivity, maximum aftershock magnitude, Omori decay rate, and the spatiotemporal relationship between stress changes and event locations.

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Nonlinear Effects on Linear Seismic Source Inversions From Simulations of Underground Chemical Explosions

PRESTON, L., Sandia National Laboratories, New Mexico, USA, lpresto@sandia.gov; ELIASSI, M., Sandia National Laboratories, New Mexico, USA, meliass@sandia.gov; GULLERUD, A., Sandia National Laboratories, New Mexico, USA, asgulle@sandia.gov; POPPELIERS, C., Sandia National Laboratories, New Mexico, USA, cpoppel@sandia.gov

Linear moment tensor inversion is a common method used in seismology to understand the characteristics of the seismic source model. However, underground explosions nonlinearly affect the surrounding earth materials through plastic deformation, breaking rocks, and spall. Although nonlinear algorithms can accurately simulate very near field ground motions, they are computationally expensive and unnecessary for far field wave simulations. Linearized seismic wave propagation codes, on the other hand, are computationally efficient and can accurately model the far-field linear wavefield, despite their simplification of the seismic source. Thus, it is advantageous to understand the conditions under which a purely linear analysis of far-field seismic waveforms is sufficiently accurate and when nonlinear analysis is critical. We have coupled Sandia's nonlinear algorithms to a linearized elastic wave propagation code using time-varying boundary conditions, to pass information from the nonlinear domain to the linear one. We find the purely linear seismic moment tensor and source time functions that optimally fit the waveforms produced by the nonlinear source and investigate how well these purely linear methods can adequately fit the synthesized data from nonlinear sources. We will present results showing the effects of geological materials, nearby structures, and frequency on linear source parameters for earth models with simulated chemical explosions at various scaled depths of burial. We will also discuss how well the linear source models are able to reconstruct the waveforms from the nonlinear source in the various scenarios.

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Microseismicity Associated With the DAG-2 Chemical Explosion

HOLLAND, A. A., Sandia National Laboratories, New Mexico, USA, holland.austin@gmail.com; ABBOTT, R. E., Sandia National Laboratories, New Mexico, USA, reabbot@sandia.gov; PRESTON, L., Sandia National Laboratories, New Mexico, USA, lpresto@sandia.gov; LARMAT, C., Los Alamos National Laboratory, New Mexico, USA, carene@lanl.gov; MORTON, E. A., Sandia National Laboratories, New Mexico, USA, eamorto@sandia.gov

The Dry Alluvium Geology (DAG) 2 chemical explosion conducted at the Nevada National Security Site (NNSS) in December, 2018, initiated a robust sequence of microseismic events immediately following the explosion. DAG-2 is a 50,000 kg TNT-equivalent charge of nitromethane detonated at 300 meters below ground surface in the alluvium of Yucca Flat, Nevada, on the NNSS. Within seconds of the detonation, a microseismic swarm, detectible on a seismic array to over 1500 m distance from ground zero, was initiated. At its peak, the swarm comprised over 100 events per minute. A high rate of seismicity (> 30 events per hour) continued for over 24 hours. We present data and analysis of this swarm in terms of event decay rate, moment release, and hypocenter distribution. Events were picked via template matching on a 500-channel array of surface geophones and accelerometers and two downhole fiber optic distributed acoustic sensing (DAS) cables deployed 80 m from ground zero. We also explore time-reversal location methods with imaging conditions adapted to microseismicity to determine hypocenter locations for comparison purposes. Early indications are that these events are associated with collapse of the stemming material above the detonation into the post-explosion cavity. Sandia National Laboratories is a multimission laboratory managed and operated by National Technology and Engineering Solutions of Sandia, LLC, a wholly owned subsidiary of Honeywell International Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525.

Analysis of Simulated and Recorded Far-Field Ground Motions for the SPE and DAG Underground Chemical Explosions

DUNN, M., University of Nevada Reno, Nevada, USA, michelledunn@nevada.unr.edu; PITARKA, A., Lawrence Livermore National Laboratory, California, USA, pitarka1@llnl.gov; LOUIE, J. N., University of Nevada Reno, Nevada, USA, louie@seismo.unr.edu; SMITH, K., University of Nevada Reno, Nevada, USA, ken@unr.edu; ECKERT, E., University of Nevada Reno, Nevada, USA, eeckert@nevada.unr.edu

We investigate the far-field ground motion from underground chemical explosions of Phase I and Phase II of the Source Physics Experiment (SPE), recorded at the Nevada National Security Site (NNSS). Previous studies of SPE far-field seismic data largely focused on shear motion at distances less than 2 km from the source. In our analysis we investigate wave propagation effects using seismic recordings from several linear arrays of broadband seismometers, including two arrays across the Yucca Flat basin, covering epicentral distances up to 25 km. To analyze wave propagation characteristics affected by the underground basin structure, we performed several simulations using 3D velocity models covering an area of 37 km x 22 km. All simulations are performed using isotropic point sources in the frequency range 0-5Hz. Simulated waveforms for SPE-5 are used to test the quality of the 3D geologic model, especially in southern Yucca Flat where recorded data are characterized by very long duration; a clear indicator of basin reverberations. Analysis of coda-envelope amplitude ratios from different explosions and stations of equal epicentral distance suggests significant path and site effects and a potential source depth dependence of coda wave amplitude. Comparisons of recorded and simulated waveforms using 1D and 3D models of shallow structure demonstrate that the 3D basin structure contributes to generation of shear motion observed at basin sites. The inclusion of 3D wave scattering, simulated by correlated small scale stochastic velocity perturbations in the 3D model, improves the fit between the simulated and recorded ground motions. Attenuation analysis using recorded and simulated coda envelopes and spectral ratios informs future model iterations and isolates the scattering effects. Ground motions recorded at NNSS from regional earthquakes, such as the 2015 Mw 4.9 Caliente event (also recorded on the SPE array), show basin structure effects that are similar to effects observed during the underground explosions analyzed here.

Constraining Stochastic Variability of the Velocity Model Using Large-N Data

PITARKA, A., Lawrence Livermore National Laboratory, California, USA, pitarka1@llnl.gov; MELLORS, R. J., Lawrence Livermore National Lboratory, California, USA, mellors1@llnl.gov; EZZEDINE, S. M., Lawrence Livermore National Laboratory, California, USA, ezzedine1@llnl.gov; WALTER, W. R., Lawrence Livermore National Laboratory, California, USA, walter5@llnl.gov; MATZEL, E., Lawrence Livermore National Laboratory, California, USA, matzel1@llnl.gov; WAGONER, J., Lawrence Livermore National Laboratory, California, USA, wagoner1@llnl.gov

In an ongoing effort to refine the velocity model of the Nevada National Security Site we used the correlation between vertical component waveforms recorded by a dense 2D array of 996 stations (4.5 Hz geophones) with spacing of 25 m and 100 m, deployed at the Source Physics Experiment (SPE) Phase I site. The overall goal is to improve the simulation of seismic waves from SPE explosions on a broad frequency range (0-10Hz). Using data from the SPE-5 chemical explosion, cross-correlations of measured and synthetic data were compared to constrain the statistical properties of the stochastic velocity perturbations. The latter represent small-scale [they are not necessarily structural] heterogeneities that were added to the Yucca Flat basin model (GFM), considered as background velocity model. By trial and error, and using ground motion simulations we were able to recover sets of statistical properties of the small-scale velocity perturbations of the sedimentary basin layers. Comparisons of observed and simulated waveforms and cross-correlations decay as a function of inter-stations distance were also used to assess the enhancement of the velocity model, with and without stochastic variability.

We found that adding a depth-resolved stochastic variability of the velocity to GFM, to create the GFM+S models, improves the overall performance of ground motion simulations of SPE-5 in the desired frequency range of 0-10 Hz. The stochastic velocity fluctuations in the best performing stochastic velocity model have a horizontal correlation distance of 600m, vertical correlation distance of 120m, and a deviation of 8% from the nominal GFM velocity in the alluvium layers, and a horizontal correlation distance of 1200m, vertical correlation distance of 300m, and a deviation of 5% from the nominal GFM velocity in the underlying sedimentary layers.

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Mechanisms of Near Field Non-Radial Motion From Underground Explosions in Various Geologies

VOROBIEV, O. Y., Lawrence Livermore National Laboratory, California, USA, vorobiev1@llnl.gov

The Source Physics Experiment (SPE) is being conducted at Nevada National Security Site (NNSS) site in granite (Phase I) and alluvium (Phase II). The goal of the SPE is to study the ground motion generated by underground chemical explosion sources in various geologies. Of particular interest is the understanding of mechanisms of shear wave generation observed during underground explosions, which may look like natural seismicity in the far field. Analysing the near field ground motion during Phase I, we have found that the joints present in granite create a source of shear motion which propagates into the far field. Recent experiments in alluvium geology (DAG-1 and DAG-2) showed that shear motion is generated in the near field despite the absence of joints. The signature of this motion is very different from the one observed in granite. We have conducted numerical simulations of the ground motion for underground explosions in both geologies using detailed geophysical site characterizations conducted for both Phase I and Phase II experiments. Results of these simulations suggest that there may be different mechanisms behind the shear motion generation in both cases.

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Comparison of Seismic Detectors Applied to an Explosion Aftershock Sequence

ROWE, C. A., Los Alamos National Laboratory, New Mexico, USA, char@lanl.gov; CARMICHAEL, J. D., Los Alamos National Laboratory, New Mexico, USA, joshuac@lanl.gov; PHILLIPS, W. S., Los Alamos National Laboratory, New Mexico, USA, wsp@lanl.gov; STEAD, R. J., Los Alamos National Laboratory, New Mexico, USA, stead@lanl.gov

The chemical explosion referred to as DAG-2 was successfully detonated at the Nevada National Security Site as part of the ongoing Source Physics experiment (SPE), on 19 December 2019. This shot, like its predecessor DAG-1, was detonated within a thick sequence of sediments as part of our effort to understand the effects of a soft-rock environment on observations for the explosion source. Earlier SPE shots were detonated at a site within the Climax Stock, a granitic medium chosen to assess the seismic and acoustic observations of explosion sources at a hard rock location. Unlike the first DAG shot or the previous SPE shots, DAG-2 has produced a rich sequence of aftershocks whose description and analysis may reveal important details of the site material response to a large, underground explosion. The explosion and several days of subsequent data were recorded on a variety of sensors with varying gains and a range of positions with respect to the shot. We report on a comparison of seismic event detection methods and their relative performance in obtaining reliable detections and cross-validation of detector results.

High-Frequency Rg Modeling at the SPE Site Using Accelerated Weight Drop Sources

ROWE, C. A., Los Alamos National Laboratory, New Mexico, USA, char@lanl.gov; PATTON, H. J., Los Alamos National Laboratory, New Mexico, USA, patton@lanl.gov

We present the current status of a shallow seismic velocity modeling effort undertaken as part of the Source Physics Experiment at the Nevada National Security Site. The SPE experiment included five lines of geophones extending radially from a central drill hole in which chemical explosion sources were detonated. Because no reverse profiles were obtained and the geophones were positioned with 100 m spacing, refraction analysis of the medium is ambiguous and surface wave analysis provides limited resolution of the shallowest layers because of spatial aliasing. An Accelerated Weight Drop (AWD) source was deployed along four of the five geophone lines, providing Rg energy throughout much of their lengths with source spacings of roughly 20 m. Leveraging reciprocity, these data afford us the opportunity to refine our earlier, coarse model and examine Rg propagation at a finer scale, with resolution of higher frequencies and thus shallower structure.

Testing the Effects of Velocity Models for Seismic Location in the DNE18 Virtual Experiment

BEGNAUD, M., Los Alamos National Laboratory, New Mexico, USA, mbegnaud@lanl.gov; SYRACUSE, E. M., Los Alamos National Laboratory, New Mexico, USA, syracuse@lanl.gov; GAMMANS, C., Los Alamos National Laboratory, New Mexico, USA, cgammans@lanl.gov; MACCARTHY, J. K., Los Alamos National Laboratory, New Mexico, USA, jkmacc@lanl.gov

The Dynamic Network Experiment 2018 (DNE18) was a virtual experiment designed to quantitatively assess current capabilities for multi-modal data ingestion and processing for nuclear explosion monitoring at the local/regional scale. This assessment will allow us to identify and prioritize remaining challenges that need to be met to achieve desired monitoring capabilities. The experiment was a collaborative effort between Lawrence Livermore National Laboratory, Los Alamos National Laboratory, Pacific Northwest National Laboratory, and Sandia National Laboratories. We describe efforts to test various velocity models for any bias or other recognizable patterns using two-week, analyst-built event (ABE) bulletin. The data set includes over 6000 events manually-built by the analyst using the Utah Seismic Network which includes about 182 seismo-acoustic stations, 152 of which have analyst arrival picks. There are active mines in the state of Utah, many of which are associated with clusters of events. The ABEs include mostly Pg and Lg arrivals for events within Utah and some just outside the state. Global events were also picked that included teleseismic P and S as well as core phases, etc. although these are not included in this study. We test local, regional, and global P and S velocity models (1-D, 2-D, 3-D) for their effect on the event locations, paying attention to overall epicenter shifts, residual reduction, and error ellipses. Many of the event clusters are good candidates for application of relative relocation techniques.

Characterization of Spall in Hard-Rock From Observations and Simulations of the Source Physics Experiment Phase I

FORD, S. R., Lawrence Livermore National Laboratory, California, USA, sean@llnl.gov; VOROBIEV, O. Y., Lawrence Livermore National Laboratory, California, USA, vorobiev1@llnl.gov

Spall signals from the Source Physics Experiments (SPE) are presented, analyzed, and modeled for insight to the explosion source. The observed signal is similar in nature to nearby historical nuclear explosions and the surface force-time history or velocity can be interpreted with the same model. We use the models for peak spall velocity, spalled mass, and spall depth and radius derived from historical nuclear explosions to parameterize the physical force-time history model from Stump [1985] and show that this parameterized model can be used for spall prediction. The spall signal is also investigated with a 3D numerical continuum model that incorporates gravity. Peak velocity and dwell time are well predicted but modeling the slap-down phase requires further work.

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Simulation of Underground Explosions in Anisotropic Media Using GEODYN-SW4 Coupling Scheme

EZZEDINE, S. M., Lawrence Livermore National Laboratory, California, USA, ezzedine1@llnl.gov; HIRAKAWA, E. T., U.S. Geological Survey, California, USA, ehirakawa@usgs.gov; VOROBIEV, O. Y., Lawrence Livermore National

Laboratory, California, USA, vorobiev1@llnl.gov; ANTOUN, T. H., Lawrence Livermore National Laboratory, California, USA, antoun1@llnl.gov

The Source Physics Experiment (SPE) is an ongoing effort to improve explosion monitoring by conducting a controlled series of chemical explosions at the Nevada National Security Site (NNSS) and using the resulting observations to improve and validate physics-based simulations of explosion phenomena. Phase I of SPE was conducted on the Climax Stock granite which contains a network of well-characterized joints. It has been shown through hydrodynamic source modeling that sliding on these pre-existing joints may be responsible for a large amount of the tangential motion observed during SPE. Near-field motions generated with hydrodynamic non-linear source models have been coupled to elastic wave propagation codes to propagate these resulting motions into the far-field domain which is assumed to be elastic. However, one simplification that has been made is that the far-field elastic media is isotropic. This is likely not the case as the network of pre-existing joints also continues outside of the inelastic source region of the SPE and can be shown to result in an anisotropic stiffness for the granite.

In the present study we use a hybrid modeling approach with one-way hydrodynamic-to-elastic coupling. Near source hydrodynamic motions are computed using GEODYN-L while anisotropic elastic wave propagation is modeled using SW4, a fourth order finite difference code. Motions are coupled between the two codes by introducing hydrodynamic motions from GEODYN-L as an internal boundary source to SW4. The anisotropic material model employed in the SW4 domain is derived from the properties of an observed fracture network with relatively well-constrained joint orientations, spacing, and stiffnesses. We show that consideration of anisotropic material in the elastic regime has an important effect on the propagation of tangential motion. Propagation of motions generated in an anisotropic source region into an isotropic far-field domain will introduce some biases. The current GEODYN-L/SW4 coupling is being applied to SPE DAG series.

Variations in Aftershock Behavior Following a Large Underground Chemical Explosion in Alluvium

SYRACUSE, E. M., Los Alamos National Laboratory, New Mexico, USA, syracuse@lanl.gov; PHILLIPS, W. S., Los Alamos National Laboratory, New Mexico, USA, wsp@lanl.gov; EULER, G. G., Los Alamos National Laboratory, New Mexico, USA, ggeuler@lanl.gov; ROWE, C. A., Los Alamos National Laboratory, New Mexico, USA, char@lanl.gov

On 19 December 2018, a large chemical explosion (51 metric tons TNT equivalent at 300 m depth) was detonated at the Nevada National Security Site in alluvium as part of the second phase of the Source Physics Experiment (SPE). Unlike previous explosions in granite that were a part of SPE, this explosion was followed by a rich sequence of aftershocks with varying waveform features, suggesting a combination of rockfall, fracturing, overburden collapse, and other responses to changes in the in situ stresses. We report on observations of aftershock migration, energy release, decay rates, and other fundamental seismic parameters associated with this sequence.

Chemical Explosion/Nuclear Explosion Equivalences and Differences as Identified in the Near-Field Data From the SPE Program

STEEDMAN, D. W., Los Alamos National Laboratory, New Mexico, USA, dwsteed@lanl.gov; EULER, G. G., Los Alamos National Laboratory, New Mexico, USA, ggeuler@lanl.gov; BRADLEY, C. R., Los Alamos National Laboratory, New Mexico, USA, cbradley@lanl.gov; BONNER, J. L., Mission Support and Test Services, LLC, Nevada, USA, bonnerjl@nv.doe.gov

The Source Physics Experiment (SPE) is improving understanding of explosion phenomenology. SPE consists of a series of chemical explosions in each of two phases: Phase I in granite and Phase II in dry alluvium. A concern in explosive effects studies is the equivalence between nuclear and chemical sources and the efficacy of using chemical explosives to study nuclear effects.

The SPE near-field includes accelerometers with individual transducers selected based on the expected environment predicted using the work of Perrett and Bass (P&B). P&B is a compendium of nuclear event free-field data, with yield-scaled attenuation fits for peak acceleration, peak velocity, and peak displacement in several geologies, including the two SPE geologies described above plus wet tuff and dry tuff. The fits describe two distinct attenuation regimes: close to the source is a "non-linear" regime dominated by plasticity effects; at distance the "elastic" regime has a slower attenuation rate.

We found that the P&B hard rock fit is a good predictor for SPE Phase I in granite. However, we identified shortcomings of P&B for the dry alluvium Phase II data. The data gathered thus far indicate agreement with the P&B fits in the non-linear regime. However, the break to the linear attenuation regime for SPE alluvium occurs at a closer scaled range than for the nuclear dataset. But once achieved, the Phase II linear rate of attenuation matches that for P&B. In a separate analysis, Bonner *et al.* describe that the Phase II surface measurements are similarly underpredicted by P&B. The implication is that P&B appears to be a poor indicator of expected ground motion with distance in porous media such as alluvium and possibly tuff. By extension, these results provide some evidence for insufficient efficacy of using chemical sources to replicate nuclear effects.

From Drifting to Anchored: Advances in Improving Absolute Hypocenter Location Accuracy for Natural, Induced and Explosion Seismic Events

Poster Session · Wednesday · 24 April · Grand Ballroom

Obtaining Accurate Earthquake Location with Cabled Seismic Networks on the Juan de Fuca Spreading Center

BAILLARD, C., University of Washington, Washington, USA, baillard@uw.edu; WILCOCK, W. S. D., University of Washington, Washington, USA, wilcock@uw.edu; ARNULF, A. F., Institute for Geophysics, University of Texas, Texas, USA, aarnulf@ig.utexas.edu; TOLSTOY, M., Lamont-Doherty Earth Observatory, New York, USA, tolstoy@ldeo.columbia.edu; WALDHAUSER, F., Lamont-Doherty Earth Observatory, New York, USA, felixw@ldeo.columbia.edu; HEESEMANN, M., Ocean Networks Canada, University of Victoria, Victoria, Canada, mheesema@uvic.ca; FARRUGIA, J. J., Ocean Networks Canada, University of Victoria, Victoria, Canada, jfarrugia@uvic.ca

Background seismicity at mid-ocean ridges result from tectonic extension, magmatic inflation and hydrothermal cooling, and intense seismic swarms accompany volcanic spreading events. Because most of the earthquakes are small, long-term local seismic networks are required to characterize background seismicity and capture infrequent spreading events. In the Northeast Pacific Ocean, two regional cabled observatories extend to the Juan de Fuca Ridge (JdFR). Since 2011, the Ocean Networks Canada (ONC) observatory has monitored seismicity on the Endeavour segment starting with a single station that expanded to 4 in 2016. Since late 2014, the Oceanic Observatories Initiative (OOI) Cabled Array has hosted a 7-station seismic network at the summit of Axial Seamount.

Axial Seamount lies at the intersection of the JdFR and Cobb-Eickelberg hotspot chain, rises ~0.8 km above the rest of the JdFR, and erupted in 1998, 2011 and 2015. Over 100,000 earthquakes were located beneath the summit caldera leading up to and during the 2015 eruption. The Endeavour segment is a typical intermediate spreading rate ridge and supports particularly vigorous hydrothermal system. It has not erupted for at least 25 years and the last non-eruptive spreading event occurred in 2005.

We are developing catalogs of accurate earthquake locations at both sites. At Axial Seamount, we have obtained a 3D S-wave velocity model by inverting earthquake data using LOTOS, to complement an existing 3D tomographic P-wave model. Using the 3D velocity models in a non-linear location algorithm (NLLoc) improves locations and reveals faults beneath the caldera that were previously unseen. At the Endeavour we are developing a one-station location technique that uses waveform polarization and P , S and sea-surface reflected P_W times. 3D P- and S-wave velocity models already exist from a previous tomography experiment and will be used to accurately locate the seismicity.

Exploring Hypocenter Uncertainty in the Fort Worth Basin, North Texas

DESHON, H. R., Southern Methodist University, Texas, USA, hdeshon@smu.edu; QUINONES, L., Southern Methodist University, Texas, USA, lquinones@smu.edu; SUFRI, O., Southern Methodist University, Texas, USA, osufri@smu.edu; ARROWSMITH, S., Southern Methodist University, Texas, USA, sarrowsmith@smu.edu; SAVVAIDIS, A., University of Texas at Austin, Texas, USA, alexandros.savvaidis@beg.utexas.edu; HAYWARD, C., Southern Methodist University, Texas, USA, hayward@mail.isem.smu.edu

From 2008 to 2018, local seismic research networks operated by Southern Methodist University (SMU) provided basic earthquake data needed to assess seismic hazard related to induced earthquakes in the Fort Worth Basin, north Texas. Network design strategies focused on providing accurate hypocenter and focal mechanism information, and resulting catalog generated using GENLOC algorithms within Antelope is called the North Texas Earthquake Study (NTXES) catalog. As the research evolved, the location algorithms and 1D velocity models used for earthquake location have changed. Using the NTXES catalog, we explore how the formal uncertainties, represented by 68% confidence ellipses, capture or do not capture bias due to velocity model or location algorithm. We show that when at least one sensor is within hypocentral depth (2-10 km), the NTXES catalog changes due to velocity model and standard algorithms deviate on the order of 100-300 m. We will also present tests using double-difference relative techniques and Bayesian methods. Note, however, for studies of induced earthquakes even a systematic deepening ~150 m is enough to move many earthquakes from the rock unit used for injection into the crystalline basement, and can be considered significant for detailed research studies. Using co-located 3D seismic reflection data where available, we establish the NTXES dataset as best estimate of ground-truth and compare locations in space to epicenters reported by the National Earthquake Information Center (NEIC) and the Texas Seismic Network (TexNet). We seek to better quantify and understand hypocentral uncertainty in NEIC and TexNet hypocenters in the Fort Worth Basin over time because 1) many significant felt earthquakes in the basin, including the first earthquakes along most triggered faults, were only reported by the NEIC and 2) TexNet location operations are now well-established and the catalog readily available online, whereas SMU operations and catalog are temporary in nature.

Investigating Seismicity and Structure With a 25-Node 3-Component, 5-Hz Geophone Network in the Delaware Basin Around Pecos, TX

KARPLUS, M., The University of Texas at El Paso, Texas, USA, mkarplus@utep.edu; VEITCH, S. A., The University of Texas at El Paso, Texas, USA, saveitch@utep.edu; DOSER, D. I., The University of Texas at El Paso, Texas, USA, doser@utep.edu; FAITH, J. L., The University of Texas at El Paso, Texas, USA, jlfaith@miners.utep.edu; SAVVAIDIS, A., University of Texas at Austin, Texas, USA, alexandros.savvaidis@beg.utexas.edu

The region around Pecos, TX in the Delaware Basin is one of the most seismically active areas of Texas, with ~56 events with M2.0+ reported by the Texas Seismic Network (TexNet) in the first 11 months of 2018. Much of this seismicity appears to be located at less than 6-km depth, but the earthquake depths remain poorly-constrained due to the low number of seismic stations in the Pecos area. In order to improve earthquake locations, especially depths, and in order to develop improved structural, fault, stress, and velocity models of the region, the University of Texas at El Paso (UTEP) has partnered with the University of Texas Bureau of Economic Geology (BEG) to design and install a flexible, regional nodal network around Pecos, TX.

Our nodal array includes 25 3-component (3C) Fairfield Geotechnologies LLC Z-Land 5-Hz nodal seismometers in a flexible deployment pattern around Pecos, TX in Reeves and Ward Counties. The first stations were fielded in November of 2018, and included a station co-located with a TexNet broadband station in Pecos, TX. Our use of small, easy-to-deploy nodal seismometers allows us to improve our network geometry in response to our results, observations of station noise, or changes in the pattern of regional seismicity. We expect to continue to improve our station coverage as we work with local and county governments, landowners in Reeves and Ward Counties, and the BEG's industry partners to fill gaps.

The node network data will be archived after the initial research period. Seismologists at UTEP and the BEG will collaborate to provide improved earthquake locations and improved regional velocity and structural models including anisotropy. The Delaware Basin is located near the complex transition from the Rio Grande Rift to the Great Plains. Especially in Pecos, TX there' a high interest in the reported seismicity from TexNet, and we hope this collaboration will result in an improved understanding of the contemporary stress field and faulting in this complex area that will be useful to stakeholders in government, academia, and industry.

Feasibility of Detecting Shallow Events in Dense Array Data With the Source Scanning Method

CHENG, Y., University of Southern California, California, USA, chengyif@usc.edu; LI, F., University of Georgia, Georgia, USA, fangyu.li@uga.edu; BEN-ZION, Y., University of Southern California, California, USA, benzion@usc.edu

Dense seismic arrays provide important opportunities for high resolution detection and location of microearthquakes. Here we examine with synthetic tests the detection/location capability of the source scanning method based on summing square amplitudes (brightness) of predicted arrivals at different stations for various assumed source locations and times. The tests are done in the context of a rectangular array with 100 sensors separated by 100m and S wave arrivals calculated using an assumed S wave velocity model for the shallow crust. We first place a simple explosion source at the array center and 1 km depth and search for the source in model space with 25m horizontal grid intervals, 125m vertical intervals and 0.01s time intervals. We calculate the maximum brightness at each grid point and use the volume with more than 80 percent of peak brightness value as possible location. The vertical and horizontal ranges in the detection volume define the minimum resolvable length (MRL). We separate input signal into multiple frequency bands and apply the detection process to obtain spatial resolution under different frequencies. Then we choose the frequency band with high location resolution and apply the detection process to sources with different epicenters, depths to estimate the spatial dependency of location resolution. The results indicate that the horizontal and vertical MRLs of sources at the array center and 1km depth are larger than 150m and 650m at frequencies below 9Hz and above 15 Hz, respectively. Both horizontal and vertical resolutions decrease with increasing source depth. With increasing epicentral distance, horizontal resolutions decrease but vertical resolutions increase. When the epicentral distance from the array center is larger than 300m, a source located at 1km depth has horizontal MRL > 200m and vertical MRL < 500m. We are currently making corresponding tests using assumed P velocity models and larger aperture arrays. The results of the synthetic tests provide guidelines that will be used to apply the method to recorded dense array data.

Machine Learning in Seismology

Poster Session · Wednesday · 24 April · Grand Ballroom

What Triggered the Tremors in Nigeria on Sept 5-7, 2018?

LU, Y., University of Rochester, New York, USA, luyingping2017@gmail.com; ADEPELUMI, A. A., Obafemi Awolowo University, ILE-IFE, Nigeria, adepelumi@gmail.com; KOLAWOLE, F., University of Oklahoma, Oklahoma, USA, folarin@ou.edu; OLUGBOJI, T. M., University of Rochester, New York, USA, tolulope.olugboji@rochester.edu

On September 5-7, 2018, a series of low-magnitude tremors hit the capital city of Nigeria in Mpape, Abuja. This event follows a series of earthquakes felt on a stable, intra-plate region not expected to be earthquake-prone. This is bringing renewed attention to earthquakes as a potent natural hazard in the West Africa region. No global catalog reported this earthquake event, and preliminary analysis has resulted in speculations that this tremor was not local or regional, but could have been teleseismic. Due to the sparsity of seismic arrays in this region of the world, we explore single-station multi-frequency phase detection and polarization analysis to identify the epicenter and arrival direction of the tremors. We then cross-reference our detections with global catalogs and identify candidate locations and associated probabilities for their spatial targets. We propose improvements to the low-magnitude detection threshold of regional catalogs by conducting an extensive search of the waveform database using unsupervised machine learning techniques like convolutional neural networks.

Detecting Low Magnitude Seismic Events Using Convolutional Neural Networks

FORREST, R., Sandia National Laboratories, New Mexico, USA, rforrest@gmail.com; YOUNG, C. J., Sandia National Laboratories, New Mexico, USA, cjyoung@sandia.gov

Currently, many traditional methods are used to detect arrivals in three-component seismic waveform data collected at various distances. Accurately establishing the identity and arrival of these waves in adverse signal-to-noise environments is vital in detecting and locating seismic events. Autocorrelation and template matching techniques are just a few of the various methods that may be used, yet, each have their own limitations.

In this work, we present updated results using convolutional neural networks (CNNs). CNNs have been shown to significantly improve performance at local distances under certain conditions such as induced seismicity. In this work we expand the use of CNNs to more remote distances and lower magnitudes. We explore the advantages and limits of a certain architecture of CNN and update results previously presented.

We describe in detail performance results of our method tuned on a new dataset with expert defined arrival picks. The dataset used is from the Dynamic Network Experiment 2018 (DNE18) and comes from sensors in Utah. We demonstrate the ability to train the CNN on events from the dataset and achieve significantly higher test set performance than standard methods. Furthermore, we validate performance on streaming data, including very low magnitude expert picked arrivals.

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Automatic Phase Picking by Deep Learning

UCHIDE, T., Geological Survey of Japan, AIST, Tsukuba, Japan, t.uchide@aist.go.jp

The phase picking is one of the most fundamental process for seismic data. In this decade, the matched filter method has been often used. Then, template waveforms are required. This means that the phase pick data is needed for the additional phase picking in the case of the matched filter analyses. It is critical, especially in the case of campaign observation, where there is no pick data at first.

This study constructs the automatic picking system by the deep neural network with the inception module. I introduced the dropout and batch normalization techniques for preventing the overfit.

I use seismograms from Hi-net for earthquakes in the northern Ibaraki prefecture and the Fukushima Hamadori areas, where the seismicity rate is high since the 2011 Tohoku-oki earthquake. The P and S arrivals are the manually picked ones in the JMA Unified Earthquake Catalog. I introduce the picking data as one-hot vectors.

Generally, the deeper neural network gives better results, but the trend is weak. This may suggest that we seismologists should focus more on how to use the seismic data, rather than the design of the neural network. My neural network gives P arrivals within 0.02 s from the JMA data for more than 70 % of seismograms. We empirically relate the output to the probability, which will give the accuracy of the arrival times given by the neural network.

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An Automated Station Assessment Based on Deep Learning

SEO, K., Chonnam National University, Gwangju, Korea, Republic of, milreir@gmail.com; SHEEN, D., Chonnam National University, Gwangju, Korea, Republic of, dhsheen@jnu.ac.kr; KIM, G., Chonnam National University, Gwangju, Korea, Republic of, kgm621@naver.com; LEE, H., Chonnam National University, Gwangju, Korea, Republic of, hjl4888@gmail.com; KWAK, D., Chonnam National University, Gwangju, Korea, Republic of, rjatks1234@naver.com

As the number of seismic stations increasing, it helps to improve the completeness of earthquake catalogue and the understanding of seismic hazard. However, it has become more difficult to ensure the quality of seismic data and, thus, equally important to develop a method for allowing only good data to be used in real-time earthquake monitoring system, especially in earthquake early warning system. Therefore, an automated method for quality control of seismic data is required. In this study, we proposed a new method for seismic station performance assessment based on deep learning.

This study used the power spectral density (PSD) of seismogram for the assessment, which has been used for investigating characteristics of background seismic noise over a wide range of frequencies. The shape of the PSD also varies depending on the condition of a station, which can be used for training data of deep learning-based pattern recognition. We used 2 years of PSDs of the Korea Meteorological Administration as our training data, which were estimated every 30 minutes from seismograms of broadband seismic stations. The PSDs were manually classified into three categories: quiet or normal condition for background seismic noise, bad or abnormal condition for system transient or instrumental glitch, and event condition for local or teleseismic earthquake. The total number of data is 8298; 2922 PSDs for good condition, 3000 PSDs for bad condition, and 2376 PSDs for event condition.

Supervised learning model was implemented by the convolutional neural network, which has produced extremely promising results for various fields such as image recognition, natural language understanding, and even recently seismic phase detection. The training was performed with 70 % of data and the rest was used for validation. It is found that the precision and recall are very high (more than 99 %), indicating that most of PDSs were classified very well. Therefore, it is expected that this can be used for a real time station assessment tool for reporting of quality issues to network operators.

Network Analysis to Characterize Seismic Ground Motion Variability

SHENG, Y., Stanford University, California, USA, yixiao2@stanford.edu; KONG, Q., University of California, Berkeley, California, USA, kongqk@berkeley.edu; BEROZA, G. C., Stanford University, California, USA, beroza@stanford.edu

Spatial variability of seismic ground motion plays an important role in earthquake hazard analysis. It has particularly strong impacts on large structures, for which different parts of the foundations may experience different levels of shaking during an earthquake. It also should have a strong influence on the spatial distribution of damage. A better understanding of ground motion spatial correlation would help the guide policy to quantify and mitigate the risks posed by earthquakes

Among previous efforts, Boore *et al.* (2003), computed spatial correlation of peak ground acceleration (PGA) of the 1994 Northridge earthquake and Jayaram and Baker (2009) characterized PGA residuals from the Northridge earthquake and Chi-Chi earthquakes. However, ground motion in these studies was only sparsely sampled and such that important aspects of spatial correlation were difficult to constrain.

We propose to use the techniques of network analysis to study spatial variability. We treat each station as a node and the whole network as a graph while the link between each pair of nodes is weighted by the similarity between the recorded seismograms. Communities, within which the nodes are strongly correlated, are determined from the graph using community detection algorithms. Community detection allows us to consider the connections beyond individual station pairs, extending to multiple stations that are distributed over wide areas.

We apply the algorithm on the dense array in Long Beach, which had ~100 m station spacing over distances of over five km, which allows us to study the ground motion spatial variability to short scale lengths. We explore the method by varying the selected window length on the seismograms, different earthquakes with varying azimuth and depth, as well as different estimates of signal similarities either in time domain or time-frequency domain. Our detected communities yield reasonable comparisons to the 3D shear wave velocity (Lin *et al.*, 2013) and site amplification (Bowden, 2015) that were independently estimated for the same array.

Operational Real-Time Automatic Seismic Catalog Generator Utilizing Machine Learning: Performance Review Over a One Year Period in Production

REYNEN, A., Nanometrics Inc., Kanata, Canada, andrewreynen@nanometrics.ca; KARIMI, S., Nanometrics Inc., Kanata, Canada, sepidehkarimi@nanometrics.ca; BATURAN, D., Nanometrics Inc., Kanata, Canada, dariobaturan@nanometrics.ca

Real-time seismic event catalogs which are accurate and complete provide valuable insight into, among other things, public safety strategies and induced seismic risk management. The construction of such catalogs is traditionally labor intensive, hence automated processes have been developed to reduce the manual workload involved in catalog production. Many machine learning oriented approaches have been proposed, however, their performance is commonly reviewed with relation to a static seismic catalog. As machine learning algorithms can be prone to overfitting, the ability to generalize for use in a real-time system is critical.

In this study, we focus on the temporal stability of a real-time automatic seismic catalog generator algorithm (Feature Weighted Beamforming, FWB) which has been applied on over 15 networks over a one year period in a production environment. We present detailed results from an induced seismic monitoring array over the Duvernay Formation (Duvernay Subscriber Array, DSA), as well as some higher level statistics on other seismic networks. The initial results from DSA in comparison to standard STA/LTA picking and associations show that FWB reduced the number of false positives by 75% without loss of sensitivity, it also reduced the average difference in the event location between automatic and manually picked solutions by 82%. Similar to DSA, for all networks which included a large variety of training data FWB demonstrated consistent detection of all real seismic events compared to a sensitive STA/LTA pick associator regarding system sensitivity and location accuracy. We confirmed that the average difference in automated event locations output by FWB relative the analyst reviewed solutions are consistent over time. New clusters of seismic activity not seen during training are also correctly detected and located. We also discuss cautions for use of FWB when provided a limited training data set.

A Machine Learning Approach to Identify Landslides With Seismic Waves Using Support Vector Machine Method

CHUANG, L. Y., Georgia Institute of Technology, Georgia, USA, kanglianan@gmail.com; PENG, Z., Georgia Institute of Technology, Georgia, USA, zpeng@gatech.edu; ZHU, L., Georgia Institute of Technology, Georgia, USA, lijun.zhu@gatech.edu; MCCLELLAN, J., Georgia Institute of Technology, Georgia, USA, jim.mcclellan@ece.gatech.edu

Landslides are a common natural geologic hazard that can cause significant damage to human life and properties. The typical ways to study landslides and evaluate their susceptibilities are through in-situ measurement and remote sensing techniques (*i.e.*, satellite imagery, GPS, InSAR). These measurements, in general, provide good constraints on bulk properties of landslides, such as the area, overall shapes, and mass volumes, but not as much on their dynamic processes or the occurrence times, due to the lack of temporal resolution. On the other hand, landquake, a term that refers to landslide signals being recorded by seismometers, can provide information on the evolution time history as well as the dynamic processes, and even source mechanisms. Identification of landquakes on seismograms is challenging, as they have emerging onsets and complicated long-duration wave trains with relatively low SNR. One can potentially identify them in a very low-frequency band (*e.g.*, 0.02~0.05 Hz) where the phase is cleaner, or in a higher frequency band (*e.g.*, 1~3 Hz) when the events contain more high-frequency energy. But it's easy to misclassify them with teleseismic earthquakes, or regional earthquakes/tectonic tremors without manually analyzing the origin of the source carefully. Taking the advantage of recent developments in machine learning techniques, we built an automatic detector based on a support vector machine (SVM) to detect and classify various types of events (*e.g.*, local earthquake, teleseismic, tectonic tremor, and landquakes) using the Broadband Array in Taiwan for Seismology (BATS) network. The model can help with identifying more landslides and separating landquakes from background noise and other natural or anthropogenic sources. Our next step is to apply the SVM-based detector to continuous seismic data recorded in landslide-prone regions to build a more complete landslide catalog. We hope that complete landslide catalogs can contribute to better understanding of landslide dynamics and source mechanisms and eventually help in mitigating landslide hazards.

Automatic Waveform Quality Control for Surface Waves Using Machine Learning Techniques

CHAI, C., Oak Ridge National Laboratory, Tennessee, USA, chaic@ornl.gov; KINTNER, J., Pennsylvania State University, Pennsylvania, USA, jvk5803@psu.edu; CLEVELAND, K. M., Los Alamos National Laboratory, New Mexico, USA, mcleveland@lanl.gov; LUO, J., University of Virginia, Virginia, USA, jl6zh@virginia.edu; MACEIRA, M., Oak Ridge National Laboratory, Tennessee, USA, maceiram@ornl.gov; AMMON, C. J., Pennsylvania State University, Pennsylvania, USA, charlesammon@psu.edu; SANTOS-VILLALOBOS, H. J., Oak Ridge National Laboratory, Tennessee, USA, hsantos@ornl.gov

Large seismic waveform data sets are common as a result of additional seismic station and seismic network deployments grow in frequency and size. Unfortunately, not all waveforms have sufficient signal-to-noise characteristics and contribute useful information when employed in specific analysis techniques. For this reason, waveform data are usually examined before they are included in analyses sensitive to noisy signals. Quality control of waveform data, however, requires substantial time and effort, that can be a significant burden with large datasets. In some cases, data quality control becomes the most time-consuming part of the analysis. We screened roughly 400,000 surface-wave waveforms to assign quality levels (A, B, C etc.) to each waveform as part of efforts to improve earthquake locations in remote regions. The complexity of surface wave signals makes reliable automation of the quality control process a challenge. In this study we describe how using machine learning algorithms such as logistic regression, support vector machine, K-nearest neighbors, random forest, and neural networks, we are able to achieve a test accuracy of over 90 percent using subsets of labeled waveforms that we gathered from previous studies. We also developed interactive visualization tools to examine waveforms the algorithms are not able to categorize correctly. Preliminary results show that many of the incorrectly categorized signals are in fact human errors (wrong labels) in the training and assessment data. The resulting machine learning models can be used to assess signal quality for investigations involving surface-wave waveforms.

Convolutional Neural Network for Seismic Phase Picking, Performance Demonstration in the Absence of Extensive Training Data

WOOLLAM, J., University of Liverpool, Liverpool, United Kingdom, jack.woollam@liverpool.ac.uk; RIETBROCK, A., Karlsruhe Institute of Technology, Karlsruhe, Germany, andreas.rietbrock@kit.edu; BUENO, A., University of Granada, Granada, Spain, angelbueno@ugr.es; DE ANGELIS, S., University of Liverpool, Liverpool, United Kingdom, s.de-angelis@liverpool.ac.uk

We present a Convolutional Neural Network (CNN) for classifying seismic phase onsets over local seismic networks, where the CNN is trained over a relatively small dataset for deep-learning purposes. The training catalogue consists of 411 events located throughout northern Chile. CNN based classifiers have recently achieved unprecedented success in seismic phase picking, outperforming traditional autopicking methods and achieving results comparable to the picks of an expert seismologist; these previous studies utilised extensive catalogues (~millions of examples) during the training process. We now investigate the limiting case of supervised learning-based methods such as the CNN approach, where extensive training data are not available. Our results show that in the absence of extensive training data, with appropriate regularisation constraints, the CNN approach to seismic phase picking still demonstrates exceptional performance, outperforming traditional methods in seismic phase classification. The CNN method is compared against an optimised STA/LTA autopicker applied to the same region. We perform a further test again comparing the trained CNN against the STA/LTA approach in picking phases for a separate catalogue of events throughout northern Chile. Based on station travel-time residuals, the CNN outperforms the STA/LTA approach, achieving a location residual distribution close to the manual picks of an expert seismologist. These results further corroborate the potential of supervised-learning based methods in solving the problem of seismic phase classification.

A Neural Network Based Multi-Component Earthquake Detection Method

LIN, Y., Los Alamos National Laboratory, New Mexico, USA, ylin@lanl.gov; ZHANG, Z., Los Alamos National Laboratory, New Mexico, USA, zhongping@lanl.gov; CHEN, T., Los Alamos National Laboratory, New Mexico, USA, tchen@lanl.gov

We present a method to detect earthquake events from continuous 1-D seismic data. Many traditional earthquake detection methods detect events by the use of amplitude threshold and similarity in data. Currently, machine learning based earthquake detection methods have shown promising detection results. Among all those machine learning techniques, neural networks have been a used as popular method. However, most of the existing neural network frameworks for earthquake detection are based on one component seismic data. In our work, we propose an end-to-end framework which take the full advantage of the three components from the seismic data. A series of experiments are conducted to validate the effectiveness of our proposed model. The classification results and visualization results validate that our framework can significantly improve the detection accuracy.

Inversionnet: A Real-Time and Accurate Full Waveform Inversion With CNNs and Continuous CRFs

LIN, Y., Los Alamos National Laboratory, New Mexico, USA, ylin@lanl.gov; WU, Y., Los Alamos National Laboratory, New Mexico, USA, euyuw2@gmail.com

Full-waveform inversion problems are usually formulated as optimization problems, where the forward-wave propagation operator f maps the subsurface velocity structures to seismic signals. The existing computational methods for solving full-waveform inversion are not only computationally expensive, but also yields low-resolution results because of the ill-posedness and cycle skipping issues of full-waveform inversion. To resolve those issues, we employ machine-learning techniques to solve the full-waveform inversion. Specifically, we focus on applying the convolutional neural network~(CNN) to directly derive the inversion operator f^{-1} so that the velocity structure can be obtained without knowing the forward operator f. We build a convolutional neural network with an encoder-decoder structure to model the correspondence from seismic data to subsurface velocity structures. Furthermore, we employ the conditional random field~(CRF) on top of the CNN to generate structural predictions by modeling the interactions between different locations on the velocity model. Our numerical examples using synthetic seismic reflection data show that the propose CNN-CRF model significantly improve the accuracy of the velocity inversion while the computational time is reduced.

Machine Learning Models for Classifying Variations in Emergent and Impulsive Seismic Noise

JOHNSON, C., University of California, San Diego, California, USA, cwj004@ucsd.edu; VERNON, F. L., University of California, San Diego, California, USA, flvernon@ucsd.edu; BEN-ZION, Y., University of Southern California, California, USA, benzion@usc.edu

The proper classification of emergent and impulsive noise signals is critical for reducing false detections of microearthquakes and understanding ongoing ground motions. Continuous seismic waveforms contain numerous natural and anthropogenic signals whereas tectonic seismic events occupy only a small percentage of each day. A dense array of 1,100 vertical geophones recorded ground motions at the San Jacinto fault zone for 30 days in 2014 that provides detailed test data to detect microearthquakes and observe surface/atmospheric processes that manifest as impulsive and emergent seismic signals. Recent studies utilizing the spatially dense seismic array have demonstrated that ongoing low-amplitude seismic motion is dominated by various weak sources originating at the surface from anthropogenic and atmosphere interaction. Labeling classes of waveforms from wind generated ground motions, air-traffic, automobiles, and other non-tectonic signals can provide insightful information for designing a training data set. We apply a new methodology that uses subtle changes in correlations to label continuous waveforms as random noise, non-random noise, or a mixture of sig-

nals, and focus our efforts on identifying different classes of non-tectonic signals in the non-random noise to build a machine learning training data set. The data allow us to produce millions of 1 second labeled waveforms and present results showing the variability in the noise signals. The noise signals are used to train a convolutional neural network (ConvNet) to classify continuous waveforms. The ConvNet contains 4 convolution layers and 2 fully connected layer using rectified linear unit activation functions on each layer and a softmax activation function for the output layer. Results of coherent non-tectonic signals across the array provide insight on shallow crustal deformation and surface generated ground motions.

Two Combinatorial Optimization Methods That Determine On-Fault Earthquake Magnitude Distributions

GEIST, E., U.S. Geological Survey, California, USA, egeist@usgs.gov; PARSONS, T., U.S. Geological Survey, California, USA, tparsons@usgs.gov

Machine learning associated with earthquakes viewed as discrete events often involve a combinatorial structure. Two combinatorial optimization methods have been developed to determine the spatial distribution of earthquakes along a single fault or among faults within a fault system. For a synthetic earthquake catalog that spans millennia, the objective is to determine the optimal arrangement of earthquakes that minimizes misfit to target fault slip rates. The first method is a spatial gap-filling method that uses a greedy-sequential algorithm in which earthquakes are sequentially placed in a locally optimal sense. The second method is integer programming (IP) that globally optimizes earthquake placement subject to a number of constraints, including slip-rate uncertainty (minimum and maximum limits). The binary decision vector in the IP model is composed of every possible location that each earthquake in the synthetic catalog can occur. General mixed-integer programming (MIP) software is used that consists of a number of different algorithms, including the simplex algorithm for the initially relaxed binary constraints and the branch-and-cut algorithm to recursively search a tree of binary solutions. We find that the greedy-sequential algorithm efficiently scales to long catalog durations and complex fault systems. Global optimization, in contrast, is likely a nondeterministic polynomial-time (*i.e.*, NP-Hard) problem, similar to the pure knapsack and bin-packing problems well known in operations research. MIP software has greatly advanced in recent years, making fault-scale problems tractable, although high-performance computing platforms are required for the largest problems. We apply both of these methods to both a single fault (Nankai subduction megathrust) and a complex fault system (California transform system) and compare the results. We demonstrate that, in general, combinatorial optimization methods provide a valuable and independent way to determine on-fault earthquake magnitude distributions.

Modeling and Understanding of High-Frequency Ground Motion

Poster Session · Wednesday · 24 April · Grand Ballroom

Nonlinear Attenuation at PS10 During the 2002 Denali Earthquake Associated With Interaction of High-Frequency S Waves With the Near-Field Velocity Pulse

SLEEP, N. H., Stanford University, California, USA, norm@stanford.edu

Seismic station PS10 recorded reliable records of strong seismic waves ~3 km from the main fault of the 2002 Denali earthquake. The near-field velocity pulse reached 1.8 m s^{-1}. The peak ground acceleration of 3.5 m s^{-2} was kinematically associated with the velocity pulse. However, high-frequency *S* waves were weak, ~1 m s^{-2}. Two nonlinear attenuation mechanisms diminished high-frequency *S* wave amplitudes. (1) For context, the *S* waves attenuated within the uppermost layer of gravel. Well-known scaling relationships are relevant. The Coulomb ratio of dynamic resolved horizontal shear traction on horizontal planes from *S* waves approximately equals the normalized resolved horizontal acceleration. The acceleration in g's remained around the effective coefficient of friction, ~0.35, for a circularly polarized third-cycle during the near-field pulse. This strong shaking likely reduced the shear modulus and resonance frequently of the shallow gravel, providing indirect evidence for shallow nonlinear behavior. (2) The near-field velocity pulse brought the upmost uppermost hard rock perhaps down to ~2 km depth beneath PS10 into nonlinear failure. High-frequency *S* waves passing through this failing region attenuated nonlinearly. Site response formalism is inapplicable as the effect occurred along much of the S wave's paths. The process is mathematically similar to strong linear attenuation of high-frequency S waves. Observed horizontal spectra show this decay with frequency with a quality factor Q of ~20. These observations are compatible with a nonlinear rheology where the inelastic strain rate within the hard rock increases gradually with deviatoric stress. In contrast, high-frequency waves with stress antithetical to the in the near-field velocity pulse should propagate through the hard rock with an ideal plastic rheology.

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Validation of Two Approaches for Expressing Spectral Decay Characteristics of Ground Motions in High Frequency Range - Fmax and Kappa Models -

TSURUGI, M., Geo-Research Institute, Osaka, Japan, turugi@geor.or.jp; TANAKA, R., Geo-Research Institute, Osaka, Japan, tanaka@geor.or.jp; KAGAWA, T., Tottori University, Tottori, Japan, kagawa@cv.tottori-u.ac.jp; IRIKURA, K., Aichi Institute of Technology, Toyota, Japan, irikura@geor.or.jp

Spectral decay characteristics in high frequency range of observed ground motions during inland crustal earthquakes have been evaluated using two different approaches: f_{max} (Hanks, 1982) and kappa (Anderson and Hough, 1984) models. We analyzed 105 events (M_w 3.3-7.0) including seven large earthquakes (M_w 5.9-7.0). For large earthquakes, we estimated cut-off frequency f_{max} to range from 6.5 to 9.9 Hz and the power coefficient of spectral decay *s* from 0.78 to 1.60 in the f_{max} model, and kappa to range from 0.0142 to 0.0505 and f_E from 2 to 4.5 Hz in the kappa model in our previous study (Tsurugi *et al.*, 2017). The f_E in the kappa model is a specific frequency at which a spectrum starts to decrease linearly with increasing frequency in log-linear space.

In this paper, we examined the validity of the two models in expressing high-frequency spectral decay characteristics by calculating the residual error between the observed Fourier amplitude spectra and two theoretical spectra, one from the omega-squared source model (Aki, 1967; Brune, 1970) and the f_{max} model, and the other from the kappa model. We calculated residual errors for each frequency and for each earthquake. As a result, we can say that both approaches using the f_{max} model and the kappa model are appropriate to evaluate spectral decay characteristics in high frequency range, if the parameters for the spectral decay characteristics (*i.e.*, f_{max} and the power coefficient of spectral decay *s* in f_{max} model, or the parameter kappa and the specific frequency f_E in kappa model) are appropriately evaluated by observed spectra. This study is a part of the regulatory-supported research project funded by the Secretariat of Nuclear Regulation Authority, Japan.

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Comparing Eastern and Western Canada Kappa Values

PALMER, S. M., Western University, London, Canada, spalme22@uwo.ca; ATKINSON, G. M., Western University, London, Canada, gatkins6@uwo.ca

The rate of diminution of high frequency ground-motion amplitudes is modelled using the parameter kappa (Anderson and Hough, 1984 BSSA), which measures the slope of the Fourier amplitude spectrum. Kappa is an important and consequential parameter for the response of critical infrastructure (such as nuclear power plants and dams), especially on rock site sites. This study compares kappa values on rock sites in eastern and western Canada for M>3 earthquakes recorded within 150 km. In general, we find that kappa values in western Canada are larger

than those in eastern Canada, reflecting greater high-frequency attenuation, possibly due to softer average rock conditions. We examine a range of potential factors that may influence kappa, including source, path, and site effects.

A New Ground Motion Model for Iran

FARAJPOUR, Z., The University of Memphis, Tennessee, USA, zfrjpour@memphis.edu; PEZESHK, S., The University of Memphis, Tennessee, USA, spezeshk@memphis.edu

Ground-motion models (GMMs) are the key element of a probabilistic seismic hazard analysis (PSHA), in which their validity is dependent on the sufficiency of the data. The quality and quantity of the recorded data have increased over the last couple of decades; as the result, researchers are trying to develop models that are based on more recent and more accurate data.

In this study, we develop a partial non-ergodic horizontal empirical GMM for Iran considering five major seismotectonic provinces. This study uses a newly developed database of strong ground motion for Iran. We used moment magnitudes **M** ranging from 4.8 to 7.5 and shortest distances from site to a rupture surface, R_{rup}, less than 400 km for shallow earthquakes with focal depths less than 35 km. We used a mixed-effects regression algorithm to determine inter-event and intra-event residuals. The functional form used includes 14 coefficients which we obtain by prescribing the event- and site-specific uncertainties associated with the magnitude and the average shear-wave velocity.

The GMPEs are derived for the peak ground acceleration (PGA) and 5%-damped pseudo-acceleration response-spectral ordinates (PSA) at periods ranging from 0.01 to 4 s. The proposed GMM is developed for a reference site defined as rock with V_{S30} = 760 m/s. The database used also includes ground motion information and source characterization and parameters.

The proposed GMM for Iran includes a nonlinear site-response term in the functional form. We do show that it is important to consider a nonlinear term in the functional form. Finally, we compare our GMM with recent published GMMs for Iran.

Spatial Characteristics of High Frequency Ground Motion Along the Chilean Subduction Zone

AZIZ ZANJANI, A., Saint Louis University, Missouri, USA, asiye.azizzanjani@slu.edu; HERRMANN, R. B., Saint Louis University, Missouri, USA, robert.b.herrmann@gmail.com

The Chilean Subduction Zone is known for large megathrust earthquakes originating at the interface of the subducting Nazca Plate beneath the South American Plate. We characterize high frequency ground motion along the Chile trench using earthquakes shallower than 40 km with magnitudes of 2.5-6.3. We analyze broadband three-component waveforms recorded by multiple networks (C1, CX, XY, ZE, XS) in the frequency range of 0.25-20 Hz and epicentral distances of 40-500 km. The northern Chile (NCH) data set includes 810 earthquakes recorded at 35 stations while the central Chile (CCH) data set uses 1174 earthquakes at 138 stations. The use of broadband data provides >> 10,000 observations at each frequency. We perform regressions on bandpass filtered ground velocities and Fourier velocity spectra to construct source-attenuation models. Comparison of the distance functions shows discernible differences in distance scaling between the data sets with a more rapid attenuation of seismic amplitude for the CCH paths compared to those of the NCH. At hypocentral distances greater than 250 km, the contribution from paths through deep structure at high frequencies (>8Hz) shows that a simple propagation model fails to fit all frequencies. We use two-corner frequency spectral source models to fit the low-frequency excitations for large-magnitude earthquakes. Given the source spectral and attenuation models and empirical durations of the ground motion, Random Vibration Theory is used to model the excitations using 28 and 48 earthquakes with known Mw in the NCH and CCH, respectively. While the high-frequency roll-off controlled by kappa doesn't show significant spatial dependence, the shape of excitations in NCH significantly differs from those in CCH. For large magnitudes, the excitation levels in the NCH are higher at low frequencies and are lower at high frequencies compared to the CCH . Estimated spectral accelerations and maximum accelerations with distance using source-attenuation models are consistent with results of other studies but show some spatial variations.

Attenuation of Ground Motion Spectral Amplitudes in the Longmenshan Belt and Its Surrounding Regions in Southwestern China

WEI-MIN, W., Institute of Tibetan Plateau Research, Chinese Academy of Sciences, Beijing, China, wangwm@itpcas.ac.cn; JIAN-KUN, H., Institute of Tibetan Plateau Research, Chinese Academy of Sciences, Beijing, China, jkhe@itpcas.ac.cn; ZHAO, L., Institute of Geology and Geophysics, Chinese Academy of Sciences, Beijing, China, zhaolf@mail.iggcas.ac.cn; XIE, X., University of California, Santa Cruz, California, USA, xxie@ucsc.edu; ZHEN-XING, Y., Institute of Geology and Geophysics, Chinese Academy of Sciences, Beijing, China, yaozx@mail.iggcas.ac.cn

On 12 May 2008, the magnitude 8.0 Great Wenchuan Earthquake occurred in Longmenshan belt in Southwestern China. As part of the eastern boundary of the Tibetan Plateau, this region experienced intense tectonic movements and strong seismic activity. Large amount of strong ground motion data were recorded at epicentral distances between 15 and 400 km by strong ground-motion networks installed before and after the Wenchuan earthquake. We collected horizontal-component waveforms of these strong ground-motions, and extracted shear waveforms including S, SmS, Lg, Sn phases which usually cause building damages. Considering uncertainties of the origin times and source locations, we adopted a floating group velocity window to sample shear wave phases. The noise series were picked from time windows immediately before the first arriving P waves. The Fourier spectra were calculated for both shear waves and noise. The spectral amplitudes at 11 frequencies log-evenly distributed between 0.5 and 20.0 Hz were sampled and used to construct a seismic wave attenuation model in this region. By using linear regression, we obtained a frequency-dependent Q model, geometric spreading parameters and site corrections for the studied region. The geographical distribution of site corrections show prominent differences at various tectonic divisions along the Longmenshan belt. Along the side of the Tibet Plateau and to the west of the Longmenshan belt, relatively lowerQ values are observed, whereas to the east of this belt, the Sichuan Basin is characterized by relatively higher Q values. This research was supported by the National Natural Science Foundation of China (grants 41674104, 41630210).

Numerical Investigations on the Effect of Crustal Heterogeneities on the High Frequency Attenuation

COLVEZ, M., Laboratoire MSSMat, Gif-sur-Yvette, France, martin.colvez@centralesupelec.fr; GATTI, F., Laboratoire MSSMat, Gif-sur-Yvette, France, filippo.gatti@centralesupelec.fr; LOPEZ-CABALLERO, F., Laboratoire MSSMat, Gif-sur-Yvette, France, fernando.lopez-caballero@centralesupelec.fr; COTTEREAU, R., LMA, Marseille, France, cottereau@lma.cnrs-mrs.fr; BONILLA, L., IFSTTAR, Marne-la-Vallée, France, luis-fabian.bonilla-hidalgo@ifsttar.fr; GELIS, C., Institut de Radioprotection et de Sûreté Nucléaire, Fontenay-aux-Roses, France, celine.gelis@irsn.fr

Predicting the observed attenuation at high frequency remains an open issue of strong ground motion modelling. The main reason is the interaction of many factors such as intrinsic attenuation, crustal heterogeneity, source rupture mechanism among others. In practice, usually this phenomenon is taken into account via regression coefficients, such as kappa parameter introduced by Anderson and Hough in 1982 which will be used in ground motion prediction equations. The site response prediction and engineering design however, may be critically influenced by the choice of those parameters, regardless of the accuracy of the statistical analyses behind it.

In recent years, source-to-site numerical simulations have gained momentum due to the increasing availability of High Performance Computing resources. This allows the possibility to investigate some phenomena, such as the dispersive attenuation of seismic wave motion.

The heterogeneous nature of the crustal 3D scatter distribution leaves a high-frequency footprint on the wave-field recorded at the surface. The aim of this study is to show the impact of the 3D crustal heterogeneities on the travelling wave towards the surface, using high-fidelity earthquake numerical simulations. The objective is to highlight the apparent attenuation and the possible trapping effect due to the heterogeneities and also to characterize the high frequency part of the radiated seismic motion. This task is accomplished by inspecting the broadband (0-25 Hz) obtained synthetic wave-forms for different scenario realizations. An estimation of the kappa value is provided at different locations, giving further insights on the uncertainty related to it.

Within Station Variability and Uncertainty in Kappa Estimations: Insights From Various KiK-Net Downhole Arrays

JI, C., North Carolina State University, North Carolina, USA, cji3@ncsu.edu; CABAS, A., North Carolina State University, North Carolina, USA, amcabasm@ncsu.edu; COTTON, F., GFZ German Research Centre for Geosciences, Potsdam, Germany, fabrice.cotton@gfz-potsdam.de; PILZ, M., GFZ German Research Centre for Geosciences, Potsdam, Germany, marco.pilz@gfz-potsdam.de; BINDI, D., GFZ German Research Centre for Geosciences, Potsdam, Germany, dino.bindi@gfz-potsdam.de

The high-frequency spectral decay parameter Kappa (kappa_r) is one of the most used parameters to describe seismic attenuation at high frequencies, but it is still not well understood. There is a critical need to understand the physics behind the parameter, as well as potential factors that lead to large scatter in estimated values of kappa_r and its site component kappa_0. Such improvements would not only impact ground motion modeling, but the assessment of seismic hazards at large. However, the uncertainties in individual kappa_r estimations associated with different events at a selected site (which are hereafter referred to as the within station variability of kappa_r and kappa_0) remain uncharacterized and unquantified. Hence, robust estimates of kappa_0 and their interpretation remain a challenge. Recent research efforts have focused on studying epistemic uncertainties in kappa_r (and kappa_0) at specific site conditions (*e.g.*, hard rock sites), and the variability in kappa_0 among different sites classes (*e.g.*, the correlation between kappa_0 and the 30-m time-averaged shear wave velocity, Vs30). In order to understand the within station variability of kappa_r (and kappa_0), the uncertainties associated with individual kappa_r (estimated by the acceleration slope approach, kappa_r_AS) are categorized as site, path, and source components. Factors contributing to uncertainties in each component include: the type of seismicity, epicentral depth, directionality of the ground motion, and azimuths. In this paper, we use the Japanese Kiban-Kyoshin network (KiK-net) database to investigate how these factors influence the within station variability of kappa_r (and kappa_0). Finally, this paper provides recommendations for kappa estimations and record selection.

Inclusion of Frequency-Dependent Spatial Correlation into the SDSU Broadband Ground-Motion Generation Method

WANG, N., San Diego State University, University of California, San Diego, California, USA, naw021@ucsd.edu; TAKEDATSU, R., San Diego State University, California, USA, rtakedatsu@sdsu.edu; OLSEN, K. B., San Diego State University, California, USA, kbolsen@sdsu.edu; DAY, S. M., San Diego State University, California, USA, sday@sdsu.edu

Seismic losses (such as disruption of distributed infrastructure and losses to portfolios of structures) are typically dependent upon the regional distribution of ground-motion intensities, rather than the intensity at only a single site. Ground motion time series recorded at stations separated by up to a few tens of kilometers show a frequency-dependent spatial coherency structure, and measures such as PGVs, PGAs, and peak spectral accelerations are found to be correlated. Quantifying ground motion over a spatially-distributed region is therefore important and requires information on the correlation between the ground motion intensities at different sites during a single event, where the spatial correlation can be significant within 50 km. The significance of excluding spatial correlation in ground motion simulations can result in an under-estimation of the seismic risk. The San Diego State University (SDSU) module on the Southern California Earthquake Center (SCEC) Broadband Platform (BBP) is a hybrid method that merges low-frequency deterministic synthetics and high-frequency stochastic scattering functions. We have implemented frequency-dependent spatial correlation into the SDSU method on the SCEC BBP using a post-processing method. This method makes use of a two-dimensional Gaussian random variable that has covariance corresponding to the spatial cross-correlation model developed by Loth and Baker (2013) for spectral accelerations. Our results for the Loma Prieta, CA, event show that the frequency-dependent spatial correlation in our broadband synthetics compares well to that estimated from seismic observations.

A Seismic Intensity Survey of the 16 April, 2016 Mw 7.8 Muisne, Ecuador Earthquake and a Comparison With Strong Motion Data

SMITH, E. M., University of Montana, Texas, USA, ellenmsmith22@gmail.com; MOONEY, W. D., U.S. Geological Survey, California, USA, mooney@usgs.gov

We conducted a regional seismic intensity field survey in Ecuador following the April 16, 2016 M7.8 Muisne earthquake to document the geographic distribution and level of damage caused by the earthquake. We observed several collapsed and partially collapsed structures which we infer is due to a combination of poorly constructed buildings, loose and unconsolidated soil, and the high frequency ground shaking experienced during this earthquake. This earthquake nucleated at a depth 20 km and produced extensive amounts of damage in the cities of Pedernales, Chone, Manta, and Portoviejo. The Modified Mercalli Intensities (MMIs) reached a maximum value of VIII, and the Peak Ground Velocities (PGVs) and Peak Ground Accelerations (PGAs) reached a maximum value of 82 cm/s and 1,410 cm/sec^2. Our highest observed MMI intensities correlate with PGA and PGV values. We determined empirical relationship between instrumental peak ground motions and observed intensities for this earthquake. Additionally, our observed MMI intensities strongly correlate with high frequency radiation determined by the seismic back projection technique. These results contribute to a growing database of field observations of seismic intensities and strong motion measurements for large subduction zone earthquakes.

Influence of Coupling and Installation Depth of Accelerometric Station on Signal High-Frequency Content

HOLLENDER, F., CEA - DEN - Cadarache, Saint Paul lez Durance, France, fabrice.hollender@cea.fr; MAUFROY, E., ISTerre, University Grenoble-Alpes / USMB / CNRS / IFSTTAR / IRD, Grenoble, France, emeline.maufroy@univ-grenoble-alpes.fr; ROUMELIOTI, Z., Aristotle University of Thessaloniki, Thessaloniki, Greece, zroum@auth.gr

Numerous accelerometric stations are assumed to be installed in free field conditions and hence, considered to be able to record the true ground motion without any alteration. However, recent experiments showed large differences in high frequency content between stations located very close to each other (less than 2 m) depending on whether the station is buried and firmly coupled to soil (classical 'post seismic' survey setup) or whether the station in anchored on a small concrete slab inside a shallow manhole (classical permanent network setup).

With respect to soil site conditions and based on the analysis of earthquake records, we observed large amplification above 10 Hz and up to a factor of 3 at 20 Hz for a station installed on concrete slab with respect to a collocated buried one. The differences between buried and slab-anchored stations seem to be much smaller in case of rock site conditions.

Stations may also be installed at shallow depths (few meters) within a seismic vault or cave and still considered as "free field". In such configuration, the down-going waves interference with the up-going ones may induce important deamplification of the signal within a frequency band, which, although in the high frequency part of the earthquake spectrum, is still of importance for earthquake engineering.

The effect of the sensor installation practices on recorded high-frequency ground motion need to be better characterized and pertinent information should be disseminated as part of the station's metadata in order to be taken into account for a better use of records. Indeed, the high frequency content of ground motion records has become an increasingly important topic within the framework of site-specific seismic hazard studies. A lot of studies, involving the "kappa" parameter concept, scattering analysis, etc., are using the high frequency part of the accelerometric signals provided by seismological networks.

Science Gateways and Computational Tools for Improving Earthquake Research

Poster Session · Wednesday · 24 April · Grand Ballroom

Processing and Review Interface for Strong Motion Data: Prism Software Version 2.0

KALKAN, E., U.S. Geological Survey, California, USA, ekalkan@usgs.gov; JONES, J., U.S. Geological Survey, California, USA, jmjones@usgs.gov; STEPHENS, C., U.S. Geological Survey, California, USA, cdstephens@usgs.gov; NG, P., U.S. Geological Survey, California, USA, png@usgs.gov; STEIDL, J. H., U.S. Geological Survey, California, USA, jsteidl@usgs.gov; BRODY, J., U.S. Geological Survey, California, USA, jbrody@usgs.gov; GEE, L., U.S. Geological Survey, California, USA, lgee@usgs.gov

Processing and Review Interface for Strong Motion data (PRISM) software (Jones *et al.* 2017) was developed by the National Strong Motion Project (NSMP) of the U.S. Geological Survey (USGS). PRISM can be used in combination with the Advanced National Seismic System Quake Monitoring System (AQMS) to provide automated processing of strong-motion records, or it can be used in stand-alone mode to perform batch-processing. PRISM is Java based and open source. The software can be installed and run on common operating systems, including Linux, OS X, and Windows. The software consists of two major components – 1) a record processing engine composed of core processing modules, and 2) a graphical user interface (GUI) review tool for manual review, edit, and processing. PRISM is currently limited to handling only data in the Consortium of Organizations for Strong-Motion Observation Systems (COSMOS) V0 format. Thus, all retrieved acceleration time series data need to be converted to this format in order to be used in PRISM. COSMOS-formatted output products generated from PRISM processing include V1 (raw acceleration time series in physical units with mean removed), V2 (baseline-corrected and filtered acceleration, velocity, and displacement time series), and V3 (response spectra, Fourier amplitude spectra, and other common earthquake-engineering intensity measures). PRISM version 2.0, which is currently in development, will include several new signal processing algorithms and additional features, including 1) frequency-domain integration, 2) frequency-domain decimation, 3) de-spiking, 4) signal-to-noise ratio computation, and 5) auto-detecting band pass-filter corner frequencies.

MUSTANG: Advances in a Resource for Seismic Noise Measurements and Data Quality Metrics

SHARER, G., Incorporated Research Institutions for Seismology, Washington, USA, gksharer@gmail.com; WEERTMAN, B. R., Incorporated Research Institutions for Seismology, Washington, USA, bruce@iris.washington.edu; KEYSON, L., Incorporated Research Institutions for Seismology, Washington, USA, laura@iris.washington.edu; TEMPLETON, M. E., Incorporated Research Institutions for Seismology, Washington, USA, met@iris.washington.edu; CASEY, R., Incorporated Research Institutions for Seismology, Washington, USA, rob@iris.washington.edu; AHERN, T., Incorporated Research Institutions for Seismology, Washington, USA, tim@iris.washington.edu

MUSTANG is a system for calculating, storing, and disseminating Power Spectral Densities (PSDs), Probability Density Functions (PDFs), and data quality metrics encompassing the 40+ years of seismic data in the IRIS Data Management Center primary archive. This information is a seismological community-wide resource that is designed to improve earthquake research at a variety of levels: ambient seismic noise studies, network operator quality assurance efforts, and large data set culling based on metrics, among others. Access to MUSTANG is provided through a suite of web services and visualization tools at http://service.iris.edu/mustang.

In the past year, MUSTANG has reached the milestone of nearly complete archive coverage for most seismic channels including high gain, low gain, accelerometer, gravimeter, and geophone channels. Its database contains PSDs, PDFs, and quality metrics for over 137,000 unique station-channels and 98 million station-channel-days, resulting in an extensive collection of measurements that are useful for examining both short-term and long-term trends. We will highlight the newest web service, noise-spectrogram, which provides spectrogram plots using daily PDF-mode values, and also improvements to MUSTANG Databrowser and MUSTANGular, which are tools for generating quality metric plots and map views.

Developing a Web-Based Interface to the SCEC Community Fault Model (CFM)

SU, M., University of Southern California, California, USA, mei@usc.edu; MAECHLING, P. J., University of Southern California, California, USA, maechlin@usc.edu; MARSHALL, S. T., Appalachian State University, North Carolina, USA, marshallst@appstate.edu; HEARN, E., Capstone Geophysics, California, USA, hearn.liz@gmail.com; NICHOLSON, C., University of California, Santa Barbara, California, USA, craig.nicholson@ucsb.edu; PLESCH, A., Harvard University, Massachusetts, USA, andreas_plesch@harvard.edu; SHAW, J., Harvard University, Massachusetts, USA, shaw@eps.harvard.edu; PAUK, E., University of Southern California, California, USA, pauk@usc.edu

The SCEC Community Fault Model (CFM) is an object-oriented, three-dimensional representation of active faults in southern California and adjacent offshore basins that includes 105 complex fault systems (Plesch *et al.*, 2016; Nicholson *et al.*, 2017) composed from more than 380 individually named fault representations. The model incorporates more than 820 objects, which include triangulated surface representations (GOCAD t-surfs) and associated metadata. The CFM 3D faults are defined based on surfaces traces, seismicity, seismic reflection profiles, wells, geologic cross sections, and various other types of models. The CFM serves the Southern California Earthquake Center (SCEC) as a unified resource for physics-based fault systems modeling, strong ground-motion prediction, and probabilistic seismic hazards assessment. The latest release of the CFM is version 5.2 which includes many new and revised fault representations (Nicholson *et al.*, 2017, 2018). In past years, the SCEC CFM has been distributed as a collection of files, including fault information and metadata in an Excel spreadsheet, and fault geometry files in 2D GIS shapefile and 3D GOCAD t-surf formats. To make the CFM more accessible and useful to researchers, we are developing a web-based interface to the CFM. Our current prototype CFM website provides a map-based interface to the CFM model, and it enables users to view and download the CFM 5.2 faults and fault metadata. The current site also allows users to download CFM fault geometry files in user-selected format and resolution. SCEC's science and software groups are developing the CFM website using an iterative software development process in which SCEC scientists identify and prioritize desired capabilities, the SCEC software group rapidly prototypes new features, and SCEC researchers review the site capabilities to ensure they provide value and ease of access to the science community.

Developing a GeoGateway User Community

GRANT LUDWIG, L., University of California, Irvine, California, USA, lgrant@uci.edu; MIRKHANIAN, M., University of California, Irvine, California, USA, mmirkhan@uci.edu; DONNELLAN, A., Jet Propulsion Laboratory, California Institute of Technology, California, USA, andrea@jpl.caltech.edu

Science gateways allow research communities to access shared data, software and services. GeoGateway (http://geo-gateway.org) is a science gateway that provides online tools for analysis, modeling, and response using geodetic imaging data. The main application of GeoGateway is to analyze and model crustal deformation related to earthquakes, and measure fault slip. The tools focus on airborne InSAR data from NASA's airborne UAVSAR platform and Global Positioning System (GPS) position time series, displacements, and velocities. The purpose of GeoGateway is to increase the value of existing geodetic imaging products to researchers and allow users to efficiently find and use NASA geodetic imaging data products. GeoGateway is intended to bridge the gap between production and end-use of data products by 1) simplifying the discovery of geodetic imaging products; 2) enabling researchers to explore and integrate data products; and 3) allowing researchers to easily share, publish and collaborate. Development efforts have focused primarily on implementation of technologies for facilitating data access and analysis by end users. Initial users and testers were members of the development team, and their close associates. Publication of several scientific papers showing GeoGateway applications and results led to interest by potential outside users, but growth of the user community would occur more quickly with clear documentation. Informal surveys revealed technical challenges encountered by new users. To overcome this entry barrier, we are developing a GeoGateway User Guide, geared toward novice users at the upper division undergraduate level. The User Guide is scheduled for release in spring 2019.

Earthquake Source Parameters: Theory, Observations and Interpretations

Oral Session · Thursday · 8:30 AM · 25 April · Cascade I

Session Chairs: Vaclav Vavrycuk, Douglas S. Dreger, Grzegorz Kwiatek.

Bayesian Dynamic Finite-Fault Inversion of the 2016 Mw 6.2 Amatrice, Italy, Earthquake

GALLOVIC, F., Charles University, Prague, Czech Republic, gallovic@karel.troja.mff.cuni.cz; VALENTOVA, L., Charles University, Prague, Czech Republic, valent@karel.troja.mff.cuni.cz; AMPUERO, J., Géoazur, University Côte d'Azur, Valbonne Sophia Antipolis, France, ampuero@geoazur.unice.fr; GABRIEL, A., Ludwig Maximilian University of Munich, Munich, Germany, gabriel@geophysik.uni-muenchen.de

In 2016, Central Italy was struck by three normal faulting earthquakes with Mw>6. The first Mw 6.2 Amatrice event (08/24), caused building collapse and about 300 casualties. The event was recorded by a uniquely dense network of seismic stations. Kinematic source inversions based on such data can be used to characterize the spatio-temporal evolution of earthquake slip, but provide only indirect constraints on rupture physics. Therefore, here we perform dynamic source inversion to directly infer the fault friction parameters and stress conditions that controlled the earthquake rupture. We consider dynamic rupture governed by a linear slip-weakening friction law with spatially variable parameters along the fault. The inversion approach utilizes a novel Bayesian framework, which combines efficient finite-difference dynamic rupture simulations by the FD3D code and a Parallel Tempering Monte Carlo algorithm to sample the posterior probability density function. The main advantage is that subsequent analysis of the posterior samples yields stable features of the results and associated uncertainties. The inversion results in a million of visited models and ~5,000 accepted model samples revealing intriguing dynamic features. In agreement with previous kinematic inversions, the rupture initiated by localized transient nucleation followed by bilateral rupture propagation across two asperities. The rupture accelerates towards the heavily damaged city of Amatrice where peak acceleration of 0.8 g was measured. Dynamic stress drop reaches locally 10-15 MPa, with a mean of 4-4.5 MPa. Friction drop ranges from 0.1 to 0.4. The critical slip-weakening distance spatially varies between 0.2 and 0.8 m. The radiation efficiency is between 0.1-0.2, indicating that approximately 80-90% of the total available energy is spent in the fracture process, while only 10-20% is radiated by seismic waves. This study demonstrates how Bayesian exploration of the parameter space and abundant strong motion data can provide constraints on earthquake source physics of well recorded earthquakes.

Uncertainty Analysis of Back-Projection Methods

ZENG, H., Earth Observatory of Singapore, Nanyang Technological University, Singapore, Singapore, hyzeng@ntu.edu.sg; WEI, S., Earth Observatory of

Singapore, Nanyang Technological University, Singapore, Singapore, shjwei@ntu.edu.sg; WU, W., Princeton University, New Jersey, USA, wenbow@princeton.edu

Back-Projecting high frequency (HF) waves is routinely used to image rupture processes of large earthquakes. However, HF waves are strongly affected by source depth, focal mechanisms and the Earth's 3D velocity structures, causing large uncertainties in back-projection (BP). So far these uncertainties have not been thoroughly investigated. Here we perform 1D and 3D synthetic tests to investigate uncertainties in two representative BP methods, Multiple SIgnal Classification and Compressive Sensing. We generate synthetics for sources embedded in 1D or 3D velocity models with different depths and focal mechanisms, and then back-project them using the two methods based on array configurations. The focal depth test shows that depth phases can be back-projected as artifacts swimming towards the array with offsets proportional to the source depth, suggesting that depth phases are mapped to their reflection points in the surface. For a multiple point source model involving varied focal mechanisms, the seismograms differ significantly between arrays. Using the 2016 Mw7.8 Kaikoura earthquake as a scenario, both real and synthetic data show that the South American and Australian arrays image inconsistent rupture evolution, especially for late segments. We attribute this to varied focal mechanisms at varied rupture stages. We also test the impact of 3D velocity structures by simulating an event in the Java subduction zone. The 3D trench and coast structure can generate strong and long lasted codas, which are mirrored as artifacts far from the input. Finally, we model an offshore event in the Sumatran subduction zone and show that the generated wavefields feature the frequency-dependence, leading to frequency-dependent BP results. In summary, our analyses indicate that the preceding factors can affect various aspects of BP results. Thus, we suggest target-oriented synthetic tests, such as simulations of megathrust earthquakes with 3D source-side velocity structures, should be conducted when we interpret detailed BP images to infer the earthquake kinematics and dynamics.

An Objective Method for Estimating Earthquake Rupture Dimensions From Early Aftershock Distributions Across a Wide Magnitude Range

MEIER, M., California Institute of Technology, California, USA, mmeier@caltech.edu; AMPUERO, J., Géoazur, University Côte d'Azur, Nice, France, ampuero@gps.caltech.edu; ROSS, Z. E., California Institute of Technology, California, USA, zross@caltech.edu; HAUKSSON, E., California Institute of Technology, California, USA, hauksson@caltech.edu

Aftershock distributions are commonly used to constrain some of the most fundamental macroscopic properties of seismic ruptures, such as rupture source dimensions. Although any individual aftershock sequence may exhibit complicated aftershock patterns, there are well-defined average patterns of aftershock behavior in space, time, and with respect to magnitude. Here we propose a simple new method for characterizing seismicity sequences in a data-driven way. The method is based on an eigenvalue decomposition of earthquake hypocenter clusters and provides an objective characterization of the evolution of event sequences in space and time. We apply the method to relocated seismicity catalogs from California and Japan. Our preliminary tests show that the method is able to provide consistent cluster descriptions from the largest observed earthquakes down to relatively small magnitude events (with rupture dimensions on the order of location uncertainties). We use the cluster descriptions i) to develop source dimension scaling relations that are consistent across a very wide magnitude range, and ii) to test a series of earthquake triggering hypotheses regarding on- and off-fault aftershock triggering and aftershock deficits in the primary rupture areas.

Seismic Source Inversion Using Hamiltonian Monte Carlo and a 3D Earth Model for the Japanese Islands

SIMUTE, S., ETH Zurich, Zürich, Switzerland, saule.simute@erdw.ethz.ch; FICHTNER, A., ETH Zurich, Zürich, Switzerland, andreas.fichtner@erdw.ethz.ch

We present a database of full-waveform seismic source solutions for the Japanese Islands. Our method is based on the Bayesian inference of source parameters and a tomographically derived 3-D Earth model, used to compute Green's strain tensor. With this approach, we infer moment tensor, location and timing of the seismic events.

To compute spatial derivatives of Green's functions, we use a previously derived regional Earth model. The model is radially anisotropic, visco-elastic, and fully heterogeneous. It was constructed using full waveforms in the period band of 15–80 s.

Green's strains are computed numerically with the spectral-element solver SES3D. We exploit reciprocity, and by treating seismic stations as virtual sources we compute and store the wavefield across the domain. This gives us a strain database for all potential source-receiver pairs. The displacements are then promptly obtained by linear combination of the pre-computed strains scaled by the moment tensor elements.

We infer ten model parameters – six moment tensors elements, three location parameters, and the origin time of the event. A feasible number of model parameters and the fast forward problem allow us to infer the unknowns using a Bayesian approach. The sampling is performed with a variant of Hamiltonian Monte Carlo (HMC) algorithm, which we developed previously.

HMC takes advantage of the derivatives of synthetic data with respect to the model parameters. Therefore, it converges to the posterior probability density with fewer samples compared to the derivative-free Metropolis-Hastings algorithm. Advantages of HMC become more prominent in the case of weak prior knowledge, high-quality data, and increasingly empty high-dimensional space.

We apply our method to the Izu-Bonin trench, where many events have a non-double-couple component. We expect to shed more light on the events in complicated tectonic settings by i) taking into account the complexity of the medium, ii) exploiting full-waveform information and iii) presenting the uncertainties and trade-offs between the source parameters.

Comprehensive Analysis of the 2010 Mw 7.2 El Mayor-Cucapah Foreshock Sequence

YAO, D., University of Michigan, Michigan, USA, dongdony@umich.edu; HUANG, Y., University of Michigan, Michigan, USA, yiheh@umich.edu; PENG, Z., Georgia Institute of Technology, Georgia, USA, zpeng@gatech.edu; CASTRO, R. R., Centro de Investigación Científica y de Educación Superior de Ensenada, Baja California, Mexico, raul@cicese.mx

Large earthquakes can sometimes be preceded by foreshocks, while the exact relationship between foreshocks and mainshock nucleation is still unclear. Here we conduct a comprehensive analysis of the 2012 Mw7.2 El Mayor-Cucapah foreshock sequence, including detection of small missing foreshocks, refined relocations and source parameter analysis. We used 66 relocated foreshocks listed in the SCSN catalog as templates, and applied the template-matching technique to continuous recordings within 150km epicentral distances starting from 21 days prior to the mainshock until the main event. 550 additional events were detected, and the results indicated nearly continuous foreshock sequence, with two most intensive bursts around March 21st and within last 2 days prior to the mainshock. By fitting the detected foreshock sequence using the Epidemic Type Aftershock Sequence (ETAS) model, we found that the first active burst around March 21st fits the mainshock-aftershock type sequence, while the other one within last 2 days before the mainshock exhibits swarm-like behavior. We also identified the potential timing issues of the EHZ component at certain stations during this time period, and compared the different detection results with or without those stations. Additionally, we selected master and empirical Green's function (EGF) pairs based on both relative locations and waveform similarity. Source areas and stress drops were then estimated using the spectral ratios of master and EGF pairs. By closely examining the spatio-temporal evolution and source parameters of the foreshock sequence from a more complete template-matching catalog, we are aiming to better understand the evolution of the foreshock sequence and its role in the mainshock nucleation.

Representation of Complex Seismic Sources by Orthogonal Moment Tensor Fields

JORDAN, T. H., University of Southern California, California, USA, tjordan@usc.edu; JUAREZ, A., University of Southern California, California, USA, alanjuar@usc.edu

Seismic radiation from indigenous sources can be represented by the excess of model stress over actual stress, a second-order tensor field that Backus named the stress glut. We prove a new representation theorem that exactly and uniquely decomposes any stress-glut (or strain-glut) density into a set of orthogonal tensor fields of increasing degree, up to six in number, ordered by their first nonzero polynomial moments. The zeroth-degree field is the projection of the stress-glut density onto its zeroth polynomial moment, which defines the seismic moment tensor, Aki seismic moment M_0, and centroid-moment tensor (CMT) point source. The higher-degree fields describe mechanism complexity—source variability that arises from the spacetime variations in the orientation of the stress glut. The representation theorem generalizes the point-source approximation to a sum of multipoles that features the CMT monopole as its leading term. The first-degree field contributes a dipole tensor with a mechanism orthogonal to the CMT, the second-degree field contributes a quadrupole tensor, and so on, up to six orthogonal fields in all. We define the total scalar moment M_T to be the integral of the scalar moment density, and we use the representation theorem to partition this total moment into a sum of fractional moments for each degree. If the faulting is simple enough, M_0 approximates M_T. When the faulting is more complex, however, $M_0 < M_T$; the higher-degree fields will contribute more

to the radiation, and this contribution will increase with frequency. We decompose stress-glut realizations from the Graves & Pitarka (2016) rupture simulator; typical values of M_0/M_T are 0.82-0.92. We compute synthetic seismograms to illustrate the radiation patterns of the higher-degree fields and their frequency dependence. Decomposition of source models for the 2016 Kaikoura earthquake indicates that the radiation from the higher-degree fields was large enough (M_0/M_T = 0.67-0.82) that it should be possible to invert global datasets for the low-degree multipoles.

Representation of the 2016 Mw 7.8 Kaikoura Earthquake by Orthogonal Moment Tensor Fields

JUAREZ, A., University of Southern California, California, USA, zu.alan.zu@gmail.com; JORDAN, T. H., University of Southern California, California, USA, tjordan@usc.edu

The Mw 7.8 Kaikoura, New Zealand, earthquake of 2016 is one of the most complex earthquakes ever recorded. It ruptured more than twenty crustal faults with different strikes, dips, and rakes, and the subduction interface beneath New Zealand. We use the stress-glut representation theorem of Jordan & Juarez (GJI, 2018) to analyse finite fault models of the Kaikoura earthquake and quantify the complexity of the source. The representation theorem decomposes the stress-glut density into a set of up to six orthogonal moment tensor fields of increasing degree. These fields are ordered according to their first non-zero polynomial moments, which can be uniquely factored into a unit moment tensor (source mechanism) and a shift-invariant multipole tensor. The centroid moment tensor (CMT) is the monopole (0th-degree) term in the tensor multipole expansion of the general point source defined by the representation theorem. We decompose source models that include the Hikurangi subduction interface and compare them with models that do not. We estimate the source mechanisms and multipole tensors associated with the 0th- and higher-degree moment tensor fields. The 0th-degree source mechanisms of the models with subducting slab are in good agreement with the Global-CMT solution. The higher-degree fields quantify the complexity of the source that contributes to the seismic radiation not excited by the 0th-degree field. The characteristics of the source given by the magnitude and orientation of the dipole and quadrupole tensors are consistent among the models. We find that the Aki seismic moment represents 0.67-0.82 of the total moment (M_T), depending on the model. The stress-glut representation theorem allows to compute the fractions of M_T released by the higher-degree fields; their sum accounts 0.25-0.45 of M_T. Our results are consistent with the analytical calculations of Jordan & Juarez (2018) using a stochastic parametrization of source complexity, and they suggest that it may be possible to estimate low degree multipoles directly from seismic data.

Quasi-Automated Estimates of Directivity and Related Source Properties of Small to Moderate Southern California Earthquakes With Second Seismic Moments

MENG, H., University of Southern California, California, USA, haoranme@usc.edu; MCGUIRE, J. J., Woods Hole Oceanographic Institution, Massachusetts, USA, jmcguire@whoi.edu; BEN-ZION, Y., University of Southern California, California, USA, benzion@usc.edu

We develop a method for quasi-automated estimation of directivity, rupture area, duration, and centroid velocity of earthquakes with second seismic moments. The method is applied to 27 earthquakes with magnitude in the range 3.5-5.2 in southern California. Apparent Source Time Functions (ASTFs) of P and S phases are derived using time domian deconvolution with 3 stacked empirical Green's functions (seGf) selected by spatial and magnitude criteria and performance in the individual eGf deconvolution. The use of seGf suppresses non-generic source effects such as directivity in individual eGfs. The stack of eGfs, with weights determined by grid search to optimize waveform fits, helps to correct small differences in focal mechanism between the eGfs and target event. Compared with a single eGf, analysis with a weighted stack can significantly improve waveform fits and typically allows the inclusion of 5 to 15 more ASTFs. Most analyzed target events in the Trifurcation area of the San Jacinto Fault system have directivities towards the northwest, while events around Cajon Pass and San Gabriel Mountain propagate towards the southeast. The results are generally consistent with predictions for dynamic rupture on a bimaterial interface and the imaged velocity contrasts in the study area. The second moment inversions are also used to explore constraints on upper and lower bounds of rupture areas in our dataset. Stress drops and uncertainties are estimated with the expression of Eshelby [1957] for elliptical ruptures using the derived characteristic rupture length and width. We note that the stress drop can be significantly underestimated by assuming circular crack. The quasi-automated second moment method with stacked eGfs can be sued for routine application to moderate earthquakes in southern California.

Relative Moment Tensors Revisited

PLOURDE, A. P., University of British Columbia, Vancouver, Canada, aplourde@eoas.ubc.ca; BOSTOCK, M. G., University of British Columbia, Vancouver, Canada, bostock@eoas.ubc.ca

We introduce new relative moment tensor (MT) inversion methods for clusters of nearby earthquakes. P-wave relative amplitudes are obtained from the best-fit ratio of aligned waveforms, with no need to pick pulse amplitudes. For S-waves we produce constraints on MT elements involving three events, where one event is described as a linear combination of the other two. This approach does not require modal decomposition into SV and SH. Singular-value decomposition on aligned waveforms is presented as an efficient means to derive the relative MT constraints. Non-linear methods are introduced to efficiently find best-fit tensile earthquake and double-couple solutions for relative MT systems. Using synthetic data, we demonstrate the effectiveness of the P and S constraints both individually and combined. We then apply the method to a set of 16 intermediate-depth earthquakes from southern Alaska, in the subducted Yakutat terrane, and compare unconstrained, deviatoric, tensile earthquake, and double-couple MT solutions. We observe earthquakes with antiparallel slip occurring 5 km apart, indicating that complex deformation in this region of the Yakutat. The relative MT method is also applied to two larger clusters in the continental crust of northern Washington, both containing several hundred events.

Green's Functions Determined From Moment Tensors

VAVRYCUK, V., Institute of Geophysics, Prague, Czech Republic, vv@ig.cas.cz; ADAMOVA, P., Institute of Geophysics, Prague, Czech Republic, adamova@ig.cas.cz; DOUBRAVOVA, J., Institute of Geophysics, Prague, Czech Republic, doubravka@ig.cas.cz

The determination of moment tensors of earthquakes requires observations from many stations, good station coverage of the focal zone, accurate locations, and good knowledge of the velocity model. All this information is needed for calculating a large set of Green's functions, which is the key and most difficult point in the moment tensor inversion. Obviously, if the Green's functions cannot be calculated for some stations because of a complex structure, unknown site effects or unknown amplification of sensors, such data are lost for the inversion. In this paper, we propose a method of retrieving the Green's functions for such 'problematic' stations. If the target focal zone is active and sufficiently small with respect to the epicentral distance, a set of available moment tensors calculated from a network of reliable stations can be used for determining the Green's functions of the problematic stations. Once the Green's functions are obtained, moment tensors of the other earthquakes that occurred in the target focal zone can be calculated using a full network of stations. The efficiency of the proposed method is tested on synthetic data. Finally, the method is applied to local observations of micro-earthquakes in West Bohemia, Czech Republic.

Near-Field Observations of the Rupture for the M5.5 Orkney, South Africa Earthquake

MORI, J., Kyoto University, Uji, Japan, mori@eqh.dpri.kyoto-u.ac.jp; YASUTOMI, T., Kyoto University, Uji, Japan, d.silva21212121@gmail.com; OGASAWARA, H., Ritsumeikan University, Kusatsu, Japan, ogasawar@se.ritsumei.ac.jp; SOMALA, S. N., Indian Institute of Technology Hyderabad, Hyderabad, India, surendra@iith.ac.in; SANGARAJU, S., Indian Institute of Technology Hyderabad, Hyderabad, India, sriharisangaraju@iith.ac.in

We examined the near-field records for the 2014 Orkney earthquake (M5.5) to infer source properties for this moderate-sized earthquake. The event was the largest recent earthquake associated with the deep gold mines of the region. Different from usual normal-faulting events that are induced on known structures of the mines, the M5.5 earthquake took place significantly below the mining horizon with a strike-slip mechanism on an unknown geologic structure. Seismic activity close to the Moab Khotsong and Great Noligwa mines is very well monitored by instruments installed on the surface and in the mine tunnels. The high sample-rate (6 khz) geophones installed in the mine at depths of 1 to 3 km provide high-quality recordings of the mainshock and aftershocks.

The waveforms show that there is a small foreshock (about M1.8) located 1.6 km south of the mainshock hypocenter and at 0.6 sec before the mainshock. There is no evidence of any unusual character of the foreshock, or any significant deformation between the foreshock and mainshock.

Using lower frequency (<1.0 hz) data, the waveforms can be modeled using a finite fault slip inversion. The higher frequency waves are less coherent and more difficult to explain. We use both closely spaced subsurface stations in the mine and closely spaced aftershocks to evaluate source and path related effects for the high frequency waves. Both the source and propagation contribute significantly to the high-frequency content of the recorded waves.

Observational Evidence of the Early and Persistent Supershear Rupture of the 2018 Mw 7.5 Palu Earthquake

BAO, H., University of California, Los Angeles, California, USA, hbrandon@ucla.edu; AMPUERO, J., California Institute of Technology, California, USA, ampuero@gps.caltech.edu; MENG, L., University of California, Los Angeles, California, USA, meng@epss.ucla.edu; FIELDING, E. J., Jet Propulsion Laboratory, California Institute of Technology, California, USA, eric.j.fielding@jpl.nasa.gov; LIANG, C., California Institute of Technology, Seismological Laboratory, California, USA, cunrenl@caltech.edu; MILLINER, C. W. D., Jet Propulsion Laboratory, California Institute of Technology, California, USA, christopher.milliner@jpl.nasa.gov; FENG, T., University of California, Los Angeles, California, USA, tianfengseis@ucla.edu; HUANG, H., University of California, Los Angeles, California, USA, oldyellow9451@gmail.com

The speed at which an earthquake rupture propagates affects its energy balance and ground shaking impact. Supershear earthquakes (faster than shear-wave speed Vs) often start at sub-shear speed and later run faster than Eshelby's speed ($\sqrt{2}$Vs). Here we present robust evidence of early and persistent supershear rupture at sub-Eshelby speed of the 2018 Mw 7.5 Palu, Indonesia earthquake. Slowness-enhanced back-projection of teleseismic data provides a sharp image of the rupture process, along a path consistent with the surface rupture trace inferred by sub-pixel correlation of interferometric synthetic-aperture radar images. The rupture propagated at a sustained velocity of 4.1 km/s from its initiation to its end, despite large fault bends. The persistent supershear speed is further validated by seismological evidence of far-field Rayleigh Mach waves. The unusual features of this earthquake may reveal connections between rupture dynamics and fault structure. Early supershear transition can be promoted by fault roughness near the hypocenter. Steady rupture propagation at a speed unexpected in homogeneous media could result from the presence of a damaged fault zone.

Regional Estimates of Radiated Energy for Crustal Japanese Earthquakes

ROSS, Z. E., California Institute of Technology, California, USA, zross@gps.caltech.edu; KANAMORI, H., California Institute of Technology, California, USA, hiroo@gps.caltech.edu; RIVERA, L., University of Strasbourg, Strasbourg, France, luis.rivera@unistra.fr

We calculate the radiated energy for 29 crustal earthquakes in Japan with $5.6 \leq M_w \leq 7.0$ using the regional method of Gutenberg and Richter (1942). The goal is to establish the accuracy of the procedure with respect to azimuthal variations in radiation pattern, propagation and site effects, and other factors not considered by Gutenberg and Richter. Empirical attenuation factors are determined to correct for the missing energy as a function of distance. We compare energy estimates between surface and borehole stations, and find that the surface stations overestimate the energy by about a factor of 2, with significantly larger scatter across stations. To further evaluate the accuracy of the method, synthetic seismograms are generated for the exact station distribution and moment tensor of each earthquake, and the energy estimated from the seismograms is compared with analytical estimates.

New IRIS Data Product: Dynamic Surface Wave Radiation Patterns

ROESLER, B., Northwestern University, Illinois, USA, boris@earth.northwestern.edu; VAN DER LEE, S., Northwestern University, Illinois, USA, suzan@northwestern.edu; ELAVSKY, F., Northwestern University, Illinois, USA, frankelavsky@gmail.com; BAHAVAR, M., Incorporated Research Institutions for Seismology, Washington, USA, manoch@iris.washington.edu

We present the theory and implementation of a new data product at the IRIS DMC. The Surface Wave Radiation Pattern (SWRP) product shows the azimuthal variations of radiated seismic-wave spectral amplitudes for Rayleigh and Love waves computed for frequencies between 0.01 and 0.06 Hz. The amplitudes are obtained from a database of computed excitation coefficients in a layered, spherical Earth, using interpolated normal-mode frequencies to represent the fundamental-mode surface wave branch.

The event-based product generates static plots for every known earthquake with magnitude Mw ≥ 6.0 based on the source mechanisms reported by the Global CMT Project. For hypothetical earthquakes, dynamic radiation pattern plots are based on arbitrary source mechanisms chosen by the user. The database of the interactive product contains the spectral amplitudes of Green's functions computed for a particular hypocenter at virtual stations located around it. These spectral amplitudes are convolved with the components of a moment tensor to display the associated surface-wave radiation pattern. The dynamic plots are displayed in a web browser and updated without delay for every change in frequency of the seismic waves and in source mechanism except its depth.

The radiation pattern product supports researchers in estimating azimuthal variations in earthquake-generated ground motion amplitudes as well as in identifying nodes and anti-nodes of surface wave amplitudes to understand signal-to-noise ratios at seismic stations in the context of moment tensor inversions, wave propagation studies, and seismic tomography.

The ground motion predicted by the surface-wave radiation pattern product is reflected in the ShakeMaps of shallow large earthquakes provided by the USGS. This is not surprising for the modeled areas of the ShakeMaps, but the semblance holds for the areas that are based on observations.

The purpose of the surface-wave radiation pattern is to provide a reference for all researchers studying surface waves from a specific or hypothetical seismic event.

High Resolution Imagery at the Source Physics Experiment Using Large Seismic Arrays

MATZEL, E., Lawrence Livermore National Laboratory, California, USA, matzel1@llnl.gov; MELLORS, R. J., Lawrence Livermore National Laboratory, California, USA, mellors1@llnl.gov; MAGAÑA-ZOOK, S. A., Lawrence Livermore National Laboratory, California, USA, maganazook1@llnl.gov

We use several methods of seismic interferometry to obtain highly detailed images at the site of the Source Physics Experiment (SPE). SPE is a series of experiments in varying geologies with the objective of obtaining a physics-based understanding of how seismic waves are created at and scattered near seismic sources. Phase I of the experiment involved chemical explosions in granite, with waves traveling across volcanics, carbonates and alluvium. Phase II of the experiment is currently ongoing and involves chemical explosions in dry alluvium geology (DAG). The records vary dramatically as energy passes through the different geologies. To separate source-specific effects from those due to geological structure, we need precise 3D models at scales ranging from tens of meters to tens of kilometers.

In April 2016, a large, dense array of 996 geophones were deployed south of the Phase I source point. In December 2018, a second deployment of 500 instruments was deployed around the DAG site. In each case, several weeks of continuous data were recorded, capturing ambient noise, distant earthquakes and records of the experimental sources, providing a rich and diverse data collection.

We apply several interferometric techniques: Source interferometry (SI) uses the explosions as rich sources of high frequency, high signal energy. Coda interferometry (CI) isolates the energy from the scattered wavefield. Ambient noise correlation (ANC) uses the energy of the ambient background field. In each case, the data recorded at one seismometer are correlated with the data recorded at another to obtain an estimate of the Green's function (GF) between the two. These GFs are then inverted to obtain the final seismic image. Our objective is to obtain a 3D model that is precise enough to calculate synthetics matching the scattering effects seen in the data.

Resolving Stress Drop Variation Along San Andreas Fault at Parkfield and Its Implication

ZHANG, J., University of Oklahoma, Oklahoma, USA, jwzhang914@ou.edu; CHEN, X., University of Oklahoma, Oklahoma, USA, xiaowei.chen@ou.edu; ABERCROMBIE, R. E., Boston University, Massachusetts, USA, rea@bu.edu

Earthquake stress drop is an important source parameter that is related to high-frequency ground motion and source scaling. Estimation of stress drop can be subject to significant uncertainty, such as sampling rate, source complexity, noise level, etc. The most significant source of uncertainty is the tradeoff between source term and path effects, which can systematically bias the stress drop results. In this study, we try to improve the stress drop estimations with improved stacking method, and spatial binning in both along-strike and along-depth directions. We collect data from both surface and borehole networks from 1984 to 2016, then we perform spectral analysis using an improved stacking-based spectral decomposition method that solves an empirical-correction-spectrum (ECS) based on a group of selected events, as well as spectral ratio analysis based on empirical-green's-function (EGF) with carefully selected event pairs to address stress drop uncertainties and help resolving the tradeoff.

Using borehole data, we find that the stacking-based analysis can be systematically biased by the ECS correction, which relates to in-situ attenuation correction. In addition, spatial distribution of events is the root for stress drop spatial trends (such as depth trend), which can be ascribed to spatial attenuation variability. To reduce the issue of attenuation, we constrain the stress drop of lowest magnitude bin to obtain ECS for different spatial grids. The results significantly reduce the standard deviation of stress drops for all events. The improved stress drop observation implies increased stress drop in the creeping zone (NW of Parkfield) and decreased stress drop in the locked zone (SE of Parkfield) after the 2004 M6 earthquake. Future study will include assessing whether the stress drop change is related to attenuation changes by applying time-dependent ECS correction; analysis using surface stations with lower sampling rates and likely higher noise level; and comparison between stacking and individual pair EGF analysis. Updated results will be presented.

Uncertainties in Stress Drop Estimates and Their Tectonic Consequences

NEELY, J. S., Northwestern University, Illinois, USA, james@earth.northwestern.edu; STEIN, S., Northwestern University, Illinois, USA, s-stein@northwestern.edu

Stress drop, although ideally the difference in stress before and after faulting, is actually a kinematic parameter commonly calculated for earthquakes. Estimating stress drop involves a combination of observable and assumed parameter values. It depends on the cube of a factor reflecting the fault dimension, which is inferred in two ways. One method uses the corner frequency of an earthquake's spectrum, whereas the other relies on rupture duration calculated from an earthquake's source time function. Both require scaling by the cube of an assumed rupture velocity and by a factor reflecting the assumed fault shape. If the model assumptions are appropriate, the two methods should produce similar stress drop estimates for the same earthquake.

We explore the uncertainties involved by comparing stress drops inferred from corner frequency and rupture duration for ~900 earthquakes. Although both yield stress drops generally in the 1-1000 bar range, we find little correlation between stress drops estimated by the two methods, even for the same assumed rupture velocity and fault shape. This situation arises because the corner frequency and the time function methods often give inconsistent estimates of the fault dimension.

The weak correlation between the stress drop estimates from the two methods would be enhanced by the variability of the shape factor and rupture velocity between earthquakes. These uncertainties in stress drop values need to be considered when making any tectonic interpretation from them, such as differences between interplate and intraplate earthquakes.

Determination of Focal Depths, Moment Magnitudes and Focal Mechanisms of Small Magnitude Local and Regional Earthquakes Recorded by a Sparse Seismic Network

DAHAL, N., Boston College, Massachusetts, USA, dahaln@bc.edu; EBEL, J. E., Boston College, Massachusetts, USA, john.ebel@bc.edu

Determination of precise focal depths, moment magnitudes and focal mechanisms of small magnitude earthquakes using regional network stations is important in order to understand earthquake source processes and seismic hazard. We present a technique that can accurately determine focal mechanisms, moment magnitudes and focal depths of small magnitude earthquakes ($2.5 < M < 4$) using only a few regional seismic stations. We filter observed seismograms as well as synthetic seismograms through a higher frequency band like1-3 Hz and 1.5-2.5 Hz, which has a good signal-to-noise ratio (SNR) for the small earthquakes of the magnitude that we are working with. The waveforms are processed to their envelopes in order to make the waveforms relatively simple for the modeling. We have tested the method on 17 aftershocks of modified duration magnitude (M_D*) between 3.6 and 2.5 and 1 aftershock of magnitude M_w 3.14 of the 2011 Mineral, Virginia M_w5.7 earthquake. We have also tested the method on 5 aftershocks of 2013 Ladysmith, Quebec M_w4.5 earthquake of magnitudes between Mn 2.8 and Mn 3.7. Our depths, moment magnitudes and focal mechanisms are consistent with the depths, moment magnitudes and focal mechanisms that were previously reported for these events. This study confirms that the envelopes of the seismic waveforms can be used to extract the focal mechanisms and focal depths of an earthquake as low as M2.5 using only a few regional seismic network stations at epicentral distances of 200-500 km, and an accurate estimate of the focal depth and moment magnitude is possible using data from just one seismic station. This method is applied to study the aftershocks of Mw 7.8 2015 Nepal earthquake.

Empirical Green's Functions Analysis of Induced Earthquakes in the Duvernay Play Near Fox Creek, Alberta

ZECEVIC, M., University of Calgary, Calgary, Canada, megan.zecevic@ucalgary.ca; EYRE, T. S., University of Calgary, Calgary, Canada, thomas.eyre@ucalgary.ca; EATON, D. W., University of Calgary, Calgary, Canada, eatond@ucalgary.ca

The rate of earthquakes in the Western Canadian Sedimentary Basin has increased significantly since 2010. The increase in seismicity rate is thought to be anthropogenic in origin due to strong spatial and temporal correlations between observed seismicity and hydraulic fracturing operations in the region. Some of the largest induced events attributed to hydraulic fracturing have occurred within the Duvernay play in the Fox Creek region of Alberta, Canada. In January 2016, a Mw 4.1 event was induced by a nearby hydraulic fracturing program which resulted in the cessation of injection, in line with the seismic hazard protocol, as the red-light threshold (ML >4) had been exceeded. A recent study showed that the moment tensor solution of this event contained significant non-double-couple components (~20%), and it was postulated that the non-double-couple component was either a manifestation of fracture growth or slip on non-coplanar faults (Wang *et al.*, 2018). Through empirical Green's function analysis we observe a complex spectral source signature for the Mw 4.1 event which may indicate simultaneous rupture along two fault strands, coherent with the latter model. Furthermore, high precision double-difference re-locations image two fault strands that were lit up immediately after the Mw 4.1 event occurred. The combined lateral extent of these two fault strands is ~ 1km, which is coherent with expected fault dimensions for a Mw 4 event.

Working Towards Including Rotational Ground Motions for Regional Long Period Full-Moment Tensor Inversion

ICHINOSE, G. A., Lawrence Livermore National Laboratory, California, USA, ichinose1@llnl.gov; FORD, S. R., Lawrence Livermore National Laboratory, California, USA, ford17@llnl.gov; MELLORS, R. J., Lawrence Livermore National Laboratory, California, USA, mellors1@llnl.gov

There is a potential benefit from adding rotational motions to moment tensor (MT) inversions because they provide information about the wavefields spatial gradients on the free surface that cannot be directly obtained using only three-component (3-C) particle displacements (*e.g.*, Donner *et al.*, 2016; Li and van der Ban, 2017). Rotational data may provide additional constraints in resolving $M_{xz}$and $M_{yz}$for shallow seismic events which are poorly resolved due to the free-surface vanishing traction and provide an additional radiation pattern in cases of sparse station coverage. Seismology is also long awaiting a broadband rotational seismometer and fiber-optic gyroscope technology appears promising. We computed 3-C particle and 3-C rotational displacements synthetics using f-k reflectivity method from a 1-D velocity model. Rotational Greens functions are formed by making spatial gradients from displacement synthetics. To compare data with synthetics, we use array particle displacements to derive rotational motions. We examined 4 earthquakes recorded from the small aperture Piñon Flats Observatory Array in California and Golay gradiometer array deployed during the IRIS Community Wavefield Demonstration Experiment in Oklahoma. We verified the observed array derived rotational motions by comparing them with translational motions to estimate phase velocity and back-azimuth. We obtained similar phase velocity and back-azimuth results using seismic gradiometry. Well-constrained MT solutions were estimated for each earthquake using long-period regional waves and then the MT solutions were used to model the observed array derived long-period rotational ground motions. We obtained good fit to the data with the rotational synthetics. Future work will include statistical tests to show when rotational motions best improve MT inversion. Prepared by LLNL under Contract DE-AC52-07NA27344.

Science, Hazards and Planning in Subduction Zone Regions (Part II)

Oral Session · Thursday · 8:30 AM · 25 April · Cascade II
Session Chairs: David Schmidt, Lori Dengler, Will Levandowski, Kathy Davenport, Jamey Turner, Rick Wilson, Brendan W. Crowell.

Sediments From Lower Squaw Lake, OR, Contain Evidence of the 1700 AD Cascadia and 1873 AD Intraplate Earthquakes and Suggest a New Method for the Precise Dating of Earthquake Deposits

MOREY, A. E., Oregon State University, Oregon, USA, morey@coas.oregonstate.edu

Accurate dating of earthquake-triggered deposits is essential. This is especially important for Cascadia paleoseismology, given the most recent Cascadia earthquake occurred in 1700 AD. Here we present results from an investigation of the historic record of sedimentary disturbances from Lower Squaw Lake, OR, in which we find that earthquake-triggered deposits can be differentiated from flood deposits because they are complex deposits with long, organic-rich tails. The deposits have two parts: a lower unit composed of lake-margin sediment, and an upper unit composed of dense, fine-grained silt with a watershed composition. Both units have organic-rich tails composed of short-lived plants, including diatoms and algae, and degraded organic matter and fine inorganic particles. The fine-grained, watershed-sourced sediment is not a turbidite because the composition is very well-sorted and the basal contact shows evidence of "loading," also observed in ash-fall deposits. We suspect the organic-rich tail results from flocculation: mixing of negatively charged algal matter with Ca+2 ions and fine-particles (as described by Avnimelech *et al.*, 1982) is likely to cause aggregation, flocculation and rapid settling of water column organics and trapped fine inorganic particles to occur as a result of liquefaction of the lake's delta. This suggests an opportunity for precise dating of earthquake deposits. Radiocarbon dating of tail material from the deposit assumed to result from the 1700 AD earthquake produced an age of 110 ±25 RCY. Calibration produces multiple intersections with the radiocarbon production curve, however the position on the curve can be limited based on other radiocarbon data and the position of the earthquake deposit from 1873 AD above it. We suggest a strategy using bulk tail material for replicate radiocarbon ages, along with samples selected to limit the possible positions on the curve, to accurately identify and date earthquake deposits.

Calibrating Cascadia Paleoearthquake Magnitudes and Ground Motions From the Paleoseismic Record

GOLDFINGER, C., Oregon State University, Oregon, USA, gold@oce.orst.edu

The Cascadia paleoseismic record is long and composed of land, lacustrine and offshore paleoseismic records. One of the elusive issues remaining is a reliable catalog of approximate magnitudes for the 10 ka record. Currently, the 1700 CE event is the only link to magnitude, and that link is somewhat tenuous given its reliance on a transoceanic tsunami model. We suggest a second calibration point exists in the deep water turbidite record, a bed that may have been the result of a turbidity current from the 1992 Mw 7.1 Petrolia earthquake. The turbidite record contains two events stratigraphically younger than the dated 1700 event that have not previously been investigated in detail. Specifically, the two beds named T0, and T0a are found in numerous southern Cascadia cores above the likely 1700 CE bed. These beds can be traced from Trinidad Plunge Pool northward variable distances, terminating at or south of the Rogue Canyon. The ages of the upper thousand years of record have been carefully refined using an age-depth model, improved analyses of the sediment intervals, and recalibration of the ages, including the youngest event using bomb-carbon methods. The model age for the likely 1700 large event bed remains close to that time, with a mean of 270 BP (1950) and 2 sigma range of 200-330 BP (1950). The three younger beds have 2 sigma model ages of T0 = 1962-2009, median 1994 CE; and T0a = 1824-1963, median 1899 CE. There are significant flooding events in 1913, 1937, 1955, 1964, 1974 and 1995 that can be considered, and further work is required to test the upper beds origin. However, we suggest a reasonable interpretation of the upper beds may be T0 as the 1992 Petrolia earthquake, and T0a as the 1906 San Andreas earthquake. The likely presence of the 1992 Petrolia event in the offshore record and the lack of evidence of flooding events allows better calibration of approximate magnitudes given upper and lower bounds are both represented, resulting in a downsizing of many of the southern Cascadia events.

Complicated Kinematics in the Southern Cascadia Subduction Zone

MCPHERSON, R. C., Retired, California, USA, bob.mcpherson@humboldt.edu; SMITH, S. W., University of Washington, Washington, USA, stew@geophysics.uw.edu; WILLIAMS, T. B., Cascadia Geosciences, California, USA, todd.brian.williams@gmail.com; PATTON, J., Cascadia Geosciences, California, USA, quakejay@gmail.com; HEMPHILL-HALEY, M., Humboldt State University, California, USA, mark.hemphill-haley@humboldt.edu

Strain accumulation along the southern Cascadia subduction zone, within the overriding North American plate, is pulsed by frequent offshore earthquakes within the Gorda plate. These strike-slip earthquakes, responses to the Gorda plate being forced through a tectonic die between the Pacific and Juan de Fuca plates, result in triangular-shaped plate fragments moving beneath North America. The integrated effect of the movement of these fragments is to increase strain coseismically, in addition to interseismic strain, within the coupled zone from north of Humboldt Bay south to the Mendocino triple junction.

The style of strain accumulation in southern Cascadia differs from the rest of the subduction zone to the north, which is not complicated by the effects of offshore, oceanic plate deformation. As a result of this episodic strain character we propose that the southern Cascadia subduction zone is a distinct part of Cascadia. This southern portion has a pervasively sheared offshore deformation zone, a fold and thrust belt onshore, a profoundly different rate and style of seismicity, a different episodic tremor periodicity and slip character, a transitional geodetic signal that includes both the transform margin to the south and subduction margin to the north, and a different offshore turbidite record than the rest of Cascadia. We propose, based on these differences, it should be considered separately in seismic source and and hazard models.

Repeating Earthquakes in the Cascadia Subduction Zone and Their Ties to Seismogenic Zone Heterogeneities

MORTON, E. A., New Mexico Institute of Mining and Technology, New Mexico, USA, emily.morton@student.nmt.edu; BILEK, S., New Mexico Institute of Mining and Technology, New Mexico, USA, susan.bilek@nmt.edu; ROWE, C. A., Los Alamos National Laboratory, New Mexico, USA, char@lanl.gov

The Cascadia Subduction Zone (CSZ) has long been noted to be seismically quiet, but paleoseismic studies indicate an active history of earthquakes up to M9. Given the potential of a future megathrust rupture, mapping high coseismic slip patches/strong asperities on the plate interface, as well as the downdip extent of the seismogenic zone, is imperative in order to best estimate expected ground motions and tsunami inundation potential for the high population centers along the margin. Because the seismogenic zone resides mostly offshore, we improve our detection capability by using the amphibious Cascadia Initiative (CI; 2011-2015) seismic array to identify small earthquakes (< M4) and map along-strike variations in frictional conditions on the plate interface.

We apply subspace detection to find our small events, using templates derived from existing earthquake catalogs. Preliminary results suggest aseismic subduction in the vicinity of a subducted seamount offshore central Oregon, while the central portion of the fault appears to be strongly locked with very little seismicity. At the Olympic Peninsula, a cluster of small events may suggest a change in the nearby asperity modeled for the M9 1700 event. Here we present new events recorded during the full CI experiment, and corresponding fault-zone heterogeneities delineated by their locations and source parameter analysis. We tie these interpretations to previous along-strike variations: the presence of the accreted crystalline Siletz terrane, the location of forearc basins, the 1700 M9 slip distribution model, and segment boundaries estimated from paleoseismic studies.

Repeating Earthquakes Record Fault Weakening and Healing Following a Megathrust Earthquake

CHAVES, E. J., Volcanological and Seismological Observatory of Costa Rica, Heredia, Costa Rica, esteban.j.chaves@una.cr; SCHWARTZ, S. Y., University of California, Santa Cruz, California, USA, syschwar@ucsc.edu; ABERCROMBIE, R. E., Boston University, Massachusetts, USA, rea@bu.edu

Repeating earthquakes (REs) rupture identical fault patches allowing variations in the mechanical behavior of specific areas to be interrogated over the earthquake cycle. We study several families of repeating earthquakes that reveal fault weakening after a large earthquake in Costa Rica followed by fault recovery. We find shorter RE recurrence intervals and increased RE rupture areas immediately following the large earthquake that both gradually return to pre-earthquake values. This is consistent with other studies and the interpretation that an increase in post seismic loading rate speeds up the time to RE failure and drives conditionally stable regions surrounding REs to slip unstably increasing their rupture areas. However, unlike most other observations that report an increase in post seismic RE magnitudes (expected if RE rupture areas increase), our postseismic REs show no change in magnitude. This requires a reduction in RE slip that we interpret as evidence of fault weakening. This is consistent with experimental work showing slip amplitudes and stress drop decrease with loading rate.

Probabilistic Tsunami Hazard Maps for Application Through the California Seismic Hazard Mapping Act

WILSON, R., California Geological Survey, California, USA, rick.wilson@conservation.ca.gov; THIO, H., AECOM, California, USA, hong.kie.thio@aecom.com; MCCRINK, T., California Geological Survey, California, USA, tim.mccrink@conservation.ca.gov

The California Tsunami Program has reviewed and finalized Probabilistic Tsunami Hazard Analysis (PTHA) maps for all 20 coastal and Bay Area counties, including those directly impacted by the southern Cascadia Subduction Zone (CSZ). A logic-tree approach of tsunami source characterization of the southern CSZ mirrored that of the most recent USGS National Seismic Hazard Maps. The associated coseismic land deformation was incorporated into the underlying digital elevation model prior to running numerical inundation models so that realistic inundation results would be represented.

The PTHA maps will be used for various community-level tsunami planning activities, primarily those related to life safety, land use, and construction. Evacuation time modeling was performed by partners at the USGS on three PTHA maps (475-, 975-, and 2475-year average return periods) to identify areas where evacuation challenges exist and constructing vertical evacuation or other mitigation solutions might be needed. The program developed a Scientific Review Panel to evaluate the accuracy and applicability of the PTHA products for use. A separate Tsunami Technical Application Panel, comprised of a dozen engineers and planners, is providing guidance to the state regarding the application of PTHA and evacuation products through the Seismic Hazard Mapping Act (SHMA). The SHMA provides a regulatory framework of hazard mitigation for project planning and construction of multi-unit developments and moderate-to-

high capacity structures. Tsunami zones under the SHMA will be completed for California during the 2019-20 time frame.

Efficient Methods for Site-Specific Probabilistic Tsunami Hazard Analysis

THIO, H., AECOM, California, USA, hong.kie.thio@aecom.com; POLET, J., California State Polytechnic University, California, USA, jpolet@cpp.edu

Probabilistic Tsunami Hazard Analysis is a computationally intensive process due to the use of numerical methods to compute source excitation and wave propagation, because significant sources may be thousands of miles away from the target site, resulting in a very large computational domain. For site-specific studies, the cost of such a procedure might be prohibitive. To solve this problem, we have developed an efficient method for site-specific offshore Probabilistic Tsunami Hazard Analysis (PTHA) using reciprocal Green's functions. Reciprocity, where a basin-wide tsunami response to an uplift event at the site is computed, allows us to compute tsunami Green's functions from seafloor uplift over a very wide area using a single finite-difference run (in principle) which also gives us great flexibility in terms of source geometry. This approach even allows us to compute the hazard from submarine landslide sources, as well as combined hazard from landslides and earthquakes, and thus provides a computational framework for a comprehensive tsunami hazard analysis.

We have applied this method to two test-cases for site-specific tsunami hazard analysis, one near Cook Strait, New Zealand and one along the Sunda Arc. This methodology allows us to compute the hazard from a range of sources including more unusual or infrequent ones like tsunami earthquakes and submarine landslides in a single framework. For the Sunda Arc, the occurrence of tsunami earthquakes, events that produce a larger tsunami than would be expected for their magnitude, the flexibility of using seafloor uplift as basis for the Green's functions enables us to explore a wider range of potential mechanical models that could explain their anomalous character. For the Cook Strait area, an existing probabilistic model for submarine landslides is used in addition to a more traditional earthquake recurrence model, and preliminary results show that submarine landslides may become a significant contributor to the local tsunami hazard for relatively short (2500 year) return periods.

The Effect of Kinematic Earthquake Rupture on Tsunami Hazards Along Subduction Zones

WILLIAMSON, A. L., University of Oregon, Oregon, USA, awillia5@uoregon.edu; MELGAR, D., University of Oregon, Oregon, USA, dmelgarm@uoregon.edu; RIM, D., Columbia University, New York, USA, dr2965@columbia.edu; LEVEQUE, R., University of Washington, Washington, USA, rjl@uw.edu

Tsunamis are one of the most destructive effects generated from submarine subduction zone earthquakes. Directly observing and understanding the generation and propagation of tsunamis remains challenging due to limited offshore instrumentation and a sparse catalog of recent events. This makes linking characteristics of the earthquake rupture to their effect on tsunami generation difficult. While past studies explored how varying earthquake source geometries affect tsunami nucleation, little has been done to examine the role of the kinematic component of rupture on the tsunami. For the purposes of initiating a tsunami model, seismically generated deformation is oftentimes handled as an instantaneous and static perturbation to the water column. While this may be a sufficient approximation for small events, it can introduce non-negligible errors for earthquakes with large length scales (> 500 km) and long rupture durations (> 100 s). In this study, we demonstrate the effect of kinematic rupture on the near-field tsunami. We identify how the kinematic rupture affects the open-ocean directivity of tsunami energy, its effect on coastal tsunami amplitudes, and the effect on tsunami arrival times at offshore pressure gauges. This analysis first uses examples on simplified megathrust environment, and then through synthetic real-word scenarios using realistic megathrust-type events along the Cascadia Subduction Zone. Synthetic events range in magnitude, size, and rupture duration allowing for the exploration of how these factors are affected in the near-field. We recommend including a kinematic component to tsunami modeling when studying events with source durations over 100 s and using recordings from open-ocean pressure gauges. However, when focusing purely on coastal gauge data, the kinematic component is a much smaller contribution to the source uncertainty.

Building a Geologic Record of Earthquakes and Tsunamis of the Guerrero Seismic Gap, Mexican Subduction

RAMÍREZ-HERRERA, M., Universidad Nacional Autónoma de México, Mexico City, Mexico, maria_teresa_ramirez@yahoo.com; CERNY, J., Universidad Nacional Autónoma de México, Mexico City, Mexico, 17.sci.geo@gmail.com; SUGAWARA, D., Museum of Natural and Environmental History, Shizuoka, Japan, sugawara.daisuke.sendai@gmail.com; CORONA, N., The College of Michoacán, La Piedad, Michoacan, Mexico, corona@colmich.edu.mx; CABALLERO, M., Universidad Nacional Autónoma de México, Mexico City, Mexico, maga@igeofisica.unam.mx; DURA, T., Virginia Tech, Virginia, USA, tinadura@gmail.com; MACHAIN, M., Universidad Nacional Autónoma de México, Mexico City, Mexico, machain@cmarl.unam.mx; GOGICHAISHVILI, A., Universidad Nacional Autónoma de México, Morelia, Mexico, avto@geofisica.unam.mx; RUIZ-FERNÁNDEZ,, A., Universidad Nacional Autónoma de México, Mazatlan, Mexico, caro@ola.icmyl.unam.mx

The Guerrero seismic gap (GSG) is located along the Mexican subduction zone (MSZ). No large subduction thrust earthquakes have occurred in the NW part of the gap since 1911. Historical M>7 earthquakes occurred in A.D. 1899. If the gap were to rupture in a single earthquake, it would give rise to an event of magnitude Mw of 8.1 - 8.4. Because of the seismic hazard to large cities such as Acapulco and to Mexico City (>20 million people), this region has been highly instrumented onshore and now offshore relatively to other segments of the MSZ.

GPS evidence suggests that long-term slow slip events (SSEs) occur every 4 yr, invading the seismogenic zone within the GSG, with equivalent Mw up to 7.6, the largest measured in the world. Understanding this phenomenology, which seems to be present in different subduction zones, results of critical importance to produce reliable hazard assessments for future earthquakes and tsunamis. Achieving this in the GSG requires identifying whether or not large earthquakes and accompanying tsunamis have occurred in pre- and historic time, their chronology, and eventually to determine their recurrence.

Previous paleoseismology studies in the GSG documented geologic evidence of coseismic deformation and tsunamis extending back to 3400 – 3500 BP. We aim to extend this record to better constrain the timing of great earthquakes and tsunamis in the GSG. We collected samples (1,800 samples) from five geoslices (2.5 m long each) along coast-perpendicular transect at 2 different sites in the coastal area of GSG. To evaluate possible stratigraphic evidence of coseismic land-level changes and tsunamis, we employed sedimentological, microfossil, geochemical, magnetic properties, and radiometric dating – C14 and Pb210 analyses. Sharp basal contacts between stratigraphic units with concurrent anomalous sand beds and diatom evidence indicative of environmental change and marine inundation suggest the occurrence of three additional(?) potential earthquakes and tsunamis in the GSG segment. Ongoing dating would confirm the precise timing of these events.

Ground Motions From Tsunami Earthquakes: An Example From Indonesia and Implications for Hazard and Warning

SAHAKIAN, V. J., University of Oregon, Oregon, USA, vjs@uoregon.edu; MELGAR, D., University of Oregon, Oregon, USA, dmelgarm@uoregon.edu; MUZLI, M., Earth Observatory of Singapore, Nanyang Technological University; Agency for Meteorology, Climatology and Geophysics of Indonesia, Singapore, Singapore, muzli@ntu.edu.sg

Tsunami earthquakes are highly destructive because the runup produced by their associated tsunami is significantly higher than expected for most megathrust events of the same magnitude. These events rupture close to the trench with slow rupture velocities and large slip. At most subduction zones, tsunami first arrivals are expected within the first 5 - 15 minutes after origin time. Reliable and unsaturated estimates of the moment magnitude are not generally available in this time frame. While new advances in Global Navigation Satellite System (GNSS) algorithms significantly speed up magnitude estimation, magnitude alone is not an indication of a tsunami earthquake, thus these events continue to be very challenging for warning systems.

In this study, we propose a new method to distinguish tsunami earthquakes in real-time using both near-field high-rate (HR) GNSS data and strong-motion data. We focus on the 2010 M7.8 Mentawai earthquake which produced runup to ~15m. This is the only tsunami earthquake to date with near-field seismic and geodetic data. We combine rapid magnitude estimation from the HR GNSS data from peak ground displacement (PGD), with strong ground-motion engineering intensity measures. Our key observation is that at low frequency and from GNSS data, tsunami earthquakes are similar to other megathrust events. However, at short period strong-motion observations, these events are indeed fundamentally different from other earthquakes of the same magnitude. We show that rapid discrimination is possible within seconds of PGD magnitude being obtained.

Finally, we study source parameters of similarly-sized events and explain why the Mentawai event displays this distinct behavior. Our findings imply that because other tsunami earthquakes are inferred to have similar source properties, our methodology should be applicable to other events. Local tsunami early warning is possible for these challenging earthquakes but only through combination of geophysical sensors.

Imaging Subduction Zones

Oral Session · Thursday · 1:45 PM · 25 April · Cascade II
Session Chairs: Min Chen, Eric D. Kiser, Zhongwen Zhan.

Significant Bulk Attenuation in the Tonga-Lau Mantle Wedge

WEI, S., Michigan State University, Michigan, USA, swei@msu.edu; WIENS, D. A., Washington University in St. Louis, Missouri, USA, doug@wustl.edu

Seismic attenuation measures energy loss during seismic wave propagation and quantifies relaxation of rocks' elastic moduli. Abundant seismic studies have observed shear attenuation, but few have quantified bulk attenuation (bulk modulus relaxation), and these studies controversially locate finite bulk attenuation in different parts of the Earth, from asthenosphere to inner core. Here we present the first conclusive evidence localizing bulk attenuation to a specific region of the uppermost mantle. By analyzing amplitude spectral decay of *P* and *S* waves from Tonga earthquakes recorded at local seismic stations, we observe unusually low Q_P/Q_S ratios (< 1.5) in the Tonga-Lau mantle wedge. Analysis also shows that the data are best fit by the assumption of a weak frequency dependence with $\alpha \approx 0.3$, suggesting that the observed attenuation anomalies are mostly intrinsic (anelastic) rather than elastic scattering. All seismic rays with significant path-average bulk attenuation ($Q_\kappa^{-1} > 0.01$ or $Q_\kappa < 100$) are confined immediately beneath the Lau back-arc spreading centers west of the Tonga Trench. Tomography results show that the highest bulk attenuation ($Q_\kappa^{-1} \approx 0.03$ or $Q_\kappa \approx 33$) is about 70% of the in-situ shear attenuation. The observed high bulk attenuation anomalies coincide with an inferred zone of partial melting, invoking mechanisms involving mantle melts.

Autocorrelation Reflectivity Imaging of the Magmatic Plumbing System Under Mount St. Helens

LEVANDER, A., Rice University, Texas, USA, alan@rice.edu; KISER, E., University of Arizona, Arizona, USA, ekiser@email.arizona.edu; ULBERG, C. W., University of Washington, Washington, USA, ulbergc@uw.edu; CREAGER, K. C., University of Washington, Washington, USA, kcc@uw.edu; SCHMANDT, B., University of New Mexico, New Mexico, USA, bschmandt@unm.edu; HANSEN, S., Macquarie University, Sydney, Australia, quasielliptic@gmail.com; DELPH, J. R., Rice University, Texas, USA, jrdelph@rice.edu; ABERS, G. A., Cornell University, New York, USA, abers@cornell.edu

We present autocorrelation reflectivity imaging (Claerbout, 1968) of Mount St Helens (MSH) using ~5900 short period and 75 broadband seismographs from the iMUSH project (imaging Magma Under Saint Helens). Short period data include ~40-72 hours of noise from Texan and 2 weeks of noise from Nodal seismographs. These autocorrelations provide only P-wave reflectivity due to use of vertical geophones. The 3-component broadband array recorded noise from 2014-2016, and provides P and S reflectivity. Different normalization and filtering schemes were tested including windowing, temporal balancing (Bensen et al, 2007), spectral balancing, and/or sign bit normalization (Oren and Nowack, 2018) followed by band pass filtering. Changes in normalization and filtering resulted in minor image differences. Time-to-depth conversion used 2D and 3D tomography velocity models derived from the active source (Kiser et al, 2016, 2018) and local earthquake travel times (Ulberg et al, 2017).

The images show shallow layering in the Chehalis, Portland and other sedimentary basins, and volcanic stratigraphy around MSH and the Indian Heaven volcanic field. They also show reflection events at shallow to mid-crustal depths that we interpret as the suture between Siletzia and the modern Cascades arc.

In the upper crust under MSH, the reflectivity images are well correlated with complex sill-like structures in the magma storage zone at ~7-12 km depth estimated to have low volume partial melt from P-wave tomography. At the base of the crust beneath MSH, the images are consistent with the high-velocity (Vp > 7.5 km/s) potential restite body identified by 2D tomography. To the southeast, sill-like structures are found across the Moho in a ~10-15 km thick, 20-30 km wide low velocity zone. We identify this feature as a possible MASH (magma assimilation, storage, and homogenization) zone. The autocorrelation reflectivity observed here is consistent with PmP reflectivity (Hansen et al, 2016) and sub-Moho reflections observed in active source data.

Insights Into the Transitions in the Banda Arc-Australian Continental Collision From Seismic Imaging of Deep Slab Structures

MILLER, M. S., Australian National University, Canberra, Australia, meghan.miller@anu.edu.au; HARRIS, C. W., University of Southern California, California, USA, cwharris@usc.edu; PORRITT, R. W., University of Texas, Texas, USA, rwporritt@ig.utexas.edu; SUN, D., University of Science and Technology of China, Hefei, China, sdy2014@ustc.edu.cn; ZHANG, P., Australian National University, Canberra, Australia, ping.zhang@anu.edu.au; SUPENDI, P., Institute of Technology Bandung, Bandung, Indonesia, pepen_geophysics@yahoo.com; WIDIYANTORO, S., Institute of Technology Bandung, Bandung, Indonesia, sriwidiyantoro@yahoo.com.sg; BECKER, T. W., University of Texas, Texas, USA, twb@ig.utexas.edu

We investigate the structure of the subducting Indo-Australian slab by utilizing data from 30 recently installed, temporary broadband seismometers (YS network) in the Banda Arc region of the Indonesia archipelago. This region is of particular tectonic interest as it is the archetypal example of a young arc-continent collision along with known varied lithospheric structure of the incoming plate. Previous (*e.g.* Widiyantoro *et al.* 2011) and preliminary body wave tomography indicate complex subducted slab structures, where gaps in fast velocity anomalies in the upper mantle are interpreted as slab tears and are linked to the variation in the incoming plate structures. The detailed shape and location of these tears are important for kinematic reconstructions and understanding the evolution of the entire subduction system. We image the mantle structure using a combination of methods, including body and surface wave tomography and infer mantle flow from seismic anisotropy. However, tomographic images are inherently smooth due to being produced with damped inversions and will then underestimate the sharpness of these structures. Therefore, we also investigate possible sharp-sided structures within and at the edges of the subducted plate with deep focus earthquakes beneath the Banda Arc that occur beneath the seismic stations. This combination of methods provides insight into not only imaging deep slab structure, but also assessing of the spatio-temporal evolution of the collision of oceanic to continental lithosphere of the Indo-Australian plate with the active volcanic arc.

Seismic Evidence of Mantle Wedge Controls on Volcano Distribution Along Aleutian-Alaska

YANG, X., University of Massachusetts Amherst, Massachusetts, USA, xiaotaoyang@geo.umass.edu; GAO, H., University of Massachusetts Amherst, Massachusetts, USA, haiyinggao@geo.umass.edu

The along-strike variation of volcanic activities has been observed at many subduction zones. However, direct structural constraints on how volcano distribution is influenced by slab geometry and mantle wedge properties are limited. Using full-wave ambient noise tomography, here we present a high-resolution shear-wave velocity model for the Aleutian-Alaska subduction zone. The new model reveals multiple slab segments with varied mantle wedge velocities, correlating with the distribution of active volcanoes and a volcanic gap. Low shear-wave velocities are observed within the mantle wedge associated with all of the three volcanic areas along strike, suggesting a wet environment. In particular, the distinct low-velocity mantle forearc atop the Pacific slab implies a highly hydrated mantle wedge associated with the Aleutian volcanic arc. The hydrated mantle wedge may facilitate melt and, consequently, the production of magma feeding the volcanoes. Contrastingly, the mantle wedge beneath the Denali volcanic gap, with much higher velocities, reflects a relatively dry environment. The tomographic result presented in this study provides evidence for the control of mantle wedge hydration states on magmatism at subduction zones and serves as a detailed structural framework for future modeling of slab deformation and mantle wedge dynamics.

Lithospheric Structure of the Pampean Flat Slab Region From Double-Difference Tomography

LINKIMER, L., Universidad de Costa Rica, San José, Costa Rica, linkimerl@gmail.com; BECK, S., University of Arizona, Arizona, USA, slbeck@email.arizona.edu; ZANDT, G., University of Arizona, Arizona, USA, gzandt@email.arizona.edu; ALVARADO, P., CONICET, Universidad Nacional de San Juan, San Juan, Argentina, alvarado@unsj.edu.ar; ANDERSON, M., Washington Geological Survey, Washington, USA, megan.anderson@dnr.wa.gov; GILBERT, H., University of Calgary, Calgary, Canada, hersh.gilbert@ucalgary.ca; ZHANG, H., University of Science and Technology of China, Hefei, China, zhang11@ustc.edu.cn

We obtain earthquake locations and a 3D velocity model of the flat slab subduction zone in west-central Argentina using a regional-scale double-difference tomography algorithm with earthquake data recorded by two temporal broadband networks. In this region, the flat subduction of the Nazca Plate including the Juan Fernandez Ridge is spatially correlated with a volcanic gap and the Sierras Pampeanas in the overriding South American Plate. Our results show the subducting Nazca Plate as a continuous band of increased P-wave velocities coinciding with the Wadati-Benioff Zone. In the overriding South American Plate the lithosphere mantle appears to be heterogeneous but mostly characterized by a Vp/Vs of 1.75-1.77, which is consistent with depleted peridotites. Two Vp/Vs anomalies deviate from this mantle with lower (1.70-1.73) and higher (1.78-1.82) Vp/Vs, which are interpreted as localized dry and hydrated regions, respectively.

The lower Vp/Vs is consistent with an enrichment of 40-80 % of orthopyroxene and the higher Vp/Vs with up to 5% mantle hydration. The size, orientation, and location of these anomalies suggest the progressive eastward dehydration of the subducting slab and the presence of an east-dipping large-scale lithospheric suture, which is interpreted as evidence of an ancient subduction zone and also as a weak zone that facilitates the hydration of the upper plate. Finally, the relocated slab earthquakes illuminate the slab geometry and suggest that at depths of ~100 km the flat slab segment is 240-km wide and has a slight westward dip (2°) before it resumes its descent into the mantle. We support the interpretation that the hydrated and moderately overthickened oceanic crust of the Juan Fernandez Ridge may be an important factor that contributes to the flat slab geometry, but the observation of a wider flat slab segment than the width of the ridge offshore (~100 km) also implies that there might be additional contributing factors for the flattening.

Three Dimensional Seismic Velocity Structure Beneath Japanese Islands From Sea of Japan to Pacific Ocean Including NIED S-Net Data

MATSUBARA, M., National Research Institute for Earth Science and Disaster Resilience, Tsukuba, Japan, mkmatsu@bosai.go.jp; SATO, H., Earthquake Research Institute, University of Tokyo, Bunkyo, Japan, satow@eri.u-tokyo.ac.jp; UEHIRA, K., National Research Institute for Eearth Science and Disaster Resilience, Tsukuba, Japan, uehira@bosai.go.jp; MOCHIZUKI, M., Ministry of Education, Culture, Sports, Science and Technology, Tokyo, Japan, mochizuki@mext.go.jp; TAKAHASHI, N., National Research Institute for Earth Science and Disaster Resilience, Tsukuba, Japan, narumi@bosai.go.jp; SUZUKI, K., Japan Agency for Marine-earth Science and Technology, Yokohama, Japan, kensukes@jamstec.go.jp; KAMIYA, S., National Research Institute for Earth Science and Disaster Resilience, Tsukuba, Japan, kamiya@bosai.go.jp; KANAZAWA, T., Association for the Development of Earthquake Prediction, Tokyo, Japan, kanazawa@8f.adep.or.jp

1. Introduction

We investigate the 3D seismic velocity structure of the Japanese Islands including beneath the Sea of Japan and Pacific Ocean. NIED constructed Hi-net after the 1995 Kobe earthquake, S-net after the 2011 Tohoku-oki earthquake, and DONET constructed by JAMSTEC was transferred to NIED in April 2016. We apply the seismic tomography for arrival time data detected by these networks operated by NIED as well as other organizations.

2. Data and method

The target region, 20-48°N and 120-148°E, covers the Japanese Islands. In addition to the arrival time data used by Matsubara *et al.* (2017), we used P- and S-wave arrival times for 32952 earthquakes recorded at about 1500 stations including the NIED S-net and DONET from April 2016 to June 2018. We also added the arrival time data of events near the coast of the Sea of Japan detected at the stations operated by universities from 2000 to 2004. Totally 6356481 P arrival data and 3534482 S arrival data from 112631 events are available.

3. Result and discussion

We clarified the seismic velocity structure beneath the Sea of Japan at depths of 10-20 km from off Hokkaido to Wakasa Bay. Vp beneath the Sea of Japan is high at depths of 10-35 km. Vp along the coast of Sea of Japan in western Japan is moderate. The lithospheric velocity structure in this region is strongly affected by the mid-Tertiary break up and formation of the Sea of Japan. Through the reactivation of the younger compression, tsunamigenic source faults has been developed. The information of the lithospheric structure provides the essential information to the structure of faults.

Due to the contribution of S-net, the velocity structure of the overlying plate beneath Pacific Ocean has been improved. One important feature is the probable Mesozoic rift structure trending NS from the coast of Tohoku to the west of Hidaka collision zone. Recent the 2018 Iburi-Tobu earthquake (M6.7) may be related to the reactivation of the rift related structure in the upper mantle to the lower crust, where marked by high-Vp.

Searching for the Deep Roots of Arc Volcanoes: Results From IMUSH Seismic Imaging in the Washington Cascades

ABERS, G. A., Cornell University, New York, USA, abers@cornell.edu; MANN, M., Cornell University, New York, USA, mem533@cornell.edu; CROSBIE, K. J., Cornell University, New York, USA, kjc233@cornell.edu; SOTO CASTANEDA, R., Cornell University, New York, USA, ras656@cornell.edu; ULBERG, C. W., University of Washington, Washington, USA, ulbergc@uw.edu; CREAGER, K. C., University of Washington, Washington, USA, kcc@uw.edu

Many arc volcanoes erupt mantle-sourced basalts and high-temperature lower-crustal magmas, yet seismic images of this deep plumbing are almost non-existent. Are deep partial-melt bodies too small for seismology to see, or are typical seismic arrays too limited to detect them? We address these questions with a 2014-16, 70-station broadband array around Mount St. Helens (MSH), termed iMUSH (imaging Magma Under St. Helens). iMUSH provides some of the highest resolution 3D images of arc crust and underlying upper mantle anywhere. Local earthquake signals only sample the upper crust, requiring teleseismic and ambient wavefield methods. Receiver functions image 35-40 km of upper-plate crust and a subducting plate 65-68 km directly beneath MSH. This leaves very little mantle to melt, yet basalts are present. As elsewhere in the Cascades, the upper-plate Moho vanishes in the forearc (west of MSH), an observation usually interpreted as serpentinized mantle. Ambient-noise tomography shows low wavespeeds here consistent with hydrated mantle, requiring temperatures low enough for serpentines to be stable, as does low forearc heat flow. Seismic body-wave attenuation also confirms large temperature contrasts between the forearc and back arc. However, much of the reduction in Moho strength is a consequence of upper-plate geology: very high wavespeeds are observed in the lower crust west of MSH, likely the mafic Siletz terrane, while typical crustal wavespeeds are seen to the east. This lithological variation controls the wavespeeds, with little evidence for melt except far east of MSH. Overall, these observations show little sign of the deep magma plumbing system beneath MSH, and they imply that the lower crust and uppermost mantle are too cold directly beneath the edifice to generate the observed melts. To reconcile these observations with the volcanism at MSH requires significant lateral melt transport within the crust. However, these pathways are not directly visible with seismic imaging techniques currently available, motivating the need for other approaches.

Investigating Anomalous Crustal Thickness of the Subducting Iquique Ridge

MYERS, E. K., University of Washington, Washington, USA, ekmyers@uw.edu; TRÉHU, A., Oregon State University, Oregon, USA, trehu@coas.oregonstate.edu; DAVENPORT, K., Oregon State University, Oregon, USA, davenpka@oregonstate.edu; ROLAND, E., University of Washington, Washington, USA, eroland@uw.edu

The Iquique Ridge (IR) is a broad bathymetric high on the subducting Nazca plate that serves as a potential source of crustal heterogeneity influencing seismogenesis along the Peru-Chile Trench. Lithospheric buoyancy and reduced seismic velocities of the IR swell are thought to be produced by over thickened crust or anomalously low density mantle, either of which could affect interplate coupling where the ridge is subducted but has not yet been explored with comprehensive subsurface imaging. The nearby, prominent Nazca and Juan-Fernández Ridges, show thick crust with low lithospheric velocities explained by different sources, including underplated magma and hydrated upper mantle respectively. The subduction of both features has been associated with changes in seismicity and slab geometry. Here, we present a P-wave velocity model of the Nazca plate and incoming IR neighboring the 2014 Mw 8.1 Iquique earthquake rupture zone. This model is determined from 2D tomographic inversions of travel time data from the 2016 PICTURES (Pisagua/Iquique Crustal Tomography to Understand the Region of the Earthquake Source) experiment. Arrivals from eight ocean bottom seismometers (OBS) cover an uninterrupted ~220 km profile, with dense ray coverage of both crustal and upper mantle phases at up to ~70 km offset. Our resulting model shows at least a kilometer of crustal thickening relative to typical Nazca plate oceanic crust, with a maximum overall thickness of ~10 km beneath the IR and prominent outer rise. We also resolve shallow crustal velocities approaching the trench beneath the faulted landward slope. To further investigate the source of these velocity variations, we use coincident multi-channel seismic (MCS) shots recorded on a 12.5 km streamer, enhancing the imaging resolution of the shallow structure. Information about velocity and faulting structure from the combined MCS and wide-angle data should help characterize inputs to the subduction system and constrain controls on seismogenesis within the 2014 Iquique earthquake rupture segment.

Synthesis of Results From a Dense Nodal Geophone Array Deployed Along the Cascadia Subduction Zone

WARD, K. M., South Dakota School of Mines & Technology, South Dakota, USA, kevin.ward@sdsmt.edu; WANG, Y., University of Utah, Utah, USA, yadong.wang@utah.edu; DUNHAM, A. M., University of Arizona, Arizona, USA, amd95@email.arizona.edu; LIN, F., University of Utah, Utah, USA, fanchi.lin@utah.edu; KISER, E., University of Arizona, Arizona, USA, ekiser@email.arizona.edu; SCHMANDT, B., University of New Mexico, New Mexico, USA, bschmandt@unm.edu

In the summer of 2017, the University of Utah in collaboration with the University of Arizona, the University of Oregon, the University of New Mexico, and the PASSCAL Instrument Center deployed 174 3-component 5-Hz nodal geophones in central Oregon. The approximately trench perpendicular line started near the coast in Waldport, OR and traversed the Coastal Range, the

Willamette Valley, and the Western Cascades with ~500-meter station spacing and recorded continuous data for ~40 days. The specific array design was chosen to be comparable to a previous broadband deployment with ~5-kilometer station spacing that recorded continuous data for ~1 year. The results from this ambitious deployment have yielded three publications and formed the basis of two larger subsequent nodal deployments in Alaska (~400 nodes, winter 2019) and Cascadia (~700 nodes; summer 2020).

Our receiver function results (Ward *et al.*, 2018) show notable agreement with first-order features interpreted in previous studies. We also employ double beamforming of the interstation ambient noise cross-correlations to extract Rayleigh wave phase velocities and invert them for a shallow (<25 km) 2-D crustal shear-wave velocity structure (Wang *et al.*, in-revision). Local earthquake P-wave tomography (Dunham and Kiser, in-prep) agrees particularly well with our shear-wave model and existing 3-D magnetotellurics imaging. Between the three methods, we interpret a prominent low-velocity zone in the mid crust under the Willamette Valley in central Oregon as fluids from the mantle wedge percolating through the mafic Siletzia terrane. The top of the Siletzia terrane is well imaged by the receiver functions as a shallow positive arrival (1-5 km) and is consistent with offshore seismic imaging of the terrane. Both velocity models image a high velocity crust consistent with previous estimates of the eastward extent of the accreted Siletzia terrane. Cumulatively, these results illustrate how this deployment strategy could be scaled for detailed 3-D imaging of a subduction zone.

Seismic Attenuation Structure of Nazca Plate Subduction Zone in Southern Peru

JANG, H., Seoul National University, Seoul, Korea, Republic of, hyoihnjang@gmail.com; KIM, Y., Seoul National University, Seoul, Korea, Republic of, yh1230@gmail.com; CLAYTON, R. W., California Institute of Technology, California, USA, clay@gps.caltech.edu

Significant subduction-zone complexity in southern Peru has been attributed to the subducting Nazca Ridge along the South American margin between 10°S and 20°S latitude. In this study, we provide the first attenuation models (Qp, Qs, and Qp/Qs structures) that represent complex Nazca Plate subduction system associated with the passage of Nazca Ridge. The subduction geometry of the Nazca Plate changes from nearly horizontal in NW to normal-dip in SE in southern Peru, and present location of Nazca Ridge coincides with the southern end of the flat slab segment (Hampel 2002).

We use data from three temporary seismic arrays (PeruSE, PULSE, and CAUGHT) and one permanent station to estimate seismic attenuation in terms of quality factors, Qp and Qs using P and S phases, respectively. We measure t*, which is integrated attenuation through the seismic raypath between the regional earthquakes and stations. The measured t* are inverted to construct 3-D Qp, Qs and Qp/Qs models. Our Qp and Qs models from the inversion recover features that can be closely associated with slab morphology and dynamics, as well as geological features in the upper plate. Our Q models show well-defined along-arc slab structure in high Q overall, and also show several notable differences between the flat slab region (above 15°S latitude) and normal-dip slab region. First, high-Q anomaly in the lower crust below the region including Lake Titicaca (below 16°S latitude) may correspond to Brazilian shield. Second, low Q near and above the subducting plate beneath the volcanic arc can be related to the slab dehydration. Third, relatively low Q features in the subducting plate in the region above 12°S latitude extend laterally about 200 km from the trench. This may be a feature related to delayed eclogitization process, which can explain the flat slab geometry, or the tear of the slab.

Numerical Modeling of Earthquake Ground Motion, Seismic Noise, Rupture Dynamics and Seismic Wave Propagation

Oral Session · Thursday · 8:30 AM · 25 April · Elliott Bay
Session Chairs: Peter Moczo, Steven M. Day, Jozef Kristek.

The Internal Structure of the Dead Sea Transform and Ground Motions in Northern Israel

TSESARSKY, M., Ben-Gurion University, Beer-Sheva, Israel, michatse@bgu.ac.il; SHIMONY, R., Ben-Gurion University, Beer-Sheva, Israel, shimonyr@post.bgu.ac.il; GVIRTZMAN, Z., Geological Survey of Israel, Jerusalem, Israel, zohar@gsi.gov.il

The Dead Sea Transform (DST) fault system forms the eastern boundary of the state of Israel. The DST is a left-lateral strike slip fault with an average slip rate of 4 mm/yr, with numerous historic earthquakes of M > 7. The 1927 M 6 Jericho earthquake, the last major event on the DST, predated instrumentation of the region. This makes the assessment of ground motions during future earthquakes difficult and highlights the importance of computational methods to bridge the instrumental data gap.

The DST forms a deep and narrow valley (DSTV) comprised of deep sedimentary basins separated by structural highs. North of the Dead Sea depression these are the Bikaa (BV), the Kinnarot (KV), the Sea of Galilee (SG), and the Hula (HV) valleys. Branching westward from the DST is the Carmel Fault Zone (CFZ) along which the Jezreel, Harod and Bet-Shean valleys are found. Within the deep basins, the young sedimentary fill is several km thick, overlying the hard carbonates of the Judea Gr. The SG and HV are separated by the structural high of the Korazim Saddle (KS).

In this work, we studied the impact of the DSTV internal structure on ground motions and seismic energy distribution in northern Israel, using a series of 3D numerical models (SW4). We developed schematic, yet realistic, geological models, of increasing complexity for the northern DSTV , based on well-log data, seismic surveys and structural maps. We simulated three different source scenarios based on past activity and slip deficit.

We show that the DSTV structure creates a significant ground motion amplification by trapping of seismic waves between the valley walls. We also show that the KS acts as a seismic barrier with a strong edge effect. When source location is south of the KS it effectively shields the HV hence reducing ground motions. When the source location is east of the KS the edge effect amplifies waves traveling in the N-S direction. Northward deepening of the BV refracts waves traveling from the south, focusing them to the surface where they constructively interfere with waves reflected by the KS.

3D Simulation of Large San Andreas Scenario Earthquakes Using a Multi-Surface Plasticity Model

ROTEN, D., San Diego State University, California, USA, droten@sdsu.edu; OLSEN, K. B., San Diego State University, California, USA, kbolsen@sdsu.edu; DAY, S. M., San Diego State University, California, USA, sday@sdsu.edu

Strong ground motions recorded on vertical arrays indicate that site response formalism (decoupled from source and path effects) fails to reproduce empirical surface-to-borehole transfer functions in the majority of cases due to the presence of lateral heterogeneities. Understanding ground motions as the coupled response of inelastic off-fault and shallow nonlinear behavior requires 3D wave propagation codes which reproduce laboratory observations of the hysteretic stress-strain relationship in sediments and weathered rocks more accurately than bilinear (*e.g.*, Drucker-Prager) yield criteria used in past scenario simulations.

Towards this goal we have implemented an Iwan-type plasticity model in the 3D finite difference (FD) code AWP. The code, named AWP-Iwan, reproduces Masing re-loading and unloading behavior in three dimensions by tracking an overlay of individual von Mises yield surfaces arranged in a parallel-series configuration. The implementation was verified against the 1D FD code Noah by simulating the response of the KiK-net site KSRH10 using plane strain and periodic boundary conditions. We also performed verification runs against Noah2D by carrying out 2D P-SV simulations for an asymmetric sediment-filled basin. Synthetic ground motions computed by AWP-Iwan using 20 yield surfaces were found to be consistent with the reference solutions in the time and frequency domain.

AWP-Iwan was deployed on NCSA Blue Waters to simulate a M 7.8 earthquake on the southern San Andreas fault with realistic near-surface nonlinear behavior in the sedimentary basins. These simulations confirm the importance of nonlinear effects on long-period surface waves during a ShakeOut-type earthquake scenario, with spectral accelerations at 3s reduced by 50% in Whittier Narrow and downtown Los Angeles with respect to a linear solution. Normalized shear modulus reductions reach values of up to 75% in the San Bernardino basin and up to 50% in the main waveguide along the Whittier Narrows corridor, indicating that peak strains exceeded the reference strain of 0.1% at the surface.

Effects of Structural Parameters on Characteristics of Earthquake Ground Motion in Water-Saturated Sedimentary Basins

MOCZO, P., Comenius University Bratislava, Bratislava, Slovakia, moczo@fmph.uniba.sk; KRISTEK, J., Comenius University Bratislava, Bratislava, Slovakia, kristek@fmph.uniba.sk; STRIPAJOVA, S., Comenius University Bratislava, Bratislava, Slovakia, svetlana.stripajova@fmph.uniba.sk; GREGOR, D., Comenius University Bratislava, Bratislava, Slovakia, gregor28@uniba.sk; BARD, P., ISTerre, Grenoble, France, pierre-yves.bard@univ-grenoble-alpes.fr; KRISTEKOVA, M., Slovak Academy of Sciences, Bratislava, Slovakia, kristekova@savba.sk

Sedimentary basins and valleys generate strong effects on earthquake ground motion (EGM). These effects are rarely accounted for even in site-specific studies due to the cost of the required geophysical surveys to constrain the site model, lack of data for empirical prediction, and poor knowledge of the key controlling parameters.

We investigated effects of a variety of structural parameters on 10 EGM characteristics in sedimentary basins and valleys. We used a set of representative models defined by a major Research & Development project SIGMA (SeIsmic Ground Motion Assessment), jointly organized by energy giants EDF, AREVA, CEA and ENEL – Mygdonian basin, deep Alpine Grenoble valley, and 4 other typical valleys in France – two small, one mid-sized and one relatively large.

The valleys differ considerably in size, geometry of sediment-bedrock interface, velocity structure and attenuation. The variety of structural parameters is considerably extended by model modifications which include a) variations in interface geometry, velocity and velocity distribution in sediments, velocity in bedrock, attenuation in sediments, b) small-scale random heterogeneities in P-wave velocity, S-wave velocity and density described by three different autocorrelation functions and three different values of standard deviation, c) presence of a porous water-saturated sediment layer described by a depth of a water table, porosity and permeability.

We calculated amplification factors, and 2D/1D and 3D/2D aggravation factors for 10 EGM characteristics, using a set of recorded accelerograms to account for input motion variability.

We used robust statistical analysis as well as specific targeted analysis of the calculated EGM characteristics for thousands of receivers. We identified a few key structural parameters and quantified their impact on amplification and geometrical aggravation factors for a few key characteristics.

The amplification factors may largely exceed the values that are usually considered in GMPEs between soft soils and rock sites.

Validation of Ground Motions From a Deterministic Earthquake Sequence Simulator

MILNER, K. R., University of Southern California, California, USA, kmilner@usc.edu; SHAW, B. E., Lamont-Doherty Earth Observatory, New York, USA, shaw@ldeo.columbia.edu; RICHARDS-DINGER, K. B., University of California, Riverside, California, USA, keithrd@ucr.edu; GOULET, C. A., University of Southern California, California, USA, cgoulet@usc.edu; CALLAGHAN, S., University of Southern California, California, USA, scottcal@usc.edu; MENG, X., University of Southern California, California, USA, xiaofenm@usc.edu; GILCHRIST, J. A., University of Southern California, California, USA, jacquig@gmail.com; DIETERICH, J. H., University of California, Riverside, California, USA, dieterichj@ucr.edu; MAECHLING, P. J., University of Southern California, California, USA, maechlin@usc.edu; JORDAN, T. H., University of Southern California, California, USA, tjordan@usc.edu

The Collaboratory for Interseismic Simulation and Modeling (CISM) is investigating the efficacy of a multi-cycle deterministic earthquake simulator as an extended earthquake rupture forecast (ERF) for use in generating synthetic ground motions for probabilistic seismic hazard analysis (PSHA). While use of deterministic ground motion simulations in PSHA calculations is not new (*e.g.* CyberShake, Graves *et al.* 2011), prior studies relied on kinematic rupture generators to extend empirical ERFs. Fully-dynamic models, which simulate rupture nucleation and propagation of static and dynamic stresses, are computationally intractable for the large simulation domains and many seismic cycles required to perform PSHA. Instead, we use the Rate-State Earthquake Simulator (RSQSim), developed by Dieterich & Richards-Dinger (2010), to efficiently simulate millions of years of M>6 earthquake sequences on the California fault system. RSQSim produces full slip-time histories for each rupture, which, unlike kinematic models, emerge from frictional properties, fault geometry, and stress transfer; all intrinsic variability is deterministic. We use these slip-time histories directly as input to wave propagation codes with the SCEC BroadBand Platform (BBP) for one-dimensional models of the Earth and SCEC CyberShake for three-dimensional models to obtain simulated deterministic ground motions.

We compare median and variance of RSQSim ground motions and magnitude-scaling with recordings and models (empirical and kinematic). Validation exercises include reproduction of the SCEC BBP "Part B" criteria (Goulet *et al.* 2014), and comparison of the partitioned variance structure (source, site, path) of computed ground motions to that obtained from the NGA-West2 ground motion database (Ancheta *et al.* 2014). These validation exercises inspired a number of enhancements to the RSQSim model, and promising initial results suggest that RSQSim is a suitable source model for deterministic PSHA calculations.

Homogenization and Very High Degree Spectral Elements for Elastic and Acoustic Waves Propagation in Multi-Scale Geological Media

CAPDEVILLE, Y., Centre National de la Recherche Scientifique, Nantes, France, yann.capdeville@univ-nantes.fr; CHAO, L., Université de Nantes, Nantes, France, chao.lyu@univ-nantes.fr

Non-periodic homogenization is a tool designed to upscale complex deterministic elastic and acoustic multi-scale media with no specific scale separation. For a given signal frequency band, it makes possible to compute an effective version of a true model. Waveforms computed in a true model and its effective version are the same up to the desired accuracy, including for backscattered, refracted or surface waves. In the forward modeling, context homogenization can be used as a preprocessing tool relaxing the meshing constraint and leading to a low numerical cost to solve the wave equations. In the full waveform inversion context, it can be used to constrain the solution space. Effective media are always anisotropic, even for isotropic true media. In the acoustic case, an interesting aspect is that homogenization leads to an anisotropic density.

In this work, we focus on three aspects: the homogenization of elastic media with fluid inclusions, source heterogeneity iterations and the option to use very high degree spectral elements. Even if fluid inclusions in an elastic matrix are theoretically prohibited in the non-periodic homogenization framework, we show that effective media of true media with fluid inclusions give very good results for a specific range of inclusion sizes. We will discuss how the interaction of the source with the small fluid heterogeneities strongly affects the source apparent moment tensors. And finally, we will discuss how homogenization open the door to the use of very high degree spectral element (up to degree 40) leading to an as low as 2.5 points per wavelength spatial sampling without degrading computing time performances despite the time marching stability criteria.

Dynamic Rupture and Strong Ground Motion Simulations Performed on the Northern and Eastern Boundaries of the Sichuan-Yunnan Block, China

YU, H., University of Science and Technology of China, Hefei, China, yuhouyun@mail.ustc.edu.cn; ZHANG, Z., Southern University of Science and Technology, Shenzhen, China, zhangzg@sustc.edu.cn; CHEN, X., Southern University of Science and Technology, Shenzhen, China, chenxf@sustc.edu.cn

The Sichuan-Yunnan block is one of the most seismicity active regions in China and it give birth to many documented devastating earthquakes in history on its boundaries. In general, the northern and eastern boundaries of this block are more active than the southern and western boundaries. The northern boundary of the Sichuan-Yunnan block mainly consisted of the Ganzi-Yushu fault system and the Xianshuihe fault system, while the Anninghe-Zemuhe fault system and the Xiaojiang fault system are acting as the eastern boundary of the block. Motivated by the potential seismic risk posed to the neighboring residences, we first simulated some typical historical earthquakes using the curved grid finite difference method (CG-FDM), and then we compared the synthetic surface displacement, magnitude and seismic intensity distribution with the documented data to get optimized modeling parameters, such as maximum principle stress azimuth, static friction coefficient μ_s and dynamic coefficient μ_d. After that, we simulated earthquake scenarios on the above boundary with different nucleation points and initial stress states, in order to give a glance at disastrous earthquakes that may happen in the future. Our preliminary simulation results demonstrated that the maximum principle stress orientation along the northern and eastern boundary changes regularly, clockwise from north to south, the effective friction coefficients are similar between different fault systems. The modeling also illustrates that the dynamic rupture propagation is close controlled by the fault geometries. The sharp changes in strike arrest the rupture spontaneously. Future scenario earthquakes show that no matter which the seismogenic fault is, there is possibility of occurring catastrophic event with moment magnitude larger than 7 on that fault.

Pushing the Limits of Regional-Scale Fully Deterministic Large Earthquake Ground Motion Simulations on High-Performance Computers with Three-Dimensional Earth Structure and Topography: Hayward Fault Scenarios and Generic Ruptures in Simple Models

RODGERS, A. J., Lawrence Livermore National Laboratory, California, USA, rodgers7@llnl.gov; PITARKA, A., Lawrence Livermore National Laboratory, California, USA, pitarka1@llnl.gov; PETERSSON, A., Lawrence Livermore National Laboratory, California, USA, andersp@llnl.gov; MCCALLEN, D. B., University of Nevada Reno, Nevada, USA, dmccallen@unr.edu

Numerical simulations of earthquake ground motions can account for region-, path- and site-specific three-dimensional (3D) earth structure and fault geometry and complement limited empirical data for large events. Advances in numerical methods, improvements in rupture models and 3D earth structure and the inexorable growth of computational power enable higher resolution earthquake ground motion simulations. We are modeling ground motions to frequencies of 5 Hz and higher from large earthquakes (moment magnitude M_W 6.5-7.2) on regional scales (~100 km). Simulations rely on world-class high-performance computing at DOE National Labs, including GPU-accelerated platforms. Simulations include generic faults with simple basin structures and stochastic heterogeneity and site-specific simulations of large ruptures on the Hayward Fault in the San Francisco Bay Area (SFBA). Simulations rely on the SW4 finite difference code with rupture models from Graves and Pitarka (2016) and a 3D geologic/seismic model from the United States Geological Survey (USGS) including topography. We have shown that simulated motions are consistent with ground motion models, such as those from the PEER NGA-West2 project (Bozorgnia, *et al.*, 2014). In the SFBA, we demonstrate how path- and site-effects in the 3D model bias intensity values and propose a method to account for these epistemic effects in a non-ergodic ground motion model. Within the SFBA, we have shown how the assumed minimum shear wavespeed in the near-surface geotechnical layer can impact the response. For the Hayward Fault, 3D geometry of the fault plane plays a role in controlling near-fault motions, akin to hanging wall effects for normal and thrust ruptures. Generic ruptures in simple basin models allow us to study near-fault motions which are particularly sensitive to the distribution of slip on the fault, the depth to the top of the rupture and directivity. We show how velocity pulses and displacement steps result in large near-fault motions and intensities can vary by a factor 10 close to the fault.

The Existence and Cessation of the Free-Surface-Induced Supershear Rupture: Depth-Dependent Stress Effects

HU, F., University of Science and Technology of China, Hefei, China, hufengustc@gmail.com; WU, B., University of California, Riverside, California, USA, bwu015@ucr.edu; CHEN, X., Southern University of Science and Technology, Shenzhen, China, chenxf@sustc.edu.cn; OGLESBY, D., University of California, Riverside, California, USA, david.oglesby@ucr.edu

It is well known that rupture on a strike-slip fault can accelerate to supershear rupture speed when it encounters the free surface and continues to propagate, which is termed the free-surface-induced supershear rupture. However, through 3D dynamic rupture simulations, we find that this effect is strongly dependent on the fault stress conditions. For a homogeneous stress distribution, the background normal stress plays a key role in the initiation of the free-surface-induced supershear rupture. A low initial normal stress may prevent the initiation of the free-surface-induced supershear, causing the rupture to propagate at sub-rayleigh speed. Depth-dependent initial stress, which is likely more realistic in nature, is another important factor controlling the appearance of the free-surface-induced supershear rupture. The free-surfaced-induced supershear rupture may be constrained to the layer close to the free surface under certain conditions, and may even transition back to sub-shear rupture propagation after an ephemeral supershear period. Our work may provide a physical explanation for the somewhat rare observations of free-surface-induced supershear rupture in nature.

Stick-Slip Induced Source Ground Vibration in Sheared Granular Fault

GAO, K., Los Alamos National Laboratory, New Mexico, USA, ke.gao.ut@gmail.com; ROUGIER, E., Los Alamos National Laboratory, New Mexico, USA, erougier@lanl.gov; GUYER, R., Los Alamos National Laboratory, New Mexico, USA, guyer@physics.umass.edu; JOHNSON, P., Los Alamos National Laboratory, New Mexico, USA, paj@lanl.gov

The devastating potential of earthquake to society calls for a thorough understanding of earthquake source physics and dynamics. Stick-slips in sheared granular fault, as being the laboratory equivalent of natural earthquakes, are intensively studied in recent years. In these existing studies, numerous attentions have been paid to the kinematics and mechanics of the granular gouge, with few detailed results being reported regarding the response of confining plates to the stick-slips. Since the motion of the plates is analogous to the ground vibration in fault blocks, investigating the stick-slip induced ground vibration in sheared granular fault is necessary for unveiling the complex mechanism of earthquakes and may also shed light on the prediction of ground shaking and determination of hazard for future earthquakes.

Here, a two-dimensional implementation of the combined finite-discrete element method (FDEM), which merges the finite element method (FEM) and the discrete element method (DEM), is used to explicitly simulate a sheared granular fault system. In the FDEM model, the deformation of plates and particles is simulated using the FEM formulation while particle-particle and particle-plate interactions are modeled using DEM-derived techniques. The results demonstrate that during the stick phases, both plates move at an approximately constant velocity in the direction of shearing. Whereas when slip occurs, the bottom of the upper plate bounces to the right and the top of the lower plate resets towards left. As the normal load increases, the plates are more vibrant during slips when the model is subjected to larger normal loads. Additionally, for all the normal load scenarios, the *x*-velocities at the sensor points during slips could be three orders larger than that during the stick phases. The simulations not only reveal the behavior of stick-slip dynamics in granular fault gouge, but also demonstrate the capabilities of FDEM for studying stick-slip type behavior of granular fault gouge system.

Numerical Modeling of Experimental Rock Friction Data for Rough Surfaces

TAL, Y., California Institute of Technology, California, USA, yuvaltal82@gmail.com; AVOUAC, J., California Institute of Technology, California, USA, avouac@gps.caltech.edu; GOEBEL, T. H. W., University of California, Santa Cruz, California, USA, tgoebel@ucsc.edu

There is experimental evidence that frictional sliding along a non-planar surface depends on its roughness, with more stable slip for rougher surfaces. Here we design a numerical scheme to reproduce such experimental data and analyze the mechanisms governing this behavior. We model numerically the tri-axial stick-slip experiments performed by Goebel *et al.* (2017) on pre-fractured and roughened pre-cut Westerly granite samples, using an idealized 2-D model. Our numerical approach includes four main features: (1) To enable slip that is large relative to the size of the elements near the fault, friction laws are implemented into the mortar finite element method, in which non-matching meshes are allowed across the fault and the contacts are continuously updated; (2) To accurately represent the fault geometry, the mesh is refined near the fault with hanging nodes; (3) To model a sequence of slip events, the method uses variable time steps with quasi-static and fully dynamic schemes; and (4) Using implicit return mapping algorithm, the bulk is modeled with Drucker–Prager viscoplastic rheology. We assume that the rough interfaces are governed by a combined rate and state and enhanced dynamic weakening friction law and search for a set of frictional parameters on the interfaces that give frictional behaviors, integrated for the whole model, similar to that observed in the experiments. The model captures the transition between slow slip and fast slip events observed in the experiments for different amplitudes of roughness, as well as the corresponding static stress drops.

Mechanical Weakening of Near-Surface Rock Layers Due to the Scattering of Seismic Waves

MOHAMMADI, K., California Institute of Technology, California, USA, kamimohamadi@caltech.edu; ASIMAKI, D., California Institute of Technology, California, USA, domniki@caltech.edu

When an elastic shear wave impinges on a sloped traction-free boundary, mode conversion takes place to satisfy the boundary conditions. For post-critical incidences, scattered energy forms a waveguide parallel to the ground surface. Depending on the angle of incidence and material properties (Poisson's ratio), these surface shear waves can have amplitude 5^+ times larger than the incident wave. Furthermore, the converted compressional wave does not carry any energy away from the boundary, and instead creates a zone of concentrated energy that propagates near the surface. Therefore, the resultant wavefield is amplified enough to initiate mechanical weakening (fracturing) of the shallow rock layers. Once weakening is initiated, the phenomenon is self-reinforcing, that is, weakening leads to increasingly larger impedance contrast between the intact and fractured rock; to increasingly larger amplification of the incident waves transmitted and trapped in the weathered rock layer; and hence increasingly larger damage induced by repeated events over large periods of time. In this study, we seek to develop a theoretical model to quantify the thickness and material strength of this weakened zone aka critical zone. We use a hybrid continuum-discrete technique to investigate the response of hillslopes subjected to a seismic motion for a range of material (rock and joint) and excitation (angle of incident, intensity and frequency content) parameters. The results of the systematic study on progressive rock fracturing helps us to characterize the critical zone for various seismic scenarios, to evaluate the earthquake as both a transient preparatory factor and a triggering mechanism of slope failure, and to predict the potential failure mechanisms in hillslopes.

A CyberShake PSHA Model for Northern California

CALLAGHAN, S., Southern California Earthquake Center, California, USA, scottcal@usc.edu; MAECHLING, P. J., University of Southern California, California, USA, maechlin@usc.edu; GOULET, C. A., University of Southern California, California, USA, cgoulet@usc.edu; MILNER, K. R., University of Southern California, California, USA, kmilner@usc.edu; SU, M., University of Southern California, California, USA, mei@uscedu.onmicrosoft.com; GRAVES, R. W., U.S. Geological Survey, California, USA, rwgraves@usgs.gov; OLSEN, K. B., San Diego State University, California, USA, kbolsen@

sdsu.edu; CUI, Y., San Diego State University, California, USA, yfcui@sdsc.edu; AAGAARD, B., U.S. Geological Survey, California, USA, baagaard@usgs.gov; WOODDELL, K. E., University of California, Berkeley, California, USA, katie.wooddell@gmail.com; KOTTKE, A. R., Pacific Gas and Electric Company, California, USA, arkk@pge.com; JORDAN, T. H., University of Southern California, California, USA, tjordan@usc.edu

The Southern California Earthquake Center (SCEC) has developed CyberShake, a software platform which performs 3D physics-based probabilistic seismic hazard analysis (PSHA) using deterministic wave propagation simulations. CyberShake calculations are performed by simulating Strain Green Tensors, then convolving these with slip time histories for hundreds of thousands of individual events from an earthquake rupture forecast. Synthetic seismograms are post-processed to obtain intensity measures, which are combined with event probabilities to produce hazard curves. Typically PSHA results from hundreds of locations are interpolated to produce a regional hazard map.

We have previously used CyberShake to calculate multiple hazard models for Southern and Central California. We have now expanded CyberShake to a large Northern California region which includes the San Francisco Bay Area. PSHA calculations up to 1 Hz for locations of interest in Northern California were performed on the NCSA Blue Waters and OLCF Titan supercomputers as part of CyberShake Study 18.8. To support simulation volumes that included most of California, we tiled three separate 3D community velocity models into a composite statewide model and applied smoothing along interfaces to minimize unrealistic reflections and refractions. To improve the representation of the near-surface velocity structure in the tomographically-derived models, we inserted a geotechnical layer (GTL) in the top 500 meters by applying the Ely (2010) method on Vs30 values from the Wills *et al.* (2015) map. Tesults from this new region can be combined with previous CyberShake models to produce physics-based PSHA results for much of California.

We will present the unified CyberShake results for all three California regions, with a special emphasis on the new Northern California results. We will compare CyberShake PSHA results to those obtained from GMPEs, investigate the impact of basin structures on hazard, and discuss our future plans.

Dynamic Rupture Modeling on the Hayward Fault, Northern California – Estimating Coseismic and Postseismic Hazards of Partially Creeping Faults

LOZOS, J., California State University, Northridge, California, USA, julian.lozos@csun.edu; FUNNING, G., University of California, Riverside, California, USA, gareth@ucr.edu

The hazards associated with partially creeping faults are not fully understood. In particular, the degree to which earthquake rupture is able to propagate into creeping areas of the fault, and the amount of shallow accelerated creep that would follow an earthquake are both uncertain. Both of these questions are gaps in our understanding of the physics of fault slip in general, but they are brought to particular societal relevance by the Hayward Fault, a partially-creeping fault which underlies the densely populated eastern San Francisco Bay Area, and has been identified as one of the two highest-hazard faults in California.

In this study, we explore the likely controls that frictional conditions, fault geometry, and accumulated elastic stresses will have on probable rupture lengths, and on the ability of rupture to propagate into sections of the fault that creep interseismically. We use dynamic rupture modeling incorporating rate-state friction, which allows for mode switching between aseismic and coseismic deformation, to calculate scenario ruptures. We find that frictional heterogeneity alone can strongly limit the extent of rupture, and that the associated decrease in shear stress that comes from interseismic creep further confines rupture to locked patches. We then integrate these with static boundary element models, which allows for a physics-based assessment of interseismic stress evolution, to develop our pre-stress conditions and to account for rapid postseismic creep. While our study focuses on the Hayward Fault, our methods and findings will also enable more accurate scenario modeling and hazard analysis for earthquakes on other partially creeping faults.

Finite Frequency Sensitivity Kernel for the Differential Measurements of Ambient Noise Correlations: Theory and Numerical Tests

LIU, X., Stanford University, California, USA, liuxin@stanford.edu; BEROZA, G. C., Stanford University, California, USA, beroza@stanford.edu

Full waveform adjoint tomography has achieved great success in applications from global structure using earthquakes to exploration seismology using active sources. When combined with ambient seismic noise interferometry, however, the shape of the sensitivity kernel can be distorted with significant sensitivity outside the inter-station region due to non-isotropic distribution of far field noise sources. We compute the sensitivity kernel for ambient noise cross-correlation differently from existing approaches by introducing an additional station to the classic two-station setting. We compute sensitivity kernels for differential travel time and amplitude measurements. The differential sensitivity kernels show prospect for canceling the overlapping part of the original source and structure kernels for two pairs of stations in interferometry, thus reducing the effect of non-isotropically distributed and non-stationary noise sources. We derive analytically and calculate numerically the differential sensitivity kernel for seismic interferometry and show examples based on 2D membrane waves. Our results for multiple station pairs show promise for future velocity and attenuation tomography based on seismic noise interferometry (Liu & Beroza 2019, submitted).

Broad Band Trajectory Mechanics

VASCO, D. W., Lawrence Berkeley National Laboratory, California, USA, dwvasco@lbl.gov; NIHEI, K. T., Lawrence Berkeley National Laboratory, California, USA, ktnihei@lbl.gov

We present a trajectory-based solution to the elasto-dynamic equations of motion that is valid across a wide range of seismic frequencies. That is, the derivation of the solution does not invoke a high frequency assumption or require that the medium have smoothly-varying properties. The approach, adopted from techniques used in quantum dynamics, produces a set of coupled ordinary differential equations for the trajectory, the slowness vector, and the elastic wave amplitude along the ray path. In the limit of large frequencies, the coupling term approaches zero and the trajectories converge to high-frequency raypaths. Synthetic tests with interfaces and layers containing increasingly narrow transition zones indicates that the conventional high-frequency trajectories bend too sharply into high velocity regions as the wavelength exceeds the transition zone width. Test models based upon velocity structures from the Geysers and an exploration geophysics salt model indicate that discrepancies between the high-frequency and broad band trajectories can exceed several hundred meters to several kilometers at wavelengths of 1 Hz.

Large Data Set Seismology: Strategies in Managing, Processing and Sharing Large Geophysical Data Sets

Oral Session · Thursday · 4:00 PM · 25 April · Elliott Bay
Session Chairs: Chad Trabant, Jonathan K. MacCarthy.

Efficient Storage and Processing of Segmented Waveform Data for the Generation of a Signal Quality Machine Learning Classifier

MAGAÑA-ZOOK, S. A., Lawrence Livermore National Laboratory, California, USA, maganazook1@llnl.gov

Archives holding seismological waveform data already store hundreds of terabytes of data and are growing exponentially each year. Having access to these rich datastores enables researchers to ask data-intensive science questions, but the sheer volume of data makes it infeasible for researchers to perform analysis at scale using traditional methods. In this work, we assess tools from the Big Data space to show efficient ways of storing and processing segmented waveforms. Segmented data tends to involve vast amounts of small files which harm I/O throughput, and exhaust distributed filesystem resources, so we look at emerging file formats for efficient solutions.

Our research aim was to produce a quality control machine learning model capable of classifying segments as containing either a signal or an artifact. To accomplish this, we computed nine statistical metrics on over 700,000 labeled waveform segments for use as training features. The availability of scalable machine learning frameworks allowed efficient grid search-based hyper-parameter optimization over 160 different Random Forest hyper-parameter combinations, resulting in a model that achieved a 10-fold cross-validation mean accuracy of 99.96%. The trained model can now be used on archived data, and as part of ingestion pipelines, to assign quality control metadata that researchers can use to inform selection of data for their studies.

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Ambient Noise Processing With Julia

CLEMENTS, T., Harvard University, Massachusetts, USA, thclements@g.harvard.edu; DENOLLE, M. A., Harvard University, Massachusetts, USA, mdenolle@fas.harvard.edu; YU, E., Southern California Seismic Network, California, USA, eyu@gps.caltech.edu; ROSS, Z. E., California Institute

of Technology, California, USA, zross@gps.caltech.edu; HAUKSSON, E., California Institute of Technology, California, USA, hauksson@caltech.edu

As the total amount of global seismic noise data reaches beyond a Petabyte in the next decade, a new paradigm will be required to process large datasets. This will be particularly relevant for Distributed Acoustic Sensing (DAS) datasets going into the future, which can generate Terabytes of data a day. Here, we present a new solution for high performance seismic processing - the Julia computing language. Julia is the first dynamic, high-level language to achieve petaflop performance. Julia was designed to easily scale across CPU and GPU compute clusters. We test newly developed ambient noise cross-correlation codes written in Julia on one year of seismic data from the entire Southern California Seismic Network (SCSN).

Managing Large Data Sets for British Columbia Earthquake Early Warning

KREIMER, N., Ocean Networks Canada, Victoria, Canada, nadiakreimer@uvic.ca; JENKYNS, R., Ocean Networks Canada, Victoria, Canada, reyna@uvic.ca; PARKER, G., Ocean Networks Canada, Victoria, Canada, glp@uvic.ca; TIMMERMAN, R., Ocean Networks Canada, Victoria, Canada, revt@uvic.ca; SCHLESINGER, A., Ocean Networks Canada, Victoria, Canada, schlesin@uvic.ca; ROSENBERGER, A., Arescon Ltd., Sidney, Canada, andreas@arescon.com; FERGUSON, E., Ocean Networks Canada, Victoria, Canada, elif@uvic.ca; WAGNER, S., Ocean Networks Canada, Victoria, Canada, swagner@uvic.ca; DOROCICZ, J., Ocean Networks Canada, Sidney, Canada, jdorocic@uvic.ca; HEMBROFF, D., Ocean Networks Canada, Sidney, Canada, degnanh@uvic.ca; KEY, R., Ocean Networks Canada, Sidney, Canada, rkey@uvic.ca; GUNDERSON, C., Ocean Networks Canada, Sidney, Canada, cgunderson@uvic.ca; ROBINSON, J., Ocean Networks Canada, Victoria, Canada, jrobinson@uvic.ca; PIRENNE, B., Ocean Networks Canada, Victoria, Canada, bpirenne@uvic.ca; MORLEY, M., Ocean Networks Canada, Victoria, Canada, mmorley@uvic.ca; HEESEMANN, M., Ocean Networks Canada, Victoria, Canada, mheesema@uvic.ca; LI, M., Natural Resources Canada, Sidney, Canada, mingzhou.li@canada.ca; NYKOLAISHEN, L., Natural Resources Canada, Sidney, Canada, lisa.nykolaishen@canada.ca; LU, Y., Natural Resources Canada, Sidney, Canada, yuan.lu@canada.ca; BRILLON, C., Natural Resources Canada, Sidney, Canada, camille.brillon@canada.ca; COLLINS, P., Natural Resources Canada, Sidney, Canada, paul.collins@canada.ca; CAISSY, M., Natural Resources Canada, Ottawa, Canada, mark.caissy@canada.ca

Ocean Networks Canada (ONC) has been developing and installing an earthquake early warning system (EEW) for southwestern British Columbia since February 2016 for the Government of BC. The project leverages on ONC's experience operating real-time sensor networks underwater and on land using an advanced data management system, "Oceans 2.0". A unique aspect of this network is the existence of underwater accelerometers and tilt meters, strategically positioned with respect to the Cascadia subduction zone. The land-based system comprises of joint Natural Resources Canada (NRCan) and ONC sites, as well as ONC-only sites, with stations having accelerometers and Global Navigation Satellite System (GNSS) instruments. As of December 2018, the EEW system has 25 on-land and 7 seafloor sites, with a total number of approximately 96 instruments. Data transmission and reliability is a concern for remote sites, which is alleviated by having high quality satellite communications. Those sites that have a reliable and acceptable bandwidth are suitable for streaming raw acceleration data, while the remaining ones stream only the data indispensable to the EEW system (JMAs, Pd, Pgd, etc). Each instrument type follows a specific workflow best suited for the tasks required for its optimal metadata and data integrity. For most instruments installed at an EEW site, the metadata is stored in a PostgreSQL database accessible to users via Oceans 2.0, including calibrations, receiving and installation dates, coordinates, calibration formulas, manufacturer, model, serial numbers, and more. To guarantee metadata and data curation standards, all data stewardship tasks are reviewed by another team member. The Data Search tool in Oceans 2.0 and the API web services encourage EEW data use for research purposes. This presentation will share the challenges and current efforts in managing data for an EEW system, from deployment to issuing an earthquake event notification.

Putting the Commercial Cloud to Work for Seismology

MACCARTHY, J. K., Los Alamos National Laboratory, New Mexico, USA, jkmacc@lanl.gov; MARCILLO, O., Los Alamos National Laboratory, New Mexico, USA, omarcillo@lanl.gov

While most types of research in seismology still fit comfortably into a desktop computer, data-hungry algorithms such as quality assessment, signal detection, noise correlation, and certain kinds of machine learning can quickly become impractical over large data volumes. Traditionally approaches often involve prolonged data acquisition from a data center and substantial storage, but the commercial cloud offers an alternate workflow that has the possibility to accelerate data collection and analysis. We report on a streaming workflow for seismology, in which data are requested on-the-fly and not stored, that leverages private clusters in Amazon Web Services EC2 and the scientific Python ecosystem.

The Promise of the Cloud and the IRIS DMC

TRABANT, C., Incorporated Research Institutions for Seismology, Washington, USA, chad@iris.washington.edu; AHERN, T., Incorporated Research Institutions for Seismology, Washington, USA, tim@iris.washington.edu; WATSON, I., Incorporated Research Institutions for Seismology, Washington, USA, inge@iris.washington.edu; WEEKLY, R., Incorporated Research Institutions for Seismology, Washington, USA, rtweekly@iris.washington.edu; CARTER, J., Incorporated Research Institutions for Seismology, Washington, USA, jerry@iris.washington.edu

The IRIS Data Management Center (DMC) has operated a repository of time series data for 3 decades using its own computational and storage infrastructure. The rise of cloud computing comes with many promises, such as nearly unlimited compute and storage capacity, load-driven dynamic scaling, turn-key data replication and more. We have started exploring which of these cloud resources could potentially be leveraged by the DMC in the GeoSciCloud project, which is supported by the National Science Foundation's (NSF) EarthCube program. One of the project goals is to evaluate how some of our core systems operate within a cloud environment. For this project, we selected Amazon's AWS and XSEDE's Jetstream and Wrangler systems. Web services were deployed in these environments using Docker and Kubernetes running across a cluster of virtual machines. This architecture proved to be powerful, allowing for relatively simple scaling of service capacity and an abstraction of service instances. Looking ahead, the platform created by Docker + Kubernetes is an enticing model for a large data processing framework. Initial results, common to both cloud systems, indicate two clear advantages for DMC users. First, the ability to scale data access capacity allow for servicing more concurrent requests than the DMC is currently capable of handling. Second, providing the data in close proximity to powerful compute infrastructure used by researchers eliminates the significant bottleneck of transferring data over the internet. A number of downsides were also identified including monetary cost, uncertainty regarding long term operation, cost in adapting to cloud resources, and reduced insight into systems. The DMC is currently exploring the potential to partner with peer data centers that are members of the Council of Data Facilities and an infrastructure operator to develop shared infrastructure that would provide the advantages of cloud computing and mitigate most of the disadvantages.

Explore the Fault2SHA Paradigms Across the Ponds

Oral Session · Thursday · 8:30 AM · 25 April · Pike

Session Chairs: Laura Peruzza, Edward H. Field, Richard Styron, Alessandro Valentini.

Developing Next Generation PFDHA and Confidence Limits on Geologic Slip Rates Using High-Resolution Geodetic Imaging Data

MILLINER, C. W. D., Jet Propulsion Laboratory, California Institute of Technology, California, USA, christopher.milliner@jpl.nasa.gov; CHEN, R., California Geological Survey, California, USA, rui.chen@conservation.ca.gov; DAWSON, T. E., California Geological Survey, California, USA, timothy.dawson@conservation.ca.gov; MADUGO, C., Pacific Gas and Electric Company, California, USA, c7m0@pge.com; DOLAN, J., University of Southern California, Los Angeles, United Kingdom, dolan@usc.edu

Understanding how inelastic, co-seismic shear strain decreases with distance from the primary fault rupture is important for accurately characterizing the hazard it poses to the critical infrastructure and estimating the full geologic slip rate. Probabilistic Fault Displacement Hazard Analysis (PFDHA), estimates the exceedance probability of distributed faulting off the primary fault, and has so far been constrained solely from traditional field observations of surface ruptures. Here we assess how measurements of the near-field surface deformation pattern of several large magnitude earthquakes ($M_w > 7$), derived from different geodetic imaging techniques (optical image and radar amplitude correlation), can be used to better constrain the 'fall-off' of inelastic strain away from the primary fault. From the high-resolution displacement maps we can measure the full across-fault surface strain at multiple points along the surface rupture (n>1000 for each event), providing a more consistent and reliable estimate of the probability of occurrence of inelastic deformation and exceedance with distance from the fault, both key terms in the PFDHA hazard equation. From the correlation maps we also investigate how parts of the rupture undergoing compression and extension effects the distribution of inelastic strain across the surface rupture. We then discuss how our probability estimates of strain width derived from surface ruptures can characterize the probability a geologic slip rate measurement captures the full, across-fault geologic strain release. High-resolution geodetic measurements of near-field deformation from surface ruptures can help better quantify the aleatory variability and reduce the epistemic uncertainty in PFDHA models, providing more precise information to structural engineers, and place empirical uncertainties on geologic slip rates, an important input for Probabilistic Seismic Hazard Assessment.

Fault2SHA Working Group: Linking Faults to Seismic Hazard Assessment

PERUZZA, L., Istituto Nazionale di Oceanografia e di Geofisica Sperimentale, Sgonico, Italy, lperuzza@inogs.it; SCOTTI, O., Institut de Radioprotection et de Surete Nucleaire, Paris, France, oona.scotti@irsn.fr

The objective of the Fault to Seismic Hazard Assessment (Fault2SHA) Working Group is to build a community of active fault-related researchers to exchange data, tools and ideas on how to best model faults in seismic hazard assessment in specific tectonic contexts. Use of fault-related information in the assessment of seismic hazard is slowly finding its way in Europe. Progress is slow because the data collection process is time-consuming, the quality of data used to represent faults in databases is heterogeneous and methodologies to incorporate fault information in hazard studies are not necessarily agreed upon across Europe. Indeed, complex ruptures observed in the last years (*e.g.* the 2016 Mw 7.8 Kaikōura, NZ earthquake that ruptured 21 different faults over 180 kilometers, but also the three main Mw 6.0-6.5 events in Central Apennines, Italy in 2016 that partially re-ruptured the same patches) confirm the need to relax the "segmentation" concept, raising numerous questions in the seismic hazard community, in terms of its capacity to anticipate such events. Since its formalization inside the European Seismological Commission (ESC General Assembly in 2016), the WG promoted several interdisciplinary sessions at international conferences, a "residential" workshop for about fifty participants in Barcelonette (F) in May 2017, editorial initiatives, and micro-training courses (https://fault2sha.net/). In 2018, two natural laboratories were established (one in the central Apennines and a second one in south-eastern Spain) to face the challenges of transdisciplinary discussions among geophysicists, earthquake geologists, geodesists and seismologists. The WG contributed to another international initiative, sponsored by the Saudi Arabia KAUST University (https://eqhazard.kaust.edu.sa/), aimed to integrate geological and seismological observations into physics-based rupture simulations.

In this meeting, we aim at widening the discussion beyond the European context and to open to new potential Fault2SHA members the opportunity to join the next activities.

Presenting the 2018 Gem Global Seismic Hazard Map and Global Active Faults Database

STYRON, R. H., GEM Foundation, California, USA, richard.h.styron@gmail.com; PAGANI, M., GEM Foundation, Pavia, Italy, marco.pagani@globalquakemodel.org; GARCÍA-PELAEZ, J., GEM Foundation, Pavia, Italy, julio.garcia@globalquakemodel.org; POGGI, V., GEM Foundation, Pavia, Italy, valerio.poggi@globalquakemodel.org; GEE, R., GEM Foundation, Pavia, Italy, robin.gee@globalquakemodel.org; JOHNSON, K., GEM Foundation, Pavia, Italy, kendra.johnson@globalquakemodel.org

The Global Earthquake Model (GEM) Foundation has the mission to promote earthquake resilience worldwide by creating and maintaining earthquake hazard and risk models, and associated datasets and software for probabilistic seismic hazard and risk analysis. In late 2018, GEM released the firstversions of several of these products, including the Global Seismic Hazard Map, the Global Seismic Risk Map, and the Global Active Faults Database.

The Global Seismic Hazard Map (version 1.0- 2018) is based on a mosaic of 30 national or regional PSHA models developed by various institutions including the GEM Secretariat; each model is implemented in the OpenQuake engine (regardless of the original format). The map describes the spatial distribution of the peak ground acceleration with an annual probability exceedance of 10% in 50 years on an (almost) global equally spaced grid. It is the combination of 30 hazard maps computed for each individual model includedin the mosaic. Unlike previous global hazard maps, the GEM Global Seismic Hazard Map (and underlying Model) is a dynamic, evolving product that will be updated regularly as the regional models are updated.

The GEM Global Active Faults database is similarly an evolving mosaic of regional catalogs of active fault traces and metadata describing the geometry, kinematics, slip rates, and other relevant parameters of each fault, and released as a vector GIS dataset. Fault catalogs developed for seismic hazard as well tectonic research have been included, with preference for hazard sources. New catalogs have been mapped by GEM for North Africa, Central America and the Caribbean, and northeastern Asia, with ongoing mapping in Canada and East Africa. Currently the database contains ~15,000 faults. Catalog assembly and harmonization are done programmatically whenever new data are available. These data products are free and released under a Creative Commons open license, and available at globalquakemodel.org.

Simple Faults With Complex Slip Patterns: Theoretical Arguments for Non-Characteristic Ruptures on Homogeneous Planar Faults

CATTANIA, C., Stanford University, California, USA, camcat@stanford.edu; SEGALL, P., Stanford University, California, USA, segall@stanford.edu; HAINZL, S., GFZ German Research Centre for Geosciences, Potsdam, Germany, hainzl@gfz-potsdam.de

While the concepts of earthquake cycle and characteristic earthquake are often used in seismic hazard, they are poorly supported by observations and have been heavily criticized in recent years. The statistical properties of regional seismicity - power law distributions in seismic moment and temporal clustering (aftershocks) - are antithetical to characteristic and periodic behavior. In contrast, some small quakes have well defined cycles: locked patches surrounded by creep can rupture periodically in repeating events. Regional statistics could simply reflect the distribution of lengthscales in a fault system; alternatively, large faults may be inherently less characteristic than small asperities.

We explore this question using fracture mechanics ideas and numerical simulations of rate-state faults with velocity-weakening (VW) regions loaded by adjacent creep, such as vertical antiplane faults with downdip creep. We suggest that slip patterns are determined by two timescales: T_f, the time required to accumulate elastic energy for full rupture; and the nucleation time T_n, controlled by creep penetrating in the VW region. The energy needed for a full rupture, and T_f, increase with fault dimension L; while the energy required for nucleation, and T_n, increase with L_n, a characteristic length determined by frictional and elastic properties. If $T_n < T_f$ partial ruptures occur; for large faults, $T_n << T_f$ and we expect multiple partial ruptures. Simple crack models predict the ratio between the number of nucleations and the number of full ruptures on a 1D fault to increase as $\sim(L/L_n)^{1/2}$. Numerical simulations confirm these arguments, and exhibit a transition from characteristic, periodic cycles at $L/L_n <\sim 10$ to a power law moment distribution and temporal clustering for larger L/L_n. For $L/L_n > \sim 100$, interevent times are power law distributed, consistent with Omori decay modulated by afterslip in the creeping region. We suggest that L/L_n alone can lead to variability in seismic behavior even without heterogeneous frictional properties or prestress.

How Physics-Based Earthquake Simulators Might Help Improve Earthquake Forecasts

FIELD, E. H., U.S. Geological Survey, Colorado, USA, field@usgs.gov

Questions have persisted on the usefulness of Physic-Based Earthquake Simulators with respect to forecasting earthquakes, due mostly to the inevitable assumptions, approximations, and uncertainties. Whether any model is reliable or trustworthy depends entirely on what questions we are asking of it, so the point of this presentation is to outline a number of currently anticipated and desired inferences, informed largely by recent forecasting efforts in California. This presentation does not provide an in-depth review of physics-based simulators, nor does it render judgement on the usefulness question. The intent, rather, is to provide an explicit list of potential uses, or inferences, to enable more informed discussions among physics-based modeling experts.

Central and Eastern North America and Intraplate Regions Worldwide

Oral Session · Thursday · 10:45 AM · 25 April · Pike
Session Chairs: Will Levandowski, Weisen Shen, Christine A. Powell.

A Comprehensive Seismological Investigation of the Anninghe-Zemuhe Fault Zone With a Dense Array

FANG, L., Institute of Geophysics, China Earthquake Administration, Beijing, China, flh@cea-igp.ac.cn; WU, J., Institute of Geophysics, China Earthquake Administration, Beijing, China, wjpwu@cea-igp.ac.cn; WANG, W., Institute of Geophysics, China Earthquake Administration, Beijing, China, wangwl@

cea-igp.ac.cn; WANG, C., Institute of Geophysics, China Earthquake Administration, Beijing, China, wangchangzai@cea-igp.ac.cn

The Anninghe-Zemuhe fault zone is located at the junction of the Chuandian block, the Bayanhar block and the Southern China block, and is an important eastern boundary of the Chuandian block. The fault is approximately 240 km long with prominent left-lateral slip. Previous geological and seismicity studies conjecture that the fault has a potential for generating a M7.0 earthquake in the near future. We have deployed 30 temporary broadband seismic stations along Anninghe-Zemuhe fault zone since January of 2013. The inter-station distance varies from 8 to 20 km. Each station is equipped with CMG-3T (120s) seismometers and Ref Tek 130 digitizer. The array records more than 13,600 local earthquakes. The magnitude ranges from M_L-0.9~M_L5.0. The micro seismicity delineates several faults which are not identified before. The seismicity and focal mechanism reveal clear segmentation of the fault. Most of the earthquakes occurred in the north part of the Anninghe fault. We find obvious change in focal depth in Shimian city. To the east of the fault, the earthquakes are concentrated in 17~35 km. While to the west of the fault, the earthquakes are in 0~17 km. We conducted travel time tomography with local earthquakes and ambient noise. Compared with previous studies, the lateral resolution has been improved greatly. The resolution is about 20 km in the central Anninghe-Zemuhe fault zone, and 20~40 km in other regions. The velocity structure is basically consistent with the surface geological structure. Fault zone head wave and body wave travel time tomography show clear velocity contrast along the both sides of the Anninghe fault. The P-wave velocity in the eastern side is faster than that in the western side. We propose that the focal depth changes perpendicular to the Anninghe fault is mainly controlled by velocity structure.

Seismic Evidence of Thickened Crust Beneath Eastern Part of Chhotanagpur Plateau, India

DAS, M. K., Indian Institute of Technology, Dhanbad, India, mukeshkumardas@agp.ism.ac.in; AGRAWAL, M., Indian Institute of Technology, Dhanbad, India, mohit@iitsim.ac.in; PATEL, A., Indian Institute of Technology, Dhanbad, India, anupam2372@gmail.com

The Chhotanagpur Plateau is mostly composed of old cratonic rocks of Proterozoic age where seismological studies have rarely been accomplished to decipher the underlying seismic velocity structure of lithosphere. To solve the mystery associated with deep geological and tectonic features of this part of Indian shield, we use teleseismic earthquake data (5.5 ≤ M ≤ 8.0) from years 2007 to 2017 recorded at two broadband seismic stations located in Indian cities of Dhanbad and Bokaro, respectively. The complementary constraints imposed by disparate datasets such as Ps and Sp receiver functions and Rayleigh wave group velocity dispersion curves are utilized to jointly model the P-and S-wave velocity profiles. The optimization of the cost function is performed via Very Fast Simulated Annealing (VFSA). This joint inversion technique conducts its multiple searches in predefined model space to find various acceptable velocity profiles to quantify the uncertainties associated with the best fitting model.

Our results suggest that the eastern part of Chhotanagpur plateau which is mostly composed of Granite Gneiss Complex has thickened crust as compared to the central and western part of Indian Shield. From the surface to the depth of ~150 km, the Vp and Vs range between 6.1-8.4 km/s and 3.2-4.8 km/s, respectively. We estimate the Moho at ~43 km and ~44 km for seismic stations located in Dhanbad and Bokaro, respectively. The large values of Poisson's ratios (~0.29) in the crust of eastern part of Chhotanagpur Plateau indicate that the partial mafic material may be present in the lower crust.

Crustal Underplating Beneath the Mid-Continental Rift System Imaged by USArray and SPREE

SHEN, W., Stony Brook University, New York, USA, weisen.shen@stonybrook.edu; WIENS, D. A., Washington University in St. Louis, Missouri, USA, doug@wustl.edu; VAN DER LEE, S., Northwestern University, Illinois, USA, suzan@northwestern.edu; DARBYSHIRE, F., Université du Québec à Montréal, Montreal, Canada, darbyshire.fiona_ann@uqam.ca; FREDERIKSEN, A., University of Manitoba, Winnipeg, Canada, andrew.frederiksen@umanitoba.ca; REVENAUGH, J., University of Minnesota, Minnesota, USA, justinr@umn.edu; WYSESSION, M., Washington University in St. Louis, Missouri, USA, michael@wucore.wustl.edu; ALEQABI, G., Washington University in St. Louis, Missouri, USA, ghassan@wucore.wustl.edu; STEIN, S., Northwestern University, Illinois, USA, seth@earth.northwestern.edu; JURDY, D., Northwestern University, Illinois, USA, d-jurdy@northwestern.edu; WOLIN, E., U.S. Geological Survey, Colorado, USA, ewolin@usgs.gov; BOLLMANN, T., Northwestern University, Illinois, USA, trevor@earth.northwestern.edu

More than 10-years of USArray deployments together with Flexible Array deployments have enabled us to compile a suite of seismic observables for constructing sharp images of the lithosphere beneath the contiguous US, particularly the central and eastern parts. In this presentation, we discuss the latest results with USArray and SPREE (Superior Province Rifting EarthScope Experiment) data using a combination of multiple seismic observables including 1) Rayleigh wave phase/group speeds from ambient noise and teleseismic earthquakes, 2) receiver functions, and 3) Rayleigh wave horizontal-to-vertical ratios (H/V). These observables are combined through a Bayesian Monte Carlo algorithm to invert for a shear-velocity model of the lithosphere with associated uncertainties. The new seismic images confirm a finite-gradient/complex Moho discontinuity beneath the rift from receiver-function data and reveal additional lithospheric characteristics beneath the Precambrian failed rift. A lower crust-uppermost mantle anomaly near the Moho is characterized by a shear-velocity speed of ~4.0-4.2 km/sec, representing the crustal underplating associated with the initiation of the rift. The spatial distribution of this anomaly extends beyond the west arm of the rift. By incorporating SPREE and USArray data near the central-eastern US, we find that the underplating extends north to Lake Superior and east toward the Michigan basin. Incorporating these observed features, an estimate of the total volume of the Proterozoic underplating can be obtained.

Seismic Characteristics of the Eastern North American Crust With Ps Converted Waves: Terrane Accretion and Modification of Continental Crust

LI, C., University of Massachusetts Amherst, Massachusetts, USA, conli@geo.umass.edu; GAO, H., University of Massachusetts Amherst, Massachusetts, USA, haiyinggao@geo.umass.edu; WILLIAMS, M. L., University of Massachusetts Amherst, Massachusetts, USA, mlw@geo.umass.edu; YANG, X., University of Massachusetts Amherst, Massachusetts, USA, xiaotaoyang@geo.umass.edu

Eastern North America represents an iconic example of the Wilson cycle tectonics, which recorded at least two episodes of supercontinent assembly and breakup over the past 1.3 Ga. A long-term question remains about the impact of the past tectonic events on the growth and modification of the continental crust. In this study, we use teleseismic Ps receiver functions to image detailed distribution of the crustal thickness, as well as some distinctive intra-crustal features, beneath eastern North America. Our results show clear variations of the Moho depth within and across major tectonic units, which provides insights into the evolution of the crust during and after the major orogenic events in the eastern North America. More specifically, the Moho depth increases northwestward across the Appalachian front, with a west-east Moho offset of up to ~12-15 km. The gradient of the Moho offset varies along the Appalachian front, which probably reflects differences in the style and intensity of the Acadian, post-Acadian, and Alleghenian collisions. Along the Grenville front, a shallow Moho is seen in the northernmost part, while an abrupt Moho deepening appears along the southern front. The deepened Moho might be related to the collisions during the Grenville orogeny, or a combination of collisions and underplating due to failed rifts. The crustal thickness within the Grenville Province demonstrates a distinct difference between the northern part in Canada and the southern part in the United States. A portion of stations in the central Grenville Province of the United States show strong intra-crustal signals. The depth of this intra-crustal phase gradually increases eastward from the Grenville front to the Appalachian front over a distance of ~ 700 km. The heterogeneous seismic features observed within the Grenville crust may indicate a fundamental difference in the orogenic processes between the northern and southern parts.

Imaging the Cratonic Lithosphere Beneath the Illinois Basin and the Adirondack Mountains

YANG, X., University of Massachusetts Amherst, Massachusetts, USA, xiaotaoyang@geo.umass.edu; GAO, H., University of Massachusetts Amherst, Massachusetts, USA, haiyinggao@geo.umass.edu; PAVLIS, G. L., Indiana University Bloomington, Indiana, USA, pavlis@indiana.edu

Although cratons are usually thought to be relatively stable, basins and plateaus are widely distributed around the globe. Understanding the formation and evolution of these intractatonic features has significant implications on the modification of continental lithosphere in general. Here we investigate and compare the lithospheric structure beneath the Illinois Basin in the central United States and the Adirondack Mountains in the northeastern United States. We present a crustal thickness model beneath the Illinois Basin, using plane-wave migration of teleseismic receiver functions recorded by the Ozark, Illinois, Indiana, and Kentucky (OIINK) seismic array. For the Adirondack Mountains area and its vicinities, we construct a high-resolution crust and upper mantle shear-wave velocity model using full-wave ambient noise tomography. Beneath the central and southeastern Illinois Basin area, we image an unusually thick crust (up to 62 km), which contradicts to horizontal stretching or lithospheric flexural subsidence model. Multiple mechanisms may have thickened the crust. Remnants of ancient magmatic underplating might be the primary mechanism responsible for the density increase of the crust and, consequently, the subsidence at the surface due to negative buoyancy. In comparison, beneath the Adirondack Mountains, the velocity model reveals a distinctive low-velocity column immediately below the Moho. This anomaly is connected with the large-scale low-velocity volume beneath southern New England and eastern New York at greater depths, which may reflect asthenosphere upwelling induced by a combined effect of the Great Meteor hotspot and edge-driven convections. The buoyancy of the upwelling asthenosphere, together with possible thermal expansion, may have uplifted the Adirondack Mountains. The imaging results for both the Illinois Basin and the Adirondack Mountains suggest the dominance of vertical forces, primarily buoyancy, in the evolution of cratonic interiors.

Wave Propagation Analysis of the SP Headwave Observed in the Charlevoix Seismic Zone and Its Application for Constraining Source Depth

FADUGBA, O. I., University of Memphis, Tennessee, USA, oluwaseun_fadugba@yahoo.com; LANGSTON, C. A., University of Memphis, Tennessee, USA, clangstn@memphis.edu; POWELL, C. A., University of Memphis, Tennessee, USA, capowell@memphis.edu

The Charlevoix seismic zone (CSZ) occurs along the ancient St. Lawrence rift zone in southeastern Quebec at the location of a Devonian impact crater. The crater is superimposed on major basement faults. Over 200 earthquakes are recorded each year in the CSZ and hypocenters have a bimodal distribution with peaks at 10 and 25 km depths. We observe a large, secondary P-wave arrival before the S-wave after a critical epicentral distance with a constant time difference relative to the first P wave arrival. We interpret the seismic phase as an SV to P (SP) head wave that propagates near the surface in the relatively homogeneous Charlevoix crust. Even though the amplitude of the SP headwave is smaller than the S wave amplitude, it could be confused with the S wave near the critical distance and misinterpreted as seismic anisotropy. To explore the characteristics of the SP headwave, we perform a wave propagation study for local earthquakes in the CSZ through computation of synthetic seismograms using wavenumber integration and generalized ray theory methods. In particular, we investigate the origin of the SP headwave using relative phase travel times and particle motions determined from a polarization filter. We also address the characteristics of the headwave for different source mechanisms, its response to different source depths and complex near-surface structures such as a low-velocity zone. We also investigate its use as an additional phase to constrain the focal mechanism. The travel time of the SP head wave relative to S offers a sensitive constraint on source depth for events in the seismic zone, validating earthquake locations. The formation of this seismic phase is of importance in understanding the structure of the CSZ and constraining earthquake source parameters.

Earthquakes and Faults of the Western Quebec Seismic Zone and Their Relationship With the Great Meteor Hot Spot Track

LAMONTAGNE, M., Geological Survey of Canada, Ottawa, Canada, maurice.lamontagne@canada.ca; BROUILLETTE, P., Geological Survey of Canada, Quebec, Canada, pierre.brouillette@canada.ca; KJARSGAARD, B., Geological Survey of Canada, Ottawa, Canada, bruce.kjarsgaard@canada.ca; ASHOORI PARESHKOOHI, A., Geological Survey of Canada, Ottawa, Canada, azadeh.ashooripareshkoohi@canada.ca

The Western Quebec Seismic Zone (WQSZ) includes a series of historical earthquakes as large as M 6.2 (Temiscaming, 1935) and frequent low level seismic activity. The activity mainly occurs within two elongated bands: one oriented NW-SE where most local earthquakes occur, and one that parallels the Ottawa River (where faults of the Ottawa-Bonnechere Graben (OBG) are mapped).

Since the mid-1970s, a relationship between the earthquake activity and the track of the Great Meteor Hot Spot has been suggested. This project aims at producing a digital map of the faults and lineaments of the entire WQSZ. The digital map will help defining the relationships between earthquakes and faults, one component of seismic hazard assessment.

A digital map of the faults and lineaments of the entire WQSZ has just been released as a GSC Open File Report. The digital map helps defining the relationships between earthquakes and faults. Lineaments were observed mostly from the Digital Elevation Model (DEM) of the Canadian National Topographic Data Base (NTDB) at a scale of 1:250,000. The DEMs illuminated from two directions were used to visually recognize lineaments and georeferenced their surface traces in a Geographic Information System. Since the final goal is to better map the brittle faults that could be reactivated in earthquakes, the ductile structures of the Grenville orogeny were removed from the final product

We have analyzed the fault orientations to determine sub-areas within the seismic zone. Areas affected by the Ottawa-Bonnechere Graben and its related failed arms were put in evidence.

The picture that was obtained shows the prevalence of the E-W faults of the (OBG). Other fault systems are not as well developed and do not have a trend similar to the alignment of most epicentres. At this time, the earthquake activity and the main trends of the brittle faults do not show an unambiguous correlation with the postulated Great Meteor Hot Spot trend.

Structure and Anisotropy of the Crust and Upper Mantle Along the St. Lawrence Corridor, Eastern Canada, From the Charlevoix Seismic Zone to the Gulf of St. Lawrence

BENT, A. L., Natural Resources Canada, Ottawa, Canada, allison.bent@canada.ca; KAO, H., Natural Resources Canada, Sidney, Canada, honn.kao@canada.ca; DARBYSHIRE, F., Université du Québec à Montréal, Montreal, Canada, darbyshire.fiona_ann@uqam.ca

The St. Lawrence corridor in eastern Canada comprises three active seismic zones separated by regions of low seismicity. Understanding the unequal distribution of seismicity has potential implications for hazard assessment of this highly populated region and its critical infrastructure. Despite its intraplate setting, the region is tectonically complex. The St. Lawrence River, underlain by the St. Lawrence Platform, delineates much of the boundary between the Canadian Shield to the north and the Appalachians to the south. To better define the structural complexities of this important region, shear wave velocity models were derived from teleseismic receiver functions for seismograph stations along the St. Lawrence. Gaps in the broadband coverage of the Canadian National Seismograph Network were supplemented by temporary stations deployed for this project and by taking advantage of any other deployments in the region. The current study focuses on the region between the Charlevoix Seismic Zone and the Gulf of St. Lawrence, complementing previous work that covered the region between Charlevoix and Montreal. All stations modeled show a high velocity lid to a depth of ~5km and a Moho at 38-45 km. The structure is consistent from one station to the next. Discontinuities can be correlated allowing for the development of a pseudo-3D model. Evidence for mantle anisotropy is obtained from SKS splitting. Fast-polarization directions are subparallel to the strike of the St. Lawrence valley in the study region and parallel to the valley further west, with a slight rotation of fast orientation from west to east. The average delay time of ~1 second requires an upper-mantle component, which is likely a combination of contributions from “fossil” lithospheric anisotropy and mineral alignments from present-day sublithospheric mantle flow.

Improving Magnitude Consistency in Eastern Canada Through Regionally Appropriate Attenuation Relations

PERRY, C., Natural Resources Canada, Ottawa, Canada, claire.perry@canada.ca; BENT, A. L., Natural Resources Canada, Ottawa, Canada, allison.bent@canada.ca

The Nuttli magnitude scale, MN or mbLg, developed for use in the intraplate regions of North America is the magnitude scale most commonly used for earthquakes occurring in eastern Canada. As part of a larger study to ensure uniformity of magnitudes across Canada for hazard assessments, MN magnitudes have been scrutinized and several problems, predominantly systematic inconsistencies, have been discovered. One of these is that for any given earthquake, stations in the Appalachians tend to underestimate magnitudes with respect to those in the Canadian Shield, suggesting possible differences in seismic attenuation. Analysis of site corrections and felt reports are consistent with this interpretation. Regional analysis of Lg amplitudes from high quality waveforms provides constraints on crustal attenuation with direct applications to magnitude scaling relations and strong ground motion estimates. The predominant uncertainty in the magnitude relations is the attenuation value prescribed. To reduce this uncertainty, velocity-windowed Lg rms amplitudes over a range of frequency bands (0.5-16Hz) and distances are used to determine crustal attenuation in both regions. An average, frequency-dependent Q(f) is determined using a single frequency Q inversion method for the Appalachian and Grenville provinces. The Lg-Q results show that attenuation is significantly higher in the Appalachians compared to the neighbouring Grenville (Shield) province. Magnitudes are recalculated for a suite of earthquakes in eastern Canada applying appropriate attenuation values for earthquake-station paths. Replacing the generic attenuation term with the new Lg-Q values consistently reduces and, in some cases eliminates the differences between Appalachian and Shield magnitudes. Our tests to date employ frequency-independent attenuation, and the next steps will be to evaluate the use of frequency-dependent attenuation in the magnitude relations.

NGA-East: A Ground Motion Characterization Model for Central and Eastern North America

GOULET, C. A., Southern California Earthquake Center, California, USA, cgoulet@usc.edu; BOZORGNIA, Y., University of California, Los Angeles, California, USA, yousef.bozorgnia@ucla.edu; ABRAHAMSON, N., University of California, Berkeley, California, USA, abrahamson@berkeley.edu; KUEHN, N. M., University of California, Los Angeles, California, USA, kuehn@ucla.edu; AL ATIK, L., Independent Consultant, California, USA, linda.alatik@gmail.com; YOUNGS, R. R., John Wood Group PLC, California, USA, bob.youngs@woodplc.com; GRAVES, R. W., U.S. Geological Survey, California, USA, rwgraves@usgs.gov; ATKINSON, G. M., Western University, London, Canada, gmatkinson@aol.com

The Next Generation Attenuation project for Central and Eastern North America (CENA), NGA-East, is a major multi-disciplinary project coordinated by the Pacific Earthquake Engineering Research Center (PEER). NGA-East involved a large number of participating researchers from various organizations in academia, industry and government and was carried-out as a combination of 1) a scientific research project and 2) a model-building component following the Seismic Senior Hazard Analysis Committee (SSHAC) Level 3 process. The science part of the project led to several data products and technical reports while the SSHAC component aggregated the various results into a ground motion characterization (GMC) model. The GMC model consists of a set of ground motion models (GMMs) for median and standard deviation of ground motions and their associated weights, combined into logic-trees for use in probabilistic seismic hazard analyses (PSHA).

The final NGA-East GMC model includes a set of 17 median models for hard rock sites defined for 24 ground-motion intensity measures, applicable to CENA in the moment magnitude range of 4.0 to 8.2 and covering distances up to 1500 km. Standard deviation models are also provided for site-specific analysis (single-station standard deviation) and for general PSHA applications (ergodic standard deviation). Adjustment factors are provided for consideration of source-depth effects, hanging-wall effects, and hazard computations for sites in the Gulf Coast region. We summarize the key features of the final NGA-East GMC model and we present hazard results.

The 2018 Lake Muir Earthquakes: Australia's Ninth Surface Rupturing Earthquake Sequence in 50 Years

ALLEN, T., Geoscience Australia, Canberra, Australia, trevor.allen@ga.gov.au; CLARK, D., Geoscience Australia, Canberra, Australia, dan.clark@ga.gov.au; LAWRIE, S., Geoscience Australia, Canberra, Australia, sarah.lawrie@ga.gov.au; BRENN, G., Geoscience Australia, Canberra, Australia, gregory.brenn@ga.gov.au; DIMECH, J., Geoscience Australia, Canberra, Australia, jesse.dimech@ga.gov.au; GARTHWAITE, M., Geoscience Australia, Canberra, Australia, matt.garthwaite@ga.gov.au; GLANVILLE, H., Geoscience Australia, Canberra, Australia, hugh.glanville@ga.gov.au; KEMP, T., Geoscience Australia, Canberra, Australia, tristan.kemp@ga.gov.au; LINTVELT, C., Australian Government Department of Defence, Canberra, Australia, cassandra.lintvelt@ga.gov.au; LUMLEY, D., The University of Texas at Dallas, Texas, USA, david.lumley@utdallas.edu; PEJIC, T., Geoscience Australia, Canberra, Australia, tanja.pejic@ga.gov.au; SAYGIN, E., The University of Western Australia, Perth, Australia, erdinc.saygin@uwa.edu.au; STANDEN, S., The University of Western Australia, Perth, Australia, 21117429@student.uwa.edu.au

A shallow M_W 5.3 earthquake near Lake Muir in southwest Western Australia on the 16 September 2018 was followed on the 8 November by a co-located M_W 5.2 event in the same region. Sentinel-1 synthetic aperture radar interferograms (InSAR) allowed for the timely identification and mapping of the surface deformation relating to both earthquakes. Field mapping, guided by the InSAR observations, revealed that the first event produced an approximately 3 km-long and up to 0.4 m-high west-facing surface rupture. Five seismic rapid deployment kits (RDKs) were installed in the epicentral region within three days of the 16 September event. These data, telemetered to Geoscience Australia's National Earthquake Alerts Centre, have enabled the detection and location of more than 750 dependent events up to M_L 4.6. Preliminary joint hypocentre relocation of aftershocks using data from RDKs confirms an easterly dipping rupture plane for the first M_W 5.3 event.

The main shocks were recorded throughout the Australian National Seismic Network, in addition to a local broadband network in the Perth Basin operated by University of Texas at Dallas and the University of Western Australia. These data indicate large long-period ground-motions due to *Rg* phases and basin amplification. The two main shocks were widely felt within the region, including the Perth metro region (300 km away), with over 2400 online felt reports for the 8 November event.

The Lake Muir sequence represents the ninth recorded surface rupturing earthquake in Australia in the past 50 years. All of these events have occurred in the Precambrian cratonic terranes of western and central Australia, in unanticipated locations. Paleoseismic studies of these ruptures found no evidence for regular recurrence of large events on the underlying faults. The events might therefore be considered "one-offs" at timescales of significance to typical probabilistic seismic hazard studies.

High-Resolution Topographic Analysis of the Late Quaternary Deformation of Crowley's Ridge, New Madrid Seismic Zone

JOBE, J. A. T., U.S. Geological Survey, Colorado, USA, jjobe@usgs.gov; GOLD, R. D., U.S. Geological Survey, Colorado, USA, rgold@usgs.gov; BRIGGS, R. W., U.S. Geological Survey, Colorado, USA, rbriggs@usgs.gov; DELANO, J., U.S. Geological Survey, Colorado, USA, jdelano@usgs.gov; STEPHENSON, W. J., U.S. Geological Survey, Colorado, USA, wstephens@usgs.gov; WILLIAMS, R., U.S. Geological Survey, Colorado, USA, rawilliams@usgs.gov

The New Madrid seismic zone in the central Mississippi Valley was the source of multiple major (M ~7.0-7.5) earthquakes in the past 2 ka, yet the surface expression of recent deformation remains ambiguous. Crowley's Ridge trends north-south for 300 km through the Mississippi River embayment and has been interpreted as either a fault-bounded uplift block or a non-tectonic erosional remnant. New and previously published seismic reflection data show primarily steeply-dipping apparent normal and reverse faults that bound the central and southern parts of the ridge, but the timing of most recent faulting and the lateral extent of these faults along the ridge remains unknown. Because of the uncertain origin and age of potential faults bounding Crowley's Ridge, the faults are currently not included in the CEUS-Seismic Source Characterization or the USGS National Seismic Hazard Model. To assess the proposed Pleistocene-to-recent tectonic activity of Crowley's Ridge, we use landscape-scale geomorphic analyses, such as patterns of relief, slope, hypsometry, and drainage basins, on a 10-m DEM. North-to-south variations in geomorphic indices suggest Pleistocene-to-recent tectonic uplift of the southern half of the ridge. In addition, using a <1-m lidar-derived DEM, we map scarps on late Pleistocene geomorphic surfaces. The scarps are primarily located along the southern segment of the ridge, trend parallel to the margin of the ridge discontinuously for 100 m to 1 km, and vertically offset <55 ka surfaces by 0.4 to 6 m. These landscape-scale deformation patterns and apparent fault and fold scarps, along with a synthesis of the seismic reflection data, provide evidence of low-rate (<0.2 mm/yr) late Quaternary tectonic activity along the southern segment of Crowley's Ridge. The interpretations are generally consistent with recent tectonic models suggesting the southern part of the ridge is an active compressional step-over in a right-lateral fault system within the Reelfoot Rift.

New Constraints on Reelfoot Fault Rupture, New Madrid Seismic Zone

DELANO, J., U.S. Geological Survey, Colorado, USA, jdelano@usgs.gov; BRIGGS, R. W., U.S. Geological Survey, Colorado, USA, rbriggs@usgs.gov; JOBE, J. A. T., U.S. Geological Survey, Colorado, USA, jjobe@usgs.gov; GOLD, R. D., U.S. Geological Survey, Colorado, USA, rgold@usgs.gov; ENGELHART, S. E., University of Rhode Island, Rhode Island, USA, engelhart@uri.edu

The Reelfoot fault in the New Madrid seismic zone is one of only a few documented Holocene-active faults in the central and eastern United States. Despite extensive geologic and geophysical investigation on the Reelfoot fault, historic and prehistoric fault rupture length remains uncertain, which is a necessary parameter for constraining potential earthquake magnitude. We investigate the southern extension of the reverse-slip Reelfoot fault in the Obion River valley, Tennessee, using high-resolution airborne lidar and field observations. We document evidence for broad folding and uplift of multiple late-Quaternary fluvial terrace levels that coincide with the projected surface trace of the Reelfoot fault. We test whether a monocline on the well-preserved Finley terrace (~25 ka) has a tectonic origin by comparing surface topographic profiles to stratigraphic constraints from a profile of three 7-m deep auger holes crossing the proposed surface projection of the fault. Surface profiles on the Finley terrace indicate >2 m of warping since terrace formation ~25 ka and agree with subsurface stratigraphy elevations from the auger profile. Older, higher terraces record progressive uplift and deformation on the Reelfoot fault hanging wall, which implies repeated earthquakes on this section of the fault. Modern floodplain constriction as well as historical and geomorphic records of repeated lake formation in the Obion River valley suggest coseismic fold scarp formation may have dammed the valley in the historic February 7th, 1812 earthquake as well as earlier events. This, along with terrace deformation, implies a long-lived (>30 ka) earthquake record in the Obion River valley. Our results place bounds on the southernmost extent of surface deformation on the Reelfoot fault for 1812-type events, which informs future seismic hazard models for this region.

Progress in Understanding the Geodynamics of the Eastern Tennessee Seismic Zone

LEVANDOWSKI, W., Tetra Tech, Inc., Colorado, USA, will.levandowski@tetratech.com; POWELL, C. A., University of Memphis, Tennessee, USA, capowell@memphis.edu

The Eastern Tennessee Seismic Zone (ETSZ) is an enigma. No large events have occurred historically, and no major rupture is documented paleoseismologically, but the natural rate of moment release—from small-magnitude earthquakes—is the second highest in the central and eastern United States. This presentation examines the ETSZ in the context of the tectonic and geodynamic setting of eastern North America as a whole, from the perspective of long-term stress accumulation. Stress inversions of focal mechanisms demonstrate that the ETSZ is anomalous, characterized by oblique-normal faulting that differs from the thrust faulting to the east and dominantly pure strike-slip faulting to the north and west. Additionally, in 3D density models of the crust and upper mantle (derived by simultaneously fitting gravity, topography, and seismic velocity), the ETSZ appears to host the most buoyant lower crust anywhere in the Southeast. This density model of eastern North America is fed into finite-element models of gravity-derived stress, which show that this buoyant material does indeed stress the overlying seismogenic crust in a way that encourages extension. By adding a regional, far-field tectonic stress—determined by optimizing fit to 3D stress tensors inverted from focal mechanisms—to this gravity-derived stress, it is possible to estimate spatial variations in long-term stress across the entire region. The ETSZ does host a modest high-stress anomaly, but preliminary models show that this anomaly alone does not account for the high rates of seismicity. Other factors such as low-viscosity lower crust or upper mantle, upper mantle dynamics, inherited crustal damage, or focused post-Miocene erosion may also contribute to the high rates of seismicity. Joint Pn/Sn tomography is underway to examine the former two possibilities. The remaining mystery notwithstanding, the ETSZ is demonstrably a distinct geodynamic feature, and future seismicity does appear to be most likely to recur in or near the known seismic zone.

Current and Future Challenges in Engineering Seismology

Oral Session · Thursday · 8:30 AM · 25 April · Pine

Session Chairs: Carlo Cauzzi, Ralph J. Archuleta, Fabrice Cotton, Nicolas Luco, Alberto Michelini, Stefano Parolai, Ellen Rathje, David Wald.

Physics of Near-Source Strong Ground Motions

KOKETSU, K., Earthquake Research Institute, University of Tokyo, Tokyo, Japan, koketsu@eri.u-tokyo.ac.jp

Some theories have been proposed for the cause of near-source strong ground motion. The rupture directivity effect is one that has been long studied and widely accepted, and its physics is clear. The fling effect was also proposed for the 1999 Chi-Chi, 2016 Kumamoto, and 2016 Norcia earthquakes, but its physics is unclear. Bolt and Abrahamson (2003) wrote "the other (cause) is due to the movement of the ground associated with the permanent offset of the ground." However, since both the permanent offset and strong ground motion are results of earthquake faulting, one of them cannot be a cause of the other.

Then, what is the physical entity of the fling effect? Hisada and Bielak (2003) mentioned that the fling effect "corresponds to mostly the static term." In their formulation, the static term is the time-independent part of the Green's function. Since ground motion is a convolution of the Green's function and slip time function, ground motion by the static term is proportional to slip time function. Among ground motions radiated from an earthquake, one proportional to slip time function is called "intermediate-field term." Dreger *et al.* (2011) already wrote so and "it is physically the sudden elastic rebound of the crust around the rupturing fault, which is called fling in the earthquake engineering community."

They also concluded from ground motion simulations for an Mw 6.5 earthquake: The fling effect "is only sensitive to the slip on the immediate fault surface and is very sensitive to the depth of burial of the fault" but "there are no observations in this very near-fault distance range (<100 m)." This means that there exists the fling effect for large slips shallower than 100m. For the 2016 Kumamoto earthquake, if a very shallow large slip exists, its fling effect and the rupture directivity effect by the upward rupture propagation, which all the source inversion results indicated, should produce extraordinarily large ground motions. But such ground motions have not yet been found.

What Is Fling Step? – Its Physics, Theoretical Simulation Method and Applications to Strong Ground Motion Near Surface Fault

HISADA, Y., Kogakuin University, Tokyo, Japan, hisada@cc.kogakuin.ac.jp; TANAKA, S., Toden Sekkei Co., Ltd., Tokyo, Japan, s.tanaka@tepsco.co.jp

Fling Step is displacement waveform like a step function accompanied by a permanent offset appearing in the very vicinity of the surface faulting. Despite its importance in Seismological and Engineering field, its physics and theory is not clear, and has been interpreted variously. For example, Dreger *et al.* (BSSA, 2011) interpreted it as the intermediate term of the elastodynamic equations of motion of Aki and Richards (2002). On the other hand, Koketsu *et al.* (Nature / Scientific Report 2016) interpreted it as the near field term. Here, Aki and Richards (2002) is a theoretical solution of a seismic point source in a homogeneous infinite medium (Eq. (4.32)), where it is separated into the near-, intermediate- and far-field terms.

However, the above interpretations of Fling Step are incorrect in the following points.

1. The static solution by a point source is contributed of both the near- and intermediate-terms, as presented in the equation (4.34) in Aki and Richards.

2. Since the actual ground medium is a complicated stratified half-spaces, it is not appropriated to use the solution of Aki and Richards to explain Fling Step.

3. Fling Step is the result of the elastic rebound near rupturing fault, it cannot be expressed by a point source, and it needs to be evaluated by considering the effect of the fault plane. In this case, even if the observation point approaches the fault plane, its amplitude does not diverge like a point source, but converges to a fault slip itself (Hisada and Bielak, 2003).

Hisada and Bielak (BSSA, 2003) defined Fling Step as "The contribution of static Green function in the representation theorem", which is valid in any ground media. Based on this definition, we proposed an efficient theoretical simulation method in layered half-space, and have released Fortran code for public use (http://kouzou.cc.kogakuin.ac.jp/Open/Green/). Here, we show the validity of the definition and show various simulation examples including the strong ground motions during the 2016 Kumamoto earthquake.

Double-Corner Source Spectrum Explains Earthquake Duration, Energy and High-Frequency Ground Motion

ARCHULETA, R. J., University of California, Santa Barbara, California, USA, ralph.archuleta@ucsb.edu; JI, C., University of California, Santa Barbara, California, USA, chen.ji@ucsb.edu; CREMPIEN, J. G. F., Pontificia Universidad Católica de Chile, Santiago, Chile, jocrempiend@uc.cl

We show that a double-corner source spectrum can reproduce the peak ground acceleration (PGA) and peak ground velocity (PGV) of the NGA West-2 data set for $5.3 \le M_W \le 7.7$. Earlier – Archuleta and Ji, GRL 2016 – we found an apparent moment rate function that reproduced PGA, PGV and PWA (peak Wood Anderson displacement) for $M_W \le 5.3$. This apparent moment rate also had two-corner spectrum. For $M_W \le 5.3$, the two corners scale with magnitude; however, *the scaling is different for magnitudes above and below 5.3*. For $M_W \ge 5.3$. The two corners f_{c1} and f_{c2} scale as $Log(f_{c1}) = 1.754 - 0.5M$and $Log(f_{c2}) = 3.250 - 0.5M$. Both corners are proportional to f indicating self-similar scaling with seismic moment. The lower corner f_{c1} is within 18% of the corner one would observe from the global CMT catalog, *i.e.*, it's inverse $1/(\pi f_{c1})$ corresponds to the duration of earthquakes found worldwide. Thus, the lower corner would be consistent with the average stress drop found for global earthquakes. Between f_{c1} and f_{c2} the acceleration spectrum is proportional to f. The acceleration spectral level at frequencies greater than f_{c2} is consistent with PGA and PGV for earthquakes in the NGA West-2 data. This high-frequency spectral level is proportional to the stress parameter used in time domain stochastic predictions of PGA and PGV. We find that the predicted radiated energy and the apparent stress agree with global estimates of these parameters for the same magnitude range. We will incorporate this two-corner spectrum into the UCSB method for broadband ground motion prediction.

Looking at the Between-Event Variability From the Source Parameters Point of View: A Test Case in Central Italy

BINDI, D., GFZ German Research Centre for Geosciences, Potsdam, Germany, bindi@gfz-potsdam.de; PICOZZI, M., University of Naples, Naples, Italy, matteo.picozzi@unina.it; SPALLAROSSA, D., University of Genoa, Genoa, Italy, daniele@dipteris.unige.it; COTTON, F., GFZ German Research Centre for Geosciences, Potsdam, Germany, fcotton@gfz-potsdam.de; KOTHA, S., GFZ German Research Centre for Geosciences, Potsdam, Germany, sreeram@gfz-potsdam.de

Ground-motion prediction equations (GMPEs) compute both the median predictions and the aleatory variability for any seismic scenario of interest. The between-event component of the aleatory variability absorbs repeated source effects that are not captured by magnitude differences among the analyzed earthquakes. The rapid increase of strong-motion data availability fostered studies aiming at partitioning the (apparent) aleatory variability by identifying repeatable event, source, or path effects, allowing for a seismological interpretation of specific residual component. Efforts for defining strategies to identify repeatable residuals took advantage of the availability of rich data sets. We analyze a data set of earthquakes that occurred in central Italy since 2008. We first isolate the source, propagation and site contributions to the S-waves Fourier spectra by applying a spectral inversion technique. Then, we develop a set of GMPEs to interpret the between-event residual distributions in terms of source parameters. Because different magnitude scales measure the earthquake size from different points of view, we also evaluate the impact of using moment (Mw), local (ML) or energy (Me) magnitude. We show that the between-event residuals obtained using Mw are correlated with stress drop, with correlation coefficients increasing with increasing frequency up to about 10 Hz. Contrariwise, the correlation is weak using ML and Me, in particular between 2 and 5 Hz, where most of the corner frequencies lie. The correlation with the source parameters reflects in a different behavior of the standard deviation tau of the between-event residuals with frequency. Although below 1.5 Hz tau is smaller for the GMPE using Mw, at higher frequencies the model implementing either ML or Me shows smaller tau, with a reduction of about 30% at 3 Hz. Finally, we show that the temporal changes of the between-event residuals resemble those of the stress drop which, in turn, mirrors the relative seismic-velocity variations observed in previous studies for the same area.

Insights From Residual Analyses for an Improved Parametrization of Ground Motion Models

KOTHA, S., GFZ German Research Centre for Geosciences, Potsdam, Germany, sreeram.reddy.kotha@gfz-potsdam.de; COTTON, F., University of Potsdam, Potsdam, Germany, fcotton@gfz-potsdam.de; BINDI, D., GFZ German Research Centre for Geosciences, Potsdam, Germany, bindi@gfz-potsdam.de; WEATHERILL, G., GFZ German Research Centre for Geosciences, Potsdam, Germany, gweather@gfz-potsdam.de

Every new generation of Ground-Motion Prediction Equations (GMPEs) supersedes the previous, owing to the expanding ranges of sampled magnitudes, distances, and local site conditions within the underlying ground-motion datasets. Indeed, large datasets reduce the epistemic uncertainty on GMPE median, but a reduction in residual aleatory variability has been difficult. Increasing ground-motion data, however, also means an increasing number of GMPE residuals. Advanced statistical techniques can be applied to these large datasets of GMPE residuals to quantify repeatable patterns indicative of the underlying physical processes; meaning new explanatory parameters can identified and introduced into the GMPEs to enhance their predictive power.

We used the largest engineering ground-motion datasets available worldwide to demonstrate the potential of exploratory residual analyses. With each of these datasets, we perform mixed-effects GMPE regressions to quantify the event, site, and record-specific residuals. On the site-specific residuals, we apply machine-learning techniques to classify stations with similar soil-response to seismic action, evaluate the physical meaning of such data-driven classifications and demonstrate the prospects of site-specific GMPEs at regional scales. From the record-specific residuals, which contain the path-effects, we find a previously undetected anisotropic shear-wave radiation pattern. Calibrating a cross-correlation model between theoretical and empirical shear-wave radiation coefficients, we could enhance the GMPEs to predict azimuth and style-of-faulting (depth and focal-mechanism) dependent distance attenuation. With these additional improvements to the ground-motion predictions we are able reduce the GMPE aleatory variability, which can help substantially in improving the estimation of seismic hazard and risk. Continued assimilation of ground-motion data and thorough event and site characterization, combined with the adoption of advanced statistical tools, will be indispensable to the future of ground-motion prediction.

Investigation of Ground Motion Variability Due to Source Complexities

SIVASUBRAMONIAN, J., King Abdullah University of Science and Technology, Thuwal, Saudi Arabia, jayalakshmi.sivasubramonian@kaust.edu.sa; MAI, P., King Abdullah University of Science and Technology, Thuwal, Saudi Arabia, martin.mai@kaust.edu.sa

We analyze the effect of source parameters in variability of ground motions, simulated in the near field region of large earthquakes. We quantify variabilities in simulated Peak Ground Velocity (PGV) and Spectral Accelerations (Sa) with respect to observed records and GMPE-based predictions. We compute independently, the variabilities due to complexities in source that include slip distribution, hypocenter location, rupture velocity and rise time.

In this study, we consider two past events – Mw 6.9 Iwate Miyagi Earthquake (2008), Japan and Mw 6.5 Imperial Valley Earthquake, California (1979). Assuming a 1D velocity structure, the rupture models are generated using the pseudo-dynamic approach of Guatteri *et al.* (2004) for different slip distributions (Mai and Beroza, 2002, Thingbaijam and Mai, 2016). We create a database of rupture models, 50 scenarios for each source parameter. Synthetic low-frequency waveforms (0.1-2Hz) are computed in the near field region (Rjb <150km) using the discrete-wavenumber finite element method of Olson *et al.* (1984). Our results show a large reduction in variability by fixing hypocenter locations on the fault plane. We also find that locations of asperities do not alter the waveforms significantly for a given hypocenter, rupture velocity and rise time distribution. We analyze the variabilities in these waveforms at few near field stations and conjecture that as the rupture propagates towards these sites, the on-fault rupture evolution and radiation-pattern effects are similar for all the rupture models. We also compare our results with SCEC-calibrated methods (*e.g.* GP2016).

Application of Directivity in PSHA and the Effect of Centering

WATSON-LAMPREY, J., Slate Geotechnical Consultants, California, USA, jwatsonlamprey@slategeotech.com; MURPHY, D., Slate Geotechnical Consultants, California, USA, dmurphy@slategeotech.com

The PEER Working Group report on Ground Motion Directivity Modeling for Seismic Hazard Applications is expected to be released early this year. This multi-year effort aims to provide recommendations for incorporating directivity effects from models developed during the NGA-West2 project into probabilistic seismic hazard analyses. The modeling of directivity is a complex problem due to the limited data available from large magnitude and near fault data, and the development of the majority of the models only after the ground motion models have been completed, instead of incorporated within them.

While the draft Ground Motion Directivity Modeling for Seismic Hazard Applications recommendations find that all of the directivity models considered are suitable for application to capture the effects of directivity, not all of the models are centered, as they were originally developed to be included in a ground motion prediction equation. The impact of centering on the directivity effect can be large and have a significant impact on the results of the probabilistic seismic hazard analysis.

Example seismic hazard analyses are performed in the Bay Area and Los Angeles to demonstrate the effect of the individual directivity models recommended in the draft report. The draft recommendations from the PEER report were implemented as a suite of directivity models to demonstrate the effect of the recommendations.

Additionally, to examine the effect of centering, a model was developed to center each of the directivity models and was then applied accordingly. To demonstrate the impact of centering on individual earthquakes, scenarios are presented and the change in the mean ground motion due to centering is shown. The example analyses are then rerun with the newly centered models to demonstrate the cumulative effect on probabilistic seismic hazard analyses. Recommendations are provided in the near term for centering models, and incorporating directivity parameters into ground motion models directly in the long term.

Overcoming Limitations of Ergodic GMPEs: Properly Separating Earthquake Source and Path Terms

WOODDELL, K. E., Pacific Gas and Electric Company, California, USA, katie.wooddell@gmail.com; ABRAHAMSON, N., University of California, Berkeley, California, USA, abrahamson@berkeley.edu

Ergodic ground motion prediction equations (GMPEs) are based on an average 1D velocity model and constant scaling. As a result, earthquake path terms, captured by the distance scaling, are the same everywhere, independent of location and azimuth. Standard regression methods for GMPEs include a random effect (constant) for the source term. As a result, if there are differences in the path effects for two earthquakes with equal magnitude, the path differences can be mapped into the random effect for the source term. The inability to separate source and path terms is a limitation of the ergodic framework. Non-ergodic GMPEs solve this problem because 3D velocity models and spatially-varying coefficients allow for differences in path effects for different locations and azimuths which provides for the proper separation of source and path terms.

The non-ergodic approach relies on the use of spatially-varying correlated coefficients to adjust each of the terms in the ergodic GMPE to the non-ergodic condition. The coefficients are typically plotted in map view to show the spatial variability and correlation length of each term. When viewing maps of the spatially-varying coefficient terms; however, there is a tendency to try to interpret the spatial coefficients separately, rather than as correlated sets, leading to strange implications. For example, when the source and geometrical spreading coefficients are plotted on a map, there is a clear inverse correlation between the source and geometrical spreading coefficients that can be interpreted as the ground-motion path effects still being mapped into the source term in the non-ergodic framework. To demonstrate this is not the case, we isolate the source effects by showing ground motion differences between non-ergodic and ergodic models at short distances (≤ ~10 km) where path effects are minimal.

A Non-Ergodic GMPE for Europe and the Middle East With Spatially Varying Coefficients

KUEHN, N. M., University of California, Los Angeles, California, USA, kuehn@ucla.edu; LANDWEHR, N., Leibniz Institute for Agricultural Engineering and Bioeconomy Potsdam-Bornim, Potsdam, Germany, landwehr@cs.uni-potsdam.de; KOTHA, S., GFZ German Research Centre for Geosciences, Potsdam, Germany, sreeram@gfz-potsdam.de

We estimate a fully non-ergodic ground-motion model using strong-motion data from Europe and the Middle East. The model is cast as a varying coefficient model (VCM), where the coefficients are allowed to vary by geographical location. This makes it possible to incorporate the spatially varying source, path and site effects. Different effects are modeled by different coefficients in the model, which depend on source and/or site coordinates. The model places a Gaussian process prior on the coefficients, which automatically constrains the repeatable effects to be similar for locations that are spatially close. The amount of correlation (the correlation length scale) is determined by the data. The VCM outperforms a classical, ergodic ground-motion prediction equation (GMPE) in terms of generalization error, estimated by cross-validation. Compared to the ergodic GMPE, the value of the aleatory standard deviation is reduced, which has important consequences for seismic hazard calculations. The reduction in aleatory variability trades off with changes in the median predictions for different locations.

The spatial correlation structure of the model makes to possible to extrapolate the model to new source/site locations, and trace the corresponding uncertainties. Predictions for source/site coordinates that are close to observed data are associated with small predictive uncertainty, while the uncertainty for locations lacking observations in the vicinity is large.

The results show strong differences in eh systematic effects between Italy, Greece, and Turkey, as well as within those regions. The correlation length scales are similar to those observed for a similar model in California.

Hybrid Ground Motion Prediction Equations for Southern Italy

LANZANO, G., Istituto Nazionale di Geofisica e Vulcanologia, Milan, Italy, giovanni.lanzano@ingv.it; D'AMICO, M., Istituto Nazionale di Geofisica e Vulcanologia, Milan, Italy, maria.damico@ingv.it; SANTULIN, M., Istituto Nazionale di Oceanografia e Geofisica Sperimentale, Trieste, Italy, msantulin@inogs.it

HYPSTHER (HYbrid ground motion prediction equations for PSha purposes: the study case of souTHERn Italy) is a research project funded by INGV (Istituto Nazionale di Geofisica e Vulcanologia), mainly devoted to the development of ground motion prediction models, based on the integration between recorded and synthetic data (hypsther.mi.ingv.it). We selected the Southern Italy (Calabria and Sicily regions), as study area, since the expected hazard is high, but the seismic activity was scarce in the last decades.

We present some specific project results, concerning the calibration of the Ground Motion Prediction Equations (GMPEs) for the study area. We developed an empirical GMPEs (SI17ref) for shallow active crustal regions in Southern Italy (for PGA and SA at 0.3, 1, and 3s), introducing a site category for the reference rocks in the functional form, in order to predict the ground motion of sites unaffected by soil amplifications. These empirical GMPEs are not well constrained in near fault conditions, since very few recordings are available at distance lower than 10km.

Within the project, we produced a dataset of more than 180.000 synthetic records for hard rock condition according to two different simulation methods to model (1) a set of finite sources in the magnitude range 5.0-7.5 and (2) point-like sources characterized by lower magnitudes. We developed a methodology to derive the hybrid GMPEs (SI17hyb). Model predictions are larger with respect to SI17ref in near-fault conditions for PGA and lower magnitudes. At distances larger than 50km, SI17hyb predictions are controlled by empirical data, because they attenuate faster with distances, with respect to simulated data.

Since the standard deviation (σ) of the total residuals of GMPEs has a strong influence on the results of PSHA, we propose a heteroscedastic model for SI17hyb, including a dependence on magnitude. We also investigated the dependence of the stress parameter, which is an input parameter of the numerical simulations, on the GMPEs predictions and associated standard deviation.

Which Is a Better Proxy, Site Period or Depth, in Modelling Linear Site Response in Addition to the Average Shear-Wave Velocity?

ZHU, C., GFZ German Research Centre for Geosciences, Potsdam, Germany, chuanbin.zhu@hdr.qut.edu.au; COTTON, F., GFZ German Research Centre for Geosciences, Potsdam, Germany, fcotton@gfz-potsdam.de; PILZ, M., GFZ German Research Centre for Geosciences, Potsdam, Germany, pilz@gfz-potsdam.de

This study aims to identify the best site parameter to characterize empirical linear site response in addition to the conventional average shear-wave velocity. KiK-net database is utilized, and site amplification is calculated as the surface-to-borehole spectral ratios. To minimize the influence of inhomogeneous site condition at borehole stations, we include only stations of which downhole shear-wave velocity is more than 800 m/sec. Meanwhile, we rule out nonlinearity by using only ground motions of which maximum shear-strain within a soil profile below the minimum level of a possible nonlinear effect. Besides, sites with less than three records are excluded. Finally, we selected 1840 ground-motion records (six components per record) with rupture distance up to 400 km, with corner-frequency no lower than 0.12 Hz, with signal-to-noise ratio more than three and from seismic events with moment magnitude between 3.0 and 8.0.

The linear site amplification is modelled using VSz (shear-wave velocity averaged to a depth z, where z=5, 10, 20, 30 m) as a primary site proxy, and then residuals after VSz correction are modelled using an additional site parameter as a secondary proxy, *i.e.*, T0 (site fundamental period) and Zx (site depth in meters to a layer having shear-wave velocity x, where x=0.8, 1.0, 1.5, and 2.5 km/sec). T0 was derived using the H/V technique of earthquake records. Both measured Zx from velocity profiles and inferred Zx from a regional velocity model (J-SHIS) are considered. The performances of secondary site parameters are then gauged based on the reduction in site-to-site variability due to their incorporations. Our preliminary results show that T0 is preferred as a secondary proxy over Zx to be used together with VS30 to model linear site response.

Evidence on the Effect of Weather Seasons on Soil Response

ROUMELIOTI, Z., Aristotle University of Thessaloniki, Thessaloniki, Greece, zroum@auth.gr; HOLLENDER, F., CEA - DEN - Cadarache, Saint Paul lez Durance, France, fabrice.hollender@cea.fr; GUÉGUEN, P., ISTerre, University Grenoble-Alpes / USMB / CNRS / IFSTTAR / IRD, Grenoble, France, philippe.gueguen@univ-grenoble-alpes.fr

We analyze ground acceleration time histories of the ARGONET (Argostoli, Cephalonia Isl., Greece) vertical array with interferometry by deconvolution aiming to studying the relation between changes in soil moisture due to rainfall and shear-wave velocity, V_S, variations. We identify a clear, cycling pattern in the variation of V_S at shallow depths, which correlates negatively to rainfall height and a soil moisture proxy. Lower V_S values are observed during the raining season and highest values during the dry summer, the overall variation being of the order of 20-25% within the shallowest examined depth interval (0-5.6m) and estimated up to 40% within the top 2m. Interferometry results are verified by an independent surface waves dispersion analysis, using ambient vibration data collected by a temporary, small-aperture array of 6 seismometers that was installed for several months at the ARGONET site. Phase velocity at high frequencies (>13 Hz) was found to be significantly different when data from rainy and dry seasons were examined. Further comparison of standard spectral ratios based on synthetic and actual earthquake data suggests that the seasonal variation of V_S values is capable of causing differences in the level of high frequency ground motion between dry and rainy seasons. During our analysis we also identified sporadic V_S values that deviated from the cycling pattern toward even lower values than those observed during the rainy seasons. We attributed these values to nonlinear response of the soil formations, *i.e.*, providing evidence for deviation from the linear stress-strain relationship at shaking levels lower than what is commonly believed (circa 30 cm/s^2). Such deviations seem to appear systematically at the studied site but are often "masked" by the seasonal cycling pattern of V_S, which differs during the replenishment and depletion phases of soil moisture.

Application of Mean Spectral Matching of Time Histories

HUDSON, K. S., John Wood Group PLC, California, USA, kenneth.s.hudson@gmail.com; HUDSON, M. B., John Wood Group PLC, California, USA, marty.hudson@woodplc.com; MAZZONI, S., Structural & EQ Engineering Consultant, California, USA, silviamazzoni@yahoo.com; LEW, M., John Wood Group PLC, California, USA, marshall.lew@woodplc.com

Performance-based design of buildings requires development of one or more suites of acceleration time-histories modified to result in response spectra (RS) that individually or in the aggregate are similar to a target RS. A method of modifying time histories such that the mean of the ground-motion suite matches the target spectrum was introduced by Mazzoni *et al.*, in 2012 and has now been expanded upon and implemented in practice in a number of projects in California. The method has been approved by peer review panels for the aforementioned California projects in such a way that the suite of spectra does not suffer the 10% penalty implemented in ASCE 7-16 on time histories that are tight-spectral matched (where each record is modified to match the target spectrum). The reasoning for the penalty in ASCE 7-16 is that tight spectral matching modifies the time histories to a point that they have lost their original waveform characteristics and because the suite of time history spectra all collapse onto the target so that the record-to-record and period-to-period variability and dispersion of the as-recorded suite is lost. The method of mean spectral matching avoids these problems by slightly modifying each time history such that the average of the suite of spectra matches the target spectrum, which is the goal of modification of time histories to meet building-code standards. The method of mean spectral matching can be applied to a multitude of different types of target spectra such as Uniform Hazard Spectrum (UHS) and Conditional Mean Spectrum (CMS). The method can also be applied to the current codes that apply the method of making the average of a suite of time history spectra meet a certain target requirement such as ASCE 41-13, 41-17, 7-10, 7-16, and codes that reference those. We have applied it by matching the average of RotD100, SRSS, and Fault Normal spectra of suites ranging from 7 to 11 time histories. The objective of this paper is to describe the method and provide examples of how it is applied to engineering projects to meet building-code requirements.

Extension of the Adaptable Seismic Data Format (ASDF) for Applications in Engineering Seismology

KOTTKE, A. R., Pacific Gas and Electric Company, California, USA, arkk@pge.com; THOMPSON, E. M., U.S. Geological Survey, Colorado, USA, emthompson@usgs.gov; STEIDL, J. H., University of California, Santa Barbara, California, USA, steidl@eri.ucsb.edu; AAGAARD, B., U.S. Geological Survery, California, USA, baagaard@usgs.gov

We propose an extension to the Adaptable Seismic Data Format (ASDF) for storing ground-motion intensity metrics for engineering seismology applications. The resulting data format provides a single file containing information related to the earthquake rupture, recording station, ground-motion time series, intensity metrics, and the provenance information (describing the source of the data and any subsequent processing). Typically this information has come from multiple sources and is in a variety of formats, creating obstacles to assimilating it into a common data management structure. Storing and sharing this data in a common and standardized structure will reduce the time spent on collection and migration, reduce errors and inconsistencies, and facilitate analysis with different software or programming languages.

Krischer *et al.* (2016) leveraged standard seismic data formats in developing the Hierarchical Data Format (HDF5) -based Adaptable Seismic Data Format (ASDF) container to store information about the earthquakes sources, ground-motion time histories, seismic station metadata, and the associated provenance information for use in full-waveform tomographic inversions. Krischer *et al.* provided a flexible means of including additional information through auxiliary data, as well as a C/Fortran library and a Python module to facilitate reading/writing data in the ASDF format. We propose a specific organization for ground-motion intensity metrics, such as peak amplitudes, response spectra, Arias intensity, duration, etc, within the auxiliary data. The HDF5-based ASDF container can hold data for one earthquake or a collection of earthquakes; the container is also suitable for storage of synthetic data associated with earthquake scenarios. We will present the data layout of our proposed extension of the ASDF container and examples illustrating common use cases for engineering seismology applications.

The New Shakemap in Italy: Progress and Advances in the Last 10 Years

MICHELINI, A., Istituto Nazionale di Geofisica e Vulcanologia, Rome, Italy, alberto.michelini@ingv.it; FAENZA, L., Istituto Nazionale di Geofisica e Vulcanologia, Rome, Italy, licia.faenza@ingv.it; LANZANO, G., Istituto Nazionale di Geofisica e Vulcanologia, Milan, Italy, giovanni.lanzano@ingv.it; PUGLIA, R., Istituto Nazionale di Geofisica e Vulcanologia, Milan, Italy, rodolfo.puglia@ingv.it; LAUCIANI, V., Istituto Nazionale di Geofisica e Vulcanologia, Rome, Italy, valentino.lauciani@ingv.it; RUSSO, E., Istituto Nazionale di Geofisica e Vulcanologia, Milan, Italy, emiliano.russo@ingv.it; LUZI, L., Istituto Nazionale di Geofisica e Vulcanologia, Milan, Italy, lucia.luzi@ingv.it

We describe the new configuration of the Italian ShakeMap service provided by INGV. It features i.) the adoption of recently developed GMPEs and Vs,30 grid map values for the evaluation of local site effects, and ii.) the adoption of the newly developed USGS-ShakeMap version 4 software. We adopted a subdivision in zones with the same tectonic regime, after the the 2016 Italian seismic hazard model (MPS16, Meletti *et al.*, 2017). The most appropriate GMPEs were selected after performing a ranking of the available and most suited GMPEs for the individual tectonic regions. Notably, we have adopted the new USGS-ShakeMap (v4) software (https://github.com/usgs/shakemap) which relies on the large library of GMPEs modules provided by the OpenQuake platform (https://www.globalquakemodel.org/tools-products). The Italian territory and adjacent areas has been subdivided into 4 tectonic regions - shallow active, deep active, Calabrian subduction and volcanic areas. We have found that the ITA10 (Bindi *et al.*, 2011) fits nicely the data for the shallow active crustal regions; the Bindi *et al.* (2014) relation is appropriate for the deep active region (depths>35 km); the Abrahamson et al (2016) is adopted for the subduction zone and the Tusa and Langer (2016) is proper for the volcanic areas (Aetna, Aeolian, Vesuvius and Phlegraean Fields volcanos). The Vs,30 map used for site corrections is based on the EC8 soil categories (A, B and C). The new configuration has been validated adopting the leave-one-out approach of comparing the interpolated value at the recording station with that observed. We have used 166 earthquakes for a total of about 9,000 intensity measures. The new configuration reduces significantly the ground motion bias and the number of data outliers with respect to the the original shakemap configuration (Michelini et al, 2008). Finally, the INGV system for the generation of the maps of ground shaking has been renovated to exploit fully the entire data/analysis chain implemented at INGV from the real-time data streams to the revised strong-motion waveforms.

Problem Unsolved: Knowledge Gaps at the Intersection of Earthquake Engineering Practice and Research

Oral Session · Thursday · 4:00 PM · 25 April · Pine

Session Chairs: Gilead Wurman, Youssef M. A. Hashash, Shahriar Vahdani, Brady Cox, Albert Kottke, Recep Cakir, Bahareh Heidarzadeh, David P. Teague, Gilead Wurman.

Bridging the Gap Between Input Motion Selection Protocols and Geotechnical Engineering Analyses

CABAS, A., North Carolina State University, North Carolina, USA, amcabasm@ncsu.edu; CHOWDHURY, I., North Carolina State University, North Carolina, USA, ichowdh@ncsu.edu; KAKLAMANOS, J., Merrimack College, Massachusetts, USA, kaklamanosj@merrimack.edu; KOTTKE, A. R., Pacific Gas and Electric Company, California, USA, arkk@pge.com; GREGOR, N., Consultant, California, USA, nick@ngregor.com

The importance of properly characterizing ground motion intensity measures for seismic hazard assessment is unequivocally large. Multiple protocols populate the literature concerning ground motion selection for building seismic design and performing response-history analysis; however, none of these guidelines has a particular focus on ground motions required for geotechnical engineering analyses. The overall goal of this study is to investigate the impact of input motion selection protocols on ground motion intensity measures that are most significant for geotechnical analyses, including site response, liquefaction, and seismic slope stability analyses. This study compares current practices for input motion selection, and investigates their impact on the uncertainty in critical ground motion intensity measures. Comprehensive ground response analyses are performed at two study sites, one in Seattle, WA, and the other in Boston, MA. These sites not only represent different geological and geotechnical conditions, but also different tectonic environments. Multiple sets of input motions are obtained from different definitions of the target spectrum (*e.g.*, uniform hazard and conditional mean spectra). In addition, the effects of scaling and spectral matching techniques are explored, and insights are provided on the ground motion intensity measures most sensitive to the selection of the input motion. Finally, recommendations are provided for ground motion selection for geotechnical engineering applications, and suggestions for future research in this area are proposed.

Comparison of the Seismic Design Procedures of ASCE 7-16 With Non-Ergodic Site Response Analyses

HEIDARZADEH, B., ENGEO Incorporated, California, USA, bheidarzadeh@engeo.com; TEAGUE, D. P., ENGEO Incorporated, California, USA, dteague@engeo.com

In an effort to address a shortcoming of ASCE 7-10 related to equivalent lateral force and modal response spectrum procedures for design of long period buildings on soft-soil sites, ASCE 7-16 enforces new criteria for development of risk-targeted maximum rotated (MCE_R) and design earthquake (DE) response spectra to capture the missing long period amplification. These modifications include, but are not limited to, the following cases:

Modified site-speicfic analysis requirements for Site Classes D and E
Modified deterministic lower limit spectrum
Modified design acceleration parameters

The modifications are based on a series of ergodic site-specific deterministic seismic hazard analyses (SHA) and a limited number of probabilistic SHA as described in Kircher (2015). This study found that the shapes of the response spectra were not accurately represented by the shape of the design response spectrum of ASCE 7-10 Figure 11.4-1 for the following condition: (1) Site Class D where $S_1 \geq 0.2$; and (2) Site Class E where $S_S \geq 1.0$ and/or $S_1 \geq 0.2$. Therefore, specturm adjustment factors developed by Kircher (2015) were implemented in Chapter 21 of ASCE 7-16 to adjust the previously underestimated spectral accelerations at long periods. These modifications are an interim solution until multi-period MCE_R and DE spectra directly incorporate site, basin, and other effects that influence the shape of the spectra.

We report results of SHA performed for multiple structures in the San Francisco Bay Area, using non-ergodic site response models as described in Stewart *et al*. (2017). These analyses replace global site amplification functions used in ground motion models with site-specific amplification functions derived from evaluation of local ground motion records and deep ground response analyses. Similar to Kircher (2015), results of our analyses confirm the shortcoming of ASCE 7-10 at long periods. However, our analyses indicate that modified guidelines of ASCE 7-16 sometimes overestimate spectral acceleration below the site period and underestimate it at higher periods.

Washington State School Seismic Safety Project: Soil Seismic and Structural Assessments at 220 K–12 School Buildings

WEST, L. T., Washington Geological Survey, Washington, USA, travisimo311@yahoo.com; NIELSON, T., Washington Geological Survey, Washington, USA, travis.nielson@dnr.wa.gov; CAKIR, R., Independent Researcher, cakir.recep@gmail.com; FORSON, C., Washington Geological Survey, Washington, USA, corina.forson@dnr.wa.gov

The Pacific Northwest ranks second in the nation in earthquake risk. Close to 70% of Washington schools are situated in high seismic zones and over a third of permanent school buildings were constructed with building codes that did not incorporate current estimates of shaking from Cascadia and Seattle fault earthquakes. School facilities have therefore become a top priority for seismic risk assessment in the State. To identify potential seismic vulnerability at schools, the Washington Geological Survey (WGS), in coordination with the Office of the Superintendent of Public Instruction, began implementing a comprehensive two-phase strategy for seismic assessment based on early pilot studies completed in 2010–2017. This project couples detailed engineering screenings by structural engineers with a site-specific site-class assessment. In 2018, WGS expanded its work from two school districts to 74. The Survey coordinated tier-1 screenings, performed by licensed structural engineers per American Society of Civil Engineers 41-17, and conducted site-class assessments at 95 school sites and five fire stations. The engineers screened 220 buildings for tier-1 and produced 15 concept-level seismic upgrade designs. Site-class assessments used multi-channel analysis of surface waves and the microtremor array method to determine shear wave velocity profiles. Refraction data and horizontal-to-vertical spectral ratios of microtremor were also incorporated into the assessment to identify horizontal changes in soil layers and determine site dominant period, respectively. Of the 95 sites assessed, 29 have measured site-classes that differ from those previously predicted by a statewide site-class map based mainly on 1:100,000-scale geologic maps too general for site-specific assessments. Changes in site-class can significantly impact cost of retrofit by altering design requirements, further demonstrating the value of a two-phase comprehensive seismic assessment for Washington schools.

Importance of Rotational Ground Motions on Seismic Response of Tall Buildings

SAFAK, E., Bogazici University, Kandilli Observatory and Earthquake Research Institute, Istanbul, Turkey, erdal.safak@boun.edu.tr; ÇAKTI, E., Bogazici University, Kandilli Observatory and Earthquake Research Institute, Istanbul, Turkey, eser.cakti@boun.edu.tr

Rotational components of earthquake ground motions are currently not accounted for in seismic design codes. However, records from ground stations and instrumented buildings clearly indicate that rotational components of ground shaking can be an important factor in seismic response of buildings, particularly tall buildings.

In this study, we first identify the rotational components of ground motions by analyzing the data from a T-shaped, 22-station short aperture seismic array with station separations varying from 5 to 100 meters. The array is on the grounds of Air Force Academy in Istanbul at a soft soil site near the airport. The records show that the rotational excitations are generated mainly by the displacement gradient of travelling Rayleigh waves.

In order to see the effects of ground rotations on structural response, we have calculated the seismic response of a tall building at that site first by neglecting and then by considering the rotational components of ground accelerations recorded during an M=6.5 earthquake. The results show that rotational components have a significant influence on the response of the building.

Rotational Motions Extracted From Delaney Park Downhole Array in Anchorage, Alaska

GRAIZER, V., U.S. Nuclear Regulatory Commission, District of Columbia, USA, vladimir.graizer@nrc.gov; KALKAN, E., U.S. Geological Survey, California, USA, ekalkan@usgs.gov

Strong-ground motion data recorded at the Delaney Park Geotechnical Array during a number of earthquakes including the 2018 M7.0 Anchorage Alaska event were used to extract rotational motions at different depths and different levels of shaking. The downhole array is located in downtown Anchorage, about a city block from the Atwood building, also instrumented. The ground motions are measured at the surface and at six levels below the surface (up to 61 m depth) using three-component borehole accelerometers that record motions in the glacial outwash sediments near the surface, the sensitive clays of the bootlegger cove formation and at its deepest into the glacial till. Only few direct reliable measurements of rotational component of strong-ground motions from earthquakes are obtained so far. In the meantime, high quality earthquake data recorded at downhole arrays provide an opportunity to estimate deformations based on the differences in recordings at various depths. Deformation or simple shear strain with the rate γ is the combination of pure shear strain with the rate $\gamma/2$ and rotation with the rate $\alpha = \gamma/2$. High level rotational motions, especially tilting may have adverse effects on tall buildings and bridges. High dynamic range, well synchronized and properly oriented instrumentation is necessary for reliable calculation of rotations from downhole array data. So far, the largest rotation of 0.60E-03 rad was observed at the Eureka downhole array corresponding to ground velocity of 35 cm/s during the 2010 M6.5 Ferndale earthquake in Northern California. The largest rotation rate of 0.55E-02 rad/s associated with the S-wave was observed at an epicentral distance of 4.3 km during the M_L 4.2 event in Southern California at the La Cienega downhole array (Graizer, 2017).

Advances in Tectonic Geodesy

Oral Session · Thursday · 8:30 AM · 25 April · Puget Sound
Session Chairs: Noel Bartlow, Kang Wang.

Deformation Model Inversion Dependency on GNSS Series Characteristics

PARKER, J., Jet Propulsion Laboratory, California Institute of Technology, California, USA, jay.w.parker@jpl.nasa.gov; DONNELLAN, A., Jet Propulsion Laboratory, California Institute of Technology, California, USA, andrea@jpl.caltech.edu; GROSS, R., Jet Propulsion Laboratory, California Institute of Technology, California, USA, richard.s.gross@jpl.nasa.gov; HEFLIN, M., Jet Propulsion Laboratory, California Institute of Technology, California, USA, michael.b.heflin@jpl.nasa.gov; MOORE, A., Jet Propulsion Laboratory, California Institute of Technology, California, USA, angelyn.w.moore@jpl.nasa.gov

Geophysical signals from plate motions, earthquakes and other deforming processes may be used to constrain models of the source and rheology, but this task requires adequate characterization of the observing system. For GNSS time series important characteristics include regional common mode error, temporal correlations, spatially correlated modes from other processes, and background noise. All of these features vary somewhat with the analysis center that supplies the time series. We compute characteristics for public time series supplied by the Jet Propulsion Laboratory, Nevada Geodetic Laboratory, UNAVCO, and Scripps Institute of Oceanography. The different characteristics of each center's time series sets give rise to different tables of coseismic jump and uncertainty at each station, leading to variation in fault slip and uncertainty that is linked to each center's choice of processing steps. Station jump estimates may differ by several mm, and uncertainty estimates by methods that neglect temporal correlation may be less than half of correct values, overconstraining inversions.

We apply these distinct characteristics to fitting models of fault slip from the M6 2004 Parkfield and M5.1 2014 La Habra earthquakes, and the 2012 Brawley Swarm event. The GeoGateway Simplex application will be used for nonlinear inversion, as a representative of inversion processes that process coseismic surface deformation with error ellipses. In this way we illuminate some of the subtle ways the characteristics of processing center time series sets affect geophysical models, providing guidance for selection and mitigation of imperfect observations.

A 3D Finite Element Model to Investigate Elastic Heterogeneity and Topography Effects on 2010 Mw 7.2 El-Mayor Cucapah Earthquake Coseismic Deformation Using Space Geodetic Data

PULVIRENTI, F., Jet Propulsion Laboratory, California Institute of Technology, California, USA, fabio.pulvirenti@jpl.nasa.gov; LIU, Z., Jet Propulsion Laboratory, California Institute of Technology, California, USA, zhen.liu@jpl.nasa.gov; ALOISI, M., Instituto Nazionale di Geofisica e Vulcanologia, Catania, Italy, marco.aloisi@ingv.it

The 4 April 2010 Mw 7.2 El Mayor-Cucapah (EMC) earthquake, provides a good opportunity to investigate the complex dynamic processes of transform plate boundary, where the response of the lithosphere to seismic events is influenced by the interaction among multiple faults, lithospheric heterogeneities, and topographic effects. Most of existing studies represent the EMC area as an elastic half-space or layered structure or assume overly simplified fault configurations, which leads to considerable variability in resultant fault slip models. To investigate the effects of fault geometry, surface topography and elastic heterogeneities, we developed a sophisticated realistic 3D finite element model that includes multiple faults, a digital elevation model and material heterogeneities obtained from seismic tomography studies. We first performed a series of benchmark tests to validate the model performance against analytical solution. We then run realistic forward models to assess the goodness of one of the most recent published fault slip distribution, by comparing the surface displacements predicted from our models with observations. Several comparisons were made to investigate the effects of topography and material heterogeneities on the surface displacement field computed numerically. Finally, in order to improve the chosen fault slip distribution, we performed a series of inverse models using the optimization code SNOPT. Available surface geodetic deformation data (GPS and InSAR) were used to find a new slip distribution capable to produce surface displacements that provide better fits to the observations. Checkerboard tests with synthetic datasets were used to quantify the resolution of our results.

Fusing GNSS, InSAR and Imagery to Improve Spatio-Temporal Measurement of Crustal Deformation in the Salton Trough

DONNELLAN, A., Jet Propulsion Laboratory, California Institute of Technology, California, USA, andrea@jpl.caltech.edu; PARKER, J., Jet Propulsion Laboratory, California Institute of Technology, California, USA, jay.w.parker@jpl.nasa.gov; HEFLIN, M., Jet Propulsion Laboratory, California Institute of Technology, California, USA, michael.b.heflin@jpl.nasa.gov; GRANAT, R., Jet Propulsion Laboratory, California Institute of Technology, California, USA, robert.granat@jpl.nasa.gov; LYZENGA, G., Jet Propulsion Laboratory, California Institute of Technology, California, USA, lyzenga@g.hmc.edu; GLASSCOE, M., Jet Propulsion Laboratory, California Institute of Technology, California, USA, margaret.t.glasscoe@jpl.nasa.gov; GRANT LUDWIG, L., University of California, Irvine, California, USA, lgrant@uci.edu; RUNDLE, J. B., University of California, Davis, California, USA, john.b.rundle@gmail.com; WANG, J., Indiana University, Indiana, USA, wang208@iu.edu; PIERCE, M., Indiana University, Indiana, USA, marpierc@iu.edu

The Salton Trough is a transtentional basin in southern California with high rates of deformation along a network of conjugate faults. Following the 2010 M7.2 El Mayor – Cucapah earthquake the region has exhibited highly time dependent crustal deformation. The high and variable rates of deformation and availability of observational data from a variety of geodetic techniques make the Salton Trough and southern California an ideal place to develop and test data fusion methodologies. We have developed tools to easily extract Global Navigation Satellite System (GNSS) vectors to produce long-term velocities, coseismic motions, postseismic motions separate from total motion in a given time window, and displacements over a specified time frame. Cluster analysis tools can then be used to search for, identify, and rank active faults or boundaries between blocks. The cluster analysis can be performed on all or a subset of the vector components to identify different crustal processes. GNSS data are spatially sparse with network stations on the order of 10-20 km apart in southern California. Interferometric Synthetic Aperture Radar (InSAR) data provide less frequent but high-resolution line of sight deformation maps that can be used to interpolate between GNSS stations. Airborne InSAR such as from NASA's UAVSAR platform provides data with 7m pixels, and spaceborne InSAR provides on the order of 100 m pixel data. Topographic images provide data on the order of a few cm resolution from structure from motion (SfM) observations and decimeters to sub-meter for lidar and other imaging. Fusing these data provide a comprehensive understanding of surface deformation processes that can be used to model fault processes.

Differential Lidar Derived Geometry and Kinematics of the Papatea Fault (Kaikoura, New Zealand)

DIEDERICHS, A., University of Victoria, Victoria, Canada, adiederi@uvic.ca; NISSEN, E., University of Victoria, Victoria, Canada, enissen@uvic.ca; LAJOIE, L., Colorado School of Mines, Colorado, USA, llajoie@mymail.mines.edu

Differential lidar derived surface displacements provide a unique way of parametrizing shallow fault geometry and estimating fault dip. This is especially useful in regions with sparse field measurements like the Papatea fault of the 2016 Mw 7.8 Kaikoura (New Zealand) earthquake. From fault perpendicular profiles in the E-W, N-S and vertical displacement directions, we measured fault offsets to compute local slip vectors at short intervals along the fault. Since the fault strike is known and the slip vectors lie in the plane of the fault, we calculate dip. Thus, we illustrate our estimations of fault dip and offset magnitude at profiled locations along strike of the Papatea fault. Here, fault dip inferences are especially valuable because only one measurement of fault dip has been collected in the field along the main strand. Although this fault likely played a fundamental role in the northeastward propagation of the Kaikoura earthquake, the Papatea fault is often left out of or parametrized inappropriately in kinematic rupture models. We estimate a maximum fault displacement of ~11 m with an average of 8-9 m along the main strand, exceptionally high for such a short (19 km-long) fault. Our results indicate the Papatea fault has an average fault dip of 70-75°W along the main strand, significantly steeper than the single field dip measurement of 51°W. Lastly, from far-field displacements, near the south end of the Papatea fault, we estimate a shallower-angle subsurface dip of ~25-40°W, implying a complex non-planar shape. Our findings emphasize the utility of high resolution lidar topography in parametrizing surface ruptures and demonstrate the detail preserved using this geodetic method.

In Situ Calibration for Geodetic Measurements on the Seafloor and in Oceanic Drill Holes

WILCOCK, W. S. D., University of Washington, Washington, USA, wilcock@uw.edu; MANALANG, D. A., Applied Physics Laboratory, University of Washington, Washington, USA, manalang@uw.edu; HARRINGTON, M. J., Applied Physics Laboratory, University of Washington, Washington, USA, mikeh@apl.washington.edu; FREDRICKSON, E. K., University of Washington, Washington, USA, erikfred@uw.edu; CRAM, G., Applied Physics Laboratory, University of Washington, Washington, USA, cramg@apl.washington.edu; TILLEY, J., Applied Physics Laboratory, University of Washington, Washington, USA, jtilley@apl.washigton.edu; BURNETT, J., Applied Physics Laboratory, University of Washington, Washington, USA, jburnett@apl.washington.edu; MARTIN, D., Applied Physics Laboratory, University of Washington, Washington, USA, dtmartin@apl.washington.edu; KOBAYASHI, T., Paroscientific, Inc., Washington, USA, taro@paroscientific.com; PAROS, J. M., Paroscientific, Inc., Washington, USA, paros@paroscientific.com

Geodetic observations in the oceans are challenging but important for understanding plate boundary processes. Precise pressure sensors can be used to detect changes in the elevation of the seafloor resulting from the rapid deflation of volcanoes and from slow-slip earthquakes in subduction zones. They can also be used to detect transient changes in volumetric strain in sealed boreholes. However, without a calibration method to remove sensor drift, they have limited sensitivity to long-term secular strain. Similarly, the horizontal channels of a sensitive accelerometer provide a means to measure changes in sensor tilt on the seafloor or in boreholes, but without a means to eliminate drift their sensitivity to long-term signals is also limited. We will describe ongoing efforts to assess in situ calibration techniques for pressure gauges and accelerometers that utilize resonant quartz crystal technology. The "A-0-A" calibration method for pressure sensors utilizes a valve to periodically switch the pressure measured by the sensor from the ambient external pressure to the internal pressure of the instrument housing for a calibration against the pressure measured by an accurate barometer. The "flipping" method calibrates tilt measurements on an accelerometer by periodically rotating the horizontal channels into the vertical orientation and measuring their drift relative to the acceleration of gravity which is assumed constant. We will present the results of an ongoing test of the A-0-A methods at 900 m depth on the MARS cabled observatory in Monterey Bay which shows that the drift corrections of two pressure sensors are consistent to ~1 mm/yr. A second test is planned for Axial Seamount where the A-0-A method can be directly compared to two alternative approaches to eliminate drift. Tests of the flipping tiltmeter are presently underway on Axial Seamount and at Piñon Flat Observatory and can be compared at each site to measurements obtained with other instruments.

Total Variation Regularization of Geodetically Constrained Block Models in Southwestern Taiwan

HUANG, M., University of Maryland, Maryland, USA, mhhuang@umd.edu; EVANS, E. L., California State University, Northridge, California, USA, eileen.evans@csun.edu

Plate convergence at more than 83 mm/yr makes Taiwan one of the most active tectonic regions in the world, as this strain is accommodated on a complex network strike-slip and thrust faulting. In this study, we use ascending and descending Interferometric Synthetic Aperture Radar (InSAR) data as well as CGPS measurements to reveal interseismic deformation in southwestern Taiwan. We combine InSAR and CGPS measurements from 2005-2010 and use the resulting deformation field to constrain a block model of interseismic crustal deformation. We use total variation regularization (TVR) to algorithmically assess the best-fitting block geometry based on the geodetic observations, simultaneously estimating block rotations and fault slip rates on block-bounding faults. The block model results imply that the margins of the Western Foothills accommodate most of the interseismic deformation in southwestern Taiwan. Geodetic observations show 20-40 mm/yr southwestward motion in the Pingtung plain in south Taiwan relative to west Taiwan that indicates tectonic escape due to plate collision, and more than 10 mm/yr uplift in the southern part of the Western Foothills. Our preferred grouped block model result suggests up to 4 cm/yr interseismic slip rate along the main detachment about 5-8 km below the Western Foothills, but most of the fault ramps are locked interseismically. Our approach shows an efficient and objective way to estimate fault activities and seismic hazards in the interseismic period based on dense geodetic measurements and their uncertainties.

A Logarithmic Model Based Simultaneous Co and Postseismic Slip Inversion Method with an Application to the 2017 Mw 7.3 Sarpol Zahāb Earthquake, Iran

XU, W., Hong Kong Polytechnic University, Hong Kong, China, csuwbxu@gmail.com; LIU, X., Hong Kong Polytechnic University, Hong Kong, China, 809334578@qq.com

The spatio-temporal co and postseismic slip estimation is generally derived based geodetic data such as GPS and radar interferometry (InSAR). The recent launch of ALOS-2 and Sentinel-1 satellites provide an opportunity to simultaneously estimate the spatio-temporal co and postseismic slip, while how to effectively integrating the multi-platform SAR datasets is still a problem due to the temporal discrepancy of SAR data epochs. Here, we develop a novel logarithmic model based inversion method to estimate the spatio-temporal co and postseismic slip by simultaneously integrating multi-platforms and multi-tracks (hereafter named multi-source) ALOS-2 and Sentinel-1 SAR datasets. The model is constructed by combining the differential interferograms from multi-source SAR datasets used as the observations and the logarithmic model determined by decay time constant and decay amplitudes, and solved by using a simple Least-Square Curve Fitting (LSCF) algorithm. In this method, the spatio-temporal co and postseismic slips are estimated directly using the individual unwrapped interferograms derived from multi-source SAR datasets. This process enables us to tackle the temporal discrepancy problem of multi-source SAR datasets and avoid the nonphysical smoothing constraints on the spatial distribution of afterslip. In addition, the temporal resolution of the resultant spatio-temporal co and postseismic slip will be improved greatly compared with that estimated from single dataset. A set of simulated experiments and a case study of the 2017 Mw 7.3 Sarpol Zahāb Earthquake in the Zagros mountain belt are carried out. We find that an integration of multi-source SAR datasets enables us to achieve a better understanding seismic kinematics of the event. The method might be easily implemented in other similar large thrust events in the future.

Recent Slow Slip Events in Costa Rica Detected by GPS

AFRA, M., University of South Florida, Florida, USA, mahsaafra@mail.usf.edu; MULLER, C., OVSICORI, Universidad Nacional, Heredia, Costa Rica, cyril.muller21@gmail.com; VOSS, N., University of South Florida, Florida, USA, nvoss28814@gmail.com; PROTTI, M., OVSICORI, Universidad Nacional, Heredia, Costa Rica, marino.protti.quesada@una.cr; MALSERVISI, R., University of South Florida, Florida, USA, rocco@usf.edu; DIXON, T. H., University of South Florida, Florida, USA, thd@usf.edu; HASTINGS, M., University of South Florida, Florida, USA, mshastings18@gmail.com

Slow Slip Events (SSE) are an important part of the seismic cycle in many subduction zones, releasing some portion of accumulated strain and perhaps triggering large earthquakes by loading nearby segments of the fault. We analyzed available GPS data to study SSEs in the Nicoya Peninsula of northwest of Costa Rica and the Osa Peninsula of southwestern Costa Rica. Available GPS data from 2016 to 2018 were processed, generating daily precise point positions. The resulting displacement time series are used to identify slow slip events and to evaluate their plate interface slip characteristics. The SSE in 2017 in Nicoya appears to have been accelerated by the magnitude 6.5 Esterillos earthquake which occurred in November. Slow slip occurs before and after the earthquake, but post-seismic displacements are almost 2 times the co-seismic displacements. We model the event as three stages (preseismic, coseismic, and accelerated SSE following the earthquake). We will discuss how stress along the subduction zone changed following the M 6.5 earthquake, perhaps leading to accelerated SSE behavior.

Sentinel-1 Time Series of Transient Creep on the Concord Fault, Eastern Bay Area

TYMOFYEYEVA, E., Jet Propulsion Laboratory, California Institute of Technology, California, USA, katia.tymofyeyeva@jpl.nasa.gov; FATTAHI, H., Jet Propulsion Laboratory, California Institute of Technology, California, USA, heresh.fattahi@jpl.nasa.gov; BEKAERT, D. P. S., Jet Propulsion Laboratory, California Institute of Technology, California, USA, david.bekaert@jpl.nasa.gov; AGRAM, P., Jet Propulsion Laboratory, California Institute of Technology, California, USA, piyush.agram@jpl.nasa.gov

Advances in SAR data acquisition allow the modern satellite missions to provide surface displacement observations at high spatial resolution and frequent repeat times in areas where measurements from other geodetic instruments may be sparse or unavailable. The PSInSAR technique is often used for estimating displacement time series with high precision, by confining the analysis to the most stable pixels. However, it is limited by its restriction to coherent targets and the assumptions required to identify them. The SqueeSAR technique, proposed by Feretti *et al.* (2011), mitigates some of these limitations by allowing for the combined processing of both permanent and distributed scatterers. We apply the SqueeSAR method to the study of shallow fault creep on the Concord Fault in the Eastern San Francisco Bay Area, where continuous GPS stations and other geodetic instruments are not available close to the fault to provide consistent spatiotemporal coverage. We use data from the European Sentinel-1 mission to observe a transient shallow creep event on the Concord fault. Observations from two overlapping satellite tracks with distinct look geometries (descending track 42 and ascending track 35) allow us to separate the surface displacements into fault-parallel and vertical components of motion, assuming that fault-perpendicular surface motions are negligible. We present cumulative displacements over the time period of available Sentinel-1 observations, from 2015-2018, as well as relative displacement time series for points on opposite sides of the fault. We are able to determine that the event began in the summer months of 2017, with variable slip along the fault, and a peak cumulative slip amplitude of approximately 15 mm in the direction parallel to the fault trace.

Chaos and Slow Earthquakes Predictability

GUALANDI, A., Jet Propulsion Laboratory, California Institute of Technology, California, USA, adriano.geolandi@gmail.com; MICHEL, S., Laboratoire de Geologie, Ecole Normale Superieure, Paris, France, sylvain_michel@live.fr; AVOUAC, J., California Institute of Technology, California, USA, avouac@gps.caltech.edu; FARANDA, D., LSCE-IPSL, CEA Saclay l'Orme des Merisiers, CNRS UMR 8212 CEA-CNRS-UVSQ, Universite, Paris-Saclay, Gif-sur-Yvette, France, davide.faranda@lsce.ipsl.fr

Slow Slip Events (SSEs) play a significant role in the moment budget along subduction megathrust. We use 352 continuous GPS stations spanning the time range from 2007 to 2017 to model the SSEs in the Cascadia region. In particular, we adopt a variational Bayesian Independent Component Analysis decomposition to extract the tectonic signal and perform a linear inversion to model the SSEs on the megathrust. This approach is very effective in identifying, and filtering out, non-tectonic sources of geodetic deformation (*e.g.* due to surface loads) and other tectonic sources (*e.g.*, afterslip). The results show a clear segmentation with a few major asperities interacting with one another, a behavior that recalls that of a discrete body system. We then use both classical Embedding Theory and Extreme Value Theory applied to the study of dynamical systems to show that, where the Signal to Noise Ratio is sufficiently high, a low-dimensional (< 5) non-linear chaotic system is more appropriate to describe the dynamics than a stochastic system. We calculate major properties of the strange attractor like its correlation and instantaneous dimension, its instantaneous extremal index and a possible range for the metric entropy of the system. This knowledge is important for the determination of the predictability of the system, since it is related to the rate at which two trajectories in the phase space diverge. We further validate our results with a fuzzy inference system model to check the predictability of the slip and slip rate. In conclusion, SSEs in Cascadia can be described as a deterministic, albeit chaotic, system rather than as a random process. As SSEs might be regarded as earthquakes in slow motion, regular earthquakes might be similarly chaotic and predictable.

Recent Developments in High-Rate Geodetic Techniques and Network Operations for Earthquake and Tsunami Early Warning and Rapid Post-Earthquake Response

Oral Session · Thursday · 1:45 PM · 25 April · Puget Sound

Session Chair: Brendan W. Crowell, Kathleen Hodgkinson, Alberto Lopez, Benjamin A. Brooks, Joe Henton, Jeffrey J. McGuire, David J. Mencin.

Ocean Networks Canada's EEW System: An Efficient System Architecture to Make Use of Both GNSS and Accelerometer Data

PIRENNE, B., Ocean Networks Canada, Victoria, Canada, bpirenne@oceannetworks.ca

Over the past 15 years, Ocean Networks Canada (ONC) has built a large research infrastructure consisting of a complex set of sensor networks below and above the water line. The networks support hundreds of instruments and instrument types that are producing data 24/7 in real-time or near real-time. The integrated networks span different types of environments from coastal to deep ocean basin, from polar to land-based settings and support large research projects in disciplines as diverse as marine biology, geophysics and seismology, oceanography, climate change and even particle physics.

The proximity of ONC's largest observing installations close to, or on, the Cascadia subduction zone is no accident. A focus on the science related to this active zone was always a key objective. More recently, the potential for the development of earthquake and tsunami early warning was considered and after an early prototype phase, funding was sought and received to build a fully capable Earthquake Early Warning System (EEWS) for the Province of British Columbia.

With the help of Natural Resources Canada (NRCan) colleagues, a mixed system was designed that tightly integrates accelerometer data with GNSS sensor data to be able to successfully cover a wide range of event magnitudes. In order to expand the geographical coverage of event detection, a data exchange mechanism with the Pacific Northwest Seismic Network is in place.

The system is now entering a thorough commissioning phase prior to be taken on-line in April 2020.

This contribution review the design aspects and the architecture of the system, and highlight some of the early results.

Modernization of the Network of the Americas to Support Earthquake and Tsunami Early Warning

FEAUX, K., UNAVCO, Colorado, USA, kfeaux@unavco.org; HODGKINSON, K., UNAVCO, New Mexico, USA, hodgkin@unavco.org; MATTIOLI, G., UNAVCO, Colorado, USA, mattioli@unavco.org; MENCIN, D., UNAVCO, Colorado, USA, mencin@unavco.org

UNAVCO provides operations and maintenance support for a number of geodetic networks across the globe as part of the GAGE (Geodetic Facility for the Advancement of Geoscience) cooperative agreement between NSF and UNAVCO. One such network is the Network of the Americas (NOTA), a federated network from a subset of GNSS stations from the Plate Boundary Observatory (PBO), TLALOCNet in Mexico, and COCONet in the Caribbean. UNAVCO will enhance the ~1100-station NOTA with multi-constellation GNSS observations and robust, high-rate (1 Hz), real-time streaming at a growing number of existing stations, for network modernization and cost savings in data management. We will present a summary of the network modernization plan for NOTA.

High-rate GNSS data streams from NOTA, collected and distributed by UNAVCO, are currently being used in prototype earthquake and tsunami early warning systems. The 2018 Anchorage earthquake provided a unique opportunity to test our methods for estimating earthquake magnitudes using peak ground displacements derived from GNSS positions in regions where the seismic and geodetic networks are sparse. We will also present a summary of the real-time GNSS assets in Alaska along with earthquake detection thresholds for the current GNSS network in Alaska. This analysis is essential to identify critical gaps in existing GNSS networks for integration of GNSS into any operational tsunami early warning system.

Merged Real Time GNSS Positioning and Seismic Moment Estimation in Support of NOAA Operational Tsunami Warning

MELBOURNE, T. I., Central Washington University, Washington, USA, tim@geology.cwu.edu

Real-time measurements from increasingly dense Global Navigational Satellite Systems (GNSS) networks located throughout the circum-Pacific offer a growing observational platform for rapidly characterizing tsunami excitation. Currently over 17,000 GNSS instruments operate globally, many of which can provide on-the-fly characterization of transient ground displacements directly relatable to seismic slip and moment. This talk will summarize the status of a two-year effort to deliver low-latency GNSS solutions to NOAA's two operational US tsunami warning centers in Palmer, AK and Honolulu, HI, along with GNSS-based seismic moment estimation routines compatible within their operational framework.

The usefulness to NOAA of real-time GNSS depend on their latency, resolution and completeness. Two additional operational requirements are redundant sources of GNSS solutions and that solutions be statistically identical irrespective of source. As a result, three independent real-time solutions produced by each of Scripps Institution of Oceanography, JPL/Caltech, and Central Washington University (PANGA) are shared internally prior to being formally merged within a simple 3-state Kalman filter for distribution to NOAA's two tsunami centers. The merging filter runs simultaneously at each institution, allowing NOAA to access the merged solutions from a given station from any of the three providers. Solution sharing is accomplished using RMQ publication/subscription service. Merged solutions have been shown to offer lower scatter, higher resolution and completeness than what individual analysis provides, at a cost of ~10 seconds latency. We have implemented merging solutions from 110 stations, and see to expand these globally

Both NOAA operational centers operate within an Earthworm environment. Static offset picking algorithms based on STA/LTA have been ported to Earthworm, as has the PGD moment estimation algorithm of Crowell (2011).

Scaling of Peak Ground Displacement With Seismic Moment Above the Mexican Subduction Thrust

SINGH, S. K., Universidad Nacional Autónoma de México, Mexico City, Mexico, krishnamex@yahoo.com; PEREZ-CAMPOS, X., Universidad Nacional Autónoma de México, Mexico City, Mexico, xyoli@igeofisica.unam.mx; ORDAZ, M., Universidad Nacional Autónoma de México, Mexico City, Mexico, mors@pumas.iingen.unam.mx; IGLESIAS, A., Universidad Nacional Autónoma de México, Mexico City, Mexico, arturo@igeofisica.unam.mx; KOSTOGLODOV, V., Universidad Nacional Autónoma de México, Mexico City, Mexico, vladi@servidor.unam.mx

Scaling of peak ground displacement (PGD) with the seismic moment (M_0) in the epicentral zone, above the Mexican subduction thrust interface (R_{rup} ~ 24 km), is of interest in the design of long-period structures and fast estimation of M_w of large/great earthquakes for early tsunami warning. Here we define PGD = $[(U_n)_{max}^2 + (Ue)_{max}^2]^{1/2}$. We take advantage of the accelerographic network along the Pacific coast of Mexico as well as some sparse continuous GPS (cGPS) and campaign-mode GPS data to establish the PGD – M_0 relationship. Worldwide cGPS recordings of great earthquakes show that in the near-source region the PGD is dominated by the static field. Based on this observation, we compensate for the sparse PGD data of great earthquakes above Mexican subduction thrust by using theoretical static PGD computed using Okada's model. For earthquakes with $M_0 \leq 1.26 \times 10^{18}$ Nm ($M_w \leq 6.0$) the point-source, far-field approximation holds and the PGD data follows theoretically expected $M_0^{2/3}$ scaling. For great earthquakes ($M_0 > 1.26 \times 10^{21}$ Nm; $M_w > 8.0$), static PGD (≈ dynamic PGD) scales as $M_0^{1/3}$. Our preliminary results show that for a given M_0, the relations found predict PGD within a factor of about two.

Intercomparisons Between Geodetic and Seismic Algorithms for ShakeAlert

CROWELL, B. W., University of Washington, Washington, USA, crowellb@uw.edu

The current ShakeAlert earthquake early warning system under development by the USGS and university partners consists of several seismic source characterization algorithms, namely EPIC and Finder. However, seismic algorithms tend to saturate for the largest earthquakes, leading to an under-prediction of strong ground motions. For almost a decade now, many groups have demonstrated the utility of adding high-rate, real-time GNSS data for the robust characterization of large earthquakes (M > 7). Three GNSS-based algorithms, BEFORES, G-FAST and GlarmS, are currently under development for ShakeAlert. These algorithms have been tested on an array of earthquakes, however, intercomparisons in 'apples-to-apples' tests have not been performed. This task is the primary objective of the ShakeAlert Geodetic Algorithms Testing and Implementation Subcommittee (GATIS). The GATIS group has been devising a framework for effective testing and metrics definitions so that streamlined comparisons can be made between all the geodetic algorithms and the current seismic algorithms. Metrics can be segregated into three categories, ground motions, source models, and timeliness, and each category is subdivided into many different metrics. For example, timeliness is separated into warning times, MMI threshold exceedance times and computation time. For our initial tests, we have decided to focus on the

El Mayor-Cucapah, Napa, and Tohoku-oki earthquakes. From these initial tests, our testing framework will be fully streamlined to enable tests across an array of real and synthetic earthquakes.

Next Generation Earthquake Early Warning Systems: Advances, Innovations and Applications

Oral Session · Thursday · 4:00 PM · 25 April · Puget Sound
Session Chairs: Angela I. Chung, Emrah Yenier, Men-Andrin Meier, Mark Novakovic, Mitsuyuki Hoshiba, Yuki Kodera.

The First-Year Operation of the Plum Algorithm in the Earthquake Early Warning System of the Japan Meteorological Agency

KODERA, Y., Meteorological Research Institute, Japan Meteorological Agency, Tsukuba, Japan, y_kodera@mri-jma.go.jp; HAYASHIMOTO, N., Japan Meteorological Agency, Tokyo, Japan, hayashimoto@met.kishou.go.jp; MORIWAKI, K., Japan Meteorological Agency, Tokyo, Japan, k-moriwaki@met.kishou.go.jp

To overcome technical difficulties in point-source earthquake early warning (EEW) approaches for earthquakes with large finite faults and multiple simultaneous events, the Japan Meteorological Agency (JMA) has begun to operate the Propagation of Local Undamped Motion (PLUM) algorithm (Kodera *et al.*, 2018) in its EEW system since March 22, 2018. We report the first-year performance of PLUM, focusing on cases in which the system issued public warnings.

PLUM predicts ground motion without source characterization, assuming unattenuated plain wave incidence from observation points close (typically within 30 km) to a target site. The current JMA system employs PLUM and point-source algorithms and combines their results by taking the maximum. For the PLUM operation, JMA has incorporated ~400 additional stations that can only transmit observed intensities in real time.

From March 22 to December 31, 2018, the JMA system issued 13 warnings to the public (the predicted intensity threshold is 5-lower (5L) on the JMA scale, *i.e.*, ~7 on MMI). For three out of the 13 cases, warnings were issued based only on PLUM ground motion predictions for earthquakes with the maximum observed intensity of 5L, showing that PLUM contributed to reducing the missing rate of strong motion. For the Mj 6.7 Hokkaido Eastern Iburi earthquake on September 6, 2018, which caused an observed intensity of 7 (maximum on the JMA scale; ~10–12 on MMI), ground motion predictions by PLUM exceeded the warning threshold ~3 s earlier than those by the point source algorithms. PLUM successfully calculated high-intensity ground motions in the early stage directly from observed intensities, while the point-source-based approaches took longer time to obtain accurate magnitude estimates. This indicates the high robustness of ground motion predictions using direct observation of wavefields.

Finder Templates for the Pacific Northwest

HARTOG, J. R., University of Washington, Washington, USA, jrhartog@uw.edu; ANDREWS, J. R., California Institute of Technology, California, USA, jrand@gps.caltech.edu; BÖSE, M., Swiss Seismological Service, ETH Zurich, Zurich, Switzerland, mboese@sed.ethz.ch

FinDer (Böse *et al.*, 2018) is an earthquake early warning (EEW) algorithm that quickly determines the length scale of a rupture by comparing the spatial pattern of observed peak ground accelerations to pre-computed spatial templates. FinDer is one of the algorithms that contributes alerts to the West Coast wide USGS ShakeAlert system (Given *et al.*, 2018), however, that implementation currently only has a set of templates appropriate for modeling shallow crustal events. In the Pacific Northwest, in addition to hazard from shallow crustal faults, there is also significant hazard due to subduction zone interface and intraslab earthquakes. We computed a new set of FinDer templates for interface and intraslab events using several Ground Motion Models and the Slab 2.0 (Hayes, 2018) model for the Cascadia Subduction Zone. We compare the templates to spatial acceleration patterns from both simulated and observed seismic data to assess their applicability.

Earthquake Early Warning Using MyShake Global Smartphone Seismic Network

KONG, Q., Berkeley Seismological Laboratory, California, USA, kongqk@berkeley.edu; SHORT, R. M., Berkeley Seismological Laboratory, California, USA, rmartin-short@berkeley.edu; ALLEN, R. M., Berkeley Seismological Laboratory, California, USA, rallen@berkeley.edu

Earthquake early warning is an effective tool to reduce earthquake hazards and losses, but many places can not afford the luxury to have a dense seismic network. MyShake is a project aiming to build a global smartphone seismic network and bring the earthquake early warning to places where there is no or few seismic stations but dense population clusters. With an on phone algorithm to distinguish the human and earthquake movement, everyone's smartphone can be used as a portable seismometer to detect earthquakes. In addition, with the aggregation of a network of phones that detect the earthquake, we can locate, estiamte the magnitude and origin time of the earthquake and issue an earthquake early warning message to the public using only data from smartphones. In this presentation, I will talk about the recent updates of our effort to issue warnings with the smartphone network. Real-world cases, as well as simulated events, will be shown to prove the effectiveness of this approach if we have a large number of users to run MyShake application on their phones. With the practice and test in the first three years after MyShake release, we believe issue earthquake early warning through the smartphone network is feasible.

Quantifying the Value of Real-Time Geodetic Constraints for Earthquake Early Warning Using a Global Seismic and Geodetic Dataset

RUHL, C. J., The University of Tulsa, Oklahoma, USA, cruhl@utulsa.edu; MELGAR, D., University of Oregon, Oregon, USA, dmelgarm@uoregon.edu; CHUNG, A., University of California, Berkeley, California, USA, aichung@berkeley.edu; GRAPENTHIN, R., New Mexico Institute of Mining and Technology, New Mexico, USA, rg@nmt.edu; ALLEN, R. M., University of California, Berkeley, California, USA, rallen@berkeley.edu

Geodetic earthquake early warning (EEW) algorithms complement point-source seismic systems by estimating fault-finiteness and unsaturated moment magnitude for the largest, most damaging earthquakes. Because such earthquakes are rare, it has been difficult to demonstrate that geodetic warnings improve ground motion estimation significantly. Here, we quantify and compare timeliness and accuracy of magnitude and ground motion estimates in simulated real time from seismic and geodetic observations for a suite of globally-distributed, large earthquakes. Magnitude solutions saturate for the seismic EEW algorithm (we use ElarmS) while the ElarmS-triggered Geodetic Alarm System (G-larmS) reduces the error even for its first solutions. Shaking intensity (MMI) time series calculated for each station and each event are assessed based on MMI-threshold crossings, allowing us to accurately characterize warning times per-station. We classify alerts and find that MMI 4 thresholds result in only 12.3% true positive (TP) alerts with a median warning time of 16.3 ±20.9 s for ElarmS, but 44.4% TP alerts with a longer median warning time of 50.2 ±49.8 s for G-larmS. The geodetic EEW system reduces the number of missed alerts for thresholds of MMI 3 and 4 by over 30%. If G-larmS was triggered instantaneously at the earthquake origin time, the performance statistics are similar, with slightly longer warning times and slightly more accurate magnitudes. By quantifying increased accuracy in magnitude, ground motion estimation, and alert timeliness; we demonstrate that geodetic algorithms add significant value, including better cost savings performance, to EEW systems.

The Potential of Using Strain Data in Earthquake Early Warning: Near-Source Characteristics

FARGHAL, N. S., U.S. Geological Survey, California, USA, nfarghal@usgs.gov; BARBOUR, A. J., U.S. Geological Survey, California, USA, abarbour@usgs.gov

The success of earthquake early warning (EEW) depends on the system response time and the accuracy of ground motion estimates. While highly dependent on instrumental coverage density and algorithm performance, such factors need to be continuously enhanced to improve the usefulness of EEW systems. In this work, we investigate the use of strainmeter data to complement seismometer data in EEW, noting that strainmeters have a linear response at all frequencies and have been found to record seismic waves with a high signal-to-noise ratio. We focus on data from Plate Boundary Observatory borehole strainmeters (20 samples/s) deployed in critical locations along the Pacific-North American plate boundary. We present a mathematical formulation relating earthquake moment magnitudes (Mw 3.5 - 5.7) observed near-field strains (< 60 km hypocentral distance) recorded during early-time evolution of the strain seismogram. Additionally, we discuss the performance of this formulation in providing real-time magnitude updates that can be used to forecast ground motion in vulnerable areas. Furthermore, we explore the spectral characteristics of strain data, and discuss the challenges of strain data processing in general and studying near-field effects in particular.

The InSight Mission—Seismology on Mars and Beyond

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Session Chairs: Sharon Kedar, Mark P. Panning, William B. Banerdt.

SEIS: Overview, Deployment and First Science on the Ground

LOGNONNÉ, P., Institut de Physique du Globe de Paris, Paris, France, lognonne@ipgp.fr; BANERDT, W. B., Jet Propulsion Laboratory, California Institute of Technology, California, USA, william.b.banerdt@jpl.nasa.gov; PIKE, W. T., Imperial College London, London, United Kingdom, w.t.pike@imperial.ac.uk; GIARDINI, D., ETH Zurich, Zurich, Switzerland, domenico.giardini@erdw.ethz.ch; BANFIELD, D., Cornell Center for Astrophysics and Planetary Science, New Jersey, USA, banfield@astro.cornell.edu; CHRISTENSEN, U., Max Planck Institute for Solar System Research, Department of Planets and Comets, Goettingen, Germany, christensen@mps.mpg.de; BIERWIRTH, M., Max Planck Institute for Solar System Research, Department of Planets and Comets, Goettingen, Germany, bierwirthm@mps.mpg.de; CALCUTT, S., University of Oxford, Atmospheric, Oceanic, & Planetary Physics, Oxford, United Kingdom, calcutt@atm.ox.ac.uk; CLINTON, J., Institut of Geophysics, ETHZ, Zurich, Switzerland, jclinton@sed.ethz.ch; KEDAR, S., Jet Propulsion Laboratory, California Institute of Technology, California, USA, sharon.kedar@jpl.nasa.gov; GARCIA, R., Institut supérieur de l'aéronautique et de l'espace, Toulouse University, Toulouse, France, raphael.garcia@isae-supaero.fr; DE RAUCOURT, S., Institut de Physique du Globe de Paris, Paris, France, deraucourt@ipgp.fr; HURST, K., Jet Propulsion Laboratory, California Institute of Technology, California, USA, kenneth.j.hurst@jpl.nasa.gov; KAWAMURA, T., Institut de Physique du Globe de Paris, Paris, France, kawamura@ipgp.fr; MIMOUN, D., Institut supérieur de l'aéronautique et de l'espace, Toulouse University, Toulouse, France, david.mimoun@isae.fr; PANNING, M. P., Jet Propulsion Laboratory, California Institute of Technology, California, USA, mark.p.panning@jpl.nasa.gov; SPIGA, A., LMD, Sorbonne Université, Paris, France, aymeric.spiga@sorbonne-universite.fr; ZWEIFEL, P., Institut of Geophysics, ETHZ, Zurich, Switzerland, pzweifel@retired.ethz.ch

The InSight mission landed on Mars on 11/26/2018. This is the first planetary mission deploying a complete geophysical observatory on another body than Earth after the Apollo Lunar Surface Experiments Package (ALSEP) deployed on the Moon during the Apollo program. It will provide the first ground truth constraints on interior structure of the planet. The Seismic Experiment for Interior Structure (SEIS) is one of the three primary scientific investigations, the two other ones being the Heat Flow and Physical Properties Package (HP^3) and the Rotation and Interior Structure Experiment (RISE). SEIS is completed by the APSS experiment (InSight Auxiliary Payload Suite), one of which goal is to document the atmospheric source of seismic noise and signals. After a brief description of the SEIS experiment, we report the deployment process, including the evolution of the SEIS noise from on the deck measurements (with only SPs) toward on the ground (with both VBBs and SPs), without and finally with wind shield.

We compare these noise levels to those obtained on Earth during tests, to those recorded on the Moon and to those predicted prior the landing. In all configurations, we identify the contribution of the lander noise and finally discuss what might remain in term of micro-seismic background, *i.e.* uncoherent seismic waves background.

As proposed by several studies made prior the landing, atmospheric seismic signals on the ground are expected from turbulences in the planetary boundary layer or from dust devils, at both long period and short period. We expect also local time variation of the seismic noise as a consequence of weather activity as well as possible micro-seismic noise associated to trapped surface or body waves in the subsurface low velocity channel. We challenge these predictions with the data and discuss the events and spectrum identified with both the SEIS and APSS data. We finally compare them with modeling made with different subsurface structure.

Additional authors :

https://www.seisinsight.eu/en/public-2/seis-instrument/seis-working-groupsteam

Initial Results From the Heat Flow and Physical Properties Package (Hp3) on InSight

HUDSON, T. L., Jet Propulsion Laboratory, California Institute of Technology, California, USA, tlhudson@jpl.nasa.gov; SPOHN, T. C., DLR, Institut for Planetenforschung, Berlin, Germany, tilman.spohn@dlr.de; GROTT, M., DLR, Institut for Planetenforschung, Berlin, Germany, matthias.grott@dlr.de; SMREKAR, S. E., Jet Propulsion Laboratory, California Institute of Technology, California, USA, suzanne.e.smrekar@jpl.nasa.gov; KNOLLENBERG, J., DLR, Institut for Planetenforschung, Berlin, Germany, joerg.knollenberg@dlr.de; KRAUSE, C., DLR, MUSC, Cologne, Germany, christian.krause@dlr.de; MUELLER, N., DLR, Institut for Planetenforschung, Berlin, Germany, nils.mueller@dlr.de; PLESA, A. C., DLR, Institut for Planetenforschung, Berlin, Germany, ana.plesa@dlr.de; GOLOMBEK, M. P., Jet Propulsion Laboratory, California Institute of Technology, California, USA, matthew.p.golombek@jpl.nasa.gov; SIEGLER, M. A., Planetary Science Institute, Arizona, USA, matthew.a.siegler@gmail.com; PICQUEUX, S., Jet Propulsion Laboratory, California Institute of Technology, California, USA, sylvain.picqueux@jpl.nasa.gov; NAGIHARA, S., Texas Tech University, Texas, USA, seiichi.nagihara@ttu.edu; KING, S. D., Virginia Tech, Virginia, USA, sdk@vt.edu; BANERDT, W. B., Jet Propulsion Laboratory, California Institute of Technology, California, USA, william.b.banerdt@jpl.nasa.gov

On Nov 26th, 2018, the NASA InSight mission landed on Elysium Planitia, Mars, as the first geophysical observatory on another terrestrial planet. The payload includes the Heat Flow and Physical Properties Package (HP3) to measure geothermal heat flux at the landing site. By constraining planetary heat flow, HP3 data will inform models of crustal thickness, radioisotope inventory, and planetary evolution.

HP3 consists of a mechanical hammering device called the "Mole" for penetrating into the regolith, an instrumented tether for measuring the subsurface thermal gradient, and an infrared radiometer (RAD) for measuring surface brightness temperature. Reconstruction of the mole's subsurface path, to determine final depths of the temperature sensors, is accomplished with measurements of the mole orientation vector and the extracted tether length. The Mole also includes active heaters and temperature sensors to measure the regolith thermal conductivity to better than 3.5%.

Heat flow is calculated by multiplying the geothermal gradient and the regolith thermal conductivity. Modeling suggests that at Elysium Planitia the surface heat flow is close to the Mars' average value.

The properties of the landing site are favorable for HP3 with an absence of significant slopes and surface rocks. The Mole is planned to penetrate to a depth of 3 - 5 meters. Achieving the required 3 meter depth reduces contributions of surface temperature variations to within mission requirements. Greater depths further reduce these noise sources and thus total measurement time.

Assuming deployment by the end of January and Mole penetration taking the planned 44 sols, the instrument should be fully emplaced by the time of the SSA conference. The RAD is acquiring hourly measurements nearly continuously since sol 24 and determinations of surface thermal inertia are forthcoming. We expect to have measured the regolith thermal conductivity at 50 cm intervals down to the mole's final depth and will have the first data on the temperature gradient below the annual thermal skin depth.

Detecting and Locating Quakes on Mars

GIARDINI, D., ETH Zurich, Zurich, Switzerland, domenico.giardini@erdw.ethz.ch; LOGNONNÉ, P., Institut de Physique du Globe de Paris, Paris, France, lognonne@ipgp.fr; BANERDT, W. B., Jet Propulsion Laboratory, California Institute of Technology, California, USA, william.b.banerdt@jpl.nasa.gov; BÖSE, M., ETH Zurich, Zurich, Switzerland, maren.boese@googlemail.com; CEYLAN, S., ETH Zurich, Zurich, Switzerland, savas.ceylan@erdw.ethz.ch; CLINTON, J., ETH Zurich, Zurich, Switzerland, jclinton@sed.ethz.ch; VAN DRIEL, M., ETH Zurich, Zurich, Switzerland, vandriel@erdw.ethz.ch; GARCIA, R., Institut supérieur de l'aéronautique et de l'espace, Toulouse University, Toulouse, France, raphael.garcia@isae-supaero.fr; KHAN, A., ETH Zurich, Zurich, Switzerland, amir.khan@erdw.ethz.ch; STÄHLER, S., ETH Zurich, Zurich, Switzerland, simon.staehler@erdw.ethz.ch; KAWAMURA, T., Institut de Physique du Globe de Paris, Paris, France, kawamura@ipgp.fr; PANNING, M. P., Jet Propulsion Laboratory, California Institute of Technology, California, USA, mark.p.panning@jpl.nasa.gov; PIKE, W. T., Imperial College, London, United Kingdom, w.t.pike@imperial.ac.uk

A key goal of the NASA InSight mission to Mars is the detection, discrimination, location and characterization of Marsquakes. InSight landed on Mars on November 26, 2018, and the SEIS seismometer package was deployed on the surface over Christmas. Over its nominal mission duration of one martian year, SEIS is expected to register a few global events of magnitude larger than 4 and a few tens of events at local and regional distances of smaller magnitudes, in addition to a few impacts.

We have calibrated single-station procedures for: the discrimination of non-seismic pulses, by correlating with measurements of pressure, wind and magnetic anomalies; the discrimination of possible meteorite impacts, by depth estimation (using depth phases such as pP and sP) and spectral analysis; event location based on the use of differential travel-times of body waves and surface waves, and of multiple Rayleigh and Love-wave orbits; accounting for both aleatoric (*i.e.*

picking error) and epistemic (*i.e.* phase identification and model uncertainty) uncertainties; event quantification and characterization, including magnitude assessment with a new suite of Martian magnitudes and moment-tensor inversion; the iterative refinement of the model suite and event locations.

These procedures have been tested in blind tests and operation readiness tests using realistic Mars conditions preparation and expect now confirmation and calibration as part of the Marsquake Service Operations using data recorded on Mars, in conjunction with the Mars Structural Service (MSS).

Mars Structure Service: Single-Station and Single-Event Marsquake Inversion for Structure Using Synthetic Martian Waveforms

PANNING, M. P., Jet Propulsion Laboratory, California Institute of Technology, California, USA, mark.p.panning@jpl.nasa.gov; BEUCLER, E., Université de Nantes, Laboratoire de Planétologie et de Géodynamique, Nantes, France, eric.beucler@univ-nantes.fr; DRILLEAU, M., Institut de Physique du Globe de Paris, Paris, France, drilleau@ipgp.fr; KHAN, A., ETH Zurich, Zürich, Switzerland, amir.khan@erdw.ethz.ch; LOGNONNÉ, P., Institut de Physique du Globe de Paris, Paris, France, lognonne@ipgp.fr; BEGHEIN, C., University of California, Los Angeles, California, USA, cbeghein@epss.ucla.edu; XU, H., University of California, Los Angeles, California, USA, htxu@ucla.edu; MENINA, S., Institut de Physique du Globe de Paris, Paris, France, menina@ipgp.fr; BARKAOUI, S., Institut de Physique du Globe de Paris, Paris, France, barkaoui@ipgp.fr; LEKIC, V., University of Maryland, Maryland, USA, ved@umd.edu; STÄHLER, S., ETH Zurich, Zurich, Switzerland, simon.staehler@erdw.ethz.ch; VAN DRIEL, M., ETH Zurich, Zurich, Switzerland, vandriel@erdw.ethz.ch; KENDA, B., Institut de Physique du Globe de Paris, Paris, France, kenda@ipgp.fr; MURDOCH, N., Institut supérieur de l'aéronautique et de l'espace, Toulouse University, Toulouse, France, naomi.murdoch@isae.fr; CLINTON, J., ETH Zurich, Zurich, Switzerland, jclinton@sed.ethz.ch; GIARDINI, D., ETH Zurich, Zurich, Switzerland, domenico.giardini@erdw.ethz.ch; SMREKAR, S. E., Jet Propulsion Laboratory, California Institute of Technology, California, USA, suzanne.e.smrekar@jpl.nasa.gov; STUTZMANN, E., Institut de Physique du Globe de Paris, Paris, France, stutz@ipgp.fr; SCHIMMEL, M., ICTJA-CSIC, Barcelona, Spain, schimmel@ictja.csic.es

The InSight lander successfully delivered geophysical instrument package on the Martian surface on November 26th, 2018, including a broadband and a short-period seismometer (Seismic Experiment for Interior Structure, SEIS). Routine operations are split into two services: the Mars Structure Service (MSS) and the Marsquake Service (MQS), which are responsible for defining structure models and seismicity catalogs, respectively. The first "deliverable" of the MSS will be a model based on the events detected during the first 3 months of seismic monitoring of the mission, for which only a few quakes might be expected based on current estimates of Mars seismic activity. To test our approach of determining the interior model of Mars and to prepare the InSight science team for data return, we made use of a "blind test" time series for which the Marsquake parameters (location, depth, origin time, and moment tensor) and interior model were unknown to the group at large.

In preparation for the mission, the goal was to develop mature algorithms to handle the data as efficiency as possible. Synthetic seismic waveforms were computed in a 1D mantle model with a 3D crust on top using AxiSEM and Salvus. The time series were created by adding seismic noise that relies on pre-landing estimates of noise generated by the sensors, electronic system, environment, and nearby lander.

We detail and compare the results of this "blind test" using different methods including inversion of surface wave dispersion data, body waves travel times, and the waveforms themselves. Effects of fixing mars quake location and origin time are investigated. To allow for tighter constraints, we also test the use of priors based on thermodynamically-constrained models. These techniques considered here form a large part of the planned modeling of the MSS that will be ultimately employed with the first recording of a seismic event by InSight.

Constraining Mars Crust and Mantle Structure From Waveform Inversion of Fundamental and Higher Mode Surface Waves

XU, H., University of California, Los Angeles, California, USA, htxu@ucla.edu; BEGHEIN, C., University of California, Los Angeles, California, USA, cbeghein@ucla.edu; IRVING, J. C. E., Princeton University, New Jersey, USA, jirving@princeton.edu; DRILLEAU, M., Institut de Physique du Globe de Paris, Paris, France, drilleau@ipgp.fr; KENDA, B., Institut de Physique du Globe de Paris, Paris, France, kenda@ipgp.fr; LOGNONNÉ, P., Institut de Physique du Globe de Paris, Paris, France, lognonne@ipgp.fr; MURDOCH, N., Ecole nationale supérieure de l'aéronautique et de l'espace, Toulouse, France, naomi.murdoch@isae.fr; PANNING, M. P., Jet Propulsion Laboratory, California Institute of Technology, California, USA, mark.p.panning@jpl.nasa.gov; BÖSE, M., ETH Zurich, Zürich, Switzerland, maren.boese@googlemail.com; BRINKMAN, N., ETH Zürich, Zürich, Switzerland, nienkeb@student.ethz.ch; CEYLAN, S., ETH Zurich, Zurich, Switzerland, savas.ceylan@erdw.ethz.ch; CLINTON, J., ETH Zurich, Zurich, Switzerland, jclinton@sed.ethz.ch; EUCHNER, F., ETH Zurich, Zurich, Switzerland, fabian.euchner@sed.ethz.ch; GIARDINI, D., ETH Zurich, Zurich, Switzerland, domenico.giardini@sed.ethz.ch; HORLESTON, A. C., University of Bristol, Bristol, United Kingdom, anna.horleston@bristol.ac.uk; KAWAMURA, T., Institut de Physique du Globe de Paris, Paris, France, kawamura@ipgp.fr; KHAN, A., ETH Zurich, Zurich, Switzerland, amir.khan@erdw.ethz.ch; VAN DRIEL, M., ETH Zurich, Zurich, Switzerland, vandriel@erdw.ethz.ch; STÄHLER, S., ETH Zurich, Zurich, Switzerland, simon.staehler@erdw.ethz.ch

One of InSight's primary objectives is to constrain Mars crustal and mantle structure. To achieve this goal, we will use waveforms recorded by InSight's broadband seismic instrument to invert the fundamental and, when available, the higher mode surface waves.

To measure higher mode dispersion, we developed a waveform modeling technique based on a reversible jump Markov Chain Monte Carlo method within a hierarchical Bayesian framework. It can result in two outcomes: posterior probability density functions (PPDFs) for VS models of Mars interior that represent the average structure for the source-receiver path, and fundamental and higher mode dispersion curves with uncertainties, which can be seen as secondary data that can be inverted jointly with other datasets to further constrain Mars internal structure.

To prepare for the mission, we tested our technique on a blind waveform dataset generated by members of the Mars Structure Service team. The location, source parameters, noise level, and interior model were unknown to the rest of the team. Using source parameter estimates obtained by the Mars Quake Service team, we were able to fit fundamental mode Rayleigh waves at 25-50s period and obtain VS models down to 150 km depth. We found trade-offs between VS and the source parameters, but the range of VS models and the group and phase velocities did not significantly depend on whether source parameters were included in the inversion. Our group velocities and VS models were in good agreement with those obtained by other InSight team members with other techniques. It demonstrates that, although trade-offs exist, our models and measurements together with their uncertainties are robust with respect to the source parameters. It also shows that it will be important to jointly invert for VS and source parameters to get reliable uncertainties. This will be especially important when dealing with real Mars data as we may not always get reliable source parameter estimates.

Facebook and Twitter and Snapchat, Oh My! The Challenges and Successes of Using Social Media to Communicate Science to the Public

Oral Session · Thursday · 10:45 AM · 25 April · Vashon

Session Chairs: Elizabeth A. Vanacore, Sara K. McBride.

Hazards Communication in the Age of Social Media: Now, Now, Now!

BOHON, W., Incorporated Research Institutions for Seismology, District of Columbia, USA, bohon@iris.edu; BARTEL, B., UNAVCO, Colorado, USA, bartel@unavco.org

Social media (SM) can be a powerful instrument for dissemination of hazards information before, during and after hazard events. However, in order to fully capitalize on the capability of SM, the hazards community must recognize and address issues within the current science communication landscape.

The rapid expansion of SM has changed hazards communication in three fundamental ways: 1) the expected timescale of information dissemination, 2) the role of traditional media as information gatekeepers, and 3) the "experts" who are communicating with the public. Previously, there was a time lag between the event and expectation of an official response, which came from reporting agencies through traditional media channels. Now, the public and other stakeholders expect information in real time. The difference between the expectation for information dissemination and the time it takes agencies to collect, vet and distribute the information creates an information void, which is often filled with speculation, misinformation and bad advice. This misinformation propagates, in part, because traditional media are no longer the information gatekeepers who determine what to cover and who should be deemed an "expert". Now, anyone can share information on SM, which makes it is more difficult for consumers to determine who is a true expert, what information they should believe, and what advice they should follow. While individual scientists have stepped up to fill the void, scientists generally aren't trained in communication, which can lead to a host of potential issues including inappropriate framing, unintended and seemingly contradictory media narratives, and interviews seen as cold, callous or unfeeling.

While these issues are challenging, there are things the scientific community can do to improve hazards communication including 1) communication training , 2) best practice documents, and 3) more interdisciplinary collaborations between hazards scientists and social scientists.

The "Seismo Blog" at the UC Berkeley Seismological Laboratory

RADEMACHER, H., University of California, Berkeley, California, USA, horst@berkeley.edu; HELLWEG, M., University of California, Berkeley, California, USA, peggy@seismo.berkeley.edu

Seismologists face a public communications challenge. The first question anyone asks them, if there has not been a big quake, is "When is the next big one?" requiring an explanation of why we cannot predict earthquakes. If there has been a big quake, we have to answer questions from the public and media about why the effects are, or aren't, so bad. Looking for a different path to communicate earthquake science to the public, we initiated the Seismo Blog in the Autumn of 2008. The goal of this blog is to present seismological information in bite-sized pieces related to the experience of the readers in the context of current or historical earthquake events. The blog provides a different path to its audience than either a lecture, which may present detailed information but is ephemeral, or an interview, from which the information conveyed to the public is chosen by the reporter or editor.

In the Seismo Blog, we can set the tone, the wording, the content and associated figures and make our point. In addition, the reader can return to past blogs for clarification and better understanding. Each blog post is meant to be a complete story and with a concise explanation about a single aspect of seismology, covering the topic in lay terms, but still as scientifically accurately as possible. Thus, the many existing and future posts taken together can help to provide a more complete picture of seismology to the public. The Seismo Blog is great attractor to our website.

Exercises vs Real Events: Caribe Wave, ShakeOut and Real Earthquakes in Social Media

BÁEZ-SÁNCHEZ, G., Puerto Rico Seismic Network, Puerto Rico, USA, gisela.baez1@upr.edu; FELICIANO-ORTEGA, A. J., Puerto Rico Seismic Network, Puerto Rico, USA, angel.feliciano3@upr.edu; CORDERO-NIEVES, H., Puerto Rico Seismic Network, Puerto Rico, USA, haniel.cordero@upr.edu; VENTURA-VALENTÍN, W. A., Puerto Rico Seismic Network, Puerto Rico, USA, wilnelly.ventura@upr.edu; CÁLIZ-PADILLA, R. M., Puerto Rico Seismic Network, Puerto Rico, USA, rocio.caliz@upr.edu

The Puerto Rico Seismic Network (PRSN) monitors and studies seismicity in the Puerto Rico and the Virgin Islands Region (PR/VI). Within this region, thousands of earthquakes are located per year of which dozens are felt by the community. The most significant earthquake that affected the region occurred in 1918 and generated a destructive tsunami. PRSN coordinates two annual exercises, Caribe Wave and ShakeOut, in the PR/VI region. The Caribe Wave exercise in March promotes tsunami preparedness, and the Great Puerto Rico ShakeOut exercise in October promotes earthquake preparedness. For both exercises, the PRSN has developed a communications exercise in coordination with emergency agencies of PR/VI as well as an educational campaign that involves users of Social Media. One of the biggest challenges facing PRSN is the immediate need of the public for bilingual (Spanish and English) information and the standardization of social networks as a primary information source for event information. Here we present a comparison of PRSN's Facebook page and the official webpage performance for the two annual drills and major or significant earthquakes in PR/VI during 2018. Concerns such as how to reach people, knowing their expectations about our work, quantifying the reach and impact that our publications and exercises have on the community and emergency managers are now part of our daily operations and protocols. Other challenges while working with social media is the dissemination of false information by other users, damage to scientific credibility, establishment of official information sources, among others. Given the wide variety of technology consumption our protocols are designed to issue information on many platforms that reach both emergency agencies and the general public of the countries in PR/VI. Furthermore, a dynamic approach to protocol design will ensure prolonged impact on the population through any of the social media platforms.

Rapid Earthquake Information Dissemination on Social Media: Lessons Learnt From Lastquake

BOSSU, R., European-Mediterranean Seismological Centre, Arpajon, France, bossu@emsc-csem.org; FALLOU, L., European-Mediterranean Seismological Centre, Arpajon, France, fallou@emsc-csem.org; STEED, R., European-Mediterranean Seismological Centre, Arpajon, France, robert.steed@emsc-csem.org; ROUSSEL, F., European-Mediterranean Seismological Centre, Arpajon, France, roussel@emsc-csem.org; ROCH, J., European-Mediterranean Seismological Centre, Arpajon, France, julien.roch@emsc-csem.org; LANDES, M., European-Mediterranean Seismological Centre, Arpajon, France, matthieu.landes@emsc-csem.org

Social networks and smartphone apps are becoming a key component of rapid public earthquake information. Beyond their capacity to efficiently broadcast timely information, they are also an opportunity for the seismological community to better serve societal demands associated with earthquake risk, as well as an opportunity to collect data of scientific interest at little cost.

LastQuake, is a multichannel information system targeting eyewitnesses of global earthquakes. Rather than simply reporting seismically located earthquakes, LastQuake focuses on felt and damaging earthquakes only, regardless their magnitude, identifying them through the immediate online reaction they cause. These *crowdsourced-earthquake-detections* possess 2 advantages. First, they are very fast, typically few tens of seconds and offer an efficient way to engage with eyewitnesses and initiate efficient felt reports collection. Perhaps more importantly, they are a proxy for the public desire of information and this targeted information-seeking identifies "teachable moments" which can and should be exploited for raising seismological awareness.

Social networks through their 2 way communication channels can identify public expectations and gaps. Safety tips and safety checks were thus implemented in LastQuake following requests received after the 2015 Nepal earthquake. The 2018 Lombok, Indonesia earthquakes illustrated the need to serve not only the local population but also tourists who often fail to find information in their own language. The same year, in Mayotte, it was the impossibility to seismically locate felt earthquakes which led to rumors and conspiracy theories. The aim of this talk is to present lessons learnt from these past events and how we try to take them into account in the evolution of the lastQuake system.

Social Media and the Alaska Earthquake Center's Response to the November 30, 2018 7.0 Mw Anchorage Earthquake

DICKSON, I. J., University of Alaska Fairbanks, Alaska, USA, ijdickson@alaska.edu; GARDINE, L., University of Alaska Fairbanks, Alaska, USA, lagardine@alaska.edu; GARDINE, M., University of Alaska Fairbanks, Alaska, USA, mgardin2@alaska.edu; MERZ, D. K., University of Alaska Fairbanks, Alaska, USA, dkmerz@alaska.edu; RUPPERT, N., University of Alaska Fairbanks, Alaska, USA, naruppert@alaska.edu; WEST, M. E., University of Alaska Fairbanks, Alaska, USA, mewest@alaska.edu

The 7.0 mww Anchorage earthquake on Nov. 30 caused considerable damage and initiated an aftershock sequence that has kept public demand high for science and hazard information ever since. Although the Alaska Earthquake Center (AEC) has used social media since 2013, the Nov. 30 event was the first federally declared earthquake disaster in Alaska to require a social media response. The success of AEC's effort was demonstrated by rapid audience growth, praise from officials, and a Twitter-to-television pipeline where social media posts often led directly to broader media stories highlighting the center's talking points. However, those successes have created public expectations for rapid, 24/7 social media response while increasing the need to monitor accounts for rumors and pseudoscience. We have also been surprised by the extent to which AEC's accounts have become forums, in positive and negative ways, for people experiencing mental health impacts from the earthquake and its aftershocks. In this case study of AEC's social media response to the Nov. 30 earthquake, we will examine how the center's communications philosophy and Incident Command System-based procedures defined that response, what the observable outcomes were, and where unexpected challenges have cropped up throughout the sequence.

Earthquake Source Parameters: Theory, Observations and Interpretations

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Data-Driven Earthquake Detection, Localization and Source Mechanism Estimation Based on Wavefield Extrapolation and 2D Deconvolution in High-Noise Environments

VINARD, N. A., TU Delft, Delft, Netherlands, n.a.vinard@tudelft.nl; DRIJKONINGEN, G. G., TU Delft, Delft, Netherlands, g.g.drijkoningen@

tudelft.nl; VERSCHUUR, D. J., TU Delft, Delft, Netherlands, d.j.verschuur@tudelft.nl

Near real-time detection of weak induced earthquakes is a topic of active research in the field of seismic monitoring with the purpose of reducing the seismic risk and increasing the productivity of a reservoir. With low signal-to-noise ratios standard earthquake detection methods that work on a single trace time signal fail to detect earthquakes. Over the past few decades seismologists started to use data-driven methods to detect and image earthquakes recorded with spatially Nyquist-sampled arrays. By exploiting the time-invariance of the wave equation in a lossless medium, the wavefields can be extrapolated backward towards the source they originated from, thus increasing the signal-to-noise ratio, which results in an increased detection threshold.

In this study the wavefields are backward extrapolated in depth with the weighted-least squares one-way acoustic wavefield extrapolation operator in the space-frequency domain. These operators were designed to work efficiently and with high accuracy in heterogeneous media. Ideally, the amplitude of the extrapolated wavefields reaches a maximum at the location of the source, which can be used as an imaging condition to determine the hypocenter and origin time. However, the polarity changes in the P- and S-phases along the array lead to destructive interference of the extrapolated data at the source location. We propose to maximize the focused signal by computing the 2D deconvolution between the extrapolated data and a pre-computed "ideal" filter. This filter is created from a synthetic wavefield measured at the surface for a specific source mechanism that is backward extrapolated to the source location. Since the source mechanism is unknown, a database of such filters for different source mechanisms, given the P- and S-wave velocity model and the acquisition geometry as input is pre-computed. The maximum amplitude is reached when the source mechanism of the data optimally matches the filter's source mechanism. With this procedure the hypocenter, source origin time and source mechanism can be estimated simultaneously.

Source Properties of Repeating Earthquakes in Aftershocks of the 2016 ML 5.8 Gyeongju Earthquake Sequences

WOO, J., Seoul National University, Seoul, Korea, Republic of, woong1440@gmail.com; RHIE, J., Seoul National Unversity, Seoul, Korea, Republic of, junkee.rhie@gmail.com; KIM, S., Chungnam National Unversity, Daejeon, Korea, Republic of, srkim@cns.ac.kr

Repeating earthquakes (REs) represent characteristic events that repeatedly rupture on the same fault patch in a similar way and generate nearly identical seismic waves. REs are commonly observed in high-strain rate regions (*i.e.*, plate boundaries) but scarce in intraplate regions where strain-rate is low. In this study, we analyzed the high-precision relocations, focal mechanisms and slip rates of REs observed in aftershocks of the 2016 M_L 5.8 Gyeongju earthquake sequences in South Korea, located ~800 km away from the nearest plate boundary. We identified 70 clusters from 1405 aftershocks detected by matched filter analysis. Most of the clusters consist of two or three REs and their locations are scattered in aftershock area. On the other hand, two clusters having more than 10 REs are located near the lower limit of the seismogenic depth (~ 16 km), which is estimated from the focal depths of the aftershocks. Two clusters are on two parallel faults associated with the mainshock and the largest foreshock (M_L 5.1). REs for both clusters show strike slip mechanism but strikes for each cluster are slightly different. In addition, estimated stress drops and slip rates for REs in each cluster are also different. Given that all REs occurred during aftershock period (~ 100 days), we suggest that the coseismic and post-seismic stress perturbation may change frictional properties on the fault and makes occurrence of REs temporarily possible in specific regions.

Earthquake Source Mechanisms and Relationship to an Updated Fault Framework of the Greater Permian Basin in West Texas

HUANG, D., University of Texas at Austin, Texas, USA, dino.huang@beg.utexas.edu; HORNE, E., University of Texas at Austin, Texas, USA, lily.horne@beg.utexas.edu; SAVVAIDIS, A., University of Texas at Austin, Texas, USA, alexandros.savvaidis@beg.utexas.edu; HENNINGS, P., University of Texas at Austin, Texas, USA, peter.hennings@beg.utexas.edu; YOUNG, B., Bureau of Economic Geology, University of Texas at Austin, Texas, USA, bissett.young@beg.utexas.edu; WHITTAKER, S., University of Texas at Austin, Texas, USA, stefanie.whittaker@beg.utexas.edu; MARTONE, P., University of Texas at Austin, Texas, USA, patricia.martone@beg.utexas.edu

There has been elevated earthquake activity in the Permian Basin since 2008. Previous studies had suggested a link between hydrocarbon extraction, wastewater disposal, and increased seismicity for parts of West Texas. In 2015, a statewide seismic network known as TexNet has been established to monitor the earthquake activities. To date, there has been over seven thousand small earthquakes (ML<3) reported by TexNet across the state of Texas. In the Permian Basin, these earthquakes are unevenly distributed throughout the basin, often occurring in clusters. One of the main tasks of TexNet is to determine earthquakes' source mechanisms on a daily basis. In general, there is no uniform focal mechanism pattern for the Permian Basin as a whole. However, the source mechanism patterns shift from normal faulting in the Midland Basin to a mixed strike-slip and vertical-dip-slip faulting in the Delaware Basin. In the Delaware Basin, these clusters are interpreted to delineate well-oriented basement-rooting faults, which have formed as a result of the accumulation of several extensional and compressional deformation events since the Proterozoic. A vast majority of events that have been located are shown to occur below the sediment interface, corroborating the interpretation of modern reactivation along preexisting basement-rooting faults. Further integration of seismicity, source mechanisms and available geologic data, have resulted in the generation of a new 3D structural framework of the Delaware Basin. This framework has enabled basin-scale fault characterization to better understand potential controlling fabrics that affect local stress-states. First-order observations from this model highlight areas where heterogeneities in source mechanisms may be due to preexisting, basement-rooting fault patterns while the primary structural is a NW-SE oriented high-angle thrust fault. Secondary features include fault-propagation folds and smaller scaled oblique-slip sub-vertical fault zones that trend WNW-ESE. They are likely to accommodate normal and transtensional reactivation.

Stress Drops and Directivity of Induced Earthquakes in Western Canada Sedimentary Basin

HOLMGREN, J. M., Western University, London, Canada, jholmgr@uwo.ca; ATKINSON, G. M., Western University, London, Canada, gmatkinson@aol.com; GHOFRANI, H., Western University, London, Canada, hghofra@uwo.ca

The Western Canada Sedimentary Basin (WCSB) has experienced an increase in seismicity during the last decade due to primarily hydraulic fracturing. Understanding the ground motions of these induced earthquakes is critical to characterize the increase in hazard. Stress drop is an important parameter in this context because it is a measure of the high-frequency content of the energy released. We use the Empirical Green's Function (EGF) method to investigate corner frequencies and stress drops of 80 events of M2.3-4.4 in the WCSB. The EGF method is an effective technique to isolate the source effects of a target earthquake since it does not require assumptions on path and site. Instead, it extracts the source component by dividing out the path and site components in the frequency domain, using a smaller, collocated earthquake as an EGF. The corner frequency of the source displacement spectrum of the target event is solved for assuming a Brune spectral shape, and the stress drop is computed from the corner frequency.

The average stress drop observed for induced earthquakes in the WCSB is 7.2 MPa, in agreement with similar studies conducted for induced events in Oklahoma. We find that there are clear directivity effects for many events, despite their small-to-moderate size. For about half of the events, corner frequency varies by as much as a factor of 5 with azimuth. Thus directivity is an important consideration when estimating stress drop for events having large azimuthal gaps in the station coverage. We model such effects where evident, using a Haskell source model assuming unilateral rupture. By placing constraints on source parameters, the results of this study are useful to reconcile the source, path and site contributions to observed ground motions in the WCSB.

Relocations and Tectonic Implications of the Nine Mile Ranch Sequence From 2016-2018: 3 Mw 5.4-5.6 Near Hawthorne, Nevada

HATCH, R., University of Nevada Reno, Nevada, USA, rhatch@nevada.unr.edu; SMITH, K., Nevada Seismological Laboratory, University of Nevada Reno, Nevada, USA, ken@unr.edu; ABERCROMBIE, R. E., Boston University, Massachusetts, USA, rea@bu.edu; RUHL, C. J., The University of Tulsa, Oklahoma, USA, cjr7269@utulsa.edu; HAMMOND, W., Nevada Geodetic Laboratory, University of Nevada Reno, Nevada, USA, whammond@unr.edu; PIERCE, I. K. D., University of Nevada Reno, Nevada, USA, ian@nevada.unr.edu

On Dec. 28th, 2016 three moderate sized earthquakes occurred within the Walker Lane, southwest of Hawthorne, NV. The sequence began with a Mw 5.6 at 08:18 UTC and was followed 4 minutes later by an Mw 5.4. The third large event, a Mw 5.5, occurred at 09:13 UTC, 55 minutes after the initial earthquake. Our aim is to detect structures, characterize the spatio-temporal evolution, and place our observations within the context of the active tectonics in the region, which are poorly understood. These events give us the opportunity to investigate the area, in addition to compare to a 2011 sequence in the immediate vicinity. We update relocations, gather focal mechanisms and moment tensor solutions, and add a stress tensor inversion, GPS, and InSAR analysis to understand the aspects of the sequence. We hope to provide insight into triggering processes, stress release, and the initial stress environment. The Nevada Seismological Laboratory has located over 7000 events from the sequence, with depths ranging from 4-12 km. Moment tensor solutions show high-angle strike-slip faulting for the three main events, with focal mechanisms of smaller events showing predominantly strike-slip and normal ruptures. Relocations indicate several substantial unmapped structures. The largest structure in the sequence implies right-lateral strike slip faulting on a ~N45W striking fault plane. This fault plane is also dipping at a high angle to the NE. Two conjugate SW striking, vertical-dipping fault planes lie at both ends of the larger fault plane. The three main events are located very near one another at the intersection of the right lateral fault plane and the southern-most SW-striking conjugate structure. We compare the features of the Nine Mile Ranch Sequence to the 2011 Hawthorne sequence, which had over 50 earthquakes of M 3+, with the largest event at Mw 4.6. The 2011 and 2016-2018 Nine Mile Ranch sequences occur in the northwest corner of the Mina Deflection, a major structural right step within the Walker Lane, characterized by ENE-trending normal and sinistral faults.

Self-Adapting Bayesian Fault Slip Inversion With Green Functions Uncertainty: Demonstration on the 2016 M7 Kumamoto, Japan, Earthquake

HALLO, M., Charles University, Prague, Czech Republic, hallo@karel.troja.mff.cuni.cz; GALLOVIC, F., Charles University, Prague, Czech Republic, gallovic@karel.troja.mff.cuni.cz

Earthquake slip inversions infer kinematic parameters of spatial-temporal rupture propagation and slip distribution over the fault. Nevertheless, such inversions are subject of significant uncertainty (Mai *et al.* 2016). Probabilistic kinematic slip inversions taking into the account an uncertainty have been introduced by several recent studies. For example, Kubo *et al.* (2016) treats the Green functions (GFs) variance as an unknown parameter with uniform prior probability density function (PDF). Duputel *et al.* (2014, 2015) show the importance of considering the full covariance matrix in inversions, and propose to estimate the full covariance matrices by considering a linear relationship between the GFs and random perturbations of the velocity model.

Such Bayesian finite-fault inversions estimate the solution uncertainty for the particular choice of parametrization of the source model (*e.g.*, spatial smoothing, temporal parametrization, etc.). The choice of parametrization may have a big influence on the inferred solution (*e.g.*, Beresnev 2003), and hence also on the estimated uncertainty. Therefore, it is advisable to choose the source model parametrization considering the resolution power of the observed data. Over-parametrization is associated with overfitting the observed data, while under-parametrization with too rough source models.

Our work introduces a non-linear Bayesian fault slip inversion with effective trans-dimensional parametrization of the slip-rate function and implemented uncertainty of GFs (following Hallo and Gallovič 2016). The performance of our parametric slip inversion method is demonstrated on the inversion of the Mw7.1 mainshock of the 2016 Kumamoto, Japan, earthquake sequence. We infer an ensemble of more than 6 million possible finite-source models, representing samples of the posterior PDF. Such massive ensemble of solutions is then statistically processed to reveal which features of the source model are reliable and which are rather artifacts.

Rupture Behavior and Interaction of the 2018 Hualien Earthquake Sequence and Its Tectonic Implication

JIAN, P., Institute of Earth Sciences, Academia Sinica, Taipei, Taiwan, prjian@earth.sinica.edu.tw; HUNG, S., National Taiwan University, Taipei, Taiwan, shung@ntu.edu.tw; MENG, L., University of California, Los Angeles, California, USA, meng@ess.ucla.edu

The Mw 6.4 disastrous 2018 Hualien earthquake hitting the city of Hualien in eastern Taiwan on 6 February 2018 was preceded by unusual foreshock activities, starting with the largest Mw 5.9 foreshock two days earlier. To better understand the source processes and tectonic significance of this earthquake sequence, we investigated the rupture behaviors of both the largest foreshock and mainshock by the backprojection (BP) method. Results reveal that the foreshock ruptured northeastward and downward on a west-northwest-striking, north-northeast-dipping subhorizontal fault, and the mainshock propagated southwestward along a north-northeast–south-southwest-striking high-angle subvertical fault. The mainshock was not properly represented by a single point-source model, as suggested by a significant compensated linear vector dipole (CLVD) component of the moment tensor solution. A multiple point-source model clarifies the cause of a high CLVD and indicates that the mainshock was composed of one M w 6.2 and three smaller subevents. The largest one is an east-dipping sinistral strike-slip fault distinct from the other predominant thrusting subevents. The largest subevent was triggered by receiving the increased stress of at least 10 bars induced from the foreshock and initial subevent of the mainshock through the static Coulomb stress-transfer mechanism. The 2018 Hualien earthquake sequence represents a combined consequence of oblique subduction and lateral compression ongoing concurrently beneath the northern tip of the Taiwan–Luzon arc collision zone.

Characterizing Moderate-Magnitude Earthquakes and Their Aftershocks Using Montana Regional Seismic Network Data

STICKNEY, M. C., Montana Bureau of Mines and Geology, Montana, USA, mstickney@mtech.edu

Regional seismograph networks provide critical data for quantifying seismic hazards, however instrumentation and station density affect analytic results. Analysis of two recent moderate-magnitude earthquakes along the northern Intermountain Seismic Belt demonstrates the use and limitations of Montana Regional Seismograph Network (MRSN) data. The 2005 Dillon earthquake, M 5.6, occurred on a normal fault. The 2017 Lincoln earthquake, M 5.8, occurred on a strike-slip fault. The MRSN recorded no foreshocks for the Dillon earthquake and a single magnitude 2.3 foreshock for the Lincoln earthquake. Vigorous aftershock sequences followed both main shocks. A magnitude 4.4 aftershock 36 hours after the Dillon earthquake was the only aftershock above magnitude 4.0. The Lincoln aftershock sequence was significantly more energetic with magnitude 5.0 and 5.1 aftershocks 5 and 67 minutes, respectively, after the main shock, and eight aftershocks in the magnitude 4.0 to 4.7 range. B-values for both sequences are similar at about 0.8. Aftershock decay rates (p-values) are also similar; Dillon 0.81 and Lincoln 1.08 (provisional). However, Lincoln aftershock hypocenter depths are—on average—deeper (12.5 km) than the Dillon hypocenters (8.5 km). Most Dillon aftershocks occurred within 10 km of the main shock. Many Lincoln aftershocks occurred in a north-trending, 8-km-long zone centered on the main shock, but about 5% of Lincoln aftershocks lie up to 30 km northwest and southeast of the main shock, and crudely align with older WNW-trending faults. Coulomb stress changes modeled for an east-dipping normal fault explain Dillon aftershocks well. The Lincoln aftershocks are not as well modeled by coseismic stress changes inferred for sinistral slip on a NNE-trending fault. Focal mechanisms for both main shocks and the larger aftershocks are consistent with NE-SW extension. Despite older instrumentation and low station density, the MRSN provides new insights into Montana seismic hazards.

Stress Drops for Microseismicity in Asperity-Like Dynamic Fault Models: Actual Values vs. Estimates From Spectral Fitting and Second-Moment Approaches

LIN, Y., National Central University, Taoyuan, Taiwan, yylinm22@gmail.com; LAPUSTA, N., California Institute of Technology, California, USA, lapusta@caltech.edu

Stress drop, an averaged difference between the shear stress on the fault before and after an earthquake, is an important source parameter. The values estimated by typical seismological methods (*e.g.*, the spectral fitting approaches) suggest that the stress drop is moment-invariant with large scatter and that the on-fault rupture duration tw obeys the scaling of tw ∝ M0^(1/3). However, several observations show that microseismic events from the same location can have similar source durations but different seismic moments, violating the commonly assumed scaling. We use numerical simulations of earthquake sequences to demonstrate that strength variations over seismogenic patches provide an explanation of such behavior, with the event duration controlled by the patch size and event magnitude determined by how much of the patch area is ruptured. We find that stress drops estimated by the spectral fitting analyses for the sources simulated in an asperity-like fault model significantly increase with the event magnitude, ranging from 0.006 to 8 MPa. However, the actual stress drops determined from the on-fault stress changes are magnitude-independent at ~3 MPa. Our findings suggest that fault heterogeneity results in local deviations in the moment-duration scaling and in earthquake sources with complex shapes of the ruptured area, for some of which stress drops may be significantly (~100-1000 times) underestimated by the spectral fitting methods. We further apply the stress-drop estimation approach using second moments, which aims to account for rupture directivity and elliptical sources. The second-moment approach indeed works better, providing close estimates of stress drop for sources with rupture areas similar to elliptical ones, but still significantly underestimates, by a factor of up to 30, stress drops for more complex rupture shapes such as ring-like sources. Hence the estimated stress drops still overall increase with the event magnitude, ranging from 0.1 to 2 MPa, but are overall closer to the actual stress drop of ~3 MPa.

The 2007 Ning'er Mw 6.1 Earthquake: A Shallow Rupture in Southwest China Revealed by Insar Measurements

CHEN, W., Institute of Seismology, China Earthquake Administration, Wuhan, China, chenweicug@126.com; QIAO, X., Institute of Seismology, China Earthquake Administration, Wuhan, China, qiaoxuejun@gmail.com

The Ning'er Mw 6.1 earthquake on June 3, 2007, occurred in the south-central section of the South-North seismic belt in China. The epicenter is in the southwestern to the Sichuan-Yunnan rhombic block with complicated seismic structures. The focal depth determined by the U.S. Geological Survey (USGS) is only 5 km, but the field earthquake investigation did not find obvious surface ruptures in the epicenter area. In addition, the magnitude obtained by inverting the broadband waveforms is Mw6.4 that is much larger than the Mw6.1 determined by USGS and Global Centroid Moment Tensor (GCMT), indicating the complexity of the earthquake. The Interferometric Synthetic Aperture Radar (InSAR) is used to study the fault geometry, coseismic slip model, and Coulomb stress changes around the seismic region firstly. It shows that this event is mainly dominated by a right-lateral strike-slip fault with a slight thrust component. The coseismic slip is 28 km along the strike and 14 km along the dip and the most slips are concentrated within the upper 7 km of the crust. The maximum slip is up to 1.02 m at a depth of 3.6 km and the released moment is 2.57×10^{18} Nm, corresponding to a magnitude of Mw 6.25, which is between Mw 6.4 from the broadband waveform inversion and Mw 6.1 from GCMT and USGS. The shallow source of this event is related to the local tectonics and inelastic off-fault deformations along the fault. The lack of obvious surface rupture indicates that the strain is not completely released and remains underground. The coseismic Coulomb stress changes suggest that this earthquake has enhanced the stress on the Puwen fault and the Mohei fault. The seismic risks for these two faults and its adjacent regions cannot be ignored in the future since aftershocks are fewer and the accumulation of residual strain from the Ning'er event.

Long-Period Velocity Pulses at Near-Fault Region During the 2016 Kumamoto Earthquake, Japan

KIDO, T., Tokyo University of Science, Noda, Japan, 7114034@alumni.tus.ac.jp; NAGANO, M., Tokyo University of Science, Noda, Japan, nagano-m@rs.noda.tus.ac.jp

During the main event of the 2016 Kumamoto earthquake (M_W7.0~7.1), Japan, surface ruptures were confirmed in a wide region and were accompanied with wide range of permanent displacement. In the vicinity of the seismic faults, seismic intensity of scale 7 in the JMA intensity scale and large-amplitude pulse-type ground motions with period of 1 sec were observed at the Mashiki Town in the fault parallel direction. These pulse-type ground motions caused severe damage to wooden houses, which resulted in a damage zone with a width of about 1 km at the central part of the Mashiki Town. Moreover, at the Nishihara village and the K-NET Ichinomiya, a long-period pulse with dominant period of about 3 sec was observed, which could cause damage to long-period structures including super-high-rise and seismically isolated buildings. In the seismically isolated hospital building in Aso City about 3.6 km away from the K-NET Ichinomiya, the relative displacement of seismic layer from recorded orbiter showed smaller deformation at isolation devices than expected. This implies that amplitude of long-period pulses were spatially variated depending on location between sites and the seismic faults. In this study, we constructed a characterized seismic fault model and performed theoretical simulation of strong ground motions near the seismic faults. Thin Layer Method is used as a numerically effective tool for ground motions simulation for the seismic faults with surface ruptures. The spatial variation of the strong ground motions including the Aso area in the northeastern part of Kumamoto Prefecture could also be simulated by a characterized seismic fault model. The validity of the slip distribution of the fault model was also examined based on the comparison of surface distribution of permanent displacement between calculated results from the seismic fault model and those from crustal deformation by InSAR images.

Differences Between Main-Shock and Aftershock Ground Motions Using the Japan's Kik-Net Database

LEE, H., UNIST, Ulsan, Korea, Republic of, hyejinlee@unist.ac.kr; PARK, H., UNIST, Ulsan, Korea, Republic of, heonjoon@unist.ac.kr; KIM, B., UNIST, Ulsan, Korea, Republic of, byungmin.kim@unist.ac.kr

Main-shock earthquakes are followed by numerous aftershocks which aggravate damages to structures and infrastructure. There have been many studies about forecasting frequencies of aftershocks. However, there are only few controversial studies on characteristics of aftershock ground motions. Some researchers argue that there is no difference between aftershock and main-shock ground motions given the same earthquake magnitude. Others found differences: spectra accelerations of aftershock motions at short period are smaller than those of main-shock motions. We utilize the abundant ground motion data from the Kiban-Kyoshin network (KiK-net) in Japan and statistically analyzed differences between main-shock and aftershock motions. We consider the three factors influencing characteristics of ground motions: (1) the moment magnitude (M), (2) the distance from rupture (R_{rup}), and (3) the time-averaged shear wave velocity in the top 30 m of soil deposits (V_{S30}). We analyze logarithmic ratios of spectral accelerations of aftershock ground motions to those of main-shock motions ($\ln(Sa^{AS}/Sa^{MS})$) using both surface and within-rock motions for various magnitude and distance combinations. We found that spectral accelerations of aftershock ground motions are smaller than those of main-shock motions at periods less than 1s. We also found that this difference is dominant for short rupture distances ($R_{rup} \leq 60$ km) and moderate earthquake ($M \leq 5.5$). These trends are similar for both surface and within-rock ground motions.

Rupture Initiation of Small Earthquakes in the Corinth Rift, Greece

DUVERGER, C., Institut de Physique du Globe de Paris, CEA, Paris, France, clara.duverger.pro@gmail.com; COLLOMBELLI, S., University of Naples Federico II, Naples, Italy, simona.colombelli@unina.it; BERNARD, P., Institut de Physique du Globe de Paris, Paris, France, bernard@ipgp.fr; ZOLLO, A., University of Naples Federico II, Naples, Italy, aldo.zollo@unina.it

During the last decades, recent studies evidenced differences in rupture initiation between small and large earthquakes, bringing new perspectives to understand the earthquake nucleation and helping to develop early-warning systems. Whether the final event magnitude can be estimated while the rupture is still ongoing, stays an open question and opposite points of view have been proposed regarding the deterministic nature of the rupture process.

Most of the previous studies focused on large earthquakes for their interest in risk mitigation actions. We peculiarly investigate the behavior of small ruptures, taking advantage of the dense and rich database of the Corinth Rift Laboratory in Greece. Following the approach proposed by Colombelli *et al.* (2014), we looked at the time evolution of the initial P-wave peak amplitude. We analyze earthquakes of magnitude $M<5$ with the aim of understanding the feasibility of this approach and of comparing the results with larger magnitudes. For the small events ($1<M<4$), we highlight a positive scaling between the averaged P-wave peak velocity at the early stage of the rupture and the final earthquake size, opposed to the tendency found for larger Japanese earthquakes. In the Corinth Rift, we suggest that the higher the slip rate is in average, the larger the earthquake is. This interpretation can be illustrated by considering shortly distant asperities: if the slip rate is low, only one asperity breaks resulting in low-magnitude event, whereas if the slip rate is high, enough energy is released to propagate the rupture to several connected asperities.

Further analyses are needed to validate the results, especially by investigating several factors (time sampling, attenuation, etc.) to fully understand the observed behaviors. Moreover, given the availability of seismic multiplets in the Corinth Rift, which are associated to different external forcings (pore pressure, aseismic slip), it would be interesting to investigate a possible distinction in rupture initiation behavior as a function of specific forcing sources.

Frequency-Dependent Moment Tensors of Induced Microearthquakes

YU, C., GFZ German Research Centre for Geosciences, Potsdam, Germany, yu@gfz-potsdam.de; VAVRYCUK, V., Institute of Geophysics, Prague, Czech Republic, vv@ig.cas.cz; ADAMOVA, P., Institute of Geophysics, Prague, Czech Republic, adamova@ig.cas.cz; BOHNHOFF, M., GFZ German Research Centre for Geosciences, Potsdam, Germany, marco.bohnhoff@gfz-potsdam.de

Moment tensors (MTs) of 984 microearthquakes in The Geysers geothermal reservoir are calculated using the P-wave amplitudes extracted from signals filtered in different frequency bands defined by seven upper cutoff frequencies (2, 3, ..., 8 Hz). The frequency dependence of the double-couple (DC), compensated linear vector dipole (CLVD), and isotropic (ISO) percentages, and the RMS as well as the P/T-axes is analyzed. The DC, CLVD and ISO percentages vary significantly with the frequency band of the signal, while the P/T-axes are more stable. It means that the increasing bandwidth significantly changes the relative energy distribution of different MT components, but the fault plane geometry is less affected. The frequency dependence of the RMS is consistent with the spectral distribution of noise recorded by the network, which implies a strong influence of noise level on the MT inversion in different frequency bands. The percentage of the DC and ISO components tends to decrease and increase, respectively, as the upper cutoff frequency increases. This suggests that the shear rupture along the main fault plane radiates energy at lower frequencies than the tensile rupture.

Since the ISO component can be directly related to the injection and migration of fluids, the frequency dependence of the ISO component is further evaluated to separate events with a weak or strong frequency dependence. Most of events with a strongly varying ISO are characterized by an increase of the ISO with increasing frequency band of the analyzed signal. These events are mainly located within the same depth interval as most of the injection points and do not migrate downward as the other events. This might be explained by the presence of small tensile cracks adjacent to the main shear fracture created by strong thermoelastic effects in the vicinity of injection wells rather than by the poroelastic effects that are more important at larger distance.

Fault Failure in Oklahoma Is Anything but Simple

PENNINGTON, C. N., University of Oklahoma, Oklahoma, USA, colin.n.pennington@ou.edu; UCHIDE, T., Geological Survey of Japan, AIST, Tsukuba, Japan, t.uchide@aist.go.jp; CHEN, X., University of Oklahoma, Oklahoma, USA, xiaowei.chen@ou.edu

Seismicity in Oklahoma is primarily driven by wastewater injection, but where does the influence of wastewater end and the natural processes of fault failure take over? In order to answer this question, we construct finite fault models for 3 earthquakes in the region. They are of a M 4.1 earthquake that occurred near Guthrie, OK in April 2015, the M 5.0 Cushing earthquake that occurred in November 2016, and the M 5.1 Fairview earthquake that occurred in February 2016. Previous works on the Guthrie event and the Fairview event show that both events exhibit rupture complexity with more than two subevents (López-Comino and Cesca, 2018; Wu *et al.*, 2018, AGU). A previous finite-fault slip model with ground motion records of the Cushing event shows rather complex rupture history (Ji & Archuleta, 2017, EGU). The finite fault model obtained for the Guthrie event supports these findings. It shows a small slip patch occurring at the hypocenter location, which then triggers 0.4s later a 500m wide and 2000m long slip patch 0.5 km to the SE. This slip patch is composed of a number of small high slip (0.08 m) patches that represent the slip for each subevent observed in previous works. In this study, we take advantage of the abundance of clustered events around each mainshock, and apply multiscale slip inversion to resolve details of the beginning stage of the rupture, assess how fault rupture propagates along the faults, and if there is any relationship between pressure propagation direction and rupture direction. In addition, we compare our source complexity to the source complexity from a recently compiled global dataset, to assess if the intraplate setting with low tectonic strain rate influences rupture complexity. Finally, we will assess whether rupture complexity influences aftershock distributions and activation of different fault segments, as well as ground motion distributions. These results will allow for the improved understanding of earthquake rupture, aftershock activity and improve our ability to assess the seismic hazard for similar failures in the future.

Multiple Point Source Inversions on Teleseismic Waveform Data Reveal the Complex Super-Shear Rupture Process of the 2018 Mw 7.5 Palu Earthquake

SHI, Q., Nanyang Technological University, Singapore, Singapore, qshi003@e.ntu.edu.sg; WEI, S., Nanyang Technological University, Singapore, Singapore, shjwei@gmail.com; ZENG, H., Nanyang Technological University, Singapore, Singapore, hyzeng@ntu.edu.sg

Multiple Point Source(MPS) model, which is a time-space sequence of double-couple sources, fills in the earthquake source representations between single point source and the finite fault model. Here we generalized our Markov Chain Monte Carlo based MPS inversion scheme to cover teleseismic waveform and applied it to the 2018 Mw7.5 Palu earthquake. With path calibration from the 2012 (Mw6.3) and 2017 (Mw6.6) events, we selected 62 teleseismic P waves and 35 SH waves filtered to the station-dependent frequency ranges (~3-100s) for the inversion. We tested the number of sources and found that five sources can fit the observations adequately. Our results show the five subevents (S1-5) align in near N-S direction over a distance of ~140km and occurred subsequently from N to S, with a total duration of ~40s and a total Mw of 7.4. All S1-5 have similar sub-vertical strike-slip focal mechanism with slight differences in strike and dip, where S4 and S5 are featured with stronger normal slip. Their Mw, however, shows more dramatic differences with S2 (Mw7.2) and S3 (Mw7.1) dominating the moment release. S1 is located ~10km to the south of the epicentre and the distances between the neighbouring subevents (from N to S) are 17, 38, 33 and 40km, with corresponding timing separations of 7, 11, 8 and 8s. The source durations are 5~7s. The apparent rupture speed, defined by the centroid location and timing of the neighbouring events, gradually increased from 2.4km/s (S1 to S2) to 4.7km/s (S4 to S5), which agree well with the back-projection results from the Australian array. As revealed by the geodetic data, the rupture did not reach to the surface near S1 and S2 where topography feature of fault trace is not clear, although two compressional step-overs could be identified in the geodetic data. In contrast, the satellite images show clear and smooth surface rupture around S3 and S4, where clear fault-related topography can be identified . The gradual increasing rupture speed can be explained as the rupture propagation from the less active faults to the more mature Palu fault.

Finite-Source Inversion of the 14 December 2016 M5 Geysers Geothermal Field Earthquake, Post-Earthquake Velocity Changes and Finite-Source Scaling

DREGER, D. S., University of California, Berkeley, California, USA, ddreger@berkeley.edu; BOYD, S., University of California, Berkeley, California, USA, sierra@seismo.berkeley.edu; TAIRA, T., University of California, Berkeley, California, USA, taira@berkeley.edu; GRITTO, R., ARRAY Information Technology, California, USA, roland.gritto@arrayinfotech.com

Seismicity from the EGS demonstration experiment at The Geysers, CA Prati-32 injection well has been investigated for the seismic moment tensor, in situ stress, and the scaling of micro-earthquake source parameters. One objective is to develop an approach for estimating a statistical representation of the fracture network generated from the injection of fluids into hot dry rock. We have performed finite-source inversion of seismic moment rate functions obtained for earthquakes spanning the magnitude range of Mw 1.0 to 4.5 at or near the EGS demonstration site to investigate the scaling of source dimension, slip, and stress drop. We find that micro-earthquakes are not simple ruptures and can have strong directivity effects, with multiple asperities of rupture. Rupture area is found to be consistent with the Wells and Coppersmith (1994) and Leonard (2010) scaling laws developed for much larger (Mw>5.5) earthquakes. Owing to the complex nature of the kinematic finite-source models we use the method of Ripperger and Mai (2004) to compute the static stress change. We find that peak stress drops can be large, however on average they are consistent with the aforementioned source scaling laws. On December 14, 2016 a Mw 5.0 earthquake occurred approximately 1.9 km SSW of the Prati-32 injection well. We develop finite-source models using both empirical and theoretical Green's functions methods, combining seismic and geodetic data. We consider the results in the context of the average slip and rupture area scaling laws for the region and compare to the micro-earthquake (magnitude 1.0 to 4.5) results. In addition to the source characterization, we explore seismic velocity changes associated with local Geysers earthquakes. We find a systematic velocity reduction following the 2016 Mw 5.0 Geysers earthquake, which may be explained by a temporary increase of fracture density due to stress changes induced by the Mw 5.0 mainshock.

Reliable Moment Magnitudes (Mw) of Smaller Size Events Using Coda Waves

GOK, R., Lawrence Livermore National Laboratory, California, USA, gok1@llnl.gov; BARNO, J., Lawrence Livermore National Laboratory, California, USA, barno1@llnl.gov; MAYEDA, K., Air Force Technical Applications Center, Florida, USA, kevin.mayeda@gmail.com; ONUR, T., Onur Seemann Consulting, Inc., Victoria, Canada, tuna@onurseemann.com; WALTER, W. R., Lawrence Livermore National Laboratory, California, USA, walter5@llnl.gov

The uneven distribution of stations and heterogeneous structure of the earth makes it difficult to calculate reliable moment magnitudes, especially for smaller events. Such magnitudes are important for event characterization, and its applications. The complex structure of the lithosphere in many regions causes significant variation in the recorded amplitude of direct body and surface waves that travel along different paths. These 2-D and 3-D effects are most significant for small-to-moderate sized events, which are mostly observable at periods < 10 seconds.

By contrast, the coda wave calibration method for source spectra and moment magnitude estimation has proven to be very robust in many regions with complex tectonic structure (*i.e.*, Middle East, Caucasus, Central Asia). A direct moment magnitude calculation using the coda calibration technique has been successfully applied down to magnitude 3.0, thus eliminating the need for magnitude conversion (*e.g.*, M_L to Mw) that can introduce large uncertainties. The reason why it is important to estimate reliable magnitudes is twofold: 1) Almost all contemporary ground motion prediction equations used in PSHA are in terms of Mw; 2) Mw provides a better quantification of the size of earthquakes, particularly large earthquakes, for which other magnitude scales tend to saturate. We are currently developing a robust, Java-based calibration and measurement tool to compute source parameters. This tool is openly available to the scientific community to test and validate the robustness of the calibration technique.

Coseismic Slip and Early Afterslip of the m6.0 August 24, 2014 South Napa, California, Earthquake

POLLITZ, F. F., U.S. Geological Survey, California, USA, fpollitz@usgs.gov; MURRAY, J. R., US Geological Survey, California, USA, jrmurray@usgs.gov; MINSON, S. E., US Geological Survey, California, USA, sminson@usgs.gov; WICKS, C., US Geological Survey, California, USA, cwicks@usgs.

gov; SVARC, G. L., US Geological Survey, California, USA, jsvarc@usgs.gov; BROOKS, B. A., US Geological Survey, California, USA, bbrooks@usgs.gov

We employ strong motion seismic acceleration recordings (low-pass filtered at 1.5 Hz) combined with static offsets estimated from GPS, InSAR, alignment-array and mobile laser scanning observations in order to derive a kinematic coseismic slip and afterslip model of the M6.0 August 24, 2014 South Napa earthquake. This earthquake ruptured a ~13 km long portion of the West Napa fault with predominantly right-lateral strike slip. In the kinematic seismic slip inversions, we prescribe a priori a range of local rupture velocities, allowing for arbitrary shape of the local source-time function but bounding the effective rise time as measured by the second temporal moment of slip. We also couple the coseismic slip and afterslip distributions by requiring both distributions to involve predominantly right-lateral strike-slip motion with positive amplitude, with the net static slip being the sum of the two. We consider two candidate fault geometries: that of Wei *et al*. (2015) involving two steeply east-dipping planes, and that of Dreger *et al*. (2015) involving one steeply west-dipping plane. The resulting coseismic slip distribution involves up to ~1.2 m slip on a dominant shallow asperity about 10 km north of the hypocenter, associated with relatively long rise times, and on deeper asperities on the southern part of the rupture, associated with much shorter rise times. These high-slip zones define a unilateral rupture along a narrow slip zone that emanated updip and northward from the hypocenter to the maximum slip area. Afterslip of up to 1 m is concentrated along the southern part of the rupture at depths <~5 km, consistent with surface observations of afterslip. Seismic moments associated with coseismic slip and afterslip are 1.11×10^{18}N m (Mw 6.00) and 3.25×10^{17}N m, respectively.

Facebook and Twitter and Snapchat, Oh My! The Challenges and Successes of Using Social Media to Communicate Science to the Public

Poster Session · Thursday · 25 April · Fifth Avenue

The USGS Earthquake Hazard and Risk Information System

BLANPIED, M. L., U.S. Geological Survey, Virginia, USA, mblanpied@usgs.gov; MCBRIDE, S. K., U.S. Geological Survey, California, USA, skmcbride@usgs.gov; WALD, D. J., U.S. Geological Survey, Colorado, USA, wald@usgs.gov

Federal, state, tribal, and local government agencies, architects and engineers, utilities, insurance companies and other private businesses, land use planners, emergency response officials, science enthusiasts and the interested public rely on the U.S. Geological Survey (USGS) for important hazard and risk information. In response to the informational needs of our many stakeholders, the USGS provides a continuum of products that convey information about earthquake hazards and risks. This "Earthquake Information System" is widely used in order to support risk mitigation, and also includes near-real-time earthquake information products aimed at situational awareness to support decision-making, response and recovery. Rapid earthquake notifications are delivered by email and text message to over 500,000 subscribers, and a spectrum of earthquake information products including *ShakeMap*, *Did You Feel It?*, rapid *PAGER* estimates of financial and human impacts, and scientific data are automatically delivered on the web and via geoJSON feeds. In addition to releasing periodic updates to its National Seismic Hazard Model, which underlies the national-scale building codes, the USGS partners with State and local experts to produce more detailed urban seismic hazard maps for high- to moderate-risk areas, which make it possible for local officials to make precise and informed zoning and building code decisions. New products include a nationwide library of scenario earthquakes, rapid post-earthquake ground failure estimations, and aftershock forecasts. We will explore why these products exist and what messages they communicate, what audiences they are aimed at, how they address our strategic objectives, meet the needs of our many stakeholders, and how these products are interconnected to comprise an *earthquake hazard and risk information system* for the USGS.

Communicating Earthquake Science in Real Time: Tweets From the Berkeley Seismology Lab

TAGGART, J., University of California, Berkeley, California, USA, jennifer.c.taggart@berkeley.edu; STRAUSS, J., University of California, Berkeley, California, USA, jastrauss@berkeley.edu; ALLEN, R. M., University of California, Berkeley, California, USA, rallen@berkeley.edu; HELLWEG, M., University of California, Berkeley, California, USA, peggy@seismo.berkeley.edu

The Berkeley Seismo Lab's Twitter feeds, @BerkeleySeismo, @MyShakeApp, and the new @BSLQuakes, have primarily been a successful way of disseminating earthquake information. According to Twitter's analytics, @BerkeleySeismo's most popular tweets fall into two categories: information posted just after an earthquake and links to new Seismo Blog entries, which explore a particular topic in more detail. Because the post-earthquake information is so popular, we have created an interface that allows BSL seismologists to rapidly create custom maps following a quake of interest, including the quake mechanism, foreshocks and aftershocks, and important historical quakes or background seismicity from the COMCAT catalog. Our seismologists add value to this quake information by posting the map with their own brief commentary on the quake. @MyShakeApp has been effective in building interest in the MyShake project. Its tweets range from screenshots of waveforms collected by citizen scientists using the app, to maps of quakes "caught" by the app, and include invitations to participate in feedback sessions to improve the user interface. Like our main feed, Twitter analytics indicates that maps created using MyShake user data are by far the most likely to encourage engagement. Our newest feed, @BSLQuakes, rapidly provides information on Northern California earthquakes. Like the @CaltechQuake feed for Southern California, an earthquake's time, magnitude, distance to the nearest town, and other information are posted automatically within minutes.

10 Years of Tsunami-Preparedness Exercises in the Puerto Rico and Virgin Islands Region

BÁEZ-SÁNCHEZ, G., Puerto Rico Seismic Network, Puerto Rico, USA, gisela.baez1@upr.edu; COLÓN-RODRÍGUEZ, B., Puerto Rico Seismic Network, Puerto Rico, USA, benjamin.colon1@upr.edu; VENTURA-VALENTÍN, W. A., Puerto Rico Seismic Network, Puerto Rico, USA, wilnelly.ventura@upr.edu; CÁLIZ-PADILLA, R. M., Puerto Rico Seismic Network, Puerto Rico, USA, rocio.caliz@upr.edu

Puerto Rico and Virgin Islands Region (PR/VI) is the area of seismic responsibility monitored by the Puerto Rico Seismic Networks (PRSN). This area includes Puerto Rico, USVI, BVI and the Eastern Dominican Republic which are located on the tectonic border of the Caribbean and North American plates. Major events in the region throughout history have generated tsunamis that make the population aware of the risks generated by earthquakes. A significant 7.3Mw earthquake in 1918 generated a tsunami that impacted PR/VI region. More recently, a major 6.4Mw earthquake struck the region and reignited public awareness that large events and tsunamis are possible. In order to educate the population and emergency managers, the PRSN has uninterruptedly coordinated annual tsunami response exercises in PR/VI since 2009 with the Lantex Exercise. Since 2013 under initiatives from the Caribe EWS-Intergovernmental Oceanographic Commission (UNESCO), the exercise was jointly carried out as the CaribeWave/Lantex. As of 2016 the tsunami response exercise is coordinated out as the CaribeWave exercise under the IOC UNESCO framework. Some of the exercise objectives are to test and evaluate the operations of the Caribe EWS, validate tsunami response preparedness and assist tsunami-preparedness efforts of Caribbean emergency management agencies. The PRSN performs communications exercise with all the primary emergency agencies in PR/VI to test the messaging and alert distribution systems in place. The exercise also provides opportunity for state and municipal agencies to test their warning systems. In addition, an intense educational campaign is carried out to promote public preparedness for the eventuality of a tsunami. This effort to reach the people involves the use of the existing mass media which has evolved to include platforms such as social media and automated messaging systems. Here we present an analysis of the exercise evolution over the past decade and the impact the exercise on the public and local stakeholders.

The InSight Mission – Seismology on Mars and Beyond

Poster Session · Thursday · 25 April · Fifth Avenue

Comparison of the InSight Seismometer Characteristics on Mars With Tests on Earth

HURST, K., Jet Propulsion Laboratory, California Institute of Technology, California, USA, ken.hurst@jpl.nasa.gov; VERDIER, N., CNES, Toulouse, France, nicolas.verdier@cnes.fr; BIERWIRTH, M., MPS, Gottingen, Germany, bierwirthm@mps.mpg.de; FAYON, L., Institut de Physique Du Globe de Paris, Paris, France, fayon@ipgp.fr; KEDAR, S., Jet Propulsion Laboratory, California Institute of Technology, California, USA, sharon.kedar@jpl.nasa.gov; KNAPMEYER-ENDRUN, B., University of Cologne, Cologne, Germany, brigitte.knapmeyer-endrun@uni-koeln.de; TILLIER, S., Institut de Physique Du Globe de Paris, Paris, France, sylvain.tillier@gmail.com; WIDMER-SCHNIDRIG, R., Black Forest Observatory, University of Stuttgart, Schiltach, Germany, widmer@geophys.uni-stuttgart.de; BANERDT, W. B., Jet Propulsion Laboratory, California Institute of Technology, California, USA, william.b.banerdt@jpl.nasa.gov; CALCUTT, S., Oxford University, Oxford, United Kingdom, calcutt@atm.ox.ac.uk; DE RAUCOURT, S., Institut de Physique Du Globe de Paris, Paris, France, sebastien.deraucourt@gmail.com; GARCIA, R., Institut supérieur de l'aéronautique et de l'espace, Toulouse, France, raphael.garcia@isae-supaero.fr; GIARDINI, D., ETH Zurich, Zurich, Switzerland, domenico.giardini@erdw.ethz.ch; LOGNONNÉ, P., Institut de Physique Du Globe de Paris, Paris, France, lognonne@ipgp.fr; MIMOUN, D., Institut supérieur de l'aéronautique et de l'espace, Toulouse, France, david.mimoun@isae-supaero.fr; PANNING, M. P., Jet Propulsion Laboratory, California Institute of Technology, California, USA, mark.p.panning@jpl.nasa.gov; PIKE, W. T., Imperial College London, London, United Kingdom, w.t.pike@imperial.ac.uk; ZWEIFEL, P., ETH Zurich, Zurich, Switzerland, peter.zweifel@sed.ethz.ch; CHARALAMBOUS, C., Imperial College London, London, United Kingdom, constantinos.charalambous05@imperial.ac.uk; CLINTON, J., ETH Zurich, Zurich, Switzerland, jclinton@sed.ethz.ch; DRILLEAU, M., Institut de Physique du Globe de Paris, Paris, France, drilleau@ipgp.fr; MANCE, D., ETH Zurich, Zurich, Switzerland, davor.mance@sed.ethz.ch; MCCLEAN, J. B., Imperial College London, London, United Kingdom, j.mcclean15@imperial.ac.uk; MURDOCH, N., Institut supérieur de l'aéronautique et de l'espace, Toulouse, France, naomi.murdoch@isae-supaero.fr; NEBUT, T., Institut de Physique Du Globe de Paris, Paris, France, nebut@ipgp.fr; STÄHLER, S., ETH Zurich, Zurich, Switzerland, simon.staehler@erdw.ethz.ch; TEN PIERICK, J., ETH Zurich, Zurich, Switzerland, jan.tenpierick@erdw.ethz.ch; WARREN, T., Oxford University, Oxford, United Kingdom, tristram.warren@physics.ox.ac.uk

The seismometer the InSight mission placed on Mars in December of 2018 consists of a set of 3-component oblique-axis very broad band (0.01-1 Hz) and another set of 3-component short period (0.5-25 Hz) sensors, all mounted within a leveling system coupled to the surface, and isolated from the atmospheric environmental noise. A digitizing and recording system remains in the thermal enclosure of the lander. The nominal mission duration is 2 Earth years, and since it is solar powered, it may last longer.

At the time of writing, the sensor assembly package has been deployed to the surface of Mars, all sensors are working, and it is mid-way through the setup procedure.

We will compare the characteristics of the seismometer on Mars with tests done on Earth before launch and with terrestrial seismometers and installations, paying particular attention to unique features of this seismometer and its installation on Mars that are reflected in the performance of the instrument.

Marsquake Service for InSight: Methods to Locate Events in a 3D Planet

CLINTON, J., ETH Zurich, Zurich, Switzerland, jclinton@sed.ethz.ch; VAN DRIEL, M., ETH Zurich, Zurich, Switzerland, vandriel@erdw.ethz.ch; STÄHLER, S., ETH Zurich, Zurich, Switzerland, simon.staehler@erdw.ethz.ch; GIARDINI, D., ETH Zurich, Zurich, Switzerland, domenico.giardini@erdw.ethz.ch; BÖSE, M., ETH Zurich, Zurich, Switzerland, maren.boese@googlemail.com; CEYLAN, S., ETH Zurich, Zurich, Switzerland, savas.ceylan@erdw.ethz.ch; KHAN, A., ETH Zurich, Zurich, Switzerland, amir.khan@erdw.ethz.ch; KEMPER, J., ETH Zurich, Zurich, Switzerland, johannes.kemper@erdw.ethz.ch; MUNCH, F., ETH Zurich, Zurich, Switzerland, federico.munch@erdw.ethz.ch; AFANASIEV, M., ETH Zurich, Zurich, Switzerland, michael.afanasiev@erdw.ethz.ch; WIECZOREK, M., Observatoire de la Côte d'Azur, Nice, France, mark.wieczorek@oca.eu

With the deployment of the SEIS seismometer package by the Insight lander on the surface of Mars, the Mars Quake Service (MQS) has started its work to detect, locate and catalogue Martian seismicity. In preparation, a number of methods to locate seismic events based on polarization (azimuth) and traveltime (distance) have been presented and tested in a public blind test. However, both the location methods and synthetic data assumed a spherically symmetric planet.

In a second stage, we computed a synthetic data set in a 3D Mars model including ellipticity, topography, crustal thickness and lateral velocity variations in the crust. This test revealed, that 1D is likely a good approximation for body wave and long period surface waves ($T < 80s$) traveltimes, but traveltimes can be off by as much as a few hundred seconds for shorter period surface waves ($50s < T < 15s$) with the crustal thickness being the most relevant source of error. For events that only produce a single body wave phase additional to the surface waves, this translates into a significant error in the distance estimation.

In this presentation we argue how we can mitigate this problem by adding a 3D crust on top of the 1D models that fits the gravity data and hence approximate the crustal thickness, how to efficiently compute surface wave traveltimes for these models and demonstrate the efficacy of this approach in a 3D blind test.

Furthermore, we show how we select a reasonable number of models for probabilistic location methods from a very large set of a priori models based on a clustering technique and how this selection can be updated as the number of events grows.

Marsquake Service for InSight: Preliminary Observations and Operations

CEYLAN, S., ETH Zurich, Zurich, Switzerland, savas.ceylan@erdw.ethz.ch; CLINTON, J., ETH Zurich, Zurich, Switzerland, jclinton@sed.ethz.ch; STÄHLER, S., ETH Zurich, Zurich, Switzerland, simon.staehler@erdw.ethz.ch; GIARDINI, D., ETH Zurich, Zurich, Switzerland, domenico.giardini@erdw.ethz.ch; BÖSE, M., ETH Zurich, Zurich, Switzerland, maren.boese@googlemail.com; VAN DRIEL, M., ETH Zurich, Zurich, Switzerland, vandriel@erdw.ethz.ch; HORLESTON, A. C., University of Bristol, Bristol, United Kingdom, anna.horleston@bristol.ac.uk; KAWAMURA, T., Institut de Physique du Globe de Paris, Paris, France, kawamura@ipgp.fr; KEDAR, S., Jet Propulsion Laboratory, California Institute of Technology, California, USA, sharon.kedar@jpl.nasa.gov; KHAN, A., ETH Zurich, Zurich, Switzerland, amir.khan@erdw.ethz.ch; EUCHNER, F., ETH Zurich, Zurich, Switzerland, fabian.euchner@sed.ethz.ch; BANERDT, W. B., Jet Propulsion Laboratory, California Institute of Technology, California, USA, william.b.banerdt@jpl.nasa.gov; LOGNONNÉ, P., Institut de Physique Du Globe de Paris, Paris, France, lognonne@ipgp.fr

InSight landed on Mars in late November 2018, and the SEIS seismometer package was deployed on the surface over Christmas. SEIS is expected to operate for at least 1 Martian year, or two Earth years. The Marsquake Service (MQS) has been setup to create and curate a seismicity catalogue for Mars during the lifetime of the InSight mission. In preparation for operations, the MQS team have developed single station location and characterisation algorithms, created a software framework that manages the data flow that includes these approaches, and tested methods and operational procedures via a suite of blind tests. The MQS approach includes use of an *a-priori* set of plausible martian models that can be refined once constraints from observed signals are included. The MQS works in conjunction with the Mars Structural Service (MSS) on building and adopting updated models. Mars has strong topographic variations, and 3D effects on surface waves can be taken into account. The MQS consists of an international team of seismologists that, in turn, screen incoming data to identify and characterise any seismicity. The MQS has been operational since the first seismic signals started arriving from on deck. In this presentation, we present the MQS, show initial results and describe the challenges we face dealing with the true Martian dataset.

A Further Application of the Cepstral Stacking Method to Determine Focal Depths of Marsquakes

CAKIR, R., Independent Researcher, cakir.recep@gmail.com; CEYLAN, S., ETH Zurich, Zurich, Switzerland, savas.ceylan@erdw.ethz.ch; ALEXANDER, S., Pennsylvania State University, Pennsylvania, USA, judyalexander@aol.com; VAN DRIEL, M., ETH Zurich, Zurich, Switzerland, vandriel@erdw.ethz.ch

The Cepstral Stacking Method (CSM) was originally developed by Shelton S. Alexander providing accurate focal depth estimations (± 1 km or typically better) from one or more regional stations. The method was tested over single stations as well as seismic arrays around the world. For single station case, the cepstrums of a moving window in time domain, with an appropriate overlap percentage, capturing the depth phases pP and sP within P to S arrival time range were stacked. The final stacked cepstrum resulted in an enhanced peaks of the depth phases. We intend to extend use cases for the CSM by including Mars, following the successful deployment of a single seismic station on the planet's surface in December 2018 within the scope of NASA InSight mission. We currently test the method's capabilities using marsquake synthetics that were computed using Instaseis and AxiSEM. Our preliminary results show that the CSM can effectively be used for determining the focal depths of the marsquakes recorded by a single seismic station. In this study, we will present single station examples using martian synthetic seismograms with superimposed realistic noise for a range of seismic events, in an effort to promote the CSM approach as one of the standard tools for locating quakes on Mars in the future.

Innovative Ground Motion Sensors for Planets and Asteroids: Pioneers H2020-Space European Project

GARCIA, R., Institut supérieur de l'aéronautique et de l'espace, Toulouse, France, raphael.garcia@isae-supaero.fr; SHARIATI, S., iXblue, Saint-Germain-En-Laye, France, saloomeh.shariati@ixblue.com; GUATTARI, F., iXblue, Saint-Germain-En-Laye, France, frederic.guattari@ixblue.com; BONNEFOIS, J., iXblue, Saint-Germain-En-Laye, France, jean-jacques.bonnefois@ixblue.com; MIMOUN, D., Institut supérieur de l'aéronautique et de l'espace, Toulouse, France, david.mimoun@isae-supaero.fr; BERNAUER, F., Ludwig Maximilian University of Munich, Munich, Germany, fbernauer@geophysik.uni-muenchen.de; WASSERMANN, J. M., Ludwig Maximilian University of Munich, Munich, Germany, joachim.wassermann@geophysik.uni-muenchen.de; IGEL, H., Ludwig

Maximilian University of Munich, Munich, Germany, igel@geophysik.uni-muenchen.de; DE RAUCOURT, S., Institut de Physique du Globe de Paris, Paris, France, sebastien.deraucourt@gmail.com; LOGNONNÉ, P., Institut de Physique du Globe de Paris, Paris, France, lognonne@ipgp.fr; KARATEKIN, O., ORB, Bruxelles, Belgium, ozgur.karatekin@observatory.be; RITTER, B., ORB, Bruxelles, Belgium, birgit.ritter@observatory.be; DEHANT, V., ORB, Bruxelles, Belgium, v.dehant@oma.be; SCHMELZBACH, C., ETH Zurich, Zurich, Switzerland, cedric.schmelzbach@erdw.ethz.ch; GIARDINI, D., ETH Zurich, Zurich, Switzerland, domenico.giardini@erdw.ethz.ch; FERRAIOLI, L., ETH Zurich, Zurich, Switzerland, luigi.ferraioli@erdw.ethz.ch

Planetary seismology is a key technique to image the internal structure of planetary objects. It targets fundamental science objectives from the formation of planetary systems to the characterization of habitable worlds.

PIONEERS is a H2020 granted project starting from Janvier 2019. It is aimed at entering a new realm of planetary exploration with an innovative ground motion instrumentation concept relying on high precision sensors based on optical interferometry, and on 6 degrees of freedom (6 DoF, with 3 translations and 3 rotations) measurements. It will provide substantially more precise science return compared to usual seismometers. Only recently emerging for terrestrial applications, 6 DoF measurements target fundamental planetary science objectives, from the formation of planetary systems to the characterization of habitable worlds, supporting also planetary defense and asteroid resources applications.

The PIONEERS project will develop two 6 DoF instruments for measuring ground deformations of planetary objects. The first instrument is a very low noise 6-DoF engineering model dedicated to imaging the internal structure of terrestrial planets. The second one is a high TRL, reduced scale version of the same instrument dedicated to the exploration of small bodies, in order to support planetary defense and asteroid resources applications.

An improvement of instrument noise of two orders of magnitude is expected for the planetary prototype by using optical sensing technologies. Cost optimization and adaptation to CubeSat standards will drive other technological developments that will open new markets for high precision scientific instrumentation.

The PIONEER project initial specification and performance analysis will be presented.

Characterization of the InSight Landing Site Near Surface Properties Using the Heat Flow and Physical Properties Probe (Hp3) Mole as a Seismic Source

KEDAR, S., Jet Propulsion Laboratory, California Institute of Technology, California, USA, sharon.kedar@jpl.nasa.gov; BANERDT, W. B., Jet Propulsion Laboratory, California Institute of Technology, California, USA, william.b.banerdt@jpl.nasa.gov; BRINKMAN, N., ETH Zurich, Zurich, Switzerland, nienke.brinkman@erdw.ethz.ch; DELAGE, P., École Nationale des Ponts et Chaussées, Paris, France, pierre.delage@enpc.fr; FAYON, L., Institut de Physique du Globe de Paris, Paris, France, fayon@ipgp.fr; GROTT, M., Deutsches Zentrum für Luft und Raumfahrt, Berlin, Germany, matthias.grott@dlr.de; HORLESTON, A. C., University of Bristol, Bristol, United Kingdom, anna.horleston@bristol.ac.uk; HUDSON, T. L., Jet Propulsion Laboratory, California Institute of Technology, California, USA, troy.l.hudson@jpl.nasa.gov; HURST, K., Jet Propulsion Laboratory, California Institute of Technology, California, USA, kenneth.j.hurst@jpl.nasa.gov; KIELY, A. B., Jet Propulsion Laboratory, California Institute of Technology, California, USA, aaron.b.kiely@jpl.nasa.gov; KNAPMEYER-ENDRUN, B., University of Cologne, Cologne, Germany, brigitte.knapmeyer-endrun@uni-koeln.de; KRAUSE, C., Deutsches Zentrum für Luft und Raumfahrt, Berlin, Germany, christian.krause@dlr.de; LOGNONNÉ, P., Institut de Physique du Globe de Paris, Paris, France, lognonne@ipgp.fr; PIKE, W. T., Imperial College London, London, United Kingdom, w.t.pike@imperial.ac.uk; ROBERTSSON, J. O. A., ETH Zurich, Zurich, Switzerland, johan.robertsson@erdw.ethz.ch; SCHMELZBACH, C., ETH Zurich, Zurich, Switzerland, cedric.schmelzbach@erdw.ethz.ch; SCHMERR, N. C., University of Maryland, Maryland, USA, nschmerr@umd.edu; SPOHN, T. C., Deutsches Zentrum für Luft und Raumfahrt, Berlin, Germany, tilman.spohn@dlr.de; SOLLBERGER, D., ETH Zurich, Zurich, Switzerland, david.sollberger@erdw.ethz.ch; STÄHLER, S., ETH Zurich, Zurich, Switzerland, simon.staehler@erdw.ethz.ch; TEANBY, N. A., University of Bristol, Bristol, United Kingdom, n.teanby@bristol.ac.uk; VAN DRIEL, M., ETH Zurich, Zurich, Switzerland, vandriel@erdw.ethz.ch; VRETTOS, C., Technical University Kaiserslautern, Kaiserslautern, Germany, vrettos@rhrk.uni-kl.de

The InSight mission is the first Mars lander to place an ultra-sensitive broadband seismometer on the planet's surface. About 1m away from the seismometer, a Heat Flow and Physical Properties Probe (HP^3) experiment will hammer a probe down to 5m into the Martian subsurface to measure the heat coming from Mars' interior and reveal the planet's thermal history. The probe, which uses a self-hammering mechanism, will generate thousands of seismic signals that can be used to study the shallow subsurface.

The mission's science objectives focus on planetary-scale seismic and tectonic processes and their implications to rocky planet formation. Nevertheless the proximity of a repeating hammer source to a sensitive seismometer presents a unique opportunity to carry out the first geotechnical study of the shallow Martian subsurface.

The HP^3 mole hammering mechanism produces a distinct seismic signals, but using these signals for a geotechnical seismic profiling presents several challenges: (1) The InSight Seismic Experiment requires 100 samples-per-second data that results in under-sampling the HP^3 signal; (2) Although each HP^3 penetration session produces several hundred hammer strokes, the ~4s interval between them varies slightly with regolith properties and with mole temperature; (3) A second stroke, ~0.06s following the initial stroke, also varies in time, and may obscure a reflection from an anticipated basalt layer several meters below the surface.

In 2018, we conducted a field experiment to test the efficiency of data processing algorithms developed by the team. A site whose geological setting were intended to mimic the anticipated landing site was selected. A seismic survey of the shallow subsurface was conducted and a model of the underlying shallow geology was constructed. Subsequently, a simulation of the HP^3-SEIS experiment was carried out, whose data was used to asses our ability to recover the seismic velocity in the vicinity of the InSight lander and the thickness of the regolith layer. We will report details of the analysis conducted by the team.

Towards Planetary Remote-Sensing Seismology: Modeling the Airglow Signature of Venus Quakes

KENDA, B., Institut de Physique du Globe de Paris, Paris, France, kenda@ipgp.fr; LOGNONNÉ, P., Institut de Physique du Globe de Paris, Paris, France, lognonne@ipgp.fr; KOMJATHY, A., Jet Propulsion Laboratory, California Institute of Technology, California, USA, attila.komjathy@jpl.nasa.gov; BANERDT, W. B., Jet Propulsion Laboratory, California Institute of Technology, California, USA, william.b.banerdt@jpl.nasa.gov; SUTIN, B. M., Jet Propulsion Laboratory, California Institute of Technology, California, USA, brian.m.sutin@jpl.nasa.gov; CUTTS, J. A., Jet Propulsion Laboratory, California Institute of Technology, California, USA, james.a.cutts@jpl.nasa.gov; JACKSON, J. M., California Institute of Technology, California, USA, jackson@gps.caltech.edu

Performing seismology on Venus is of great interest to understanding the interior structure and the tectonic activity of the planet, which are poorly constrained by available observations. However, the extremely high temperature at the surface is challenging for a long-lived seismic station. Therefore, atmospheric and ionospheric seismology - well-established techniques on Earth - could prove very powerful on Venus, where the coupling between the thick atmosphere and the interior of the planet is strong, about 60 times larger than on Earth.

We propose the detecting quakes using an orbiting camera by observing fluctuations in the day- and night-side infrared airglows, at 4.28 and 1.27 microns, respectively. We first make use of normal-mode summation to compute synthetic seismograms in the high atmosphere of Venus, between 90 and 150 km above the surface, and then derive the induced disturbances on the airglow emission rates. The main effects turn out to be related to vertically propagating acoustic waves induced by the Rayleigh waves traveling at the surface of the planet. The resulting airglow-grams are compared to the expected noise at the camera level, and detection techniques based on the identification of circular waveforms propagating at the speed of surface waves are discussed. An advantage of this observational method is that a single camera images the wavefield, with each pixel acting as a seismometer. Preliminary estimates of detection thresholds indicate that quakes of magnitude larger than 5 to 5.8 could be observed, depending on the wavelength and intensity of airglow emissions. Finally, the propagation of the wavefronts would lead to measurements of the Rayleigh-wave velocity and thus to valuable information about the lithosphere and the upper mantle of Venus.

InSight Lessons on Science Potential From On-Deck Operation of a Broadband Seismometer

PANNING, M. P., Jet Propulsion Laboratory, California Institute of Technology, California, USA, mark.p.panning@jpl.nasa.gov; PIKE, W. T., Imperial College, London, United Kingdom, w.t.pike@imperial.ac.uk; LOGNONNÉ, P., Institut de Physique Du Globe de Paris, Paris, France, lognonne@ipgp.fr; BANERDT, W. B., Jet Propulsion Laboratory, California Institute of Technology, California, USA, william.b.banerdt@jpl.nasa.gov; BANFIELD, D., Cornell University, New York, USA, banfield@astro.cornell.edu; CHARALAMBOUS, C., Imperial College London, London, United Kingdom, constantinos.charalambous05@imperial.ac.uk; KEDAR, S., Jet Propulsion Laboratory, California Institute of Technology, California, USA, sharon.kedar@jpl.nasa.gov; MCCLEAN, J. B., Imperial College, London, United Kingdom, j.mcclean15@imperial.ac.uk; MURDOCH, N., Institut supérieur de l'aéronautique et de l'espace, Toulouse, France, naomi.murdoch@isae-supaero.fr; STOTT, A., Imperial College London, London, United Kingdom, alexander.stott10@imperial.ac.uk; WARREN, T., Oxford University, Oxford, United Kingdom, warren@atm.ox.ac.uk

The InSight mission to Mars is now returning seismic data from another planetary body for the first time since Apollo lunar data and Viking Mars data from the 1970's. Part of the reason for the lack of planetary seismic deployments is a perceived complexity of seismic instrumentation in order to have extremely sensitive instruments well-coupled with ground motion. A large reason for this is the lack of clear identification of Marsquakes in the Viking data, and the final report of the Viking seismology project, which identified direct coupling to the ground as an important future consideration to move beyond the Viking seismometer. However, there were other features of the Viking seismology project that hampered its ability to detect internal events, primarily the relatively low sensitivity of the instrument strongly peaked near a resonant frequency of 3 Hz, and much of the data was sent back in a compressed event mode consisting of an envelope amplitude sent back at approximately 1 Hz and a count of positive-going zero crossings.

Given the deployment complexity of surface instrument placement, though, it's important to better constrain the science potential of modern seismometers mounted on a spacecraft. While InSight has now deployed its seismic instrument package (Seismic Experiment for Internal Stucture, or SEIS) on the surface, the short period instrument (SP) successfully operated on the deck. Temperature limitations and other operational concerns prevented continuous operation, but over 47 hours of data were recorded over a 3-week period on the deck. While this data does not cover all portions of the diurnal cycle, it includes periods both before and after sunset and covering a range of atmospheric noise conditions. This dataset is powerful for understanding the noise characteristics of deck-deployed seismometers and can be used to better understand the science potential of future seismic deployments on landed assets on Mars and other planetary bodies, including for airless bodies when the calmest periods recorded by InSight are considered.

The Seismic Experiment for Interior Structure (SEIS) Experiment Data Distribution

PARDO, C., Institut de Physique du Globe de Paris, Paris, France, pardo@ipgp.fr; WEBER, R. C., NASA MSFC, Alabama, USA, renee.c.weber@nasa.gov; LOGNONNÉ, P., Institut de Physique du Globe de Paris, Paris, France, lognonne@ipgp.fr; PIKE, W. T., Imperial College, London, United Kingdom, w.t.pike@imperial.ac.uk; GIARDINI, D., ETH Zurich, Zurich, Switzerland, domenico.giardini@erdw.ethz.ch; CHRISTENSEN, U., Max Planck Institute for Solar System Research, Göttingen, Germany, christensen@mps.mpg.de; BANERDT, W. B., Jet Propulsion Laboratory, California Institute of Technology, California, USA, william.b.banerdt@jpl.nasa.gov; BANDFIELD, D., Cornell University, New York, USA, banfield@astro.cornell.edu; BERENGUER, J., Géoazur, University Côte d'Azur, Sophia Antipolis, France, jlbereng@gmail.com; BRAVO, T., Incorporated Research Institutions for Seismology, District of Columbia, USA, tkb@iris.edu; CONEJERO, V., Institut de Physique du Globe de Paris, Paris, France, conejero@ipgp.fr; DRILLEAU, M., Institut de Physique du Globe de Paris, Paris, France, drilleau@ipgp.fr; GABSI, T., Institut de Physique du Globe de Paris, Paris, France, gabsi@ipgp.fr; LUNO, L., CNES, Toulouse, France, laure.luno@cnes.fr; LABROT, P., Institut de Physique du Globe de Paris, Paris, France, labrot@ipgp.fr; SLAVNEY, S., Washington University in St. Louis, Missouri, USA, slavney@wunder.wustl.edu; SAURON-SORNETTE, A., ETH Zurich, Zurich, Switzerland, anne.sauron@erdw.ethz.ch; STUTZMANN, E., Institut de Physique du Globe de Paris, Paris, France, stutz@ipgp.fr

Like all NASA missions, InSight's data will be archived at the Planetary Data System (PDS), a long-term digital data archive. This includes data from SEIS, the first seismometer deployed on the Martian ground (40 years after the Viking deck-mounted instruments), as well as those of the Auxiliary Payload Sensors Suite (APSS). For SEIS, the distributed data are those of the very broad-band (VBB), short-period (SP) sensors, SEIS electronics, leveling system, and selected lander telemetry channels.

SEIS and APSS data are received from the spacecraft in raw telemetry packets and converted to both SEED format files and ASCII tables (GeoCSV) for analysis and archiving. APSS data in SEED format will permit straightforward data comparison. Both data sets will then be delivered to the Mars SEIS Data Service (MSDS) at IPGP Data Center. IPGP maintains the SEIS data portal, which will become open-access a week prior to the first public data distribution. MSDS will also deliver SEIS data to PDS for archiving and to IRIS as a second data portal.

IRIS, an InSight educational partner, has the goal of engaging students with seismic data from Mars. The IRIS Data Management Center and MSDS will make data from the seismometer available to students, the international seismological community, and the public. Data for schools will be distributed via several international "seismo@school" projects.

The initial release of raw data archive products to the PDS, covering the period from landing to the start of the science monitoring phase, will occur within 3 months of the start of the science monitoring phase (anticipated April 2019), with calibrated products and SPICE kernels following a month later. After these initial releases, the calibrated and SPICE data will be released by the PDS every 3 months, beginning in July 2019. Public release of "uncertified" seismic velocity data via IRIS will start about 7 months after the start of the science monitoring phase and will be made every 4 weeks.

Probabilistic Source Inversion Using Body Wave Coda From a Single Seismic Station (InSight)

STÄHLER, S., ETH Zurich, Zurich, Switzerland, simon.staehler@erdw.ethz.ch; BRINKMAN, N., ETH Zurich, Zurich, Switzerland, nienke.brinkman@erdw.ethz.ch; BÖSE, M., ETH Zurich, Zurich, Switzerland, maren.boese@googlemail.com; KHAN, A., ETH Zurich, Zurich, Switzerland, amir.khan@erdw.ethz.ch; VAN DRIEL, M., ETH Zurich, Zurich, Switzerland, vandriel@erdw.ethz.ch; GIARDINI, D., ETH Zurich, Zurich, Switzerland, domenico.giardini@erdw.ethz.ch; CLINTON, J., ETH Zurich, Zurich, Switzerland, jclinton@sed.ethz.ch; CEYLAN, S., ETH Zurich, Zurich, Switzerland, savas.ceylan@erdw.ethz.ch

On December 19th, 2018, a seismometer was placed directly onto the surface of a planetary body for the first time since the Apollo missions. In this study we focus on characterizing source mechanisms of potential marsquakes using only a single station, an approach that went out of fashion on Earth because of the abundance of seismic stations.

Our method fits the waveforms of seismic body waves, specifically the P- and S-wave train, including depth phases reflected at the surface above the event. We use the seismic waveform database Instaseis to generate synthetic waveforms up to frequencies of 1 Hz in combination with a Markov-Chain Monte Carlo sampler. We restrict our model space to double-couple sources, expressing the focal mechanism in three unique orientation angles: strike(ϕ), dip(δ) and rake (λ). The waveform match is estimated using a correlation-coefficient based likelihood function.

We test the method on synthetic seismograms for Mars, including modelled noise from the Clinton et al 2017 Mars blindtest. For these examples, we used different velocity models to create the synthetic seismograms, to test the effect of the a priori unknown velocity structure of Mars. Based on these examples, we show that (1) two out of three orientation angles can be obtained to high accuracies. The third orientation angle has a bimodal probability density function for many events. (2) the event depth can be constrained to less than 5 kilometer, depending on the event magnitude and therefore signal-to-noise ratio.

We tested the method on earthquakes of magnitude 5.5 to 6 recorded on single seismic stations in teleseismic distance. This magnitude range has a similar signal-to-noise ratio as a magnitude 4 on Mars, due to the presence of microseismic noise on Earth. The results are compatible with the results of our synthetic Mars test.

Lunar Seismometer and Burial System

BAILEY, S. H., University of Arizona, Arizona, USA, hbailey@email.arizona.edu; WEBER, R. C., Marshall Space Flight Center, Alabama, USA, renee.c.weber@nasa.gov; AVENSON, B., Silicon Audio, Inc., Texas, USA, brad@siaudio.com; DELLAGUISTINA, D., University of Arizona, Arizona, USA, danidg@lpl.arizona.edu; ZACNY, K., Honeybee Robotics, New York, USA, kazacny@honeybeerobotics.com; SCHMERR, N. C., University of Maryland, Maryland, USA, nschmerr@umd.edu; SIEGLER, M. A., Planetary Science Institute, Arizona, USA, matthew.a.siegler@gmail.com; BRAY, V., University of Arizona, Arizona, USA, vjbray@pirl.lpl.arizona.edu

Beginning in 1969, Apollo successfully deployed a long-lived network of seismometers on the Moon, which resulted in the only substantial seismic data set of another planet currently in existence. Many questions remain regarding the frequency and distribution of natural moonquakes. In particular, due to the exclusively near-side installation of the Apollo seismometers, it is currently unknown whether the far side of the Moon is aseismic. This translates into an incomplete understanding of the Moon's hemispherical dichotomies in crustal thickness, mare volcanism, and the distribution of heat-producing elements. A primary challenge to a future Lunar Geophysical Network mission is that the Moon is covered with a remarkably low-density regolith layer. The powdered surface regolith layer has very low P-wave seismic velocities - less than 50 m/s within the top

1 m. The regolith causes increased near-surface trapping and scattering of seismic waves effectively masking distant and low magnitude quakes.

To overcome the challenge presented by the regolith, our team is developing a novel lunar seismometer and burial system based on the Silicon Audio 3-axis seismometer and the Honeybee Robotics burial system. The effects of noise from the surface can be mitigated by deploying instruments below the scattering layer. A lander, which cannot be entirely shielded from the sun, will continuously expand and contract with the diurnal cycle. This thermal stressing creates noise at many frequencies that will contaminate seismic signals of interest for a robotically deployed surface seismometer. To realize the benefits of sensor burial, Honeybee provides a low-mass, low-power burial system developed for a NASA-funded lunar Heat Flow Probe. The system uses pressurized gas to create a vertical hole in the regolith, into which the instruments are then placed. We are merging this system with our Silicon Audio seismometer, an instrument that meets the sensitivity requirements for lunar science and is self-leveling, low in mass, volume and power.

Seismo-Acoustic Waves Propagation in the Atmosphere of Mars During the InSight mission

ROLLAND, L., Geoazur/OCA, Valbonne, France, lrolland@geoazur.unice.fr; LOGNONNÉ, P., Institut de Physique du Globe de Paris, Paris, France, lognonne@ipgp.fr; GARCIA, R., Institut supérieur de l'aéronautique et de l'espace, Toulouse University, Toulouse, France, raphael.garcia@isae-supaero.fr; BANFIELD, D., Cornell Center for Astrophysics and Planetary Science, New York, USA, banfield@astro.cornell.edu; SPIGA, A., LMD, Paris, France, aymeric.spiga@sorbonne-universite.fr

InSight (Interior Exploration using Seismic Investigations, Geodesy and Heat Transport) is a NASA Discovery Program mission that is placing a single geophysical lander on Mars to study its deep interior. This mission was launched in May 2018 and has landed successfully after a 6.5 months cruise on November 26. Meteorological sensors onboard the lander are designed to provide a continuous dataset of pressure, air temperature, wind speed and direction. The unprecedented sensitivity of the pressure sensor will allow catching signatures of a breath of infrasound sources from bolides to dust devils. e will highlight the specificities of acoustic waves propagation in the atmosphere of Mars, that is not only much more tenuous (~ 6 mbar) than the Earth atmosphere but also CO2-rich, sometimes dusty and extremely windy. We will make use of acoustic ray tracing and also of the Spectral Element Method and normal modes summation for cross-benchmarking. In particular, we show how dissipation processes due to viscosity and CO2 relaxation are taken into account. The effects of winds and dust on the propagation are also evaluated using parameters of the ambient atmosphere predicted during the lifetime of the mission (GCM) and at the location of the lander. We will finally discuss the efficiency of potential external sources to excite seismic waves to be sensed by the Insight seismometer SEIS and thus illuminating the interior of the planet.

Leveraging Researcher Data Access to Promote Student Engagement With Martian Seismic Data

BRAVO, T., Incorporated Research Institutions for Seismology, District of Columbia, USA, tkb@iri.edu; AHERN, T., Incorporated Research Institutions for Seismology, Washington, USA, tim@iris.washington.edu; TABER, J., Incorporated Research Institutions for Seismology, District of Columbia, USA, taber@iris.edu; BENSON, R., Incorporated Research Institutions for Seismology, Washington, USA, rick@iris.washington.edu

The InSight mission aims to explore the interior of Mars using seismic data from marsquakes and meteorite impacts. The data from InSight, which will be available through the IRIS Data Management Center (DMC), offers a chance for researchers to use IRIS DMC tools to access Mars data once the data have been publicly released (anticipated April 2019). IRIS will leverage existing international Seismographs in Schools networks to allow a large and growing number of students to interact with Mars seismic data as soon as it is available on Earth. Students in these networks have experience with seismic data and software and are primed to engage with this NASA Discovery mission. Some standard DMC tools have been modified as needed to handle Mars data including timing, coordinate systems, and mapping tools. To help make the data accessible to a broader audience, the data will also be available in the ASCII GeoCSV format. Data will also be available from the Auxiliary Payload Sensors Suite for comparison to the seismograph data.

Seismology offers unique opportunities to enrich earth science and physics curriculum, involving students in questioning and problem solving. School networks are preparing specially designed lessons, software, web tools, data viewers, and other resources in advance of data arrival to allow students to explore and interrogate shaking on Mars. Students will be able to observe daily variations in ground motions and to analyze 3-component data from the broadband sensor, so as to attempt to locate marsquakes and meteor strikes. Being among the first to work with Martian seismic data by accessing data through the IRIS DMC, students will have the opportunity to feel they are working alongside scientists on the next frontier of seismic exploration.

Central and Eastern North America and Intraplate Regions Worldwide

Poster Session · Thursday · 25 April · Grand Ballroom

Ambient Noise Tomography in Northeastern United States

WANG, T., University of North Carolina, North Carolina, USA, tenqei@live.unc.edu; LEES, J. M., University of North Carolina, North Carolina, USA, jonathan.lees@unc.edu; BIRYOL, B. C., University of North Carolina, North Carolina, USA, biryol@live.unc.edu

The tectonic structure of the crust in the northeast region of the U.S. is both compositionally complex and tectonically stable relative to lithospheric structures that formed during earlier geological periods. Data from the EarthScope Transportable Array collected in 2014 are used to calculate a three-dimensional shear velocity model of the crust and upper mantle in the northeastern United States. We apply ambient noise tomography and receiver function techniques to determine the Rayleigh wave phase velocities and the 3D inversion using crustal thicknesses determined by Lin 2014. The spatial distribution of the structures determined by this model is well-correlated to the observed geology at the surface, including the sedimentary coastal regions, the Appalachian orogeny, and the New England area.

The lateral distribution and depth of several slow anomalies, determined by the tomographic inversion, within the crust of the middle Appalachians correlate to Eocene volcanism. This is consistent with tomographic models presented by Porter 2016 and Wagner 2017. Since the model is highly sensitive to the crustal thickness, higher-resolved Moho depths used in this research provide a better explanation for the material below these volcanic structures. The tomography shows groups of fast velocities in the upper mantle in these regions, indicating the presence of denser materials that have been supporting the gradual volcanism since the Eocene.

A fast anomaly detected in the inversion, close to the surface of the New England crust, correlates with the igneous intrusions generated by the Great Meteor Hotspot, which formed approximately 100-130Ma. Since the initial penetration of this hotspot through the New England crust, the upper layers have cooled, while the base of the upper mantle consists of higher temperatures.

Basement Top and Moho Depth Models of West Texas From Receiver Function

LI, P., University of Texas at Austin, Texas, USA, peng.li@beg.utexas.edu; SAVVAIDIS, A., University of Texas at Austin, Texas, USA, alexandros.savvaidis@beg.utexas.edu; HUANG, D., University of Texas at Austin, Texas, USA, dino.huang@beg.utexas.edu

West Texas is composed of a series of mountains, platforms and basins. Most part of the basins in this area is covered by thick sediment layers. It is also a most seismic active area in Texas and the number of earthquakes increases dramatically in recent years. Precise depths of the basement top and the Moho are important for understanding the tectonic evolution of west Texas and improving the knowledge of the lithospheric structure of west Texas. In this study, we derived new estimates of the depths of the basement top and the Moho for west Texas from the seismic waveform data of 73 broadband seismic stations and 260 Mw ≥ 6 teleseismic events using Receiver Function Analysis. The optimal models are obtained by searching 8232 two-layer models by comparing the similarity between synthetic and real receiver function. The thickness of the sediment is consistent with the well-log data. The Delaware Basin has a thicker sedimentary layer with a thickness of about 5 – 8 km, whereas the Midland Basin has a thin sedimentary layer with 0-2 km thickness. At the same time, shallower Moho depth is found under the Delaware Basin which may be due to the extension of the basin and low density intrusive granitic batholith. A deeper Moho interface is observed beneath the Diablo Platform and Central Basin Platform.

Developing Data-Driven Stochastic Seismological Parameters of CENA from the NGA-East Database

NAZEMI, N., University of Memphis, Tennessee, USA, nnazemi@memphis.edu; PEZESHK, S., The University of Memphis, Tennessee, USA, spezeshk@

memphis.edu; ZANDIEH, A., Lettis Consultants International, Colorado, USA, arash.zandieh@live.com

The fundamental idea of this project is to obtain a set of self-consistent stochastic seismological parameters for Central and Eastern United States (CENA). We are using median 5% damped pseudo-spectral acceleration (ROTD50) with rupture distances (Rrup) less than 500 km from the NGA-East database and the point source stochastic model (Boore 2003) to determine seismological parameters that minimize the residuals over the usable frequencies of the data using a genetic algorithm. The final product of this study is a set of well correlated seismological parameters compatible with single and generalized double corner frequency models.

Parameters obtained in this study include a tri-linear geometric spreading model, site kappa, frequency dependent quality factor, eight magnitude dependent parameters of generalized additive double corner frequency model (Boore *et al.*, 2014), and magnitude dependent point-source correction factor (also known as pseudo depth). The double corner frequency can easily be converted to single corner frequency model and a magnitude dependent stress drop parameter and corner frequency, which is also data-driven and self-consistent.

The final objective of this research is to develop an updated hybrid empirical ground motion model to map the ground motion of the higher magnitudes from a richer database by scaling the ground motion in the target region (CENA) by the ratio of stochastic over empirical ground motion obtained in a target region.

Microseismicity After Pohang Earthquake in South Korea

LEE, J., Korea Meteorological Administration, Seoul, Korea, Republic of, jiminlee@korea.kr; SONG, G., Korea Meteorological Administration, Seoul, Korea, Republic of, gyssong@korea.kr; CHO, S., Korea Meteorological Administration, Seoul, Korea, Republic of, joacma11@korea.kr; LIM, D., Korea Meteorological Administration, Seoul, Korea, Republic of, aserop@korea.kr; AHN, J., Korea Meteorological Administration, Seoul, Korea, Republic of, propjk@korea.kr; LEE, D., Korea Meteorological Administration, Seoul, Korea, Republic of, dukkee@korea.kr

Earthquake activities in and around the Korean Peninsula are relatively low in number and intensity compared with those in the neighboring countries, such as Japan and China. From 1978 to 2018, a total of 1,798 earthquakes with magnitude larger than 2.0 has occurred in and around the vicinity of the Korean Peninsula. Specifically, the annual average number of earthquake occurrence increased after the largest earthquake (ML 5.8) occurred in Gyeongju area in 2016 and Pohang earthquake (ML 5.4) in 2017. We relocated the events occurred during 2018, and determined using Hypoinverse program with various crustal models and analyzed the results. The magnitudes of relocated events range from 1.0 to 2.5 on the Richter scale. The accuracy of the relocation is less than 3km of hypocenter including about 2km of depth error ranges. The newly determined origin times with error less than 0.2seconds ranges about 82~93% according to applied different crustal models. In addition, we compared the spatial and temporal distributions of events before and after two largest earthquakes.

The "Analogous Region Approach" – a New Approach to Defining Earthquake Recurrence Parameters in Regions of Low or Incomplete Earthquake Occurrence

MARTINEZ, M., Golder Associates, Santiago, Chile, mmartinez@golder.com; HULL, A. G., Golder Associates, Oregon, USA, ahull@golder.com

Estimating site-specific earthquake ground motions for seismic design of critical facilities requires the identification and characterization of regional earthquake sources that will contribute to the hazard at the site. Seismic source characterization is a complex process that requires defining earthquake recurrence parameters for each seismic source from the historical and instrumental earthquake record. While the earthquake recurrence estimation procedures are relatively well established for areas of high seismicity, regions with an incomplete earthquake record or low earthquake occurrence rate are very difficult to reliably characterize.

The "Analogous Region Approach" (ARA) has been proposed as a method to improve the definition of earthquake recurrence parameters in regions of low seismicity. The goal of the ARA is to identify and adopt acceptable earthquake recurrence parameters (*i.e.*, a- and b- values in the Gutenberg Richter equation) that can support seismic design of critical structures. The ARA is based on the identification and selection of analogous tectonic regions with similar tectonic characteristics as the seismic source zones surrounding the site of interest.

The ARA is used to validate, and where necessary, calibrate the earthquake recurrence parameters used for probabilistic and deterministic seismic hazard analyses in seismic quiescence regions. This ARA also allows definition of "preferred values" and the upper-lower bounds for the earthquake recurrence parameters used in the logic tree approach to capture the epistemic uncertainties in probabilistic modeling.

Application of the ARA allowed to develop site-specific seismotectonic models for relatively seismic-inactive and quiescent regions. Testing of the results developed from application of the ARA have shown good agreement with the results of similar studies available in the published literature and for site-specific studies undertaken by others.

Spatial Variations in the Coherence of Earthquake Body Waves in New England as a Measure of Signal to Noise

COOPER, I. P., Boston College, Massachusetts, USA, cooperia@bc.edu; EBEL, J. E., Boston College, Massachusetts, USA, john.ebel.1@bc.edu

Determination of the source parameters of a local earthquake from the full seismic waveforms requires seismograms with clear earthquake body wave signals. Noise from source energy scattering and from ambient microseismic sources can interfere with the body waveforms, especially for smaller earthquakes, and reduce the signal-to-noise ratio (SNR) of the observations. Thus, full-waveform analysis methods for studying local seismic sources require the seismograms with the highest SNR of the body waves. Coherence of the earthquake body waves at two different receivers can be used to estimate the SNR of the body wave energy radiated by the source. Coherent waveforms result from similar earth modifications to the propagating body waves while random noise affects the body waves differently at each station. Waveforms should be most coherent when the two seismic stations are spatially close. The SNR can be measured for the earthquake body waves propagating throughout a region by measuring coherence of the body waves at receiver pairs at different distances from the source. In this paper, a study of the coherence of earthquake body waves recorded in New England (NE) is performed to estimate the SNR of the body waves at different frequencies from small earthquakes within the region as functions of the source-receiver distance and the earthquake magnitude. Seismograms from the TA, NE, N4, CN, IU and US arrays are used to measure coherence between stations with mean separations of 70 km. Seismograms from the Acton Littleton Seismic Array are used to measure coherence at 5 km mean station separations. Coherence is measured at frequencies between 0.01-20 Hz for P and S first arrivals from earthquakes >M6 at distances >2500 km as well as Pn, Pg, Sn and Sg phases for NE earthquakes between M2-M4 at distances between 180-800 km. The results show that Pn waves from NE earthquakes at all frequencies show low coherence at interstation distances more than 70 km, suggesting at these interstation distances the body waveforms are dominated by scattered energy and microseismic noise.

Analysis of Crustal Anisotropy Beneath the NE Tibetan Plateau Revealed by Receiver Function Data

XU, X., Institute of Geophysics, China Earthquake Administration, Beijing, China, xuxiaoming@cea-igp.ac.cn; NIU, F., Rice University, Texas, USA, niu@rice.edu; DING, Z., Institute of Geophysics, China Earthquake Administration, Beijing, China, dingzf@cea-igp.ac.cn

The high topography, thick crust and outward growth of the Tibetan plateau are generally believed to be caused by the continuous collision between the Indian plate and the Eurasian plate since ~50 Ma. The northeastern Tibetan plateau as one of main regions where the plateau grows toward outside is an ideal place to study the crustal deformation. Here we estimated receiver functions from the three-component waveform data recorded by 676 broadband seismic stations in the northeast Tibetan plateau. Then Moho depth and Vp/Vs ratio were calculated by the modified H-κ stacking technique, and crustal anisotropy was also measured using the joint inversion scheme. The Moho depth obviously increases with about 30 km from the northeast to the southwest in the study area. The Vp/Vs ratio exhibits significant lateral variation that the lower Vp/Vs ratios are in the Qilian orogeny and Songpan-Ganzi terrane, while the higher Vp/Vs ratios locate in the western Ordos block, Hetao graben and Yinchuan graben. The significant crustal anisotropy suggests that the polarization directions are approximately parallel to the strikes of faults, sutures and surface geologic structures, and the primary cause may be derived from the middle-to-lower crust. By the combination with the GPS velocity, the surface geologic features, the absolute plate motion (APM) and the SKS/SKKS (XKS) and direct S wave splitting, we demonstrated the mechanically crustal deformation and geodynamic implications. We infer that the uniform lithospheric shortening is likely the dominant mechanism for the crustal uplift and thickening beneath the NE margin of the Tibetan plateau based on its low Vp/Vs ratio and distinctly azimuthal anisotropy.

Characteristics of Ground Motions Generated by the 2017 M5.4 Pohang, South Korea Earthquake

LEE, J., Ulsan National Institute of Science and Technology, Ulju-gun, Korea, Republic of, leejy@unist.ac.kr; AHN, J., Korea Meteorological Administration, Seoul, Korea, Republic of, propjk@korea.kr; KIM, M., UNIST, Ulsan, Korea, Republic of, miraekim@unist.ac.kr; LEE, H., UNIST, Ulsan, Korea, Republic of, hyejinlee@unist.ac.kr; KIM, B., UNIST, Ulsan, Korea, Republic of, byungmin.kim@unist.ac.kr

The November 15, 2017 M5.4 Pohang earthquake was recorded as the second largest instrumented earthquake in South Korea, causing serious damages to structures and infrastructure. The ground motions generated by this earthquake were well recorded at seismic stations of the KMA (Korea Meteorological Administration) and the KIGAM (Korea Institute of Geoscience And Mineral Resources). The KMA also installed nine temporary seismic stations immediately after the main-shock event near the epicenter. We analyzed characteristics of the ground motions measured at these regular and temporary seismic stations during the aftershocks with magnitudes ranging from 2.5 to 4.6. We found that the recorded ground motions are rich in high frequencies (around 10 Hz) and better match with the NGA-East ground motion prediction equations (GMPEs) than the NGA-West2 GMPEs. We consider this is because of that the bedrock conditions in Korea are similar with those in Central and Eastern North America (CENA). The Pohang city is mainly covered by the Quaternary and Tertiary deposits. There are small basins consisting of soft soil depths and with bedrocks located at approximately a 500-m depth. In addition, the small basins are surrounded by mountains and hills. These complex stratigraphy and soil conditions affected characteristics of the aftershock ground motions. We observed ground motions amplifications at long periods due to site effects. We also observed generation of surface waves generated by the edge of the basins. Furthermore, we clearly observed evidence of the motions reflected at the soil-bedrock boundary with a sharp impedance contrast. We found that these ground motion characteristics are related with the damage pattern.

Increasing Colorado's Seismic Network – New Developments by the Colorado Geological Survey

BOGOLUB, K. R., University of Colorado Boulder, Colorado, USA, kyren.bogolub@colorado.edu; MORGAN, M., Colorado Geological Surey, Colorado, USA, mmorgan@mines.edu; FITZGERALD, F. S., Colorado Geological Survey, Colorado, USA, ffitzger@mines.edu; PALKOVIC, M. J., Colorado Geological Survey, Colorado, USA, mpalkovic@mines.edu; BROES, L. D., Colorado Geological Survey, Colorado, USA, lbroes@mines.edu

During 2007-2008, the USArray's Transportable Array (TA) covered the state of Colorado with nearly 60 broadband seismometers in a roughly uniform 80-km spaced grid. The rolling array has since vacated the state with the exception of four stations that the Colorado Geological Survey (CGS) adopted as permanent stations. In addition to the adopted stations, CGS has installed three broadband seismometers at permanent sites and has plans to install a minimum of two more in 2019. While there are several regional networks still scattered throughout Colorado, the goal of the CGS is to cover the state in a dense, uniformly distributed permanent network. With this network, CGS can closely monitor local and small-magnitude seismicity. Many earthquakes below magnitude 2.5 are likely going uncatalogued over much of the state due to the lack of stations within adequate distance of the epicenters. Detecting and locating these events can improve and refine hazard and fault maps which provide valuable information to local and national building codes. There are also still many unanswered questions and research topics in the field of induced seismicity. In Colorado, induced events are typically small, but occasionally, damaging earthquakes occur within the state. Furthermore, there are subsurface features that could be further analyzed with high-resolution seismic tomography, such as the Rio Grande Rift and the Aspen anomaly. We will be presenting the locations of our current network of stations as well as our proposed network layout, introductions to our intended areas of research, and our preliminary event catalog locations. Our objective in sharing these plans with the seismologic community is to provide information about this new source of publicly available data, invite feedback on our proposed network and research objectives, and connect with potential collaborators.

Updated Paleoliquefaction Database and New Radiocarbon and Optically-Stimulated Luminescence Databases for the Central and Eastern United States

TUTTLE, M. P., M. Tuttle and Associates, Maine, USA, mptuttle@earthlink.net; KARRENBAUER, C. S., M. Tuttle and Associates, Maine, USA, cskarrenbauer22@gmail.com; TUCKER, K., PangaeaGIS, Tennessee, USA, pangaeapugs@gmail.com; WOLF, L. W., Auburn University, Alabama, USA, wolflor@auburn.edu

As part of a paleoliquefaction project sponsored by the U.S. Nuclear Regulatory Commission (NRC), the Central and Eastern U.S. paleoliquefaction database has been updated to include new paleoliquefaction information that has become available in the past five years. This information was collected in the Central Virginia seismic zone, the New Madrid seismic zone, and the region between the New Madrid and Wabash Valley seismic zones. In addition, new radiocarbon and optically-stimulated luminescence (OSL) databases have been created of dating results for sites listed in the paleoliquefaction database. The radiocarbon database includes results for all the regions represented in the paleoliquefaction database. The OSL database includes results for the Central Virginia seismic zones, the New Madrid seismic zones, the Marianna area south of the New Madrid seismic zone, and the region between the New Madrid and Wabash Valley seismic zones. The purposes of the databases are to compile and preserve paleoliquefaction and related dating information and to make it readily available for paleoearthquake research as well as earthquake hazard assessment. The databases are searchable, expandable, and include all large regional datasets of paleoliquefaction features and related dating results. The databases, as well as lists of references cited in the databases, are included in the final report of contract NRC-HQ-11-C-04-0041 to be published in 2019 and made available online through the U.S. NRC's Agency-wide Documents Access and Management System.

A New Model for Vertical to Horizontal Response Spectral Ratios for Central and Eastern North America

HAJI-SOLTANI, A., Mueser Rutledge Consulting Engineers, New York, USA, ahaji-soltani@mrce.com; PEZESHK, S., University of Memphis, Tennessee, USA, spezeshk@memphis.edu; FARHADI, A., University of Memphis, Tennessee, USA, afarhadi@memphis.edu

It is a well-known fact that critical structures are required to be designed for the vertical effects of ground motions as well as the horizontal effects. We developed a new model for the spectral ratio of vertical to horizontal components of earthquakes (V/H ratio) for Central and Eastern North America (CENA). The proposed V/H ratio model has the advantage of considering the earthquake magnitude, source to site distance, and the shear-wave velocity of soil deposits in the upper 30m of the site for PGA and a wide range of periods (0.001 to 10.0 seconds). The model evaluation is based on a comprehensive set of regression analysis of the newly compiled Next Generation Attenuation (NGA-East) database of available CENA recordings with $M \geq 3.4$ and $R_{RUP} < 1000$ km. The median value of the geometric mean of the orthogonal horizontal motions rotated through all possible nonredundant rotation angles, known as the GMRotD50 (Boore *et al.*, 2006), is used along with the vertical component to perform regression using the nonlinear mixed effect regression. We excluded the earthquakes and recording stations in the Gulf Coast region due to their different ground-motion attenuation (Dreiling *et al.*, 2014). To compute V/H ratios for the Gulf Coast region, we refer the readers to the study of Haji-Soltani *et al.* (2017) as an independent study performed on the Gulf Coast data. Moreover, we excluded the NEHRP site class E (soft-soil) sites from consideration because of their complex site-response characteristics and their potential for nonlinear site effects. Finally, we compared the predicted ratios from the proposed model with recently published V/H ratio models. We suggest our model be used for developing the vertical response spectra for CENA sites.

Upper Mantle Anisotropy Study Beneath Abaga Area, Inner Mongolia, China

QIANG, Z., Institute of Geophysics, China Earthquake Administration, Beijing, China, qzy@cea-igp.ac.cn; WU, Q., Institute of Geophysics, China Earthquake Administration, Beijing, China, wuqj@cea-igp.ac.cn

Central Asian Orogenic Belt (CAOB) is one of the largest Paleozoic orogens on Earth, which evolved from the latest Mesoproterozoic to the late Paleozoic, with the accretion of ophiolites, island arcs, accretionary wedges, oceanic islands and microcontinental fragments. Being the middle-eastern part of the CAOB, Inner Mongolia is characterized by widespread Cenozoic intraplate volcanisms and lithospheric deformation possibly related to the closure of the Paleo-Asian Ocean. However, the mechanism of lithosphere deformation is poorly understood. Seismic anisotropy determined by the splitting of shear waves, especially the core-refracted phases like SKS, is one of the most direct and effective ways to image the deformation in the interior of the Earth. A total of 120 pairs of shear wave splitting measurements and 113 null measurements are obtained at 32 portable seismic stations in Abaga area, Inner Mongolia. Delay times vary from 0.4 s to 1.4 s with an average value of 0.77±0.21 s; while fast directions trend from N101°W to N45°E. One group of fast directions in line with the strike of regional faults, trending N82.0°E±12.3°, is caused by lattice-preferred orientation of mantle crystals; the other group of fast directions observed in the North China Craton with an average value of N146.8°E± 9.5° are parallel to the direction of lithospheric deformation in Early Cretaceous, which may origin from fossil anisotropy remaining in the lithosphere. In addition, solely null measurements in the northern part of study area may suggest small-scale hot mantle upwellings which eroded the fossil anisotropy in lithosphere.

Directionality of Ambient Noise in the Mississippi Embayment: Ocean and Local Source Locations

ASLAM, K., University of Memphis, Tennessee, USA, ksaslam@memphis.du; LIU, C., University of Memphis, Tennessee, USA, cliu5@memphis.edu; LANGSTON, C. A., Center for Earthquake Research and Information, University of Memphis, Tennessee, USA, clangstn@memphis.edu

We investigate the source location of primary, secondary microseisms (Rayleigh and Love) and local sources by finding the maximum signal-noise-ratio (SNR) from cross correlations of seismic ambient noise signals recorded in the Mississippi embayment region between 1990 and 2018. We do this by using 8291 pairs of cross-correlations (CC) computed from 232 stations. The SNR is defined as the ratio between the maximum amplitude of the signals and root-mean- square amplitude of the noise window. Primary analysis on 8291 pairs of CC across the Mississippi embayment suggests two major azimuths (*i.e.* 40 and 330 degrees) for the ocean microseisms. We also determine the azimuthal content and seasonal variation difference in primary and secondary microseisms. Furthermore, the SNR analysis of a dense tremor array (Y8) interstation CC in 1-2 Hz may indicate the water repeatedly flushing over the Mississippi river bank as the source. Moreover, besides from the traditional ~3 km/s group velocity surface wave observed in the cross-correlation, we also recognize < 1 km/s, high amplitude surface wave in the frequency band of 0.3 – 1 Hz. Determination of the source location of the slow-propagating surface wave could use to monitor local natural or anthropogenic activities. Understanding the source location is fundamental importance to understand the generation of microseisms and also helpful to estimate the accuracy and reliability of the ambient noise tomography results.

Estimating Seasonal Seismic Velocity Variation in the Mississippi Embayment From Ambient Noise Cross-Correlation Analysis

LIU, C., University of Memphis, Tennessee, USA, cliu5@memphis.edu; ASLAM, K., University of Memphis, Tennessee, USA, ksaslam@memphis.edu; DAUB, *E.g.*, University of Memphis, Tennessee, USA, egdaub@memphis.edu

We estimate seasonal seismic velocity variations in the Mississippi embayment from 300 interstation pairs. Comparing 30 days moving-stacked ambient noise cross-correlations with a yearly averaged cross-correlation, we observe velocity variation negatively correlating with the water-table and temperature in the frequency band of 0.3 -1 Hz, 0.5-1.2 Hz, 0.7-1.5 Hz, and 1-2 Hz. The maximum seismic velocity variation (MSVV) fluctuates around 0.05% for interstation distance 10 - 100 km, but could also reach 1% for one dense tremor network (Y8) with interstation distance less than 100 meters. We compute the correlation coefficient of seismic velocity variation with water-table, temperature, and atmospheric stress in the predefined frequency bands, and observe best coefficients (> 0.6) for pairs with interstation distance 10 - 60 km and in the low-frequency passband 0.3 - 1 Hz. The MSVV does not show a clear dependence on the frequency but nonlinearly decrease with interstation distance. Furthermore, the MSVV does not depend on the interstation azimuth, suggesting that it is not related to the seasonal variation of the ambient noise sources. We also regionalize the MSVV based on the sediment thickness of the embayment and find the MSVV negatively correlates with the thickness which implies same amount change of water-table or temperature impacting more on the edge rather than the center of the embayment. We also compute 4 pairs long-term velocity variations and find 4-year velocity variations generally show velocity increasing trends which may reflect the ongoing closing of cracks in the uppermost crust or the sediments as the continuous stress loading from the plate motion.

Probabilsitic Seismic Hazard Estimates for Zacatecas, Central Mexico

HULL, A. G., Golder Associates, Oregon, USA, ahull@golder.com; MARTINEZ, M., Golder Associates, Santiago, Chile, mmartinez@golder.com; ROSSITER, M., Golder Associates, Washington, USA, mrossiter@golder.com

Four regional uniform-area crustal seismic source zones are used in a probabilistic seismic hazard analysis for the Zacatecas region of Central Mexico. The preferred, lower and upper bound earthquake recurrence parameters (*a-* and *b-values*) in the four seismic source zones are based on the short (~10 years) instrumental earthquake record from Zúñiga *et al.* (2017), the tectonic development in the surrounding physiographic regions of Mexico, and comparison to analogous regions of North America that have more robust earthquake recurrence parameters. Hazard curves confirm the relatively low seismic hazard, with 5%-damped, mean PGA values of 0.05 g, 0.14 g and 0.28 g for 475-year, 2,475-year and 10,000-year return periods, respectively. Hazard deaggregation analysis indicates that the PGA to 0.2 s spectral accelerations at a 475-year return period arise from moderate-magnitude earthquakes (*i.e.*, M_W5.0 to M_W6.0) at distances of about 50 km. Larger magnitude earthquakes (M_W6.5+) at distances greater than 135 km dominate the 475-year return period hazard at periods longer than about 1.0 s. At the 10,000-year return period the mean PGA of 0.27 g has a dominant hazard contribution from larger ($M_W \geq 7$) far-field earthquakes. Estimated earthquake ground motions are sensitive principally to the uncertainties related to the *a-* and *b-value* recurrence parameters and the ground motion model selection and weighting. The relative tectonic quiescence and the incomplete earthquake records in the region impede the evaluation of robust recurrence parameters, and hence, increase the level of uncertainty in the seismic hazard.

Next Generation Earthquake Early Warning Systems: Advances, Innovations and Applications

Poster Session · Thursday · 25 April · Grand Ballroom

A Case Study of the Plum Earthquake Early Warning Algorithm Using Southern California Data

COCHRAN, E. S., U.S. Geological Survey, California, USA, ecochran@usgs.gov; BUNN, J., California Institute of Technology, California, USA, julian.bunn@caltech.edu; MINSON, S. E., U.S. Geological Survey, California, USA, sminson@usgs.gov; BALTAY, A. S., U.S. Geological Survey, California, USA, abaltay@usgs.gov; KILB, D., University of California, San Diego, California, USA, dkilb@ucsd.edu; KODERA, Y., Meteorological Research Institute, Tsukuba, Japan, y_kodera@mri-jma.go.jp; HOSHIBA, M., Meteorological Research Institute, Tsukuba, Japan, mhoshiba@mri-jma.go.jp

Earthquake early warning (EEW) studies use seismic data to identify large ground shaking generated by earthquakes, with the aim to alert the public. Here, we explore if the Japanese Propagation of Locally Damped Motion (PLUM) EEW algorithm can successfully be applied to Southern California data. Unlike traditional EEW methods, which estimate the earthquake location and magnitude, PLUM simply identifies regions that are likely to experience large ground motions and issues alerts to those regions (Kodera *et al.*, 2016). We apply PLUM to six years of M≥3.5 Southern California events (2012-2017; 193 events), in addition to 49 challenging earthquakes/signals that were used to test the current ShakeAlert algorithms. Instead of using the original Japanese ground motion intensity measure to identify large ground motions, we use the Modified Mercalli Intensity (MMI) scale. We explore computing MMI using various combinations of peak ground acceleration (PGA) and peak ground velocity (PGV), and also test how to optimally incorporate vertical and horizontal component data. Our results favor using both PGA and PGV values, computing the final MMI value from the weighted sum of PGA and PGV that are each computed by combining the three-components of ground motion in quadrature. Using this MMI derivation, we present results from six differently configured instances of the PLUM algorithm, exploring the benefits of using either one or two stations for alert generation, with a variety of MMI alert thresholds. We find that to optimally identify magnitude 5.0+ earthquakes, while suppressing false alerts, two-station methods perform best, favoring a MMI≥4 and MMI≥2.5 alert threshold for the first and second stations, respectively. Our findings also highlight the fact that larger magnitude events do not always generate the largest ground motions.

Envelope-Based, Real-Time Nested Grid Search: Estimates for Earthquake Early Warning

ROH, B. H., California Institute of Technology, California, USA, broh@caltech.edu; HEATON, T. H., California Institute of Technology, California, USA, heatont@caltech.edu; ROSS, Z. E., California Institute of Technology, California, USA, zross@gps.caltech.edu

One popular EEW algorithm that has been tested in real-time is the Virtual Seismologist. It uses time frequency evolution of ground motion envelopes to provide estimates for earthquake source parameters. The goal of this method is to mimic the analysis that a human seismologist would perform in a reduced amount of time. With this goal in mind, we develop an envelope-based, real-time algorithm that will rapidly recognize incoming ground motion envelopes and assign the most probable magnitude, location, and origin time estimates to the observed earthquake. For our algorithm, we take on two approaches: (i) a standard grid search that will find the approximate parameters that best describe the incoming envelopes, and (ii) a historical search of envelopes from specific past earthquakes.

The first approach is the standard grid search. The grids are predetermined based on the first-triggered station: magnitude, latitude, longitude, and origin time. Observed P- and S-wave envelopes are created using polarization analysis (Ross et al 2014) for identification of phase separation. These observed envelopes are compared with the predicted Cua-Heaton (CH) ground motion envelopes. Source parameters are described probabilistically using the uncertainties of the

CH ground motion prediction equations (GMPEs), and the grid points that maximize the likelihood are determined.

In addition to the grid search, we have the historical search as a second approach. Its intention is to find envelopes that match past events. It will check the outcome of the initial grid search, or, if available, find better estimates. To reduce searching time, many services, like GoogleMaps, use tree data structures. Similarly, we apply the kD tree search. We create a catalog of source parameters and their corresponding ground motion peak values. The traditional brute force approach would search through the whole catalog, but we construct a kD tree and search only a subset of it. Both approaches are done in real-time, updating the estimates with additional data from additional stations.

A New Multi-Sensor Network Developed for the China Earthquake Early Warning System (EEWs)

WANG, H., Hebei Earthquake Agency, CEA, Shi Jiazhuang, China, 59359701@qq.com; MOONEY, W. D., U.S. Geological Survey, California, USA, mooney@usgs.gov; GAO, J., Hebei Earthquake Agency, CEA, Shijiazhuang, China, jcgao@eq-he.ac.cn; MAO, G., Hebei Earthquake Agency, CEA, Shijiazhuang, China, 9912mao@163.com; HU, B., Hebei Earthquake Agency, CEA, Shijiazhuang, China, hubin@eq-he.ac.cn

The speed and accuracy of an Earthquake Early Warning System (EEWs) is improved by increasing network station density. Recently, a new 3-in-1 network consisting of: (1) Micro-Electro Mechanical Systems (MEMS) sensors, (2) traditional seismometers and (3) accelerometers, was installed by the China Earthquake Administration (CEA) in some regions of China for EEWs. The JJJ region in eastern China, comprising Beijing, Tianjin and Hebei is one such regions. Here the CEA has deployed 370 low-cost MEMS sensors with average spacing of 8-10 km and 220 traditional instruments (seismometers and accelerometers) in this 3-in-1 network. The EEWs in the JJJ region includes the central data processing center and 3 alert centers in Beijing, Tianjin and Shijiazhuang, respectively. The system uses a point-source algorithm (Zhang H. *et al.*, 2016) for event detection, location and magnitude determination. During online testing carried out from 2015 to 2018, the JJJ EEWs network successfully provided alerts for several earthquakes near the Beijing Capital Area. Examples include the 2015 *M*4.2 Changli, Hebei, earthquake for which the JJJ EEWs issued the first alert 5.4 seconds after the origin time with magnitude error of -0.1 and epicenter location error of 2 km compared to China Earthquake Networks Center catalog. The 2018 *M*4.3 Yongqing, Hebei, earthquake, occurred on the edge of the high density MEMS network. The first station triggered 5.7 seconds and an alert was issued 9.7 seconds after the earthquake origin time. The EEWs kept updating the analysis, with the most reliable alert just 11.8 seconds after the origin time. The alert messages, including point-source information and the intensity map, were rapidly sent to the pilot-users through three alert centers. The EEWs demonstration project in the JJJ region has successfully completed a series of evaluation and reliability tests, including data collection, transmission, processing, and alert release. The demonstration project provides a solid foundation for the implementation of the China National EEWs.

Investigating the Effect of Finite Source Processes in Single Station Based On-Site Earthquake Early Warning System

KWAK, S., Korea Institute of Geoscience and Mineral Resources, Daejeon, Korea, Republic of, kwak.sangmin@kigam.re.kr; SONG, S., Korea Institute of Geoscience and Mineral Resources, Daejeon, Korea, Republic of, sgsong@kigam.re.kr; PARK, J., Korea Institute of Geoscience and Mineral Resources, Daejeon, Korea, Republic of, jhpark@kigam.re.kr

Two consecutive moderate-sized earthquakes in southeast Korea, *e.g.*, 2016 M 5.8 Gyeongju and 2017 M 5.4 Pohang events, highlight the need for comprehensive seismic hazard assessment and mitigation efforts in the Korean Peninsula. Earthquake early warning (EEW) system is used for the seismic hazard mitigation by issuing an alert in the region where strong ground shakings are expected before their arrival, using a modern seismic network. Caruso *et al.* (2017) developed an on-site P-wave based EEW algorithm, called on-Site Alert level (SAVE), which uses a single station to speed up the alert process especially in near-source regions. However, the single station based on-site EEW systems can be significantly affected by the relative location of the station used with respect to the spatio-temporal geometry of earthquake rupture process, including the rupture directivity effect.

In this study, we investigated the effect of finite source processes in an on-site EEW system by utilizing synthetic near-source ground motions obtained by the SCEC Broadband Platform (BBP). We simulated synthetic broadband ground motions at 30 stations surrounding an M 7.0 vertical strike-slip event at a distance of 20 km and 50 km, respectively. Then, we investigated the effect of the station locations in determining the magnitude, distance of the event and expected horizontal peak ground velocity (PGV) at each station, using the P-wave based on-site EEW algorithm (SAVE). Scaling relations for the on-site EEW parameters were obtained by analyzing a training dataset of the simulated ground motions at 169 seismic stations in the South Korea for Mw 5.5, 6.0, 6.5, and 7.0 earthquakes. Our preliminary results show that the SAVE algorithm can be significantly affected by the relative station locations mostly because of the difference of P- and S-wave radiation patterns and rupture directivity effect. It seems important to understand the range of uncertainty caused by the station location for a wide range of magnitude with various rupture scenarios to improve the P-wave based on-site warning system.

Rapid Magnitude Assessment of Large Earthquakes From Recurrent Neural Networks

LIN, J., University of Oregon, Oregon, USA, jiunting@uoregon.edu; MELGAR, D., University of Oregon, Oregon, USA, dmelgarm@uoregon.edu; THOMAS, A. M., University of Oregon, Oregon, USA, amt.seismo@gmail.com; SEARCY, J., University of Oregon, Oregon, USA, jsearcy@uoregon.edu

Earthquake early warning (EEW) systems provide seconds to minutes of warning to both people and "automated systems" before strong shaking occurs at their location. Rapid and accurate magnitude estimation is critical to the success of EEW systems, however, fast magnitude determination for large (M_w8+) earthquakes is very challenging for modern systems because of the two factors: 1. the limitations of inertial-based seismic equipment and 2. the initial features of the small and large earthquakes are unable to be distinguished by the current method. Here, we demonstrate that by applying a recurrent neural network (RNN) to Global Positioning System (GPS) waveforms generated from several hundred synthetic Cascadia megathrust earthquakes, we are able to rapidly determine the moment magnitude (M_w) from the synthetic GPS data before the rupture has ended. On average, we can determine the final earthquake magnitude roughly halfway through the rupture process, which strongly supports the idea of weak earthquake determinism. This method can improve currently operating earthquake and tsunami early warning systems. We first focus on large Cascadia Subduction Zone ruptures (M8+), where there is a pressing need for such an algorithm and will ultimately expand to global subduction zones.

Reducing False Positives in the On-Site and Regional Earthquake Early Warning Systems

ZAICENCO, A. G., Weir-Jones Engineering Consultants Ltd., Vancouver, Canada, anton.zaicenco@weir-jones.com; WEIR-JONES, I., Weir-Jones Engineering Consultants Ltd., Vancouver, Canada, iainw@weir-jones.com

The on-site earthquake early warning (EEW) systems are an efficient means to reduce seismic risk to the critical infrastructure. In addition, a collection of the on-site nodes can form a backbone of the sparse regional EEW network. Oftentimes, the sensors are located in noisy urban areas, which increases the probability of a false positive. We developed a method to reduce this probability by extracting from the real-time records of the ground motion a set of features that are likely to describe the P wave of a large seismic event, and analyzing them in real time. Besides, rather than performing a point measurement, we create an on-site multi-sensor array which allows to compute statistics of the extracted features, which further reduces the false positives. We use recursive Bayesian estimation to compute the parameters of the seismic event from the on-site data and apply the same approach to the sparse seismic network. Since the on-site EEW system operates on its own LAN, there are virtually no delays in the data transmission over the local network. Remote nodes in a sparse seismic network communicate only the updates of the event parameters for the recursive Bayesian estimation, which improves the speed of the issued alarm.

Our results demonstrated that this algorithm works efficiently for the set of the on-site EEW systems installed during the last 10 years in south-western British Columbia, producing virtually no false positives. Some of the sensors are installed near the major highways, busy city streets, and railroads. The most recent effort to improve the reliability of the systems consists of redundant solutions, where the entire data acquisition path, from sensors to the on-site processing embedded computer, is parallelized, and even consists of the heterogeneous elements with different failure modes. This is particularly important for the mission-critical facilities with the high cost of downtime.

California Regional Adjustments to Ground Motion Models Used in Earthquake Early Warning Algorithms

ABRAHAMS, L., Stanford University, California, USA, labraha2@stanford.edu; BALTAY, A. S., U.S. Geological Survey, California, USA, abaltay@usgs.

gov; AAGAARD, B., U.S. Geological Survey, California, USA, baagaard@usgs.gov

Source-based earthquake early warning systems (EEWs), such as ShakeAlert EEW for the West Coast of the US, rely on ground-motion models (GMMs) to predict the expected ground motion at a user's location. We explore how (or whether) regional adjustments to GMMs improve ground-motion estimates, and hence the accuracy of EEW alerts, in California. Our approach is to first analyze the residuals (difference) between ground-motion data and GMMs, and then decompose those residuals into contributions of source, site, and path. Specifically, we propose a novel way to define the event term, using only records close to the event, as farther data is more representative of the path attenuation rather than the source.

We use the Abrahamson *et al.* (2014; ASK14) NGA-West2 compared to NGA-West2 data only in California, consisting of 374 earthquakes of M3 to M7.3, a total of 15,178 records. We consider only residuals in close proximity to determine event terms, inherently different from what is currently practiced. We look for events that were recorded on at least three stations within a 20 km radius, and increasing the radius until five station recordings are available, out to a maximum of 40 km. The goal is to use enough data to distinguish between event and site residuals but with close proximity. Both the Bay Area and Southern California exhibit regional trends; therefore, to improve the GMM, we implement regional corrections.

To test this improved GMM in an EEW application, we apply the Aagaard *et al.* (2018) cost-benefit matrix – which tells us how accurate the GMM is for early warning purposes – on several recent large California earthquakes not included in the NGA-West2 data set. We compare the predicted ground motion to ShakeMaps (considered ground truth) to determine the improvement with the adjusted GMM. We find the corrected GMM more accurately reflects the observed ShakeMap, showing that regional corrections can improve earthquake early warning alerts.

Investigating the Performance of Earthquake Early Warning Algorithms on the Cascadia Subduction Zone

THOMPSON, M., University of Washington, Washington, USA, usherm42@uw.edu; HARTOG, J. R., University of Washington, Washington, USA, jrhartog@uw.edu

Earthquake early warning (EEW) algorithms use the first few seconds of an ongoing earthquake to rapidly predict when and where strong ground shaking is expected. The usefulness of an EEW alert depends on the accuracy of ground motion predictions and whether the alert provides enough warning to take mitigating actions. The low level of background seismicity at the Cascadia subduction zone (CSZ) makes it difficult to test EEW algorithms. However, we can assess the expected performance of point-source and finite-source EEW algorithms for events on the CSZ with a global dataset of local recordings of subduction zone earthquakes and a suite of thirty 3-D ground motion simulations of M9 Cascadia megathrust rupture scenarios. By re-arranging seismic stations to mimic the station density and source-to-site distances in the Pacific Northwest, we test the accuracy and timeliness of EEW algorithms in Cascadia and estimate expected warning times.

An Amphibious Subduction Zone Earthquake Early Warning System for British Columbians— Introduction, Design and First Results

SCHLESINGER, A., Ocean Networks Canada, Victoria, Canada, schlesin@uvic.ca; ROSENBERGER, A., Arescon Ltd., Sidney, Canada, andreas@arescon.com; FERGUSON, E., Ocean Networks Canada, Victoria, Canada, elif@uvic.ca; WAGNER, S., Ocean Networks Canada, Victoria, Canada, swagner@uvic.ca; KREIMER, N., Ocean Networks Canada, Victoria, Canada, nadiakreimer@uvic.ca; DOROCICZ, J., Ocean Networks Canada, Victoria, Canada, jdorocic@uvic.ca; COLLINS, P., Natural Resources Canada, Sidney, Canada, paul.collins@canada.ca; HEMBROFF, D., Ocean Networks Canada, Victoria, Canada, degnanh@oceannetworks.ca; KEY, R., Ocean Networks Canada, Victoria, Canada, rkey@uvic.ca; HENTON, J. A., Natural Resources Canada, Sidney, Canada, joe.henton@canada.ca; NYKOLAISHEN, L., Natural Resources Canada, Sidney, Canada, lisa.nykolaishen@canada.ca; LU, Y., Natural Resources Canada, Sidney, Canada, yuan.lu@canada.ca; PIRENNE, B., Ocean Networks Canada, Victoria, Canada, bpirenne@uvic.ca; MORLEY, M., Ocean Networks Canada, Victoria, Canada, mmorley@uvic.ca; HEESEMANN, M., Ocean Networks Canada, Victoria, Canada, mheesema@uvic.ca; JENKYNS, R., Ocean Networks Canada, Victoria, Canada, reyna@uvic.ca; MOORE, T., Ocean Networks Canada, Victoria, Canada, tmoore@uvic.ca; CROSBY, B., Ocean Networks Canada, Victoria, Canada, b_crosby@telus.net

Introduction: Ocean Networks Canada (ONC), an initiative of the University of Victoria, has been implementing an Earthquake Early Warning (EEW) system starting in February 2016. The EEW project is a collaboration among government, academia, industry, and communities including: Natural Resources Canada, the BC Ministry of Transportation and Infrastructure, the University of British Columbia, United States Geological Survey and the University of Washington.

Design: The EEW system incorporates land-based stations across Vancouver Island that consist of a combined system of an accelerometer and real-time Global Navigation Satellite Systems (GNSS). Additionally, ONC operates subsea accelerometers that transect the Cascadia subduction zone from the continental slope into the deep-sea basin. For each of our sites we process raw observation data from the accelerometer and geodetic instruments, respectively, on-site and in real time. P-wave detection and parameterized displacement data are sent from remote stations to a central data centre, where the event correlator calculates earthquake epicenter location, origin time, and magnitude. For a successful event detection four sites are required to report the event as well as a converging epicenter solution. All of this must occur with very high standards for latency, reliability, and accuracy.

First Results: The first successful real-time earthquake detection was achieved from the Magnitude 6 Sovanco events on October, 22, 2018. The P-wave detections from 11 land-based sites and 5 subsea accelerometer sites were correlated and an earthquake was reported 44 seconds after the event occurred. The epicentre was reported with an accuracy of within 30 km.

An overview of the EEW system is provided in this presentation with preliminary results of earthquake event detections.

Too-Late Warnings by Estimating Mw: Earthquake Early Warning in the Near-Fault Region

HOSHIBA, M., Meteorological Research Institute, Japan Meteorological Agency, Tsukuba, Japan, mhoshiba@mri-jma.go.jp

Earthquake early warning (EEW) systems aim to provide advance warnings of impending strong ground shaking. Many of EEW systems are based on a strategy in which precise and rapid estimates of source parameters, such as hypocentral location and moment magnitude (M_w), are used in a ground motion prediction equation to predict the strength of ground motion such as PGA and/or PGV. Strategy based on rapid estimation of M_w implicitly assume that precise estimation of M_w leads to precise prediction of the strength of ground motion and that this estimation can be done earlier than the arrival of strong ground motion. Are these assumptions true?

In some regions near the causative fault this approach leads to late warnings. The peak strong ground motions often occur during earthquake ruptures before the final M_w can be estimated in the near-fault region, where large PGA and PGV are usually recorded. The 2016 Kumamoto earthquake (M_w 7.1) actually indicated that the estimation of M_w is later than the arrival of peak ground motion in the near-fault region, where the strong ground motions were recorded by a dense observation network. This phenomenon is explained by a reason that the strong ground motion in the near-fault region is controlled by instantaneous strong radiation of seismic waves caused by the local process of rupture, while M_w is finally estimated at the end of rupture reflecting the whole process. An EEW strategy based on rapid estimation of M_w thus is not suitable for regions near faults where strong shaking is usually recorded. Approaches based on real-time monitoring of ground motion are more promising for these near-fault locations.

Evaluating and Improving Earthquake Early Warning in Central America

MASSIN, F., Swiss Seismological Service, Zurich, Switzerland, fmassin@sed.ethz.ch; CLINTON, J., Swiss Seismological Service, Zurich, Switzerland, jclinton@sed.ethz.ch; PORRAS, J., Red Sismológica Nacional, San Jose, Costa Rica, juan.porrasloria@ucr.ac.cr; MARROQUIN, G., Red Sísmica Nacional de El Salvador, San Salvador, El Salvador, gmarroquin@marn.gob.sv; STRAUCH, W., Instituto Nicaragüense de Estudios Territoriales, Managua, Nicaragua, wilfried.strauch@yahoo.com; BÖSE, M., Swiss Seismological Service, Zurich, Switzerland, maren.boese@googlemail.com

El Salvador, Nicaragua and Costa Rica are exposed to frequent damaging earthquakes (23 M7+ earthquakes occurred in these countries last 100 years). Tsunamigenic thrust events occur at the Middle America Trench where the Cocos plate subducts by 72-81 mm/yr northeastward beneath the Caribbean plate. Extensive damage is also expected from on-shore shallow crustal events, as demonstrated by the 1972 Managua M6.2 earthquake. This seismotectonic setting is challenging for Earthquake Early Warning (EEW) because relevant events include both moderate-sized on-shore seismicity that is often in close proximity to densely urbanized areas, where early warning alerts for areas experiencing strong shaking would at best be very short and often late; and tsunamigenic offshore seismicity, where large lead times are possible but the finite source must be accounted for, and hypocentral distances are uncertain. Since 2016, the Swiss Development and Cooperation Fund has funded a collaboration between Swiss and regional partners to build and evaluate prototype EEW systems in Central America. The EEW algorithms Virtual Seismologist (VS) and Finite fault rupture Detector (FinDer) can be operated by any network running the popular SeisComP3 network processing and management suite. Currently, these algorithms are being run at MARN in El Salvador, RSN in Costa Rica and INETER in Nicaragua. In this contribution, we assess how fast and accurate EEW could be at these networks. We estimate the current and potential performance of EEW alerts by modeling alert time delays using various existing and possible regional network configurations, taking into account communication and processing delays. Models are compared with the on-going observed performance obtained by the VS and FinDer algorithms. We further highlight current capabilities and challenges for providing EEW alerts in Central America. We also discuss how to get a robust approach to EEW from combining different algorithms and from combining class A accelerographs with large numbers of low cost accelerographs.

ElarmS/EPIC Earthquake Early Warning System: 2018-2019 Development and Performance

CHUNG, A., Berkeley Seismological Laboratory, California, USA, angiechung07@gmail.com; HENSON, I., Berkeley Seismological Laboratory, California, USA, ihenson@berkeley.edu; ALLEN, R. M., Berkeley Seismological Laboratory, California, USA, rallen@berkeley.edu

The ElarmS Earthquake Early Warning System (EEWS) is a point-source, network-based EEWS that has been under development since early 2006. ElarmS was one of the original US West Coast ShakeAlert algorithms. Recently, significant modifications were made to the code that resulted in ElarmS version 3.0 (E3), which was deployed on the ShakeAlert production system on January 25, 2018. Because of its excellent performance as part of the ShakeAlert system, ElarmS was chosen as the basis for EPIC (Earthquake Point-Source Integrated Code), the only point-source algorithm that ShakeAlert will use in the future. EPIC replaced E3 on the ShakeAlert production system on September 28, 2018.

Since January 2018, E3 and EPIC have performed well, alerting for 18 of the 22 $M \geq 4$ earthquakes within the West Coast reporting boundary. Of the four missed events, all were $4 \geq M \geq 4.7$ at the edges of the alerting boundary (two in Baja California, one offshore Canada, and one offshore Northern California). Improvements to the system have significantly reduced the number of false alerts, however, some false alerts were still generated by the algorithms. Some false alerts were due to bugs in the code, which have since been fixed, but others were caused by teleseismic, noisy, and spurious triggers. Preventing alerts from triggers like these remains a high-priority goal for the ElarmS/EPIC team.

In this presentation, we will review modifications that were made to E3 to create the new algorithm EPIC. We will discuss the performance of E3 and EPIC for 2018-2019 and the expected performance of the algorithm based on historic replays. Finally, we will highlight new research focused on optimizing alerts and preventing false alerts.

Social Science and ShakeAlert

MCBRIDE, S. K., U.S. Geological Survey, Washington, USA, drsaramcb@gmail.com; DEGROOT, R. M., U.S. Geological Survey, California, USA, rdegroot@usgs.gov

As the full public rollout of ShakeAlert draws closer, critical questions remain about how people will understand the ShakeAlert, what protective actions they know to take, and what their responses will be when the system behaves differently than they might expect (*e.g.* false or missed alerts). Additionally, we do not yet know if people understand what the alerts mean or how the system works. Currently, there is some but not much literature about social science and Shakealert: a gap that this project aims to fill.

To evaluate whether the alerting system has been successful in answering these key research questions, the U.S. Geological Survey, in collaboration with its university and state emergency management partners, developed a social science initiative focusing on four goals:

1. Develop understanding of where populations are currently in terms of risk perception, protective action knowledge, and basic earthquake preparedness across Washington, Oregon, and California.
2. Use social science research to inform the communication, education, and outreach (CEO) program for ShakeAlert, outlined in the 2018 -2019 ShakeAlert CEO Plan (2018).
3. Develop and test an adequate alert with sound (tone), haptics (vibrations), words, and images, as well as post-alert messaging.
4. Develop a monitoring and evaluation plan for ShakeAlert.

Projects currently underway include analysis of CCTV footage from the M7.0 Anchorage Earthquake to better understand human behavior during an urban USA-based earthquake, alert message testing, a citizen science Wireless Emergency Alert project, and a perceptions baseline to determine levels of understanding about ShakeAlert. This important work will help us understand what perceptions and human behavior exist currently about ShakeAlert so the public aspects of the systems can be iterated to better suit the needs of our users.

Finite-Fault Rupture Detector (Finder): Rapid Line-Source Models for Large Crustal Earthquakes in Sichuan, China

BÖSE, M., Swiss Seismological Service, ETH Zurich, Zurich, Switzerland, mboese@sed.ethz.ch; LI, J., Institute of Geophysics, China Earthquake Administration, Beijing, China, lijw@sed.ethz.ch; HUTCHISON, A., Institut français des sciences et technologies des transports, de l'aménagement et des réseaux, Paris, France, allie.hutchison@gmail.com; CLINTON, J., Swiss Seismological Service, ETH Zurich, Zurich, Switzerland, jclinton@sed.ethz.ch; WU, Z., Institute of Earthquake Forecasting, China Earthquake Administration, Beijing, China, wuzl@cea-igp.ac.cn; ZHOU, S., Peking University, Beijing, China, zsy@pku.edu.cn

Sichuan province, China, has been hit hard in the last decade with the successive occurrence of the 2008 Mw7.9 Wenchuan, 2013 Mw6.6 Lushan, and 2017 Mw 6.5 Jiuzhaigou earthquakes, causing more than 87,000 fatalities and economic losses of about 1.5 trillion US dollars. Following the Wenchuan earthquake, the China Earthquake Administration (CEA) started building a nationwide earthquake early warning (EEW) system with about 3,200 strong-motion, ~2,000 broadband and ~10,200 low-cost MEMS sensors. Large earthquakes like the Mw7.9 Wenchuan mainshock are challenging for EEW, because traditional seismic network stations tend to saturate and source dimensions need to be known to predict seismic ground-motion at high accuracy. In this study, we run playbacks of local and regional on-scale strong-motion waveforms recorded by the China Strong Motion Networks Center (CSMNC) during the Mw7.9 Wenchuan, Mw6.6 Lushan, and Mw 6.5 Jiuzhaigou earthquakes to study the possible performance of the Finite-Fault Rupture Detector(FinDer) algorithm (Böse *et al.*, 2018). We show that the FinDer line-source models agree well with the later observed spatial distribution of aftershocks and finite-fault models determined from waveform inversion. If the available set of strong motion data had been available in real-time, more than 70 percent of sites experiencing shaking intensities of MMI IV-VII could receive ≥5 seconds of warning, and around 30 percent of sites experiencing MMI VII-IX could receive ≥10 seconds of warning. FinDer finite-fault models could also help providing faster and more accurate loss estimates for rapid response in the aftermath of devastating earthquakes.

An Automatic S-Phase Arrival Time Picker

KALKAN, E., U.S. Geological Survey, California, USA, ekalkan@usgs.gov

Accurate automated onset time determination of *S* phases is important for the automatic real-time location of local, regional and teleseismic events. A new method is developed for automatic detection of *S* phases in single-component acceleration or broadband velocity records. The algorithm "$S_{\text{PHASE}}\text{P}_{\text{ICKER}}$" transforms the signal into a response domain of a single-degree-of-freedom (SDF) oscillator with viscous damping, and then tracks the rate of change of dissipated damping energy in order to pick *S*-wave phases. The SDF oscillator has a high damping ratio (60% of critical). At this damping level, the frequency response approaches the Butterworth "maximally flat" magnitude filter, and phase angles are preserved. The relative input energy imparted to the oscillator by the input signal is converted to elastic-strain energy and then dissipated by the damping element as damping energy. The damping energy yields a smooth envelope over time; it is zero in the beginning of the signal, zero or near zero before the *P*-phase arrival, and builds up rapidly with the *S*-wave. Since the damping energy function changes considerably at the onset of the emergent or impulsive *S*-wave arrival, it is used as a metric to track and pick the arrival time. The $S_{\text{PHASE}}\text{P}_{\text{ICKER}}$ detects *S*-phase onset using the histogram method. The proposed algorithm is applied to a data set recorded by a dense regional seismic network in northern California. The picking algorithm is tested by comparing analysts' *S*-phase readings, serving as reference picks, with the corresponding automatically derived *S*-wave arrival times.

Shakealert Testing and Certification: Future Developments

SMITH, D. E., U.S. Geological Survey, California, USA, desmith144@gmail.com; MCGUIRE, J. J., U.S. Geological Survey, California, USA, jmcguire@usgs.gov; KOHLER, M. D., California Institute of Technology, California, USA, kohler@caltech.edu; ANDREWS, J. R., California Institute of Technology, California, USA, jrand@gps.caltech.edu; CHUNG, A., University of California, Berkeley, California, USA, aichung@berkeley.edu; HARTOG, R., University of Washington, Washington, USA, jrhartog@uw.edu; HENSON, I., University of California, Berkeley, California, USA, henson@seismo.berkeley.edu; GIVEN, D., U.S. Geological Survey, California, USA, doug@usgs.gov; GOOD, A., California Institute of Technology, California, USA, agood@gps.caltech.edu; GUIWITS, S., U.S. Geological Survey, California, USA, sguiwits@usgs.gov

Earthquake early warning algorithms must undergo rigorous real-time and offline testing before being accepted into the ShakeAlert production system. The ShakeAlert Testing and Certification platform attempts to simulate how the production system will perform by deploying the proposed algorithms, configurations, earthworm rings/modules, and ActiveMQ messaging on separate, nearly identical hardware. For real-time testing, the test servers are fed the same West Coast input waveform data as the production servers, and the algorithms' performance is compared between the test and existing production systems after a minimum of two weeks. For offline testing, four simultaneous instances of the algorithms are run on one machine with a historic test suite of earthworm tankplayer files (format used for replaying data into an earthworm ring with realistic timing). These tankplayer files include data from West Coast earthquakes (M4.1 to M7.2), teleseisms, regional events, and problematic data sets.

There are several areas of ongoing development in ShakeAlert testing and certification intended to extend and improve its capabilities. One key area is assessing the performance of the system for large magnitude events. These events are infrequent on the West Coast, so to augment our large magnitude data set, M5+ events from Japan are being incorporated. This will include the 2011 M9.0 Tohoku-Oki and 2016 M7.0 Kumamoto earthquakes. Evaluation of large magnitude event alert timelines will also be developed and implemented to help quantify ShakeAlert warning times. Another key area of development is refining how ground motion predictions are assessed for different algorithm results. Code is already in place for classifying alerts into True Positives, False Positives, True Negatives, and False Negatives; as well as for calculating overall quality factors for a grid of points where the alerting threshold and target threshold are equal and the minimum alert time is >0 seconds. Additional configurable features, are being added to make the calculations more flexible.

Recent Developments in High-Rate Geodetic Techniques and Network Operations for Earthquake and Tsunami Early Warning and Rapid Post-Earthquake Response

Poster Session · Thursday · 25 April · Grand Ballroom

Assessing Improvement in Ground Motion Prediction Accuracy Provided by Distributed Slip Models

MURRAY, J. R., U.S. Geological Survey, California, USA, jrmurray@usgs.gov; MINSON, S. E., U.S. Geological Survey, California, USA, sminson@usgs.gov; BALTAY, A. S., U.S. Geological Survey, California, USA, abaltay@usgs.gov; THOMPSON, E. M., U.S. Geological Survey, Colorado, USA, emthompson@usgs.gov

Earthquake Early Warning (EEW) systems aim to warn users of impending shaking before strong ground motion reaches them. Many EEW algorithms compute ground motion by using real-time source models derived from seismic and/or geodetic data as input to ground motion prediction equations (GMPEs). The ShakeAlert system currently includes two seismic algorithms. One characterizes the earthquake as a point source; the other uses a line source representation, providing the location, strike, and rupture extent. Source-to-site distance is a fundamental input for ground motion prediction (GMP), and including finite fault effects via a line source enables more accurate GMP than using a point source when rupture dimensions are comparable to or exceed source-site distances (Boese *et al.*, 2017). However, the extent to which GMP might be further improved by instead using distance measures derived from 3D source geometries and distributed slip models is less clear. We first explore this question by comparing predicted ground motion obtained using point, line, and 3D distributed slip models (DSMs) for idealized synthetic cases. To further explore best-case scenarios, we compare observed ground motion for earthquakes in the Next Generation Attenuation Relationships for the Western U.S. (NGA-West2) database to that predicted using published DSMs. We do the same using the line source representation of each DSM that best fits the observed ground motion for the corresponding earthquake in order to evaluate whether using the full DSM gives substantially better results. To assess the relative ability of GMPEs to leverage the added information provided by DSMs we compare results using four NGA-West2 GMPEs, for which the source-site distance is determined by designating a minimum slip magnitude that defines the rupture area, and a new approach developed by Thompson and Baltay (2018) that incorporates weighting based on spatially variable slip in the distance calculation.

Ionosheric Signature Recorded on the Hawaii GPS Network of the Mw 6.9 Earthquake and Tsunami

ROLLAND, L., Géoazur, OCA, Valbonne, France, lrolland@geoazur.unice.fr; MIKESELL, T. D., Boise State University, Idaho, USA, dylanmikesell@boisestate.edu; SUNIL, A., Indian Institute for Geomagnetism, Mumbai, India, sunil.as@gmail.com; TWARDZIK, C., Géoazur, Valbonne, France, twardzik@geoazur.unice.fr

On 4 May 2018, a Mw 6.9 earthquake ruptured on the south flank of the Kilauea volcano, Hawaii. The rupture of this largest earthquake in the Hawaii region since 1975 extended offshore and a small tsunami was identified on regional tide gauges. Then we expect a significant shaking of the ionosphere, the ionized layer of the Earth's atmosphere located from 80 km to 2000 km of altitude. This ionization affects Global Positioning System (GPS) signals and these perturbations can be used to image the ionosphere response triggered by large (Mw > 6.5) and shallow earthquakes. Here, we analyze data collected by receivers of the permanent GPS network of Hawaii. While no clear disturbance was detected after the 1 May 2018 crater collapse, we observe clear disturbances in the Total Electron Content (TEC) directly above the rupture area. These fluctuations are consistent with an acoustic wave originating from the rupture area of the earthquake. Using a spectral element modeling approach, we investigate the solid/ocean/atmosphere coupling efficiency. Using IonoSeis, a new software package designed for coseismic TEC studies, we conduct an acoustic ray tracing-based modeling to reconstruct the observations and show how they relate to the seafloor static deformation reconstructed using conventional data.

Tsunami Early Visualization and Warning System

JOHNSON, C., Introspective Systems LLC, Maine, USA, caryl.johnson@introspectivesystems.com

In the moments following a potentially tsunamigenic event chaos reigns as scientists scramble to gather and assess any sensor data that might be available to help them evaluate the threat. The first notification generally comes from a seismic analysis center, but then what? There is a plethora of data that can be gathered, combined and ranked in importance to make that all important decision – is a tsunami possible? Clearly the initial hypocenter is not enough to make that determination, and the in the next hour duty scientists search for and consider many different kinds of sensor data as the situation unfolds. The first supporting information is likely to be GNSS and hydroacoustic waveforms followed by moment tensors, DART (Deep-ocean Assessment and Reporting of Tsunamis) and tide gauge data as they become available. Much rides on the correctness, timeliness and accuracy of the situational assessment.

This talk demonstrates a prototype for a real-time, cognitive visualization (dashboard) that automatically searches for pertinent data and presenting it to the scientists for assessment. Computers do what computers do best and let people do what people do best to make sure that decision makers and first responders have the best information available as timely as possible. The key element is a multimodal data fusion engine - part of the real-time xQuake earthquake analysis system that was developed for the Air Force for combining multiple forms of data for detecting and characterizing clandestine nuclear testing. Based on the open source xGraph technology, it is both a program and a graph database that can be configured while operational. Data sources can be added (or deleted) and seismic network detectors can be changed to keep the system current in an age when budgets are tight and whatever data that is available must be utilized as effectively and efficiently as possible.

Platform-Based Testing of Station-Based GNSS-Positioning, Accelerometer and Ensemble Streams for Early Warning Applications With the 'HERB-SE'

HENTON, J. A., Canadian Geodetic Survey, Sidney, Canada, joe.henton@canada.ca; COLLINS, P., Canadian Geodetic Survey, Sidney, Canada, paul.collins@canada.ca; ROSENBERGER, A., Arescon Ltd, Sidney, Canada, andreas@arescon.com; FERGUSON, E., Ocean Networks Canada, Victoria, Canada, elif@uvic.ca; LU, Y., Canadian Hazards Information Service, Sidney, Canada, yuan.lu@canada.ca; CAISSY, M., Canadian Geodetic Survey, Ottawa, Canada, mark.caissy@canada.ca; PERERA, D., Department of Fisheries and Oceans, Sidney, Canada, dan.perera@dfo-mpo.gc.ca

High-rate, low-latency Global Navigation Satellite System (GNSS) data are being utilized for real-time (RT) applications focused on disaster mitigation, including tsunami early warning. By directly reporting displacement waveforms (particularly for lower frequencies and 'DC' coseismic offsets), RT-GNSS complements other geophysical monitoring (*i.e.*, accelerometer) networks to improve the robust assessment and reporting of hazards. In order to facilitate real-time testing of distributed (on-site) analyses as well as integration with other local seismic sensors, Natural Resources Canada's Canadian Geodetic Survey has implemented real-time GNSS processing on low power, Linux platforms. Currently three RT-time positioning streams may be executed *in-situ*: precise point positioning (PPP) with integer ambiguity resolution and 'float' PPP (both using RT clock and orbit correction streams delivered to the GNSS sites) as well as fully autonomous single point positioning using broadcast orbits.

To evaluate the RT-GNSS derived coordinate streams in a controlled experiment, a mechanical system is used to drive a GNSS antenna along a circular path while maintaining a fixed orientation. The result is the 'HERB-SE' – Highly Economical Rotating Base (Second Edition) – employed to test real-time single station-based position, accelerometer & combined output streams. Through the use of this platform, the reliability (amplitude and period accuracy) and noise characteristics of the currently available (and, possibly, developmental) RT-GNSS streams are evaluated. Furthermore, a strong-motion accelerometer (SMA) may be located beneath (and co-axial to) the GNSS antenna and operated simultaneously. RT-GNSS position streams and RT-SMA observations may be combined in real-time; and both streams are independently recorded producing data sets employed to further optimise algorithms and parameters used to process and/or fuse GNSS and SMA data streams. This presentation will review the testing platform, RT-GNSS processing results and the ensemble seismo-geodetic observations.

Developing Real-Time Strainmeter Data to Supplement GNSS and Seismically Determined Rapid Earthquake Magnitude Estimates

GOTTLIEB, M. H., UNAVCO, Oregon, USA, gottlieb@unavco.org; HODGKINSON, K., UNAVCO, Colorado, USA, hodgkinson@unavco.org; MENCIN, D., UNAVCO, Colorado, USA, mencin@unavco.org; VAN BOSKIRK, L., UNAVCO, Oregon, USA, boskirk@unavco.org; MATTIOLI, G., UNAVCO, Colorado, USA, mattioli@unavco.org; JOHNSON, W., UNAVCO, Colorado, USA, johnson@unavco.org; PYATT, C., UNAVCO, Colorado, USA, pyatt@unavco.org

Under the most recent GAGE (Geodetic Facility for the Advancement of GEoscience) cooperative agreement with the NSF, UNAVCO was funded for another five years of operations of the borehole strainmeter (BSM) network originally built as part of the EarthScope Plate Boundary Observatory (PBO). This network, installed between 2005 and 2008, consists of 75 borehole strainmeters and 80 borehole seismometers along the Western US and into British Columbia. Additionally, 19 of these boreholes are co-located with GNSS monuments streaming real-time 1-Hz data. Borehole strainmeters are designed to detect variations in the strain field at the nanostrain level and can easily detect transient strains caused by aseismic creep events, episodic tremor and slip events, and record dynamic strains generated by seismic events. Operating for ~14 years, the GAGE strainmeter network provides a long-term, continuous, 1-sps record of deformation.

Recent work has shown that peak values in dynamic strains recorded by PBO strainmeters scale linearly with earthquake distance and magnitude (Barbour and Crowell, 2017). Unlike GNSS, where processing is required to generate displacements, the strains are measured directly, hence potentially reducing the complexity and latency of the observations. Also, the increased sensitivity of strainmeters, when compared to real-time GNSS-estimated displacements, suggests that real-time strain observations could provide constraints on earthquake magnitudes for events <M7.

Efforts have recently begun to upgrade our strainmeter dataflow from hourly downloads to real-time streaming. This effort will be made possible by leveraging the real-time infrastructure already in place for the NOTA (Network Of The Americas) GNSS network.

This presentation will summarize the current operational status of the GAGE strainmeter network, progress made in developing the real-time data flow, and a real-time data re-distribution mechanism.

Ionoseis: A Package to Model Coseismic Ionospheric Disturbances

MIKESELL, T. D., Boise State University, Idaho, USA, dylanmikesell@boisestate.edu; ROLLAND, L., Géoazur, Université de Nice Sophia-Antipolis, UMR CNRS 7329, Observatoire de la Côte d'Azur, Sophia Antipolis, France, lrolland@geoazur.unice.fr

Over the past few years we have been developing the software package IonoSeis to model coseismic ionospheric disturbances (CIDs) systematically registered with GNSS receivers after shallow earthquakes of magnitude 6.7 and more. IonoSeis combines multiple existing pieces of code into a single package with additional modules. Our integrated approach allows rapid reconstruction of the initial acoustic phase of coseismic total electron content (TEC) perturbations. The code is written in Fortran and uses NetCDF input and output grid files and SAC time-series outputs. The ionosphere background model is derived from the International Reference Ionosphere package IRI2016, and the atmospheric model is derived from the empirical, global reference atmospheric model NRLMSISE-00. Using these two inputs, acoustic-ray tracing is performed in the atmosphere to determine arrival times and geometries of acoustic waves at ionospheric altitudes. The ray tracing is performed using the code WASP3D (Dessa *et al.*, 2005), which operates in a spherical coordinate system, and was previously used for infrasound modeling in a heterogeneous atmosphere. The ray tracing can account for non-stationary atmospheric models and we have integrated the Horizontal Wind Model (HWM) from Drob *et al.* (2015). Amplitude effects of the propagation are approximated (*e.g.* viscous attenuation); however, we are able to accurately reconstruct not only arrival times, but also perturbation amplitude and phase. The code supports line-of-sight integration with non-stationary satellites and produces both background ionosphere and perturbation TEC time series. We demonstrate the capabilities of this new package and show how it is currently being utilized for ionospheric studies of earthquakes and tsunamis. Because this modeling is based on ray-tracing, it is fast; we plan to eventually use this package for near-real time modeling and tsunami early warning. During this presentation we will discuss the existing obstacles that currently preclude this type of rapid application.

Enhancing the Network of the Americas (NOTA) GNSS Network for Early Warning Applications

AUSTIN, K., UNAVCO, Washington, USA, austin@unavco.org; FEAUX, K., UNAVCO, Colorado, USA, kfeaux@unavco.org; HODGKINSON, K., UNAVCO, New Mexico, USA, hodgkin@unavco.org; MANN, D., UNAVCO, California, USA, mann@unavco.org; MATTIOLI, G., UNAVCO, Colorado, USA, mattioli@unavco.org; PYATT, C., UNAVCO, Oregon, USA, pyatt@unavco.org; TURNER, R., UNAVCO, California, USA, turner@unavco.org; WALLS, C., UNAVCO, California, USA, walls@unavco.org; WOOLACE, A., UNAVCO, California, USA, woolace@unavco.org

The GNSS Network of the Americas (NOTA) includes 1100 Plate Boundary Observatory (PBO) sites in the US, 132 COCONet sites in the Caribbean and 40 TLALOCNet sites across Mexico. The NOTA GNSS Network component along the West Coast, funded by the NSF and operated by UNAVCO, is comprised of 754 permanent GPS and GNSS stations spanning three principal tectonic regimes. While NOTA was originally designed for tectonic and volcanic analysis using 24-hr daily files, it has proven to be of significant value to stakeholders who use real-time data streams for early warning systems. 639 of NOTA stations in California, Oregon, and Washington are currently streaming data in real-time, the majority of stations located along plate boundaries of the Cascadia subduction zone and the San Andreas Fault system. 1 Hz real-time data are available from UNAVCO in BINEX and RTCM3 formats along with PPP position estimates generated for each site and broadcast in the NMEA format. We present an update on our activities of integrating NOTA GNSS stations into the ShakeAlert Earthquake Early Warning System that is being developed for California, Oregon, and Washington. Robust GPS/GNSS real-time streams are essential for any type of GNSS-supported early warning application. For Earthquake Early Warning, high data completeness are needed to estimate peak ground displacement, location, including depth, and magnitude of an event, whereas low data latencies facilitate a rapid warning for a larger area. UNAVCO is working with the USGS and other partners to collocate seismic instruments with 54 NOTA stations. In addition another 83 stations west of the I-5 corridor are proposed to be upgraded to full GNSS during FY19/20. Providing complete, low-latency real-time streams from the site to the processing center hinges critically on operational equipment and reliable telemetry. In order to maintain this we rely on a comprehensive state-of-health monitoring system that allows us to optimize station maintenance activities and equipment upgrades, prevent data loss and telemetry outages, and optimize quality.

Metrics for Evaluating GNSS Real-Time High(er)-Rate Performance

DITTMANN, T., UNAVCO, Colorado, USA, dittmann@unavco.org; HODGKINSON, K., UNAVCO, Colorado, USA, hodgkinson@unavco.org; MENCIN, D., UNAVCO, Colorado, USA, mencin@unavco.org

The Network of the Americas (NOTA) continuously operating Global Navigation Satellite System (GNSS) network is a federated network of the NSF funded EarthScope Plate Boundary Observatory, COCONet, and NSF/UNAM TLALOCNET. When built, these foundational networks recorded 15-30s data in 24-hour files for the primary purpose of a daily point position. Data quality was primarily evaluated in the pre-processed data using metrics developed in the 1990's based on 15-30s interval data.

Advances in GNSS technology as well as data processing now provide position solutions with cm-level precision at high-rate (≥1sps) and low latency (<1s). NOTA currently has ~850 GNSS stations streaming 1sps to the UNAVCO operations center in Boulder, CO. Applications of the streamed 1sps data include large magnitude earthquake and tsunami detection (scientific), characterization, and early-warning (hazards), cadastral surveying (governmental) and virtual reference networks (commercial). All of the applications depend on high-level operational and observational quality performance. It is imperative that network operators monitor these higher-rate real-time streams with appropriate performance metrics. Additionally, it is critical that data users understand the performance of any given station when designing their experiments or operationalized infrastructure.

In this presentation we investigate both the observational and operational pre-processed quality control metrics that influence station performance in this higher sample rates. Observational metrics are a measure of the receiver and antenna hardware performance within the station's observational environment. Evidence suggests that some pre-processing metrics vary depending on sample rate for a given station. Operational quality control metrics capture station telemetry and network operations center performance, agnostic of receiver or antenna performance. Evidence suggests that current metrics, such as completeness, might not fully capture critical aspects of station real-time performance.

Advances in Tectonic Geodesy

Poster Session · Thursday · 25 April · Grand Ballroom

Postseismic Deformation Following the 2013 Mw 6.6 Lushan Earthquake, China From Continuous GPS Data

WANG, Q., Institute of Geology, China Earthquake Administration, Beijing, China, qixin0321@163.com; XU, X., Key Laboratory of Active Tectonics and Volcanos, Institute of Geology, China Earthquake Administration, Beijing, China, xiweixu@vip.sina.com; JIANG, Z., Key Laboratory of Earthquake Prediction, Institute of Earthquake Science, China Earthquake Administration, Beijing, China, jiangzaisen@126.com

The rheological structure of the crust and upper mantle has an important influence on the mechanical modeling of solid Earth deformation, which includes the deformation models of the Tibetan Plateau, China. As the easternmost boundary of the plateau, the Longmenshan Faults Zone (LFZ) may be different in crustal structure and mechanical properties compared to the region within the plateau. In recent years, with the postseismic deformation following the 2008 M_W 7.9 Wenchuan earthquake, many studies have been carried out to better understand the rheological nature of the lithosphere beneath the mid-northern segment of the LFZ [*e.g.*, Huang *et al.*, 2014]. However, many differences exist between the mid-northern and southern segment of LFZ, such as faults activities, magnitude of large earthquakes [*e.g.*, Xu *et al.*, 2009, 2013]. The occurrences of 2013 M_W 6.6 Lushan earthquakes give us an opportunity to study the rheological properties of southern segment of LFZ. After the wenchuan earthquake, a temporary continuous GPS network consisting of 7 stations was installed in and around the southern segment of the LTB. This GPS network recorded the postseismic influence of the 2008 Wenchuan earthquake on the southern segment of the LTB and the preseismic, coseismic and postseismic deformations resulting from the 2013 Lushan earthquake. We first extracted the postseismic deformation following the Lushan earthquake with exponential fit model. Then, theoretical value of postseismic deformation is estimated with half space dislocation model. Viscosities of the mid-lower crust and the lower velocity zone are inverted by comparing the observed and theoretical postseismic deformation of the Lushan earthquake. The result shows that rheological properties of different segments are not the main reason that result in differences between the Wenchuan and Lushan earthquake. A greater number of structures may contribute to weaker fault activity in the southern segment, and thus, weaker fault activity produced the difference in magnitude between the Wenchuan and Lushan earthquakes.

A Sensitivity Analysis of Seafloor Pressure Sensors for the Detection of Offshore Slow Slip Earthquakes in the Cascadia Subduction Zone

FREDRICKSON, E. K., University of Washington, Washington, USA, erikfred@uw.edu; WILCOCK, W. S. D., University of Washington, Washington, USA, wilcock@uw.edu; SCHMIDT, D. A., University of Washington, Washington, USA, dasc@uw.edu; MACCREADY, P., University of Washington, Washington, USA, pmacc@uw.edu; ROLAND, E., University of Washington, Washington, USA, eroland@uw.edu; ZUMBERGE, M. A., Scripps Institution of Oceanography, California, USA, mzumberge@ucsd.edu; SASAGAWA, G., Scripps Institution of Oceanography, California, USA, gsasagawa@ucsd.edu; KURAPOV, A. L., Oregon State University, Oregon, USA, alexander.kurapov@noaa.gov

Seafloor pressure measurements have been used to detect slow slip earthquakes (SSEs) in the updip portions of several subduction zones, typically by differencing pressure records to eliminate oceanographic signals assumed to be regionally correlated. We evaluate this assumption and explore how to optimize sensor geometry to minimize oceanographic noise and detect SSEs. Our analysis focuses on the Cascadia Subduction Zone, where bottom pressure data were collected as part of the 2011-2015 Cascadia Initiative seismic experiment, but where sensor geometry was not optimized for SSE detection. We find oceanographic bottom pressure to be strongly depth dependent with tidally filtered, detrended RMS amplitudes of >6 cm of water on the continental shelf and <2 cm on the abyssal plane. This compares to an observed 1-6 cm peak vertical displacement from offshore SSEs in other settings. Differencing pressure records can yield <1 cm RMS when depths are matched, at separations <100 km on the shelf and slope and as large as 300 km on the plane. We directly compare these data to hindcast seafloor pressure from regional oceanographic circulation models and find that differencing results are consistent between observation and model. We also calculate seafloor displacements from a half-space fault model for a range of SSE scenarios, merging these with hindcast pressure time series to simulate observational records. These synthetics show that constant-depth sensor lines can reliably detect deformation at least as low as 1.5 cm. We find that a Mw 6.3 SSE, such as detected elsewhere, would require a decadal scale observational effort to reliably detect given the local convergence rate and likely recurrence intervals. Our results suggest that future experiments should deploy sensors along lines of constant depth to maximize detectability. However, this approach needs to be evaluated in observed and hindcast pressure records from other subduction zones to determine whether it is widely applicable, as circulation patterns vary between regions.

Tsunami Generation From Coseismic Deformation During the 2018 Mw 7.5 Palu Earthquake

WILLIAMSON, A. L., University of Oregon, Oregon, USA, awillia5@uoregon.edu; MELGAR, D., University of Oregon, Oregon, USA, dmelgarm@uoregon.edu; XU, X., Scripps Institution of Oceanography, California, USA, xix016@ucsd.edu; MILLINER, C. W. D., Jet Propulsion Laboratory, California Institute of Technology, California, USA, christopher.milliner@jpl.nasa.gov

The 28 September 2018 Palu, Indonesia earthquake was an intraplate, strike-slip dominant rupture that triggered a large local tsunami. Data from Palu Bay's sole tide gauge show a large initial negative wave five minutes after the earthquake followed by a crest with an amplitude of about 1.5 m. This peak amplitude is larger than what would be expected from a strike-slip earthquake. Furthermore, reflections of the tsunami persisted within the bay for multiple hours after the rupture causing devastating damage to coastal cities, including Palu and Dongala. Because of the mechanism of the earthquake, it is not currently clear if the tsunami is directly caused from slip on one or more fault planes or if there is also an indirect generating component, possibly from landsliding. To further complicate the event, it is unclear how the earthquake's fault, which may be an auxiliary fault to the main Palu-Koro fault system, interacts as it enters the bay. In an attempt to best reconcile the tsunami's tide gauge signal to the earthquake, we build multiple fault geometries guided from optical imagery. We invert line-of-sight deformation data derived from the ALOS-2 satellite to build a source model. Then we compute the expected tsunami from our source inversion and compare it with the tide gauge recording. We show the variability in tsunami output and as well as how the geometry of the bay may affect the temporal longevity of tsunami waves along the coast.

What Happens When 250 Years of Rapid Ice Loss Induces One of the World's Fastest Crustal Uplift Rates Directly Above One of Its Fastest-Slipping Faults? Cryosphere-Solid Earth Interactions in the Glacier Bay Region, Southeast Alaska

ROLLINS, C., Michigan State University, Michigan, USA, john.c.rollins@gmail.com; FREYMUELLER, J. T., Michigan State University, Michigan, USA, freymuel@msu.edu; HU, Y., University of Science and Technology of China, Hefei, China, yanhu11@ustc.edu.cn; SAUBER-ROSENBERG, J., NASA Goddard Space Flight Center, Maryland, USA, jeanne.m.sauber-rosenberg@nasa.gov; DAVIS, J., Lamont-Doherty Earth Observatory, New York, USA, jdavis@ldeo.columbia.edu

The Glacier Bay region provides a unique opportunity to study cryosphere-solid earth interactions along a major strike-slip plate boundary. Since ~1770 AD, this region has lost >3000 km^3 of ice, with ice thinning by >1 km in some places. The viscoelastic response to the integrated ice loss and the elastic response to present-day melting are together driving some of the fastest geodetic uplift rates on Earth today (>3 cm/yr). Through this fast-deforming region runs the right-lateral

Fairweather Fault, which accommodates ~45 mm/yr of relative Pacific-North American plate motion and ruptured in multiple M>7.5 earthquakes in the 20th century. Using detailed ice models and a Maxwell viscoelastic structure [Hu *et al.*, submitted] that together produce the best available fit to present-day GPS uplift rates, we find that the post-1770 ice loss and viscoelastic rebound likely imparted ~0.5-MPa shear and normal stress changes to the nearby Fairweather Fault, mostly in the 20th century. The location of maximum Coulomb stress increase coincides nearly exactly with the epicenter of the 1958 Mw~7.9 Fairweather Fault earthquake, the largest recent event in this region. The earthquake then propagated along (and only along) a section of fault that we find had been unclamped, with the highest slip directly underlying the Yakutat Icefield [Doser, 2010] and possibly enhanced by heavy post-1770 unclamping there. We find in 1D and full forward models that incorporating a transient rheology would have little effect on geodetic uplift rates or stress changes. We also bring in constraints from postseismic deformation following the 2013 Mw=7.5 Craig earthquake, which we find is well fit by lower crustal afterslip plus viscoelastic relaxation in the mantle. We are also using GRACE data to better constrain the ongoing elastic-viscoelastic mass changes, accounting for concomitant changes in sea level that result from these processes' effect on the geoid and vice versa, and linking these processes more quantitatively to seismicity using moment balance considerations and seasonal fluctuations.

A Remote Sensing Study of the December 2017 Hojedk (Iran) Earthquake Triplet: Sequential Rupture of Conjugate Reverse Faults in a Strike-Slip Restraining Bend

SAVIDGE, E., University of Victoria, Victoria, Canada, elena.savidge@hotmail.com; NISSEN, E., University of Victoria, Victoria, Canada, enissen@uvic.ca

A triplet of Mw ~6 earthquakes on December 1-12 2017 occurred ~50 km N of the large city of Kerman in eastern Iran. The epicenters are clustered withing a major restraining bend between the Nayband-Gowk, Lakar Kuh, and Kuh Banan fault systems, which accommodate N-directed right-lateral shear between central and eastern Iran. Here we assess the source parameters of these three events using Sentinel-1 InSAR observations and modelling, couple with pixel tracking of Planet Labs satellite photographs. All three earthquakes ruptured reverse faults probably associated with the southern termination of the Lakar Kuh right-lateral strike-slip fault. The first two large events on December 1 and December 12 (08:43 UTC) likely ruptured and reruptured a previously unrecognized, blind, NE-dipping fault beneath the Mian Kuh range. The third earthquake on December 12 (21:41 UTC) ruptured a conjugate SW-dipping thrust fault in the hanging wall of the first fault, producing a clear surface rupture in alluvial fans north of the Mian Kuh range, consistent with unusually shallow peak slip at ~0-2 km. Its high ratio of surface slip (up to ~2 m) to length (~7 km) and its narrow down-dip width implies a very high stress drop. The surface rupture aligns with a larger scarp that contains uplifted and incised fan surfaces in its hanging wall. However, this faint geomorphic expression of active faulting had not been recognized prior to these earthquakes, despite detailed structural and geomorphological studies in this area. This has wider implications for seismic hazard in mountainous parts of Iran and in restraining bends globally.

Deploying a Subsea Network to Monitor Continental Drift

PELLETIER, H., iXblue, Saint-Germain-En-Laye, France, hubert.pelletier@ixblue.com; DE TOLDI, E., iXblue, Saint-Germain-En-Laye, France, elliot.de-toldi@ixblue.com; GUATTARI, F., iXblue, Saint-Germain-En-Laye, France, frederic.guattari@ixblue.com

Direct observation of geological phenomenon such as subsea continental drift, or the movement of Earth's tectonic plates, calls for very specific instrumentation.

Indeed, because crustal deformation represents only about a few tens millimeters per year, the use of highly reliable instrumentation over an extended period of time is necessary.

iXblue new Canopus transponder offers the perfect solution to do just that. Enabling accurate inter-beacon communication for highly reliable distance measurements, it embeds multiple sensors, provides up to 4 years of battery life and offers recording capabilities of 32Go. In addition the robust acoustic communication link allows distant monitoring and data recovery every time it is necessary. Canopus is thus particularly suited for such challenging geosciences applications.

The IUEM, European Institute for Marine Studies, has thus chosen Canopus for its FOCUS geodetic project. We will present the project and the use of the Canopus transponders by the IUEM.

Science, Hazards and Planning in Subduction Zone Regions

Poster Session · Thursday · 25 April · Grand Ballroom

Update on a Working Group on Tsunami Sources for Hazards Mitigation in the United States

ROSS, S. L., U.S. Geological Survey, California, USA, sross@usgs.gov; EBLE, M. C., National Oceanic and Atmospheric Administration, Washington, USA, marie.c.eble@noaa.gov; KYRIAKOPOULOS, C., University of California, Riverside, California, USA, christos@ucr.edu; LYNETT, P. J., University of Southern California, California, USA, plynett@usc.edu; NICOLSKY, D. J., University of Alaska Fairbanks, Alaska, USA, djnicolsky@alaska.edu; RYAN, K. J., Air Force Research Laboratory, New Mexico, USA, kenneth.ryan@us.af.mil; THIO, H., AECOM, California, USA, hong.kie.thio@aecom.com; WILSON, R., California Geological Survey, California, USA, rick.wilson@conservation.ca.gov

The need for a set of realistic and consistent tsunami source models was identified as a high priority for tsunami hazard mitigation at a 2016 workshop between U.S. Geological Survey (USGS) scientists and the National Tsunami Hazards Mitigation Program (NTHMP). The NTHMP, a federal/state partnership group funded by the National Oceanic and Atmospheric Administration (NOAA), is composed of representatives (emergency managers and scientists) from the tsunami-vulnerable U.S. states and territories, plus representatives from NOAA, the USGS, and the Federal Emergency Management Agency (FEMA).

Members of the NTHMP's Mapping and Modeling Subcommittee and other researchers have formed a working group, supported by the USGS Powell Center, to produce a collection of vetted earthquake and landslide tsunami sources. The work of this group will transfer decades of research on subduction zone earthquakes and coastal landslides, along with expertise on tsunami modeling, to the mitigation community. Using a logic tree process, and including regional experts, the working group will synthesize existing geological and geophysical knowledge of submarine earthquake faults and coastal landslide sources to produce a database of source models for use in creating hazards assessments for risk reduction. It will also address the scientific question of how increasing sophistication in tsunami source models impacts products such as evacuation plans, mitigation of damage, and land-use planning.

We will report on the first two Powell Center-supported workshops on tsunami sources. The first was held April 9-13, 2018, and adopted a probabilistic process, where possible. The second, focused on Alaska tsunami sources, was held October 1-5, 2018.

Variation of Young Oceanic Intraplate Energy Released With Lithosphere Age. Testing the East Pacific Rise and Its Converging to the Subduction Rivera Zone

PINZÓN, N., Universidad Nacional de Colombia, Bogota, Colombia, nipinzonma@unal.edu.co; VARGAS, C. A., Universidad Nacional de Colombia, Bogota, Colombia, cavargasj@unal.edu.co.

We have estimated empirical relationships that associate the age of Pacific oceanic lithosphere with the seismic energy that is released on both flanks of the East Pacific Rise(EPR). The equations found were tested by comparing other empirical formulas based on lithospheric age, heat flow, and bathymetric depth published by previous works. The results of this study are consistent with the seafloor age ranging between 1 and 7 Ma throughout three perpendicular cross-sections. These three cross sections are located between the diverging plate boundary of the northern Pacific Ocean up to the subduction zone of western Mexico. The results allow inferring the mechanical boundary depth of mid-oceanic ridges and the subduction zones.

The distribution of seismic energy released within the limits of the Rivera and Pacific plates shows a gradual decrease from the ridge axis to the oceanic trench. However, an increase of seismic activity is recorded near the Mesoamerican Trench, where the Rivera Plate subducts under the North American Plate with an angle of ~46°. This anomaly is a consequence of the collision and deepening of the oceanic plate. Due to the homogeneity of this plate, it is possible to infer the projection of the isochrones in the subduction zone. Although the deepening of the mechanical boundary layer may be estimated from the square root function of the seismic energy, this brittle-ductile transition in the subduction zone deepens exponentially concerning recorded energy.

Aftershock Sequence Analysis of the Mw 6.5 December 15, 2017 and the Mw 5.9 January 23, 2018 Java Earthquakes

SIRAIT, A. M. M., Lehigh University, Pennsylvania, USA, amm616@lehigh.edu; MELTZER, A. S., Lehigh University, Pennsylvania, USA, asm3@lehigh.edu; WALDHAUSER, F., Lamont-Doherty Earth Observatory, New York, USA, felixw@ldeo.columbia.edu; STACHNICK, J., Lehigh University, Pennsylvania, USA, jcstachnik@gmail.com; DARYONO, D., Meteorology, Climatology and Geophysics Agency, Jakarta, Indonesia, daryono@bmkg.go.id; FATCHUROCHMAN, I., Meteorology, Climatology and Geophysics Agency, Jakarta, Indonesia, iman.fatchurochman@bmkg.go.id; SEMBIRING, A. S., Meteorology, Climatology and Geophysics Agency, Jakarta, Indonesia, andry.syaly@bmkg.go.id; JATNIKA, J., Meteorology, Climatology and Geophysics Agency, Jakarta, Indonesia, jajat.jatnika@bmkg.go.id

The west part of Java sits at the transition from oblique subduction along Sumatra to orthogonal convergence along central and eastern Java. This region has experienced several destructive earthquakes, the Mw 7.7 July 17, 2006 earthquake and tsunami off the coast of Pangandaran and the Mw 7 September 2, 2009 earthquake, located off the coast of Tasikmalaya. Both earthquakes were widely felt in Java. On December 15, 2017, the Mw 6.5 earthquake located off the coast near Pangandaran, and on January 23, 2018, the Mw 5.9 earthquake located offshore Lebak, between Pelabuhan Ratu and Ujung Kulon. The December event is located at 115 km, deeper than the January event (46 km). Ground shaking and damage occurred locally and in Jakarta on the northern coast of Java. Both earthquakes have NE-SW orientated strike-slip mechanisms. In this study, we use the HYPODD method to relocate both mainshocks and 10 months of seismicity (228 events) following the earthquakes. The relocation result improved the mainshock locations and depth distribution of seismic events. The December event is still deep (100.4 km) and its aftershocks locate up-dip at depths 50 – 80 km depths along the plate interface or the shallow part of the subducting slab. The January event is on the plate interface at 48.5 km depth and its aftershocks are in the overlying plate between 15 and 40 km depth. We observe a shallowing upward trend in the first 24 hours after the mainshock, suggesting that fluid migration might be involved. Seven months after this event, shallow (~10 km depth), NE-SW trending seismic activity is observed close to the coast.

Preparing Communities in Western Nepal for Their Next Major Earthquake, Using Scenarios and Action Plans

ACHARYA, A., GeoHazards International, California, USA, acharya@geohaz.org; BHATTA, L., GeoHazards International, California, USA, bhatta@geohaz.org; CLAHAN, K., Lettis Consultants International, California, USA, clahan@lettisci.com; JOMO, J., GeoHazards International, California, USA, jomo@geohaz.org; JOSHI, D., GeoHazards International, California, USA, joshi@geohaz.org; KHAN, M., GeoHazards Society, Delhi, India, relations.geohaz@gmail.com; KUMAR, H., GeoHazards Society, Delhi, India, hari@geohaz.org; LIZUNDIA, B., Rutherford + Chekene, California, USA, blizundia@ruthchek.com; OJHA, U., GeoHazards International, Kathmandu, Nepal, upama@geohaz.org; RODGERS, J., GeoHazards International, California, USA, rodgers@geohaz.org; SETHI, P., GeoHazards Society, Delhi, India, hari@geohaz.org; STENNER, H., GeoHazards International, California, USA, stenner@geohaz.org; TLAU, L., GeoHazards International, Aizawl, India, rinpuii@geohaz.org; WALD, D. J., U.S. Geological Survey, Colorado, USA, wald@usgs.gov

The portion of the Main Himalayan Thrust System in western Nepal last experienced a major earthquake in 1505 AD. Communities there must prepare for a repeat of a comparable earthquake. To motivate and assist local officials to reduce the impacts of such an event, we developed earthquake scenarios for three districts in western Nepal based on scientifically derived consequences of a hypothetical, future earthquake. Our story-based narratives follow fictional characters and paint a picture of the disaster easily imagined by local, lay audiences. Appendices contain more detail and technical documentation. We offer recommendations so that local stakeholders can take steps now to reduce suffering in future earthquakes.

Our scenarios for the Dadeldhura, Rukum West, and Bajhang districts depict the consequences of a M7.8 event with peak ground accelerations up to 0.8g. Depending on the district, 3,000-4,000 people die, and 7,000-10,000 are seriously injured. We calculated that 50-67% of buildings collapse. In the dry season 700-6,000 landslides occur, with twice as many during the monsoon, blocking roads and isolating people from markets, medical services, and schools. The many who live far from municipal centers are particularly isolated, as trail bridges across rivers may take up to a year to repair. Impacts throughout the districts and in municipalities affect schools, health facilities, roads, and utilities.

Using scenario insights, we helped government leaders draft action plans focused on measures that provide the greatest, quickly realized benefits. Examples include strengthening municipal water tanks and communication towers, enforcing building and land-use codes, training local engineers and builders in seismic design and construction, stockpiling critical supplies, practicing emergency communications, and preparing schoolchildren. For each action, there is a local responsible party. Officials welcomed this approach, particularly in the rapidly growing municipalities of Amargadhi and Musikot.

MARACAS ANR Project Presentation: Marine Terraces Along the Northern Andean Coast as a Proxy for Seismic Hazard Assessment

SAILLARD, M., Géoazur, Institut de Recherche pour le Développement, Valbonne, France, saillard@geoazur.unice.fr; REGNIER, M., Géoazur, Institut de Recherche pour le Développement, Valbonne, France, regnier@geoazur.unice.fr; CISNEROS, A. L., Géoazur, Université Côte d'Azur, Valbonne, France, andrea.cisneros.medina@gmail.com; MICHAUD, F., Géoazur, Sorbonne Université, Paris, France, michaud@geoazur.unice.fr; VACA, S., Instituto Geofisico, Escuela Politecnica Nacional, Quito, Ecuador, svaca@igepn.edu.ec; PROUST, J., Géoazur, Institut de Recherche pour le Développement, Quito, Ecuador, jean-noel.proust@univ-rennes1.fr; CHLIEH, M., ISTerre, Institut de Recherche pour le Développement, Grenoble, France, mohamed.chlieh@ird.fr; HASSANI, R., Géoazur, Université Côte d'Azur, Valbonne, France, riad.hassani@geoazur.unice.fr; BRAUCHER, R., CEREGE, CNRS, Aix-en-Provence, France, braucher@cerege.fr; ESPURT, N., CEREGE, Aix-Marseille Université, Aix-en-Provence, France, espurt@cerege.fr; FONT, Y., Géoazur, Institut de Recherche pour le Développement, Valbonne, France, font@geoazur.unice.fr; HERNANDEZ-SALAZAR, M., Géoazur, Escuela Politecnica Nacional, Valbonne, France, maria.hernandez@geoazur.unice.fr; ALVARADO, A., Instituto Geofisico, Escuela Politecnica Nacional, Quito, France, aalvarado@igepn.edu.ec; BENAVENTE ESCOBAR, C. L., INGEMMET, Lima, France, cbenavente@ingemmet.gob.pe; MARTILLO BUSTAMANTE, C. E., ESPOL, Guayaquil, Ecuador, cmartill@espol.edu.ec; SEGOVIA, M., Instituto Geofisico, Escuela Politecnica Nacional, Quito, Ecuador, msegovia@igepn.edu.ec; PONCE, G., Instituto Geofisico, Escuela Politecnica Nacional, Quito, Ecuador, gponce@igepn.edu.ec; NICOLAS-CABANE, C., Géoazur, Valbonne, France, nicolasc@geoazur.unice.fr

In subduction zones, the sum of the cyclic deformation over many seismic cycles account for the long-term cumulated deformation of the forearc in the upper plate. Along the Andean coast, many studies have suggested a correlation between seismic segmentation of the megathrust and a morpho-tectonic segmentation of the forearc. Large megathrust earthquakes tend to occur on highly coupled patches on the seismogenic zone right below forearc basins. These basins are framed in between coastal peninsulas, identified as seismic barriers that stop seismic ruptures. Long-term vertical coastal movements appear in peninsula areas where the slip along the plate interface is mostly achieved by creeping. This indicates that surface expression of deformations in the long-term might be linked to the seismic regime on the megathrust whose along-strike variation seems stable through times. We wonder if we could resolve the inverse problem: could we use upper plate deformation and active structures characterization for assessing safely the margin segmentation, rupture lengths and seismic hazard? Hence the MARACAS project newly funded by the French National Research Agency proposes to develop an interesting improvement to assess seismic hazard in subduction zone that would take into account the survey of the long-term deformation of the upper plate to better identify multicycles margin segmentation. Here, we propose to introduce the MARACAS project objectives, scientific question, impacts and outreach activities. We aim 1) to identify the conditions of vertical crustal motions along the plate boundary; 2) to evaluate the lateral impact of seismic ruptures on forearc deformation in weakly coupled segments below peninsulas; and 3) to determine whether the correlation between the seismic segmentation and the morpho-tectonic segmentation is fortuitous or long-lasting.

Neotectonic of the Cipreses Fault: An Active Thrust Fault in the Metropolitan Area of San Jose, Costa Rica

RODRÍGUEZ, E., Universidad de Costa Rica, San José, Costa Rica, evelynroc15@gmail.com; LINKIMER, L., Universidad de Costa Rica, San José, Costa Rica, linkimerl@gmail.com; MONTERO, W., Universidad de Costa Rica, San José, Costa Rica, wmonteropo@gmail.com

The Cipreses fault is located in the central part of Costa Rica, 5 km east of downtown San Jose, in the most populated region of the country. This fault is part of the Central Costa Rican Deformed Belt, a 100 km-wide deformed zone that has been interpreted as the result of the relative movement between the Caribbean Plate and the Panama Microplate produced by the subduction of the Cocos Ridge. In this paper, the Cipreses fault is analyzed based on geomorphological, geological, and seismological observations. The main geomorphological evidences found are: scarps, terraces, river incisions, and deflected and dammed streams. There are three main Pleistocene geologic units in the vicinity of the fault: tuff, breccia, and andesitic lavas. These units have been observed displaced by the fault in an outcrop. From the seismological analysis, we conclude that the instrumental seismicity is low, but at least one earthquake in 2010 (4.1 Mw) was originated in the Cipreses fault. The focal mechanism solution for this event indicates a thrust fault with a nodal plane oriented N30°E/35° in agreement with the fault plane found in the field and the geomorphological observations. Based on a conceptual

model for the faulting, we interpret that the Cipreses fault corresponds to a master fault that propagates to the surface along two fault segments named Pinares and Guayabos. The displacements of these faults made two anticlinal folds, which are expressed at the surface as prominent scarps. Based on the found evidences we conclude that the Cipreses fault is an active thrust fault with a 14-km long surface expression and with a seismic potential of magnitude 5.9-6.5 Mw. The detailed study of active faults in Central Costa Rica may give insights into the understanding of the upper plate deformation related to the subduction of the Cocos Ridge and is also crucial for the appropriate determination of seismic hazards in the densely populated area of San Jose.

The Seismic Strong Motion Array Project (SSMAP) and September 5, 2012 (Mw 7.6) Nicoya, Costa Rica Earthquake Investigation During 2006-18

SIMILA, G., California State University, Northridge, California, USA, gerry.simila@csun.edu; QUINTERO, R., OVSICORI, Universidad Nacional, Heredia, Costa Rica, ronnie.quintero.quintero@una.cr

Seismic gaps along the subduction zones are locations where large earthquakes have not occurred in a long time. These areas are considered locked and are accumulating large amounts of strain energy that will ultimately be released in major earthquake. The Nicoya Peninsula in northwestern Costa Rica was considered a zone with this type of seismic gap. The previous major earthquakes in Nicoya occurred on 1853, 1900 and 1950, which indicates about a 50-year recurrence interval for the characteristic earthquake cycle. With the goals to: 1) record and locate strong subduction zone mainshocks [and foreshocks, "early aftershocks", and preshocks] in Nicoya Peninsula, at the entrance of the Nicoya Gulf, and in the Papagayo Gulf regions of Costa Rica, and 2) record and locate any moderate to strong upper plate earthquakes triggered by a large subduction zone earthquake in the above regions, a seismic strong motion array (SSMAP project) was installed in the Nicoya Peninsula, array composed of 10 sites with Geotech A900 accelerographs. Also, the OVSICORI-UNA network was upgraded with ES-T episensors that could record the large event. On September 5, 2012, a M_w=7.6 earthquake occurred in the seismic gap and appears to be the expected event based on the 50 years recurrence interval, but was instead 62 years later. The main shock focal mechanism was thrust faulting of the Cocos plate in the Middle America trench with strike N54W and dip 20 degrees NE. The mainshock location was 9.671 N and 85.878 W. The maximum accelerations from two A900 stations perpendicular to the trench, Fortuna (distance 112 km) and Pedernal (distance 128 km) were: 13.8% and 8.9 % g; although the main acceleration was recorded at Dulce Nombre de Nicoya 122% g. The October 10 (M_W 5.3) and 24 (M_w 6.6) aftershocks recorded at Tamarindo were accelerations of 2.4% and 8.2% g. We also relocated 60 events from 2006 to 2018 for moderate magnitudes ($4 < M_w < 6.5$), mainly located in Nicoya Peninsula region which are analyzed for spatio-temperal relations.

The Sensitivity of Earthquake Risk to Geodetic Data: A Case Study in Chile

NYST, M., Risk Management Solutions, California, USA, mnyst@rms.com

Traditional probabilistic seismic hazard assessment (PSHA) studies typically primarily rely on seismological and geological data sources and only in some cases also on geodetic data sources. An example of the incorporation of geodetic data is the 2015 Uniform California Earthquake Rupture Forecast, Version 3, or UCERF3. Incorporating geodetic data into a PSHA study is especially important when the deformation signal in these observations is different from that in the earthquake or fault slip data.

Catastrophe modeling companies like Risk Management Solutions (RMS) use the underlying data of hazard maps to develop risk metrics for insured risk management. Commonly used risk metrics are average annual loss (AAL) and exceedance probability (EP) curves. AAL is the product of location loss and annual rate for all events, and is used to set annual premiums, while keeping the long-term risk in mind. The EP curve is also derived from the full set of events that impact an exposure. It plots the probability of exceeding a particular loss level and provides quantification to solvency assessment and portfolio management. Regulatory agencies and sound financial management require that insurance companies have the financial capacity to pay out at a certain return period, oftentimes the portfolio's 250 or 500 year return period loss.

Earthquake hazard in Chile is high. Insurance plays a major role in its earthquake resilience, in insurance terms: earthquake insurance penetration is high. If we look at earthquake risk in terms of earthquake source types, we find that the main risk contributor to Chilean AAL as well as to the country-wide EP curve is the subduction zone. Secondary contributors are crustal faults and the background seismicity. Here we discuss the quantitative impact on the Chilean hazard and risk profile of incorporating geodetic data that monitor the subduction zone.

Secular Deformation in Southern Cascadia: Elastic Modeling as Informed by Geodetic Observation

PATTON, J. R., Humboldt State University, California, USA, jrp2@humboldt.edu; ROLLINS, C., Michigan State University, Michigan, USA, rollin32@msu.edu; MCPHERSON, R. C., Humboldt State University, California, USA, robert.mcpherson@humboldt.edu; HEMPHILL-HALEY, M., Humboldt State University, California, USA, mark.hemphill-haley@humboldt.edu; WILLIAMS, T. B., Cascadia GeoSciences, California, USA, todd.brian.williams@gmail.com; LEROY, T. H., Pacific Watershed Associates, California, USA, toml@pacificwatershed.com

Northwestern California is sheared over time by deformation along the Cascadia megathrust, the northern San Andreas fault, and subsidiary faults. We use geodetic data and modeling to shed light on the earthquake cycle and seismic hazard in this region. We synthesize tide gage, benchmark survey, and GPS data to document 20th-21st century rates of vertical land motion. These rates (corrected for glacial isostatic adjustment) range from -5 mm/yr in southern Humboldt Bay to +2 mm/yr near Crescent City. Subsidence in Humboldt Bay is apparent in all three datasets and may suggest downwarping of the surface above a local locked patch on the megathrust, motion on upper-plate faults, or possible anelastic/non-tectonic processes.

We explore these possibilities using the new Slab2.0 Cascadia geometry and inverse methods that combine these uplift rates with horizontal GPS velocities corrected for locking on the San Andreas. We also examine how the earthquake cycle on these faults would affect the local land surface.

Uniform-slip models with the Slab2.0 geometry suggest a Cascadia earthquake rupturing from the trench to 35 km depth (located ~75 km inboard of the coast) would uplift Humboldt Bay by ~15% of the slip amount (*e.g.* ~2 m for 15 m slip), but an earthquake that only ruptured offshore (where existing interseismic models put the highest locking) would instead cause Humboldt Bay to subside by this amount; this is important for coastal infrastructure and tsunami hazard.

We also explore how postseismic viscoelastic relaxation in the mantle wedge and/or below the downgoing slab could modulate these land motions; we find that if this were to mainly occur below the slab, it would contribute modest uplift following the deep-rupture event but could contribute as much as ~200% of the coseismic subsidence following the all-offshore event (*e.g.* 4 m for 15 m of slip, for a total of 6 m). This may inform interpretations of coastal subsidence in past Cascadia earthquakes.

Seismic Velocity Structure and Geologic Controls on Seismicity Surrounding the April 1, 2014 Pisagua, Chile Earthquake

DAVENPORT, K., Oregon State University, Oregon, USA, davenpka@oregonstate.edu; TRÉHU, A., Oregon State University, Oregon, USA, trehu@coas.oregonstate.edu

Correlations between crustal structure, residual gravity anomalies, and seismicity associated with the 2014 Mw 8.2 Pisagua/Iquique earthquake indicate that geologic structure plays a role in controlling subduction-related seismicity off the coast of northern Chile. The 2014 sequence of events ruptured ~200 km of a ~500 km section of the subduction zone where no significant seismicity had occurred since the late 1800s. The remaining unruptured section corresponds to a region of high residual gravity and poses a significant risk for future large earthquakes. To investigate the relationship between the observed seismic behavior and geologic characteristics, the PICTURES project used the R/V Marcus G. Langseth to acquire a 3D controlled-source seismic data set in 2016. The internationally collaborative project included contributions from Oregon State Univ., GEOMAR, the Univ. de Chile, and the Univ. of Liverpool to record ~45000 airgun sources on 70 OBS, 50 land-based stations, and a grid of ~5000 km of seismic reflection data. Seismic P-wave velocity models based on the OBS data reveal along-strike variations in the crustal structure of the forearc that correspond to the slip distribution of the Pisagua earthquake sequence and the high gravity anomaly. The 3D grid of data allows high-resolution seismic imaging of the velocity and reflectivity structure in the region that ruptured in 2014, and the high-resolution ship-board gravity data constrains the gravity anomaly associated with the southern end of rupture propagation. The relationship between geologic structure and seismic activity has implications for seismic behavior in other subduction zones with significant along-strike geologic heterogeneity. The MGL1610 Science Party includes Anne Tréhu, Emilio Vera, Michael Riedel, Kathy Davenport, Florian Petersen, Emma Myers, Carsten Lehman, Felipe Gonzalez Rojas, Sara Alhisni, Jan Handel. Additional collaborators include Andreas Rietbrock, Eduardo Contreras-Reyes, Heidrun Kopp, Diana Comte, Jacob Geersen, Bo Ma, Cristian Rodrigo, and Juan Diaz.

The Redwood Coast Tsunami Work Group: Addressing the Earthquake and Tsunami Threat on California's North Coast

DENGLER, L., Retired, California, USA, lad1@humboldt.edu

North Coast California and the adjacent offshore area is the most seismically active region of the contiguous 48 states and is at risk of tsunamis generated from nearby and elsewhere in the Pacific. 41 earthquakes of M6 or larger have been recorded in instrumental times, and 67 earthquakes have caused damage. 39 tsunamis have been detected since a tide gauge was installed in 1933, including five that caused damage. However, only three of the regionally felt earthquakes produced tsunamis, and all the damaging tsunamis came from the far-field. The relative frequency of strongly-felt earthquakes and the complexity of the tsunami threat has posed challenges in developing consistent, understandable messaging and regional preparedness efforts. It is further complicated by differences in messaging and products from neighboring states at risk of Cascadia earthquakes and the lack of full understanding of how the Gorda region of the Cascadia subduction zone differs from its characteristics in the Juan de Fuca portion. The frequency of both earthquakes and tsunamis and the relative isolation of California's North Coast has led to regional mitigation efforts and strong partnerships between the North Coast and state/federal agencies. The (Redwood Coast Tsunami Work Group (RCTWG) an organization of local, state and federal partners, has become the lead regional organization coordinating hazard mapping with state partners, TsunamiReady community development, sign and siren placement, annual tsunami communication drills, evacuation drills and ShakeOut participation, and development of risk-communication products. Some areas in which the RCTWG approach differs from other parts of Cascadia include more emphasis on the likely shaking impacts, using shaking duration to distinguish potentially tsunamigenic earthquakes from the more frequent ones that don't pose a tsunami threat, and emphasizing that because of source proximity, the first surges could arrive in as little as ten minutes.

Locking Degree for the Chilean Subduction Zone Inferred Through Bayesian Inversion of GPS Observations and Its Mechanical Link to Seismicity

MORENO, M., University of Concepción, Concepcion, Chile, marcosmoreno@udec.cl; BOLTE, J., Hamburg Univerity, Hamburg, Germany, jan.bolte@uni-hamburg.de; SIPPL, C., GFZ German Research Centre for Geosciences, Potsdam, Germany, sippl@gfz-potsdam.de; BEDFORD, J., GFZ German Research Centre for Geosciences, Potsdam, Germany, jbed@gfz-potsdam.de; LI, S., University of Iowa, Iowa, USA, shaoyang-li@uiowa.edu; MELNICK, D., Universidad Austral de Chile, Valdivia, Chile, danmelski@gmail.com; ORTEGA-CULACIATI, F., Universidad de Chile, Santiago, Chile, ortega.francisco@u.uchile.cl; CREMPIEN, J. G. F., Pontificia Universidad Católica de Chile, Santiago, Chile, jocrempiend@ing.puc.cl; TILMANN, F., GFZ German Research Centre for Geosciences, Potsdam, Germany, tilmann@gfz-potsdam.de

Kinematic models suggest that the lateral extents and magnitudes of earthquake ruptures are fundamentally controlled by the spatial distribution of locking degree, which can be used to infer variations of stress build-up along the seismogenic zone. However, estimates of locking degree rely on the wealth of the geodetic data, modeling assumptions and inversion technique, and therefore maps of locking even for same areas that use similar data are very distinct. Here, we build a spherical Finite-Element model of the Chilean Subduction Zone to generate Green Functions of back slip that takes into account the viscoelastic interseismic response. We use a Bayesian method based on the reversible jump algorithm for the inversion of a compilation of more than 500 interseismic GPS velocities along the Chilean margin. We apply this method to solve for the back slip at the plate interface and for the rotation parameters of a continental-scale forearc sliver block. We further investigate the relation between interseismic background seismicity and locking degree at different segments of the Chilean margin, aiming to describe the current stage of stress build-up within the seismic cycle. Seismicity spatial patterns surrounds the deeper regions of the locked patches, indicating a mechanical link between stress build-up and deeper seismogenic zone seismicity. Together, our study robustly characterizes the locking degree along the Chilean seismogenic zone and provides valuable insights for understanding the stress accumulation-and-release processes that lead to great megathrust earthquakes, and allow estimates of the current seismic potential of locked segments.

What Is the Potential for Large Deep Intraslab Earthquakes Beneath Northern California

WONG, I. G., Lettis Consultants International, Inc., California, USA, wong@lettisci.com

The subducting Gorda plate of the southern Cascadia subduction zone (CSZ) extends eastward to the western edge of the Sierra Nevada covering a large portion of northernmost California. If there exists an active Wadati-Benioff (WB) zone, there could be a significant seismic hazard for a large portion of northern California similar to western Washington. The USGS in the National Seismic Hazard Maps models the WB zone (depths > 40 km) uniformly north to south in terms of maximum magnitude (Mmax) but estimates the rates of large events for three regions: western Washington, western Oregon, and northwest California. There are obvious changes in the WB seismicity from north to south and in the physical, thermal, and stress conditions along the Juan de Fuca and Gorda plates (*e.g.*, Wong, 2005; Wada *et al.*, 2010). The USGS assigns Mmax of Mw 7.45 and 8.0 to the WB zone, weighted equally, based on global analogs although the largest known CSZ WB event is the 2001 Mw 6.8 Nisqually earthquake beneath Puget Sound. Despite the observation there are fewer than 20 earthquakes of Mw > 3.0 that have been observed in the Gorda WB zone deeper than 40 km since 1980, the USGS calculates that Mw 7.2 to 7.5 earthquakes have a recurrence interval of 4761 yrs compared to 1563 yrs beneath Puget Sound. The long recurrence intervals for the Gorda WB zone are obviously a significant extrapolation of the 150-year historical record where no WB earthquake larger than Mw 5 has ever been observed at depths > 40 km beneath northern California. In fact, all large earthquakes (Mw > 6) in the Gorda plate have been shallow and occurred much farther to the west generally off the coastline. Three potential issues regarding the USGS modeling of the Gorda WB zone will be addressed: 1) why are there so few deep earthquakes and is there an active internally deforming WB zone; 2) is the Mmax range of Mw 7.45 to 8.0 appropriate; and 3) how best to model the WB zone and address epistemic uncertainties based on the available including a small historical catalog.

Imaging Subduction Zones

Poster Session · Thursday · 25 April · Grand Ballroom

Preliminary Full-Wave Ambient Noise Seismic Tomography Results Along the South American Subduction Margin

LIU, M., University of Massachusetts Amherst, Massachusetts, USA, mengliu@umass.edu; GAO, H., University of Massachusetts Amherst, Massachusetts, USA, haiyinggao@geo.umass.edu

The oceanic Nazca plate subducts beneath the continental South American plate, resulting in arc volcanoes and megathrust earthquakes along the convergent margin. The non-uniform distribution of subduction-related earthquakes reflects possible along-strike slab segmentation. It is therefore desirable for us to investigate what factors contribute to seismic segmentations along the margin. Seismic tomography provides a well-constrained three-dimensional slab geometry both along strike and down dip. In this study we use the finite-difference full-wave simulation and inversion to resolve a high-resolution shear velocity model of the crust and upper mantle within the entire South American subduction system. Our goal is to understand the seismic characteristics of the slab geometry of the South American subduction, and to explore the correlation between the slab geometry, volcanism, and megathrust earthquakes. The vertical components of daily ambient noises between each station pairs are cross-correlated and then stacked in order to extract Rayleigh wave empirical Green's functions. We will calculate Rayleigh wave phase delays between the empirical Green's functions and the synthetics. The seismic velocity model will be progressively improved by iteratively minimizing the phase delay times. The preliminary tomographic results will be presented during the meeting.

Seismic Anisotropy in the Converging Lithospheric System of NW South America

GOMEZ ALBA, S. A., Universidad Nacional de Colombia, Bogota, Colombia, sagomezalb@unal.edu.co; VARGAS JIMENEZ, C., Universidad Nacional de Colombia, Bogota, Colombia, cavargasj@unal.edu.co

We present a 3D Seismic Anisotropic model of the lithospheric system NW South America based on the tomographic inversion of travel time seismic data from regional earthquakes. The dataset was provided by the Colombian Geological Survey (SGC). It combines events recorded by 52 broadband stations in the region. We use a passive source tomography algorithm, which was previously implemented to study crustal and uppermost mantle in other subduction regions of the World. In general terms, the shallowest anisotropy tends to align with the main faulted zones of the crust. As one descends in depth, anisotropy tends to aligned perpendicularly to the west coast of Colombia, indicating the influence of the westward Nazca plate subduction under the South American plate. The evidence was compared with focal mechanisms of events with magnitudes larger than Mw >5.0. The two most significant features of our observations have to do with two significant negative velocity anomalies and the direction of the anisotropy vectors associated to both regions. The first anomaly matches with the location of the Bucaramanga seismic nest and the second one is located close to the known Cauca seismic nest. Negative anomalies are both probably associated with the presence of fluids. In Bucaramanga, our hypothesis aims to the dehydration of the Caribbean plate and its break-off. In the Cauca swarm, we propose that the anomaly is due to the rise of fluids due to the dehydration of the Nazca plate and its melting in the mantle during the subduction process. In both cases, mineral transformation occurs, and the mantle behaves like a fluid. We noticed a radial pattern that velocity vectors tend to form around these two points. This circular spin does not seem to correspond with a particular structural element, but rather the rotation of the fluid mantle inside the Earth. Even more striking, has to do with the vectors rotation, since it occurs in the counter-clockwise direction. Can this last observation be scientific evidence of the Coriolis Effect inside our planet?

Intracontinental Orogenic Crustal Deformation in Transition Zone Between the NE Tibet and the Ordos Basin Revealed by a Dense Short-Period Seismic Array

TIAN, X., Institute of Geology and Geophysics, Chinese Academy of Sciences, Beijing, China, txb@mail.iggcas.ac.cn

The crustal deformation in intracontinental orogen as a far-field response of the collision between the Indian and Eurasian plates is a key problem to understanding the Asian tectonic evolution in Cenozoic. The Liupan Shan mountain, located in the transition zone between the northeastern corner of the Tibetan Plateau and the southwestern of Ordos basin, has been uplifted since Later Miocene. We carried a 170-km-long dense short-period seismic array across the northern Tibetan plateau, the Ordos basin and their boundary (Liupan Shan fault) with station spacing 500 meters. Receiver functions are calculated from the waveform of teleseismic events and used to image the crustal structure. Our results show the Moho increases eastward from 50 km beneath the Longxi Basin to 57 km beneath the Liupan Shan, and then decreases to 48 km beneath the southwest of Ordos basin. The crustal image shows that the upper-crust of the plateau is overthrust on the Ordos, and while the lower-crust of the plateau underthrust beneath the Ordos crust, while the Ordos crust is inserted as a wedge into the plateau crust beneath the Liupan Shan. We propose that this kind deformation style, which is different with that in the Qilian Shan and Longmen Shan, is attributed to a strong crust beneath Longxi Basin unlike other parts of plateau margin with a weak crust.

Preliminary Tomographic Imaging of the Puerto Rico-Virgin Islands Microplate

VANACORE, E. A., University of Puerto Rico, Mayagüez, Puerto Rico, USA, elizabeth.vanacore@upr.edu; VENTURA-VALENTÍN, W. A., University of Puerto Rico, Mayagüez, Puerto Rico, USA, wilnelly.ventura@upr.edu

The Puerto Rico-Virgin Island (PRVI) microplate, situated along the Northeastern Caribbean margin, is a component of the highly complex oblique subduction of the North American plate beneath the Caribbean Plate. The PRVI microplate is bound to North by the Puerto Rico Trench, to the West the Mona Passage, to the South the Muertos Trough (which may also be a subduction structure), and the East by the Anegada Passage. Here we present preliminary P wave tomographic results using local and teleseismic sources from the implementation of the finite marching method code FMTOMO. The preliminary results not only highlight features of the local subduction zone and crustal structure, but also highlight the need for future amphibious arrays in the region to increase imaging resolution. The need for amphibious arrays is of particular interest to image the Muertos Trough and the extensional crustal structures in the Mona Passage which are not well resolvable given the current data availability. In this presentation the preliminary tomographic results and tectonic implications will be discussed as well as the pitfalls and challenges of tomographic imaging in the region such as local 1D model selection and balancing of local seismic sources due to earthquake swarm activity.

Synthetic 2D Elastic Full-Waveform Inversion Study of the Ecuadorian Subduction Zone

GASSNER, L., Karlsruhe Institute of Technology, Karlsruhe, Germany, laura.gassner@kit.edu; THIEL, N., Karlsruhe Institute of Technology, Karlsruhe, Germany, niklas.thiel@kit.edu; RIETBROCK, A., Karlsruhe Institute of Technology, Karlsruhe, Germany, rietbrock@kit.edu

Imagiang the subduction zone interface at depth at a kilometer scale is still a huge challenge. Full waveform inversion (FWI) is widely used in the industry for exploration purposes but seismological applications are still rare. We perform synthetic tests to outline the capability of FWI to image structures in the scale of kilometers from earthquake data in a regional subduction zone setting. We utilize a realistic model of the P- and S-wave velocities (Vp and Vs) from the Ecuadorian subduction zone at 0°N and apply 2D-elastic FWI to synthetically modeled waveform data for vertical and horizontal receivers. Perturbations of the original model within the subducted plate with a size of 2 km x 2 km in vS and 4 km x 4 km in vP can be reconstructed in high quality down to approximately 70 km depth. A main frequency of 1 Hz is sufficient to achieve this resolution. In further tests we study the dependency of the results on the location of the sources and the accuracy of the estimated source orientation. The quality of the resulting models does not suffer if the orientation of the sources is not perfectly known but artifacts near the source positions arise. Results where sources are located within the subducted plate are comparable to when the sources are located underneath however the convergence of the inversion is sped up. We find that the inversion of the Vs model prior to the inversion of the Vp model is necessary to guarantee a good reconstruction of both models.

Finding Focus in the Pn Shadow Zone of the Sierra Nevada with P Coda Migration

BOGOLUB, K. R., University of Colorado Boulder, Colorado, USA, kyren.bogolub@colorado.edu; JONES, C., University of Colorado Boulder, Colorado, USA, cjones@colorado.edu; ROECKER, S., Rensselaer Polytechnic Institute, New York, USA, roecks@rpi.edu

The *Pn* shadow zone in seismic record sections across the Sierra Nevada has been a perplexing feature to interpret. For earthquakes on the west side the range, *Pn* often appears with low apparent velocities (~7.4 km/s) on stations within the mountains followed by high (~8.6 km/s) apparent velocities east of the range. Equally peculiar, for most of the seismic stations in the range, the *Pn* phase has anomalously low amplitude and, in some cases, no discernible Pn arrival at all.

The diminished amplitudes of the *Pn* phases hint at a diffusion or scattering of seismic energy. To explore this possibility, we utilize a full waveform modeling algorithm to perform a migration of the P wave coda from the stations into the medium. Because the P wave coda is formed as a scattered wavefield within the medium, a time-reversed propagation of the scattered wavefield will constructively interfere at the locations of scatterers in the medium. The procedure is similar to the gradient method of full waveform inversion, in the sense that the observed scattered field is treated as a residual field calculated in a simple background model.

We demonstrate details of this P wave coda migration method using synthetic data, as well as some preliminary results for a seismic section in the Sierra.

Local Earthquake Tomography in the Northern Hikurangi Margin (New Zealand) Using a Detailed Offshore and Onshore Microseismicity Catalog

YARCE, J., University of Colorado Boulder, Colorado, USA, jefferson.yarce@colorado.edu; SHEEHAN, A. F., University of Colorado Boulder, Colorado, USA, anne.sheehan@colorado.edu

The northern Hikurangi margin in New Zealand has produced remarkable tectonic events, including tsunami earthquakes and dozens of slow slip events in the last ten to fifteen years. Records of microseismicity over time throughout the Hikurangi trough help uncover the physical features of the subduction zone. Exploiting seismic data from temporal ocean bottom seismometers deployed during a 2014-2015 experiment and permanent land stations maintained by GeoNet, we built a comprehensive offshore and onshore microseismicity catalog with 2,313 earthquakes. The seismicity is mainly located along the plate interface and within the downgoing slab, with an interesting 20 km-wide microseismicity gap near the coast. However, this catalog was built using 1D P- and S-wave velocity models that do not fully account for the complexity of this subduction zone. To improve the hypocenter locations with a regionally-constrained velocity model and further explore the relationships of microseismicity with slow slip events, we constructed a 3D local earthquake tomography model. We use the tomography code SIMUL2000 to iteratively perform a full matrix inversion of absolute P and S-P arrival times, obtain relocated hypocenters, and generate 3D velocity models for Vp and Vp/Vs. These results can be compared to seismically image and better understand the Hikurangi subduction zone. Furthermore, increasing fluid pressure from subducted sediments has been suggested to trigger the occurrence of slow slip events in active subduction zones. The 3D velocity models enable us to test this hypothesis and probe the distribution of high and low fluid pressure regions in this subduction zone. Thus, investigating the spatial variations of velocities along the northern Hikurangi margin offer new insights into recognizing the physical mechanisms controlling the occurrence of slow slip events and microearthquakes.

Current and Future Challenges in Engineering Seismology
Poster Session · Thursday · 25 April · Grand Ballroom

Characterized Fault Model for Prediction of Long-Period Ground Motions Containing Permanent Displacement in the Near-Fault Region

TANAKA, S., Toden Sekkei Co., Ltd., Tokyo, Japan, s.tanaka@tepsco.co.jp; HISADA, Y., Kogakuin University, Tokyo, Japan, hisada@cc.kogakuin.ac.jp

A series of M6-7 earthquakes occurred from April 14 to 16 in 2016 in the Kumamoto prefecture of the Kyushu Island, Japan. The main-shock (Mw7.0, 2016/4/16) generated the extensive surface faulting, and the displacements at Mashiki City and Nishihara Village show clearly permanent displacement. We propose a new procedure for evaluating the parameters of characterized fault model for predicting long-period ground motions containing permanent displacement in the near-fault region.

First, we construct a characterized source model (Model-01) for the main shock based on Irikura recipe. Besides, we expand the Irikura recipe for shallower region than the seismogenic layer. We recommend the regularized Yoffe-type slip velocity functions by Tinti *et al.* (2005) for shallower region than the seismogenic layer. We evaluate the relation of the slip and the parameters of the regularized Yoffe function from collected source fault models based on the waveform inversion of strong motion data.

Next, we simulate observation records at KiK-net Mashiki and Nishihara village using this source fault models by the theoretical method in the period over 1s. Model-01 underestimate the observation waveforms of velocity and displacement at Nishihara village. The radiation amplitude patterns of S-waves from the seismogenic layer are small in the near-fault region (<1km), that is one of the reasons for the underestimate.

Finally, we construct two source models, Model-02 with large slip and short slip duration for shallower region than the seismogenic layer and Model-03 with the additional fault plane. The additional fault plane in Model-03 is Idenoguchi fault located 2km southeast of main fault. By and large, synthetic waveforms produced with these two models waveforms are in much closer agreement with observed waveforms. We conclude that the Model-03 can describe the actual phenomenon best. This result suggests that geometric shape of the source fault model is important for predicting long-period ground motions containing permanent displacement in the near-fault region.

The Applicability of Lognormal Uncertainty in Ground Motion Prediction Equations: Analysis, Implications and a Proposed Alternative

BULLOCK, Z., University of Colorado Boulder, Colorado, USA, zachary.bullock@colorado.edu

Lognormal uncertainty around ground motion prediction equations is ubiquitous in the literature. However, little research into the durability of lognormal uncertainty or its applicability for forward analysis has been performed. By "durability," I mean the likelihood that the original characterization of uncertainty remains applicable as more validation data are considered. This presentation reports the results of a study based on the NGA-West2 database (with a total of approximately 15,800 records after censoring) which evaluated the stability of the moments of lognormal uncertainty as validation data accumulates, as well as whether or not the original descriptions of model uncertainty continued to accurately describe the distribution of errors. Three initial database sizes were considered: approximately 1,500, 3,000, and 4,500 records. Lognormal uncertainty had stable moments only for relatively large initial databases (4,500 records), and was not durable for any scenario considered. Lognormal uncertainty may therefore not be suitable for use in forward analysis in some situations. Logistic distributions formulated to approximate the original normal distributions around the median were shown to be more likely to survive additional validation data due to their increased tail thickness. Use of alternative probability distributions may make ground motion prediction equations more resilient to possible outliers in the future and may therefore offer a more realistic description of model uncertainty. Implications for probabilistic seismic hazard analysis (PSHA) and performance-based earthquake engineering (PBEE) and the challenges presented will be discussed.

Ray-Theory Based Analysis of the P/S Ratio Behavior Within Vertical Ground Motions

FRID, M., Ben-Gurion University, Beer-Sheva, Israel, fridmich@post.bgu.ac.il

Vertical ground motions have been traditionally neglected in the seismic-hazard analysis because they were believed to have minor effects on civil structures. Specifically, the vertical site-response and the physical parameters which affect it are still poorly understood. In recently-published vertical GMPEs, the site-response component is represented only by SV dependent parameter (*i.e.* Vs30). However, several studies have shown that - depending on magnitude, distance, and other site conditions, the P-wave contribution to the vertical component of ground motion, specifically at high frequencies, could be as large as that of the SV-wave or even larger. In this study, we hypothesize that the site-response component in vertical GMPEs can be better estimated by combining P- and S-related site parameters. However, such combination can only be obtained once their relative contribution to the vertical ground motion is properly understood and well-defined. This topic has not been fully explored before and hence represents a significant knowledge-gap in the current ability to characterize vertical site-response.

In order to examine the relative contribution of P- and SV- waves on the vertical ground motion component, an analytical algorithm was developed. It allows us to calculate and present all the possible direct wave-fronts that leave a point-source and meet at a single recording point. The calculation takes into account the geometrical setting as well as the frequency-dependent attenuation and is a function of a number of independent variables, such as the thickness of the overlying soil layer, the velocity ratio, and the source-to-site distance. The computed data allows us to establish the pure separated P and S amplitudes and their ratio in the frequency domain as a function of specific physical properties. This study is expected to facilitate an improved understanding of the relative contribution of P- and S- wave types to the vertical ground motion.

Regional Effects on Style-of-Faulting Ratios in Ground Motion Models

TUERKER, E., University of Potsdam, Potsdam, Germany, etuerker@uni-potsdam.de; SANDIKKAYA, M., Hacettepe University, Ankara, Turkey, abdullahsandikkaya@hacettepe.edu.tr; COTTON, F., GFZ German Research Centre for Geosciences, Potsdam, Germany, fcotton@gfz-potsdam.de

An unremarkable number of ground-motion prediction equations (GMPEs) include the style-of-faulting (SoF) as an additional predictor variable to the invariably used magnitude, distance and site classification terms. This study focuses on regional effects on the SoF-ratios while using a large dataset of previously compiled strong ground motion recordings of the Western United States and Taiwan (NGA-West2), Europe (Engineering Strong Motion Database, ESM) and Japan (KiK-Net Database). Only records of shallow crustal earthquakes (Mw 3.5 - 8.0) with a max. depth of 35km and a maximum source-to-site distance of 300km (Rjb) are used to calculate the SoF-ratios for each region. Records with unknown SoF have been ignored. All stations are classified by measured average shear-wave velocities of the top 30m soil (V_{s30}). Firstly, the ground-motion amplitudes are scaled to reference rock site conditions ($V_{s30} = 760$ m/s) with a nonlinear soil amplification model. The functional form of the predictive model also includes a trilinear-hinged magnitude scaling factor, magnitude dependent geometrical spreading and an anelastic attenuation term. The SoF-effects are computed for ground-motion amplitudes of reverse-to-strike-slip (R:SS) and normal-to-strike-slip ratios (N:SS). Since the main purpose is to show regional effects, a regression analysis for each mentioned database has been performed separately. Our results show that the R:SS are generally higher than unity for the NGA-West2 and ESM datasets, whereas for Japanese data, reverse earthquakes produce lower amplitudes with respect to strike-slip events. On the other hand estimations made the for NGA-West2 database show that N:SS are below unity and ratios of European and Japanese datasets are significantly higher. Finally, when we merge the datasets to one large database and calculate the ratios again, the resulting trends show major differences. Thus, flags were added for each region to recompute the SoF scaling coefficients.

Does the 1D Assumption Hold for Site Response Analysis? A Study of Seismic Site Responses and Implication for Ground Motion Assessment Using Kik-Net Strong-Motion Data

PILZ, M., GFZ German Research Centre for Geosciences, Potsdam, Germany, pilz@gfz-potsdam.de; COTTON, F., GFZ German Research Centre for Geosciences, University of Potsdam, Potsdam, Germany, fcotton@gfz-potsdam.de

The one-dimensional (1D) approach is still the prevailing methodology to incorporate site effects in ground response analysis and ground motion modelling. To bridge the 1D to multidimensional site response analysis, we have developed quantitative criteria and a reproducible method to identify sites with significant deviations from 1D behaviour. For KiK-net, we found that 158 out of 354 show two- and three-dimensional (2D/3D) effects, extending the resonance towards shorter periods at which 2D/3D site effects exceed those of the classical 1D configurations and imposing an additional amplification to that due to the impedance contrast alone. Such 2D/3D effects go along with a large within-station ground motion variability. These effects are found to be more pronounced for small impedance contrasts. While it is hardly possible to identify common features in ground motion behaviour for stations with similar topography typologies, it is not over-conservative to apply a safety factor to account for 2D/3D site effects in ground motion modelling.

A Global Empirical Predictive Model for Arias Intensity, Cumulative Absolute Velocity and Significant Duration of Strong Ground Motions

CAUZZI, C., ORFEUS, SED ETH Zurich, Zürich, Switzerland, carlo.cauzzi@sed.ethz.ch; FACCIOLI, E., Politecnico di Milano & Studio Geotecnico Italiano, Milan, Italy, e.faccioli@studiogeotecnico.it

Integral measures of ground motions and estimates of the duration of significant shaking at a site are used in a broad range of engineering seismology and earthquake engineering applications including, *e.g.*, the assessment of slope stability, liquefaction potential and structural performance. We present in this contribution an empirical predictive model for Arias intensity, cumulative absolute velocity and significant duration of strong ground motions based on a global dataset of digital high-quality acceleration waveforms and carefully curated earthquake and station metadata. We complement the calibration dataset used in our previous studies with the recordings of recent major events worldwide. The new dataset comprises more than 2000 tri-axial records and allows predictions in the moment magnitude range [4.5;8] at distances within 150 km of the earthquake source, in seismically active regions characterized by shallow crustal seismicity. We compare our predictions with other empirical models as well as with theoretical expressions derived from earthquake source models

Seasonality in Site Response: An Example From Two Historical Earthquake in Kazakhstan

ALSHEMBARI, R., International Centre for Theoretical Physics, Trieste, Italy, ralshemb@ictp.it; PAROLAI, S., Instituto Nazionale di Oceanograffia e di Geofisica Sperimentale, Sgonico, Italy, sparolai@inogs.it; BOXBERGER, T., GFZ German Research Centre for Geosciences, Potsdam, Germany, tobibo@gfz-potsdam.de; SANDRON, D., Instituto Nazionale di Oceanograffia e di Geofisica Sperimentale, Sgonico, Italy, dsandron@inogs.it; SILACHEVA, N., LLC, Institute of Seismology, Almaty, Kazakhstan, silacheva_nat@mail.ru

During the past 150 years, the city of Almaty (formerly Verny) in Kazakhstan has suffered significant damage due to several large earthquakes. The Mw 7.3, 9 June 1887 Verny earthquake, a time when the city mainly consisted of adobe buildings with a population of 30,000, was nearly totally destroyed with 300 deaths. The Mw 7.8-8, 4 January 1911 Kemin earthquake saw 390 deaths, 44 in Verny itself. Remarkably, the earthquake generated in Verny (ca. 50 km from the epicenter) significant soil deformation and ground failure, in particular in the loam sandy soils, with cracks in the ground sometimes reaching 1 m in width and 5 meters in depth.

A crucial step towards preparing for future events, mitigating against earthquake risk and defining optimal engineering designs involves undertaking site response studies. With regard to this, in this study we investigate the possibility that the extreme ground failure observed after the 1911 Kemin earthquake could have been due to the presence of a shallow frozen ground layer that may have inhibited the drainage of pore-pressure excess through the surface, therefore inducing liquefaction at depth. We make use of information collected by two arrays established to measure ambient seismic noise, borehole data, and surface temperature data. From these datasets, we estimated parameters for evaluating the dynamic properties of soil, and characterized the corresponding sediment layers at the site of the observed liquefaction.

Although the estimated soil parameters are not optimally constrained, the dynamic analysis, carried out using selected strong motion recordings expected to be compatible with the 1911 Kemin earthquake, indicated that the extensive ground failure that occurred during the Kemin event (which occurred in winter), was different to that observed during the 1887 event (which occurred at the end of spring), which could be due to the presence of a superficial frozen soil layer. Our results indicate that for this region, possible "seasonal" effects should therefore be considered when undertaking site effect studies.

ORFEUS Products and Services for Strong Motion Seismology

LUZI, L., Istituto Nazionale di Geofisica e Vulcanologia, Milan, Italy, lucia.luzi@ingv.it; ÇAKTI, E., Bogazici University, Kandilli Observatory and Earthquake Research Institute, Istanbul, Turkey, eser.cakti@boun.edu.tr; CAUZZI, C., Swiss Seismological Service, Zurich, Switzerland, carlo.cauzzi@sed.ethz.ch; CLINTON, J., Swiss Seismological Service, Zurich, Switzerland, jclinton@sed.ethz.ch; KALAFAT, D., Bogazici University, Kandilli Observatory and Earthquake Research Institute, Istanbu, Istanbul, Turkey, kalafato@boun.edu.tr; KALOGERAS, I., National Observatory of Athens, Athens, Greece, i.kalog@noa.gr; MARMUREANU, A., National Institute of Earth Physics, Măgurele, Romania, marmura@infp.ro; MICHELINI, A., Istituto Nazionale di Geofisica e Vulcanologia, Roma, Italy, alberto.michelini@ingv.it; MAUFROY, E., Institut des Sciences de la Terre, Grenoble, France, emeline.maufroy@univ-grenoble-alpes.fr; SHAHVAR, M., Road, Housing and Urban Development Research Center, Teheran, Iran, Islamic Republic Of, mshahvar@gmail.com; SLEEMAN, R., KNMI, Utrecht, Netherlands, reinoud.sleeman@knmi.nl; TEPEUĞUR, E., AFAD, Istanbul, Turkey, eren.tepeugur@afad.gov.tr; THEODOULIDIS, N., ITSAK, Thessaloniki, Greece, ntheo@itsak.gr; ROUMELIOTI, Z., Aristotle University, Thessaloniki, Greece, zroum@auth.gr; RUPAKHETY, R., University of Iceland, Reykjavík, Iceland, rajesh@hi.is; WEATHERILL, G., GFZ German Research Centre for Geosciences, Potsdam, Germany, gweather@gfz-potsdam.de

ORFEUS (Observatories & Research Facilities for European Seismology) is a European collaborative effort to promote seismology through the collection, archiving and dissemination of digital seismic waveform data and metadata. Much work has been carried out in the past five years to apply the advanced level of standardization reached by the broadband seismological community to strong-motion data and metadata, that are typically used in the fields of engineering seismology. Key data providers operating in the Euro-Mediterranean area are organised within ORFEUS Strong-Motion Service Management Committee (SM-SMC). The main goals of the SM-SMC are: a) encouraging and enabling open access to event-based waveforms, derived intensity measures and to downstream ORFEUS; b) enhancing the interoperability with other disciplines, in the framework of the EU EPOS research infrastructure (www.epos-ip.org). Feedback from the users' community is ensured through a User Advisory. Two infrastructures were created for the dissemination of ground-motion parameters and response spectral amplitudes: i) a Rapid Raw Strong-Motion database (RRSM; http://www.orfeus-eu.org/rrsm), purely automatic, that makes peak-motions and spectral amplitudes available within minutes of the occurrence of any event with M≥3.5; ii) an Engineering Strong-motion database (ESM; http://esm.mi.ingv.it/), that distributes only manually processed and expert revised event-based waveforms, peak-motions, response spectra, earthquake and station metadata of events with M≥4.0. Other products/services include software for strong-motion data processing and selection of waveforms compliant to building codes, webservices to access waveforms, strong-motion parameters and USGS ShakeMap input files. A collaboration with the European seismic hazard and risk community has been established as strong-motion parameters are the necessary input to derive / rank ground motion prediction equations. A novel European ShakeMap service is envisaged, based on the USGS ShakeMap codes and the input from RRSM and ESM peak-motion webservices.

Community-Supported Ground Motion Processing Software

THOMPSON, E. M., U.S. Geological Survey, Colorado, USA, emthompson@usgs.gov; AAGAARD, B., U.S. Geological Survey, California, USA, baagaard@usgs.gov; HEARNE, M., U.S. Geological Survey, Colorado, USA, mhearne@usgs.gov; SCHOVANEC, H., U.S. Geological Survey, Colorado, USA, hschovanec@usgs.gov; REKOSKE, J., U.S. Geological Survey, Colorado, USA, jrekoske@usgs.gov; WALD, D. J., U.S. Geological Survey, Colorado, USA, wald@usgs.gov; KALKAN, E., U.S. Geological Survey, California, USA, ekalkan@usgs.gov; STEIDL, J. H., U.S. Geological Survey, California, USA, jsteidl@usgs.gov; KOTTKE, A. R., Pacific Gas and Electric Company, California, USA, arkk@pge.com

We describe ongoing efforts at the U.S. Geological Survey (USGS) to develop automated open-source ground motion processing software. Within the USGS, numerous projects have highlighted the need for standardized and automated ground-motion processing algorithms, including basic seismological research, analysis by the USGS National Seismic Hazard Model Program, and operational systems such as ShakeMap. We expect that the software will be of value to the broader engineering seismology community, and we seek to include ongoing developments in processing algorithms by groups outside of the USGS. The software is written in Python and is built on the open source ObsPy library and incorporates methods developed for the USGS Processing and Review Interface for Strong Motion Data (PRISM). To facilitate data collection, the software reads a range of diverse file formats including any format supported by ObsPy and many formats available from the Center for Engineering Strong Motion Data (CESMD). Additionally, the software can directly query webservices such as: Federation of Digital Seismograph Networks (FDSN) servers and the Istituto Nazionale di Geofisica e Vulcanologia (INGV) Strong Motions Web Service. Processing steps are modular to aid future expansion. These options currently include methods for selecting filter corner frequencies and computing rotation-independent ground motion metrics as well as a wide variety of common engineering intensity measures (*e.g.*, response spectra, duration, Arias Intensity). Our long-term goal is to integrate new algorithms developed in PRISM and by

researchers outside of the USGS into a software repository to which others may easily contribute, and which may be used by the broader scientific and engineering community. In this presentation, we describe the ground-motion processing software, demonstrate its capabilities, and present validations of our processing by comparisons with results from existing datasets processed via other methods.

Comparisons Between Single and Weighted Average NGA-West2 GMPEs in ShakeMap

HAGOS, L., California Geological Survey, California, USA, lijam.hagos@conservation.ca.gov; HADDADI, H., California Geological Survey, California, USA, hamid.haddadi@conservation.ca.gov; HELLWEG, M., University of California, Berkeley, California, USA, peggy@seismo.berkeley.edu; BALTAY, A. S., U.S. Geological Survey, California, USA, abaltay@usgs.gov

ShakeMap uses both observed input data and estimates of ground motions from ground motion prediction equations (GMPEs) to represent the ground shaking experienced in an earthquake. In the California Integrated Seismic Network, Next Generation Attenuation (NGA) GMPEs developed for the Western US are used to estimate ground motions in ShakeMaps. While NGA-West2 GMPEs are generally consistent with each other, the choice of an appropriate single GMPE in ShakeMap among the NGA-West2 GMPEs may depend on the ground motion prediction model parameters available immediately after an earthquake. In the initial post-quake interval, some model parameters needed in the GMPEs, such as hypocentral depth, rupture extent or fault orientation may not yet be available. In the absence of these parameters, defaults or proxies may be used, yet it is not clear in a ShakeMap context which GMPEs perform best in these situations. Furthermore, recent developments in ShakeMap version 4.0 allow the use of either a single GMPE or a weighted average of two or more GMPEs. This study investigates the behavior of four of the five NGA-West2 GMPEs and compares them with estimates obtained from an equally-weighted multi-GMPE approach for different intensity measure types. By evaluating their sensitivities to perturbations of the model parameters, the study will also determine if the multi-GMPE gives a good estimate of ground motions. This study will further investigate the variability of the multi-GMPE ground motion estimates with different region-specific site conditions. Adjustments to the weighting of the four NGA-West2 GMPEs are made by comparing GMPE ground motion-based estimates with recorded data from California earthquakes for a range of magnitudes.

Characteristics of Strong Ground Motions and Its Corresponding to Questionnaire Survey to Damage of High-Rise Residential Buildings During the 2018 Mw 6.4 Hulien, Taiwan, Earthquake

WANG, X., Tokyo University of Science, Noda, Japan, wangxin@rs.tus.ac.jp; NAGANO, M., Tokyo University of Science, Noda, Japan, nagano-m@rs.noda.tus.ac.jp; SI, H., Earthquake Research Institute, University of Tokyo, Tokyo, Japan, shj@seismo-r.com; CHANG, W., National Dong Hwa University, Hualien, Taiwan, wychang@gms.ndhu.edu.tw; KUO, C., National Center for Research on Earthquake Engineering, Taiwan, Taipei, Taiwan, chkuo@ncree.narl.org.tw; LIN, C., National Center for Research on Earthquake Engineering, Taiwan, Taipei, Taiwan, cmlin@ncree.narl.org.tw; SUZUKI, K., Tokyo University of Science, Noda, Japan, 7115077@ed.tus.ac.jp; WATANABE, T., Tokyo University of Science, Noda, Japan, 7115146@ed.tus.ac.jp

During the 2018 Hualien earthquake, the main shock of a seismic sequence originated offshore of the eastern Taiwan, long-period pulse-like motions near the Milun fault under the Hualien City were observed. Though the CMT focal mechanism showed that this event had mainly a strike-slip focal mechanism with a minor thrust component dipping to the west, the field investigation of surface ruptures announced another possibility that the main ground motion generation areas should belong to the Milun fault and the Lingding fault dipping to the east. High amplitude and pulse-like velocities with period of 2 to 4 sec were recorded near the Milun fault, which are considered to be dangerous to high-rise buildings. Indeed, fourbuildings with week lower stories were totally collapsed along the Milun fault. In this study, we constructed a characterized source model with the purpose to explain the generation of long-period pulse-like motions near the Milun fault. Then using the proposed source model, ground motions at the sites of damaged buildings were numerically simulated based on the thin-layer method. We selected 9 high-rise RC residential buildings locating at the southwest side, the northeast side, and the central part of the east side of the Milun fault to examine the response characteristics of buildings in Hualien City and perform questionnaire of the feeling of shaking, indoor damages, structural damages, etc. Predominant frequencies of the ground within Hualian City are about 1 Hz which are close to the inferred fundamental frequency of damaged buildings. We found that the shakings of the buildings at the northeast part was longer and stronger than those at other places. Correspondingly, the damages of these buildings were more severe. For the buildings at the central part, the shaking duration was short and building damage is relatively light. The shaking pattern at the buildings at the southwest side was more complicated and the indoor damage was the most severe.

Probabilistic Seismic Hazard Levels in France: Influence of the Source Model Choices

BEAUVAL, C., ISTerre, Grenoble, France, celine.beauval@univ-grenoble-alpes.fr; BARD, P., ISTerre, Grenoble, France, pierre-yves.bard@univ-grenoble-alpes.fr; DANCIU, L., Swiss Seismological Service, ETH, Zurich, Switzerland, laurentiu.danciu@sed.ethz.ch

Building the source model is the first step in a probabilistic seismic hazard study. The source model is intended to describe the frequencies of occurrences of future earthquakes in the area. In regions of low to moderate seismicity, the source model most often relies on an earthquake catalogue associated to a definition of seismogenic sources in space. In France, two earthquake catalogues are currently published and made public: the catalogue from the 2013 European Seismic Hazard model project (EHSM13, Woessner *et al.* 2015) and the FCAT catalogue (Manchuel *et al.* 2017). Besides, two propositions for delineation of seismogenic sources are available: again the one used in ESHM13, partly based on the Autran *et al.* (1998) model for inner France, and the Baize *et al.* (2013) model. The aim of the present study is to explore the variability of hazard levels depending on the source model uncertainty. Combining the available catalogue and seismogenic source definitions, alternative source models are built. Additionally, uncertainties related to the different steps involved in the modeling of earthquake recurrence are quantified as precisely as possible: uncertainties in the declustering, in the estimation of completeness time periods and in the estimation of Gutenberg-Richter parameters. One major difficulty to address is the quantification of uncertainties in regions of low seismicity where data is scarce. To determine probabilistic seismic hazard, a set of recent ground-motion prediction equations potentially adapted for the different French tectonic contexts and consistent with the ongoing update of the 2020 European hazard map (ESHM20) is considered. Our results at the country level as well as for selected French cities enable to better understand (1) how much the choices made to build the source model can impact hazard levels, and (2) what is the overall variability on hazard levels for different return periods considering the current state-of-the art knowledge in France.

A Simple Fault Model to Calculate Strong Ground Motions With Fling Steps for the Main Shock of the 2016 Kumamoto Earthquakes

NOZU, A., Port and Airport Research Institute, Yokosuka, Japan, nozu@p.mpat.go.jp; NAGASAKA, Y., Port and Airport Research Institute, Yokosuka, Japan, nagasaka-y@p.mpat.go.jp; WU, S., Port and Airport Research Institute, Yokosuka, Japan, u-shu@p.mpat.go.jp

A composite source model was developed to simulate strong ground motions during the main shock of the 2016 Kumamoto earthquakes which can consider both fling steps due to slips near the site and pulses from deeper asperities. The authors' intention was to develop a simple source model which can be easily handled by engineers. To this end, a simple geodetic fault model by the Geospatial Information Authority of Japan (GSI), comprising of three faults with uniform slip, was used as a starting point and parameters related to the temporal evolution of the slip were added. The added parameters included the rupture starting point, rupture propagation pattern, rupture velocity and rise time. The resultant model was used as a background region, which was combined with asperities to form a composite source model. The ground motions from the background region were calculated by the discrete wavenumber method (Bouchon, 1981). The ground motions from the asperities were calculated by what we call "the corrected empirical Green's function method" (Kowada *et al.*, 1998; Nozu *et al.*, 2009). The simulation results showed that the composite model can well reproduce near-source displacement and velocity waveforms including fling steps at KMMH16, KMM006, KMM005, Komori and Kawayo, although the model was relatively simple in a sense that the slip-velocity function and the rise time were uniform throughout the background region. A closer look at the results showed that the fling steps were slightly overestimated and underestimated at KMMH16 and Komori, respectively. It was obvious that if we had introduced more complicated slip models, the results would have been closer to the observations. However, from an engineering point of view, it was a meaningful result that such a simple source model could explain ground displacements with fling steps without significant discrepancy because, in a prediction problem, it is difficult to assign a detailed slip distribution. On the other hand, to represent pulses with approximate periods of 1 s, it was definitely necessary to consider asperities.

New Strategies to Normalize Global Engineering Demand Parameters to Compare Seismic Responses of Complex Buildings

MONTABERT, A., Ecole Normale Superieure, Paris, France, montabert@geologie.ens.fr; CLEMENT, J., IRSN, Fontenay-aux-Roses, France, julien.clement@irsn.fr; LANCIERI, M., IRSN, Fontenay-aux-Roses, France, maria.lancieri@irsn.fr; COMBESCURE, D., Fusion For Energy, Barcelona, Spain, didier.combescure@f4e.europa.eu

To assess how differently complex buildings with different shapes and masses and internal rigidity behave under seismic load, it is necessary to introduce standardized engineering demand parameters (EDPs). In this work we compare the seismic response of 15 three-dimensional buildings having different characteristics: typologies (reinforced concrete or post and beam buildings), rigidity distributions, and shapes (rectangular, horizontal L-shape and vertical L-shape). The seismic load is given by 236 real three-component accelerograms covering large range of spectral amplitude level, issued from the ITACA database. The accelerograms are baseline corrected, and rotated (45°, 90°, 135°) to average the impact of motion direction. After testing the correlation between several intensity measures and EDPs, the Euclidean peak ground acceleration is used to describe the seismic input. The 14560 dynamic analyses are performed implementing a transfer function-based method based on the assumption that all the structures behave linearly. The seismic response is assessed in terms of global-standardized EDPs describing the average response of buildings smoothing the local stress concentration. In particular, we introduce two normalization methods. In the first one, the EDPs are expressed by a dimensionless quantity (*e.g.* the ratio between normal strengths, induced by the seismic load at a given floor, and the weight of the upper floors). In the second method, we standardize each building to a cubic one having the same mass and surface of contact between walls and floor. Comparison between the EDPs issued from the complex buildings and the cubic ones is supposed to catch torsional effects. Comparing the EDPs levels in function of the building shape no relevant differences appear. EDPs for the different typologies or rigidity distributions exhibit clear seismic response differences. Finally, we test the impact of soil-structure interaction that strongly affects all the tested EDPs.

Single-Station Sigma Analysis for Romanian Seismic Network

MANEA, E., National Institute of Earth Physics, Magurele, Romania, flory.manea88@gmail.com; CIOFLAN, C., National Institute of Earth Physics, Magurele, Romania, cioflan@infp.ro; DANCIU, L., Swiss Seismological Service, ETH Zurich, Zurich, Switzerland, laurentiu.danciu@sed.ethz.ch

Romania is exposed to high seismic hazard due to Vrancea seismogenic region, where ~3 earthquakes with M>7 occurs per century at intermediate-depths (60-170 km). The impact of such strong intermediate-depth events transcends the national borders with significant damage being reported in neighboring countries (eg observed intensities of VII-VIII at more than 250 km epicentral distances during 1940 event Mw=7.7).

In this study, the efficiency of some selected GMPE's developed for active subduction zones(Sokolov *et al.*, 2008; Vacareanu *et al.*, 2016; Abrahamson *et al.*, 2015; Atkinson & Boore, 2003; Garcia *et al.*, 2005; Lin & Lee, 2008) was tested for peak ground acceleration(PGA), spectral accelerations (SA) and peak ground velocity(PGV).

The database used comprises 3550 records of 170 Vrancea intermediate depth events with Mw=4-7.4. These data were recorded by 130 seismological stations from the Romanian National Seismic Network or collected during national/international projects, since 1977.

The comparison between the computed and recorded parameters shows that three GMPEs fit well the data within the model's magnitude validity range(Mw>5) and over predict the values below this magnitude. In this context, the model developed from local seismicity (Vacareanu *et al.*, 2016) was adjusted for the actual database. Different test-scenarios performed with this version indicate that the model still needs additional site correction parameters. In order to minimize the local random variability of the computed ground motion, the single sigma station was performed for each station. In case of the stations located outside of the Carpathian bend, a strong correlation is observed between the site correction term and geological conditions. Through the assessment of single station standard deviation, the aleatory uncertainties in ground motion computation were proper quantified and will lead to significant improvements in seismic hazard and risk evaluations based on expected scenarios.

The Sigma-2 Research Program: Improved Seismic Hazard Assessment Practices Adapted to Site Conditions

DANIEL, G., EDF Group, Aix-en-Provence, France, guillaume.daniel@outlook.com

Our objective is to introduce the SIGMA-2 R&D program on seismic hazard assessment ("SeIsmic Ground Motion Assessment, 2nd edition"). Built upon SIGMA project (2011-2016) legacy, this program aims at delivering an improved representation of the seismic ground-motion, adapted to local site conditions, with a particular emphasis on low seismicity areas.

The program is funded by a consortium of industrial partners operating, managing, controlling facilities (including nuclear installations), and sharing a common interest in improving seismic hazard assessment (SHA) practices within an open collaboration framework. The program organization has been elaborated so as to strengthen the link between researchers and seismic/civil engineers, by involving international representative from private and public sectors from the realization of research actions to the Scientific Committee supervisory level. Besides, bi-annual workshops offer the opportunity to conduct extensive technical discussions/reviews with end-users and to anticipate future impacts on SHA studies.

A dedicated Scientific Committee has been constituted to monitor the quality of SIGMA-2 scientific outcomes, and to provide guidance on technical aspects. In addition, project deliverables must comply with a formal review process supervised by this Committee.

SIGMA-2 research actions are organized into 6 Work Packages with expected contributions at every step of the SHA process: Fault & tectonics; Earthquake catalogs & parameters; Characterization of ground-motion; Site response; Probabilistic SHA and Inputs for engineers.

The program will go on up to the end of 2021.

Ground Motion Prediction Equations for the Central and Eastern United States Using an Integrated Database

SEDAGHATI, F., AON | Impact Forecasting, Illinois, USA, farhad.sedaghati@aon.com; PEZESHK, S., The University of Memphis, Tennessee, USA, spezeshk@memphis.edu; TAVAKOLI, B., Bechtel Corporation, California, USA, btavakol@bechtel.com

In this study we use an integrated database of recorded events and simulated ground motion to develop a new suite of ground motion prediction equations (GMPEs) for the central and eastern United States (CEUS). For the simulated part of the integrated database, we use an improved two-stage SSGFM. An improved two-stage stochastic summation of Green's functions method (SSGFM) is a convenient and fast technique to simulate strong ground motion time histories in regions such as the CEUS where detailed information about the faults such as the slip distribution, the geometry of the fault, and the asperity location not known. This procedure stochastically captures the effect of rupture propagation for large earthquakes and the effect of propagation path on seismic waves coming from different parts of the fault. We employ synthetic weak ground motions as input motions into SSGFM because the resulting strong ground motion time histories are region-specific and are constructed based on the seismological characteristics of the CEUS. Thus, they can be used in development of ground motion models for the study region. We simulated weak motions using SMSIM for small earthquakes with M3.5, M4.0, and M4.5. Then, the improved two-stage SSGFM is implemented to simulate synthetic time histories for moment magnitudes of M5.0 to M8.0 in 0.5 increments using the generated weak motions at the JB distance range of 1 to 1000 km. A subset of NGA-East database is then combined with this synthetic database to produce an integrated database for the ground motion model development.

The coefficients of the proposed functional form are determined using a mixed effect regression. We also derive between-event, site-to-site, and event-site corrected aleatory variabilities as well as the total standard deviation. The proposed ground motion model for the CEUS is applicable for magnitudes ranging from 3.5 to 8.0 and JB distances up to 1000 km. The applicable V_{S30} for other spectral periods is in the range of 160 to 3000 m/sec.

Ground Motion Prediction Equation (GMPE) for the Intraslab Subduction Earthquakes of North East India (NEI) and Its Surrounding Region using Seismological Model

RAHMAN, T., National Institute of Technology Silchar, Department of Civil Engineering, India, tauhid_srm@yahoo.com; GHOSH, J., National Institute of Technology Silchar, Silchar, India, goush@live.com

In this study, a new ground motion prediction equation (GMPE) is developed for intraslab subduction earthquakes for North-East India (NEI) and its surrounding region for the first time. We used seismological model in deriving our

proposed ground motion equation. Recorded strong motion data for intraslab earthquakes in NEI are very sparse. With these sparse recorded events in NEI, it is not possible to developed robust ground motion prediction equation and so, we used seismological model to developed new ground motion prediction equation. In total in this study for NEI, 33,000 ground motion samples have been simulated incorporating the different key seismic parameters namely stress drop, quality factor, path parameter and attenuation model for different earthquake magnitude (M_w) 5.0-9.0 and epicentral distance 30 Km -300 Km. Sensitivity analysis has also been performed in this study to check the biasness of each key seismic input parameters used in developing the ground motion prediction equation.

We have compared and validated our model with the existing recorded events. We have also checked our model with the similar ground motion prediction equations developed for subduction zone intraslab earthquake in the world.

Identification of Site Effects and Bedrock Motion from Recorded Surface Response

GHAHARI, F., University of California, Los Angeles, California, USA, ghahari@gmail.com; ABAZARSA, F., University of California, Los Angeles, California, USA, abazarsa@gmail.com; JEONG, C., The Catholic University of America, District of Columbia, USA, jeong@cua.edu; KURTULUS, A., Ozyegin University, Istanbul, Turkey, asli.kurtulus@ozyegin.edu.tr; TACIROGLU, E., University of California, Los Angeles, California, USA, etacir@ucla.edu

Seismic analysis of structures cannot be carried out accurately unless site effects are taken into account. Moreover, presently available empirical attenuation relationships for predicting ground surface motions are only useful if site effects are considered. While an extensive collection of analytical and numerical techniques is available to analyze ground responses induced by bedrock motions, their accuracy depends on a priori knowledge of site properties and the availability of bedrock motions. In estimation of site effects, back-calculation of a site's transfer function from earthquake-induced recorded signals is an attractive alternative. Most of the existing site response identification methods rely on a strategically chosen reference station. The approach presented here obviates the need to have the bedrock motions, which are unavailable in most real-life cases. In the method proposed herein, the site response is identified from recorded ground surface accelerations at two or more nearby stations through a blind identification technique, under the assumption that the unknown bedrock motion is identical for these stations and these stations have different site properties. We demonstrate the performance of this new approach using a synthetic but adequately realistic example. The said verification study makes use of vertically propagating shear waves—a common assumption in site response analyses. Nevertheless, the proposed identification algorithm does not require this one-dimensional wave propagation assumption as long as we can write a single-input-single output transfer function relationship between the common unknown bedrock motion and the ground surface motions.

The Future of Macroseismic Intensity Assignments at the U.S. Geological Survey

WALD, D. J., U.S. Geological Survey, Colorado, USA, wald@usgs.gov; QUITORIANO, V., U.S. Geological Survey, California, USA, vinceq@usgs.gov; JAISWAL, K., U.S. Geological Survey, Colorado, USA, kjaiswal@usgs.gov; DEWEY, J. W., U.S. Geological Survey, Colorado, USA, dewey@usgs.gov; SPENCE, R., University of Cambridge, Cambridge, United Kingdom, robin.spence@carltd.com; MUSSON, R., British Geological Survey, Edinburgh, United Kingdom, roger@seismologist.co.uk; GODED, T., Geological and Nuclear Science, Wellington, New Zealand, t.goded@gns.cri.nz

The U.S. Geological Survey (USGS) "Did You Feel It?" system has been operating continuously for the last two decades (1999-2019). Although the collection and assignment of DYFI-based Macroseismic Intensity (MI) data depart from more traditional assignments, they are made more quickly, provide more complete coverage at higher spatial resolution, offer citizen input and interaction, and allow data collection at rates and quantities never before witnessed. DYFI decimal MI assignments are based on regression against traditional MI, and geocoding allows for spatial averaging; both of these strategies facilitate quantitative data analyses. New DYFI developments include Amazon Alexa-based voice activation, re-engineered software, an open API for third-party applications, and users can now replicate, filter, and update MI datasets via USGS web services. Other than DYFI, however, USGS does not maintain dedicated staff to assign traditional MI assignments. As concerning, neither DYFI nor Modified Mercalli Intensity assignments are particularly well defined for damaging level MI where buildings' vulnerability assessment and damage grading plays a crucial role in assigning macroseismic effects and thus, requires engineering expertise. USGS is thus interested in pursuing MI data collection that combines the advantages of DYFI for crowd-sourced, massive MI data collection for lower MI (<VII, which is > 95% of all MI data collected) with professional assignments at higher MI based on the more systematic European Macroseismic Scale (EMS-98) methodology. We aim to support the development of tools for domestic MI collection that utilize engineering expertise via on-site reconnaissance, remote imagery, and other rapid data collection strategies. Employing EMS-98 domestically will require its adaptation for U.S. structures, partnering with professionals to calibrate EMS-98 to U.S. earthquake damage data, and developing outreach materials to facilitate its adoption for future domestic earthquakes.

Explore the Fault2SHA Paradigms Across the Ponds

Poster Session · Thursday · 25 April · Grand Ballroom

Relationships Between the Width of Surface Rupture Zone and Related Parameters for Reverse Events

YOUNESI, K., California Polytechnic State University, California, USA, k.younesi@gmail.com; MOSS, R. E. S., California Polytechnic State University, California, USA, rmoss@calpoly.edu

Forecasting surface fault rupture is necessary for many engineering projects. In addition to the probability of the mean and maximum displacement along strike, the distribution of off-fault displacement perpendicular to fault strike is also important, particularly for reverse events with their hanging and footwall characteristics. Reverse surface faulting data was evaluated from 11 earthquakes ($5.4 \leq M \leq 7.9$) around the world. The relationship between the width of rupture zone (WRZ) and other parameters was evaluated. The data was first smoothed for Bias Weighting using Brown's simple exponential moving average (EMA) which helped to eliminate unusual large width of rupture zone. Many probability distributions were evaluated against the data and we found that a power function (axb+c) provided the best to the WRZ data. On-fault surface rupture displacement has been found to occur mostly near the center of the fault, and we expected to observe similar results for off-fault surface ruptures but we found no clear correlation between the magnitudes of the WRZ and the along strike fault distance ratio, X/L. Also, no distinct relationship was found between the WRZ and on-fault vertical displacement. However, a relationship between principle vertical off-fault displacements and distributed vertical off-fault displacements was observed.

Metamaterials, Resonances and Seismic Wave Mitigation, an Emerging Trend in Seismology

Poster Session · Thursday · 25 April · Grand Ballroom

On the Design of Seismic Metamaterials Accounting for Site Effects

PALERMO, A., California Institute of Technology, California, USA, palerman@caltech.edu; DARAIO, C., California Institute of Technology, California, USA, daraio@caltech.edu; ASIMAKI, D., California Institute of Technology, California, USA, domniki@caltech.edu

The use of elastic metamaterials, *i.e.*, artificial engineered media equipped with distributed local resonant units, has shown potential for the realization of novel earthquake isolation systems. The design of such resonant structures requires an adequate description of the local seismic response, also known as site effects, which is determined by the complex dynamics of the near-surface layers. Site effects are in fact responsible for significant changes in the amplitude, frequency and duration of seismic waves, which cannot be neglected for a meaningful assessment of seismic metamaterials performances.

In this talk, we analyze the isolation capabilities of seismic barriers realized by embedding meter size resonant units below the ground surface and accounting for complex soil profiles and realistic earthquake ground motions. We apply random vibration theory and equivalent linear analysis (EQL), to perform 1D site responses and evaluate the amplification of the ground motion at the soil surface for a representative seismic motion at the bedrock, soil profile and seismic barrier design. To this aim, we consider a set of synthetic soil profiles generated using a sediment velocity model (SVM) conditioned on VS_{30} and model the presence of the resonant barrier using an equivalent resonant layer, with frequency dependent dynamic properties. The low computational cost of the EQL method allows us to investigate a large parameter space of barrier configurations and soil profiles. We optimize the barrier for specific soil profiles and given designs constraint (overall dimensions, mass, material damping) and provide realistic estimates of reduced amplification factors at specific sites.

Towards a Seismic Cloak for Ground-Based Gravitational-Wave Detectors

MOHAMMED, S., Indian Institute of Technology Hyderabad, Hyderabad, India, ce17mtech01001@iith.ac.in; SOMALA, S. N., Indian Institute of Technology Hyderabad, Hyderabad, India, surendra@iith.ac.in; ADHIKARI, R. X., California Institute of Technology, California, USA, rana@caltech.edu

The first direct detection of gravitational waves has been possible by constructing a pair of highly sensitive detectors called Laser Interferometer Gravitational-wave Observatory (LIGO) which involve the most accurate measurement of displacements up to the order of 10^{-20}m. Since it is a ground-based interferometer, various noise sources limit its sensitivity. Ground vibrations in the range 0.01-10 Hz, generated through both anthropogenic as well as natural sources become an issue. These displacements, in turn, cause a fluctuation in the local gravitational field due to density perturbations of the surrounding geology introducing Newtonian Noise. The seismic isolation systems can suppress the displacements by several orders of magnitude, however, cannot reduce Newtonian noise. To further shield the detector building and also the walls of the vacuum chambers from such noise, we consider the idea of seismic metamaterials in this study.

Lately, using the concepts in metamaterial physicsit has beendemonstrated that judicious arrangement of either resonators or soil inclusions can largely affect the seismic wave field on the geophysical scale. In this study, the feasibility of using two different seismic metamaterials is explored; one with steel poles over the surface acting as vertical resonators and another with a periodic arrangement of vertical concrete inclusions in the soil medium. We consider the ground model at the site chosen for the upcoming LIGO-India project at Hingoli in India. To shield the ends of the interferometer, we seek to achieve band gapsbelow 10 Hz. We develop models for realistic cloak designs and perform time-domain simulations in SPECFEM3D, an open-source code which solves the elastodynamic equations using finite difference in time and the spectral-element method (O>4) in space. Thisinteresting approach to shieldthe LIGO detectors can potentially improve its sensitivity in the low-frequency range and the results from this study can have an impact on theexisting and future ground-based detectors.

Large Scale Simulations of Metamaterials for Seismic Waves Mitigation

COLOMBI, A., ETH Zurich, Zurich, Switzerland, andree.colombi@gmail.com; ZACCHERINI, R., ETH Zurich, Zurich, Switzerland, zaccherini@ibk.baug.ethz.ch

The so-called Bloch-Floquet periodic boundary conditions are often used in conjunction with metamaterials to extract dispersion curves and attenuation profiles from a single unit-cell as if the metamaterial was infinitely periodic. Practical applications however rarely meet this condition and require the metamaterial to be modeled in a more physically accurate way. Seismic metamaterials fall perfectly in this category and are an ideal case study. In this field, metabarriers and metafoundations to shield structures from seismic waves and groundborne vibrations through a periodic arrangement of resonators are increasingly attracting attention. So far a handful of design have been proposed and while a metabarrier differs from a metafoundation in that it does not need to withstand heavy vertical loads, both rely upon the same resonant physics. Local resonances between adjacent unit-cell create bandgaps allowing waves to be reflected away from the protected structure.

The performances in terms of attenuation and bandwidth of a seismic metamaterial are directly underpinned by the size and kinematics of each resonator and also by the number of unit-cell constituting the metamaterial. Since in civil engineering one aims at reducing volumes and masses while maintaining the functionalities, the total number of resonators and their mass play a key role on the applicability of metamaterials for metabarriers and metafoundations. Here, after setting up a detailed 3D spectral element model containing the metabarrier/ metafoundation, the structure to protect, the soil and the seismic wavefield, a sensitivity analysis to guide and optimize the metamaterial design is presented and discussed. In particular the effect of graded or random resonator distributions and the ground-resonators coupling are found to be among the most influent parameters on the metabarrier/ metafoundation attenuation capacity

Numerical Modeling of Earthquake Ground Motion, Seismic Noise, Rupture Dynamics and Seismic Wave Propagation

Poster Session · Thursday · 25 April · Grand Ballroom

Spatial Grid Size Limited by the Accuracy of Interface Represented by the Discrete Grid

JIANG, L., University of Science and Technology of China, Hefei, China, jianglq@mail.ustc.edu.cn; ZHANG, W., Southern University of Science and Technology, Shenzhen, China, zhangwei@sustc.edu.cn

Finite difference method (FDM) is widely used for seismic waveform modeling. Since the computational time is proportional to the number of grid points, many higher-order and optimized schemes were developed to increase the spatial grid size while maintaining the dispersion error below predefined levels. It has been reported that 3 or 4 points per wavelength (PPW) are enough for these higher-order and optimized schemes. But such statements are only valid for homogeneous velocity models. The efficiency of such schemes is questioned for velocity models with strong velocity interfaces since large error due to the interface may arise when large grid spacing is used. To solve this problem, various effective medium parameterization methods have been proposed, in which the media parameters on the grid points are set in such a way that makes the wavefield satisfies the weld condition across the interface as much as possible.

In this work, we systematically analyze existing different effective media parameterization methods and also develop a new TTI effective media parameterization method. Our results show that the proposed TTI effective media parameterization method can be used with higher-order and optimized scheme to utilize 4-6 PPW to produce satisfactory results for moderate complex velocity models.

Finite-Difference Modelling of Seismic Wavefields Around Cavity

KRISTEK, J., Comenius University Bratislava, Bratislava, Slovakia, kristek@fmph.uniba.sk; MOCZO, P., Comenius University Bratislava, Bratislava, Slovakia, moczo@fmph.uniba.sk; GALIS, M., Comenius University Bratislava, Bratislava, Slovakia, martin.galis@uniba.sk; KRISTEKOVA, M., Slovak Academy of Sciences, Bratislava, Slovakia, kristekova@savba.sk

A uniform-grid finite-difference modelling of seismic wavefields around vacuum-filled cavity still poses a non-trivial problem because the traction-free condition has to be satisfied at a curved interface between the vacuum and elastic/viscoelastic solid. We present an algorithm that we have developed using the immersed-interface approach.

We use staggered-grid finite-difference scheme 4^{th}-order accurate in space and 2^{nd}-order accurate in time, SGFD (4,2), at all grid points except those at or near the boundary of the cavity. At these points we apply SGFD (2,2). A near grid point means that for updating wavefield in this point, the FD stencil needs at least one grid point inside cavity. We calculate the wavefield at the grid point inside cavity using an immersed interface method in order to account for the vacuum-solid boundary conditions. That is, we apply special extrapolation inside a 9x9x9 grid-point cube centered at the near point. Calculation of the 9x9x9 coefficients can be performed just once – when preparing a grid model. Effectively, the FD simulation itself is then only about 10% slower compared to the case of the same model without cavity. For calculating the coefficients we use subroutines generated by the Mathematica software. The use of Mathematica is based on the suitable parameterization of the interface.

We verified our FD algorithm by comparing the FD simulations with the finite-element simulations. We have not encountered any problem with accuracy or instability even for long time windows (we testes 225 000 time levels). The level of agreement is excellent.

We have applied the developed FD algorithm for simulating seismic wavefields in the medium modified by an underground nuclear explosion.

Numerical Modeling of Seismic Wave Fields in Media Modified by an Underground Nuclear Explosions and Identification of Cavity

KRISTEKOVA, M., Slovak Academy of Sciences, Bratislava, Slovakia, kristekova@savba.sk; KRISTEK, J., Comenius University Bratislava, Bratislava, Slovakia, kristek@fmph.uniba.sk; MOCZO, P., Comenius University Bratislava, Bratislava, Slovakia, moczo@fmph.uniba.sk; LABAK, P., CTBTO, Vienna, Austria, peter.labak@ctbto.org; GALIS, M., Comenius University Bratislava, Bratislava, Slovakia, martin.galis@uniba.sk

Nuclear explosions are banned by the Comprehensive Nuclear-Test-Ban Treaty (CTBT). Obviously, the CTBT needs reliable verification tools to make sure that no nuclear explosion goes undetected. In addition to the global monitoring systems it is necessary to have reliable tools for on-site inspections (OSI) and investigations. Among other candidate methods, possibility of detecting and interpreting of the so-called resonance seismic phenomena has to be comprehensively investigated and potentially elaborated for practical use.

Numerical modelling of seismic wave fields makes it possible to investigate resonance phenomena and their signatures in free-surface records. In collaboration with the CTBT Organization and based on extensive review of the available literature we have developed 3D realistic models of the underground structure after an UNE. The most general model consists of cavity, chimney with apical void, crushed zone, fractured zone, environment and free surface. The models include a) 2 yields of the UNE (1 kt and 10 kt), b) 4 different types of the pre-shot geological environment (tuff, alluvium, granite, rock salt) characterized by P- and S-wave speeds and quality factors, and density, c) vacuum or fluid in cavity, d) 2 depths of burial (minimal and 2-times minimal).

We performed extensive parametric numerical modelling of seismic wave fields due to plane-wave excitation (representing regional and distant events), near point double-couple sources (representing aftershocks) and seismic ambient noise. We then comprehensively analyzed the simulated wave fields in the time, frequency and time-frequency domains.

In a seismic wave field due to a distant source it is possible to identify resonant motion and locate cavity. A seismic wave field generated by an aftershock is much more difficult to interpret in terms of the cavity presence due to strong effects of a radiation pattern. Analysis of seismic noise makes it possible to identify cavity at least for relatively shallow cavities.

Validation of Broadband Ground Motion From 3D Dynamic Rupture Simulations: Towards Fine-Tuning Gmpes and Supplementing Observed Ground Motions in Data-Sparse Regions

WITHERS, K., U.S. Geological Survey, Colorado, USA, kwithers@usgs.gov; MOSCHETTI, M. P., U.S. Geological Survey, Colorado, USA, mmoschetti@usgs.gov; DURU, K., Mathematical Sciences Institute, The Australian National University, Canberra, Australia, kenneth.c.duru@gmail.com

We numerically model 3D dynamic ruptures of earthquakes along complex fault-geometry and simulate ground motion time series at surface stations, computationally accurate at frequencies up to ~5-10 Hz. Our simulations focus on modeling ruptures with realistic initial conditions (matching that of empirical observations) of both friction and stress, as well as constraints arising from datasets of fault geometry. In addition, we include nonlinear effects in our model via Drucker-Prager plasticity in a 1D layered velocity structure. By including these complexities in our model, we are able to realistically simulate ground motions at frequencies across a broad bandwidth of relevance for structural engineering purposes. Here, we focus on a dip-slip event matching the geometry of the Salt Lake City segment of the Wasatch Fault Zone and investigate the role that the hypocentral location, free-surface topography, and other rupture-related components have on ground motion. We compare our synthetically generated data with GMPEs, separating ground motion as a function of both median and variability. We analyze features that can be isolated to better understand the ability of our model to fit certain characteristics observed in empirical data: directivity, the hanging wall-effect, and distance dependence. We find good comparisons with 4 leading GMPEs models applied to near-source distances from ~Mw 7 events, but see localized variations dependent on hypocentral depth (and location along strike), in addition to influences from both small and large-scale features of fault geometry. The inclusion of off-fault plasticity is seen to directly affect ground motions across the fault plane, in particular with reduction on the hanging-wall. This suggests that we may be better able to predict future ground motions (and their possible range) from modeling instances of rupture, specific to regional and localized variation in observed fault geometry and stress conditions. Next, we plan to include 3D variations in the velocity model to study path/site effects on ground motion.

Effects of 2D Random Velocity Perturbations on Short-Period (≤ 1s) Ground Motion Simulations; Application to Site Effect Assessment in the Nice (France) Sedimentary Basin

TCHAWE, F. N., Institut de Radioprotection et de Sûreté Nucléaire, Fontenay-aux-Roses, France, tflomin@yahoo.com; GELIS, C., Institut de Radioprotection et de Sûreté Nucléaire, Fontenay-aux-Roses, France, celine.gelis@irsn.fr; BONILLA, L., IFSTTAR, Marne-la-Vallée, France, luis-fabian.bonilla-hidalgo@ifsttar.fr; LOPEZ-CABALLERO, F., Centrale Supelec, Paris, France, fernando.lopez-caballero@centralesupelec.fr

Numerical simulations of seismic wave propagation have become an essential tool for surface ground motion prediction and site effects assessment. For reliable numerical simulations of seismic ground motion, detailed velocity models are needed. Due to limited resolution of geophysical investigations, such models generally do not include small scale velocity variations. However, these variations can have an influence on short-period ground-motion, which is of interest for engineering applications. To overcome this limitation, statistical methods, characterized by autocorrelation functions, are often used to describe such small scale velocity variations.

Using two-dimensional spectral element simulations and a detailed realistic velocity model of the Nice area in France, we investigate the effect of short-wavelength (≤ 100m) heterogeneities (modeled using the Von Karman autocorrelation function) on surface ground motion at the scale of the sedimentary basin. Different combinations of autocorrelation function parameters are tested and their influence on the basin response is assessed. In particular, we show that increasing the size of velocity heterogeneities inside the basin leads to a decrease of the average ground motion amplification, computed using different realizations of the medium randomness.

Numerical Simulation of Pulse-Like Ground Motions in the Coastal Area of Osaka Bay During the 2018 Osaka Earthquake

KATAOKA, T., Tokyo University of Science, Noda, Japan, 7114018@alumni.tus.ac.jp; NAGANO, M., Tokyo University of Science, Noda, Japan, nagano-m@rs.noda.tus.ac.jp

In the near future mega crustal and/or subduction earthquakes are expected to strike Osaka City, the second largest city in Japan, causing devastating structural and economic damage. Strong seismic resilience should be constructed in this area, because metropolitan development has been rapidly accelerated for the next World Expo held in Osaka Bay area in 2025. Various previous studies have been carried out for ground motion evaluation in Osaka Bay area in the middle of the Osaka Plain. Recently, the Mw 5.5 inland shallow earthquake occurred in the northern part of the Osaka prefecture on June 18, 2018. The JMA seismic intensity scale lower 6 was observed in the Osaka prefecture for the first time. It has been reported that two types of seismic faults ruptured at the same time. Short-period pulse-like motions with predominant period of less than 1 second were observed in the vicinity of the epicenter. Distinctive pulse motions with large amplitude occurred in the later phase at the KiK-net Konohana site in the Osaka bay area. The same phenomenon also occurred during the 2011 Great East Japan Earthquake and the 2013 Awaji Island Earthquake. In this study, we investigate generation mechanism of peculiar pulse observed in the later phase of ground motions through numerical approach. First, the ground motions in the near-fault area and the coastal area of the Osaka bay are simulated using finite difference method considering long period motions with more than 0.5 second. Then, we examine the influence of these two faults and their contribution to the ground motions. Finally, the generation process of the distinctive pulse in coastal area of Osaka bay is clarified by focusing on the spatial variation of ground motions in observation array crossing the source to the coast of Osaka bay.

The SCEC Broadband Platform: Open-Source Software for Strong Ground Motion Simulation and Validation

SILVA, F., Southern California Earthquake Center, California, USA, fsilva@usc.edu; MAECHLING, P. J., Southern California Earthquake Center, California, USA, maechlin@usc.edu; GOULET, C. A., Southern California Earthquake Center, California, USA, cgoulet@usc.edu

The Southern California Earthquake Center (SCEC) Broadband Platform (BBP) is a carefully integrated and validated collection of open-source scientific software programs that can simulate broadband (0-20+ Hz) ground motions for earthquakes at regional scales. The BBP is a research tool that uses earthquake rupture and wave propagation modeling software to simulate ground motions from earthquakes.

The BBP scientific software modules implement kinematic rupture generation, low- and high-frequency seismogram synthesis using 3D wave propagation through 1D layered velocity structures, a site-effects module, several ground motion intensity measure calculations, and various ground motion goodness-of-fit tools. These modules are integrated into a software system that provides user-defined, repeatable calculation of ground-motion seismograms, using alternative simulation methods, and software utilities to generate tables, plots, and maps. The BBP has been developed over the last eight years in a collaborative project involving geoscientists, earthquake engineers, graduate students, and SCEC software developers.

The SCEC BBP software can be compiled and run on recent Linux systems with GNU compilers. The Broadband Platform continues to evolve, and new versions of the BBP are released periodically on GitHub. The latest release includes seven simulation methods, nine simulation regions covering California, Japan, Central and Eastern North America, and the ability to compare simulation results against empirical ground motion models. The newest features include the ability to simulate multi-segment ruptures using several simulation methods.

And, in addition to a new simulation method, it now includes improvements to several existing ground motion simulation methods and revised Green's functions for all simulation regions. In this release, the site response module is integrated with all simulation methods and can also be used for comparing simulated data against historical earthquakes.

Broadband Ground Motion Simulation of Nonlinear Basin Effects in Kathmandu During the 2015 Mw 7.8 Gorkha Earthquake

AYOUBI, P., California Institute of Technology, California, USA, ayoubi@caltech.edu; ASIMAKI, D., California Institute of Technology, California, USA, domniki@caltech.edu

We study the 3D nonlinear basin effects in Kathmandu Valley, Nepal during the 2015 Mw 7.8 Gorkha earthquake using a hybrid broadband ground motion simulation approach. We are particularly interested in understanding the source of frequency and amplitude characteristic, and the reasons they pertain to the lack of high frequency components. In order to do that, we couple a kinematic source model with a realistic 3D geometry of Kathmandu basin, which accounts for nonlinear behavior in unconsolidated sediments, to capture low frequency component of ground motion. Moreover, a stochastic approach is used to include the high frequency portion of ground motion. We finally combine the resultant time-histories in corresponding frequency ranges to investigate the behavior of Kathmandu basin during the mainshock. Despite the scarcity of material properties, stratigraphy information, and geotechnical databases, our results show that our model significantly improves ground motion prediction compared to rudimentary 1D and 2D basin analyses. Our goal is to use the validated model to derive a synthetic Ground Motion Prediction Equation (GMPE) for the capital and the most populated region of Nepal.

Attenuation Characteristics of Central Asia

SEDAGHATI, F., AON | Impact Forecasting, Illinois, USA, farhad.sedaghati@aon.com; NAZEMI, N., The University of Memphis, Tennessee, USA, nnazemi@memphis.edu; PEZESHK, S., The University of Memphis, Tennessee, USA, spezeshk@memphis.edu; ANSARI, A., International Institute of Earthquake Engineering and Seismology, Tehran, Iran, Islamic Republic Of, a.ansari@iiees.ac.ir; DANESHVARAN, S., AON | Impact Forecasting, Illinois, USA, siamak.daneshvaran@aon.com

This study aims to determine the quality factor of P-waves Q_P, S-waves Q_S, and coda waves Q_C, in central Asia. We collected and compiled a database composed of 361 broadband seismograms from 186 local earthquakes recorded by 25 stations located in Afghanistan, Tajikistan, Uzbekistan, and Kazakhstan. These events have magnitudes ranging from 3 to 5.5 and hypocentral distance less than 200 km. Coda Q has been inferred for different coda window length of 20, 30, 40, and 50 sec using the single backscattering method. The coda Q values increase by increasing the coda window length indicating that the lower part of lithosphere is more homogenous than the upper part. For a coda window length of 40 sec, we obtained $Q_C = 294 f^{0.586}$ and $Q_C = 288 f^{0.598}$ for the vertical and horizontal directions, respectively, in the frequency range of 1 to 20 Hz. Our results show relatively low Q_0 values and strong frequency dependence behavior for coda and body waves in central Asia. Active regions often show strong frequency dependence of coda and body waves and the region under study follows a similar trend. Using the multiple-station coda normalization, we determined $Q_P = 158 f^{0.706}$ and $Q_S = 152 f^{0.856}$, in the frequency range of 1 to 20 Hz. Using the multiple-scattering interpretation of coda Q, intrinsic absorption and scattering attenuation have been separated. The intrinsic absorption is found to be very close to the coda attenuation and it dominates over the scattering attenuation particularly at high frequencies. Results from this study imply the presence of high degree of small-scale heterogeneities in the Earth's crust and upper mantle beneath this region.

Revised Estimates of Ground Shaking Hazards From Large Earthquakes Near Trinidad and Tobago

LYNCH, L. L., The University of the West Indies, St. Augustine, Trinidad and Tobago, llynch@uwiseismic.com; PAPADOPOLOUS, I., The University of the West Indies Seismic Research Centre, St. Augustine, Trinidad and Tobago, ilias@uwiseismic.com

The twin island republic of Trinidad and Tobago is located near the southern margin of the ocean-ocean convergent zone in the eastern Caribbean, where tectonic motion between the interacting Caribbean, North American and South American plates transitions from subduction to strike slip. Earthquake ground motion in this region is influenced by a variety of seismic sources located at varying hypocentral and epicentral distances. The complexity of the hazard from earthquakes is further compounded by the presence of a number of deep sedimentary basins, other tectonic and topographic structures that tend to accentuate ground shaking. Previous seismic hazard assessments of the region have been based on probabilistic estimation of ground shaking from seismicity data and seismo-tectonic inference. In this submission, we use limited strong motion/broadband data microzonation data, and simulations (*e.g.* Empirical Green Functions method) to produce revised estimates of the hazard posed by future large earthquakes. Our results show that anomalous amplification by sedimentary basins and topographic effects will account for a significant portion of the hazard.

Ground Motion Simulations for an M4.2 Aftershock of the Niigata-Chuetsu Earthquake of 2007 Using Large-Scale Wavefield Simulations

MOTAMED, R., University of Nevada Reno, Nevada, USA, motamed@unr.edu; SAXENA, S., University of Nevada Reno, Nevada, USA, swasti@nevada.unr.edu; RYAN, K., University of Nevada Reno, Nevada, USA, klryan@unr.edu

The aim of this research is to generate realistic ground motions utilizing a physics-based approach with advanced finite difference methods. These simulated ground motions are validated against recorded ground motions. To that end, SW4 code was used for large-scale wavefield simulations and the HPC cluster at University of Nevada Reno was used to overcome computational challenges. The code allows for complex geometries and heterogeneous material properties with realistic boundary and interface conditions, while achieving a 4th order accuracy of the 3D visco-elastic wave equations that are used to model the earthquake.

The site of interest is the widely studied geotechnical downhole array, Service Hall Array (SHA), at Kashiwazaki-Kariwa Nuclear Power Plant (KKNPP) in Japan, and the event simulated is a M4.2 aftershock of the 2007 Niigata-Chuetsu earthquake. This aftershock event was chosen since its epicenter, located in proximity (4 km) to KKNPP, allowed the use of a smaller computational domain and a finer grid to improve the quality of synthetic seismograms. The surface-focused structured mesh refinement (SMR) feature in SW4 allows for a finer grid to accommodate lower compressional and shear wave velocities in the shallow layers. The maximum frequency computed from the synthetic seismograms was 3 Hz.

Recorded data from SHA was utilized to validate the simulated ground motions; acceleration time histories as well as Fourier Amplitude Spectra were compared. Simulations using a Community Velocity Model (CVM) were contrasted with those using a CVM integrated with the site-specific material properties for shallow layers. Comparison of the same with recorded ground motions provided insight into the improvements in synthetic seismograms for a thoroughly studied site.

Simulating the Near-Fault Large Velocity Pulses Response of the Chi-Chi (Mw 7.6) Earthquake With Kinematic Model

CHEN, X., Institute of Geophysics, China Earthquake Administration, Beijing, China, xueliang_chen@aliyun.com; LUO, Q., Institute of Geophysics, China Earthquake Administration, Beijing, China, 120178319@qq.com; GAO, M., Institute of Geophysics, China Earthquake Administration, Beijing, China, gaomt1957@163.com; LI, Z., Institute of Geophysics, China Earthquake Administration, Beijing, China, lizongchaoigo@163.com

The large number of pulses recorded during the 1999 Mw7.6 Chi-Chi, Taiwan earthquake provided an important data base for this study. The prediction of near-fault velocity pulses generated by large earthquakes can provide some reference for the Engineering anti-earthquake design. Based on the established source model and velocity structure model, this paper attempts to use the 3D finite difference method to simulate the 33 near-fault large velocity pulses. The conclusions as the following: (1) Two-segment "shovel-like" fault model constructed by 3D bending plane can better describe the characteristics of the underground real fault. (2) The seismic moment and rise time of the 6 asperities determine the peak and period of the velocity pulse. The asperities located at shallow low angle mainly affect the horizontal pulse components, and the asperities at high angle contribute more to the vertical pulse component. (3) The difference in sliding properties between the north and south ends of the fault causes a difference in the horizontal pulse components, reflecting the characteristics of the fling-step effect and directivity effect. (4) The characteristic period of the velocity response spectrum has the maximum near the turning point at the northern end of the fault and shows a very obvious hanging wall effect in the near-fault region, resulting in the large-scale structures have severe damage because of large resonance effect. (5) PGV gradually increases from south to north along the fault and PGV on the hanging wall is significantly larger than PGV on the footwall, and the distribution of the pulse in front of the rupture is wider than that of the rear. Because the simulation results are basically consistent with the real records, this also verifies the feasibility of simulating pulse-like ground motions with the 3D finite difference method.

New Empirical Model for Vertical to Horizontal Ratio of Earthquake Components for Central and Eastern North America and Comparison With Existing Models

MALEK, M., WSP USA, California, USA, mojtaba.malek@wsp.com

An empirical ground motion model is developed for the response spectral ratio of vertical-to-horizontal (V/H) components of earthquakes for the Central and Eastern United States (CENA) and Gulf Coast region. The model can be used to develop site-specific vertical design spectrum by scaling the horizontal design spectrum resulting from a site-specific study. The functional form for the proposed model considers three distinct components for source, path, and site terms. The model evaluation is based on a comprehensive set of regression analyses of the Next Generation Attenuation (NGA-East) database of CENA recordings with the moment magnitude Mw ≥ 3.4 and the rupture distance RRup < 1000 km.

The Pseudo Spectral Accelerations (PSAs) from the NGA-East database are the 50th percentile (or median) PSA value computed from the orthogonal horizontal motions rotated through all possible non-redundant rotation angles, known as the RotD50. The RotD50 values are used along with the vertical PSAs to perform regression analysis using the nonlinear mixed-effects regression algorithm. The model is used to calculate and compare site-specific vertical design spectra for a site in New York and results were compared with existing models.

A Suite of Exercises for Testing Dynamic Earthquake Rupture Codes

HARRIS, R., U.S. Geological Survey, California, USA, harris@usgs.gov

Earthquakes are complicated, and a range of techniques are used to study them. Computational simulations are included in this toolbox of techniques. A particular type of computational simulations is called 'dynamic earthquake rupture simulations'. Dynamic earthquake rupture simulations provide a multitude of capabilities. They incorporate the fault geometry, the time-dependent stresses on and off the faults, the response of the off-fault rocks to stressing, and the behavior of fault friction. These simulations produce results that include ground and subsurface wave-propagation throughout the model, and slip-velocity patterns on the faults. With these impressive capabilities, these types of simulations are also challenging in that there are no analytic solutions with which to test them. The 30-member international SCEC-USGS Dynamic Earthquake Rupture Code Verification Group has tackled this problem by providing a suite of exercises to verify that these types of computer codes are working as expected. We have constructed 40 earthquake-rupture exercises for people to use to test their codes. These exercises are available on our website scecdata.usc.edu/cvws.

For more details about our group and the benchmark exercises, please also see our paper: Harris *et al.* (2018), A suite of exercises for verifying dynamic earthquake rupture codes, Seism. Res. Lett., 89(3), 1146-1162, https://doi.org/10.1785/0220170222.

Large Data Set Seismology: Strategies in Managing, Processing and Sharing Large Geophysical Data Sets

Poster Session · Thursday · 25 April · Grand Ballroom

Extending the Peterson Noise Models to 100 Hz Based on 24 Million Power Spectra From IRIS Mustang

WOLIN, E., U.S. Geological Survey, Colorado, USA, wolin.emily@gmail.com; MCNAMARA, D. E., U.S. Geological Survey, Colorado, USA, mcnamara@usgs.gov

Over the past 25 years, seismic data have been recorded at increasing sample rates thanks to interest in novel scientific targets and advances in instrumentation and data storage. However, the standard baselines used to assess data quality, the New High (NHNM) and Low Noise Models (NLNM) of Peterson (1993), cannot be used to evaluate the quality of data at frequencies > 10 Hz. To extend these models to higher frequencies (10-100 Hz), we downloaded the probability density functions (PDFs) of 24 million power spectral density (PSD) curves calculated from all publicly available high-sample-rate seismic data using the Incorporated Research Institutions for Seismology (IRIS) Data Services (DS) MUSTANG quality control system. High-frequency high and low noise models were computed by matching the appropriate composite PSDPDF percentile points to NHNM and NLNM power levels at overlapping frequencies and then extending to higher frequencies (10-100 Hz, or 0.01-0.1 s period) with piecewise linear fits to the same matching PSDPDF percentile.

The high-frequency noise models include a high-noise model and two low-noise models for permanent and portable seismic stations. The high-noise model reflects aftershock deployments' typical noise levels and scientific targets and is defined by the 90th percentile of a composite PSDPDF for USGS aftershock deployments. The two low-noise models are defined by the lowest noise levels (1st percentiles) observed for high-sample-rate portable deployments and for permanent stations. We anticipate that these noise models will be useful in automated quality control of high-sample-rate seismic data, and that they will evolve with advances in instrumentation and as new data become available.

Recent Advances to PASSCAL Software for Managing and Archiving Seismic Data

HESS, D., PASSCAL Instrument Center, NMT, New Mexico, USA, dhess@passcal.nmt.edu; CAROTHERS, L., PASSCAL Instrument Center, NMT, New Mexico, USA, lloyd@passcal.nmt.edu; BEAUDOIN, B. C., PASSCAL Instrument Center, NMT, New Mexico, USA, bruce@passcal.nmt.edu; FALCO, N., IRIS Data Management Center, Washington, USA, nick@iris.washington.edu

IRIS PASSCAL continues to improve existing software as well as develop new software to aid the seismic community in efficiently archiving seismic data. Recent additions to the PH5 software suite and PH5 data format to streamline processing and increase efficiency were made in response to community feedback. IRIS PASSCAL has also released a new software application, NEXUS, in response to rising community need to more easily edit and generate StationXML and to simplify the data archiving process.

PH5 is a data format and accompanying software suite designed to efficiently work with a large variety of seismic and geophysical data (*e.g.* time-series data and associated meta-data). PH5 is built on HDF5 allowing for the efficient storage and access of large time-series data sets. Recent advances in the PH5 software suite allow for a faster, simpler, and more integrated approach to creating and working with a PH5 data volume. The new PH5 graphical, integrated environment allows users to create, load, edit, and view data and meta-data stored in PH5. Integrated tools also allow a user to validate a PH5 data volume before submitting it to the IRIS DMC. FDSN compliant webservices (station, dataselect, and event) allow users to extract station meta-data, data, and event information from the PH5 data volume. The PH5 software suite also supports output in SEG-Y through a web page interface.

NEXUS is an easy to use software tool to efficiently generate SEED meta-data in StationXML format. NEXUS is designed primarily for campaign-style, temporary networks in that it exposes only a subset of meta-data fields needed to create a valid StationXML document. NEXUS leverages the IRIS Nominal Response Library (NRL) to streamline loading responses into StationXML and reduce user input for standard response information. NEXUS abstracts the details of SEED format and inspects MiniSEED data to populate many of the meta-data fields. NEXUS uses the community developed ObsPy python package and parts of NEXUS functionality have been contributed to ObsPy for community use in their own programs.

Building, Using and Validating 3D Geophysical Models

Poster Session · Thursday · 25 April · Grand Ballroom

Towards and Understanding of the Stability of Lg Amplitudes

LI, D., University of Missouri, Missouri, USA, dlyqk@mail.missouri.edu; SANDVOL, E. A., University of Missouri, Missouri, USA, sandvole@missouri.edu; KAVIANI, A., University of Frankfurt, Frankfurt, Germany, kaviani@geophysik.uni-frankfurt.de; GOK, R., Lawrence Livermore National Laboratory, California, USA, gok1@llnl.gov

Using repeated Reverse Two Station (RTS) measurements we have been able to quantify the stability and reliability of high-frequency Lg attenuation. We have noticed that for many regions Lg amplitudes can be quite unstable leading to large uncertainties in estimates of Lg Q(f). Since the reverse two station paths should effectively eliminate source and site effects, the path effects should be consistent for all repeated paths. Therefore, we are only left a number of the possible explanations for the observed large variations in the RTS amplitude reductions. In this study, we use an approach that we term the Double Two Station Method (DTSM) to measure the effect of the source depth and the source epicentral distance to Lg Q.

In this work, we have examined the behavior of the DQV (the difference of the Lg Q value multiplied by the Lg velocity) for a large number of DTSM station paths in the northern Middle East. We observe a distinct decrease in the stability of Q value as the distance between the two events increases for some station pairs in the northern Zagros Mountains. Different path lengths could likely lead to different modes of Lg propagation, which sample different parts of the crust and thus give different observed Q values. There is still overlap in the distribution of the DQV values for events located close by and those farther apart. This would suggest that there are still other significant causes for high-frequency Lg amplitude instability. One possible explanation is that the source depth could lead to significant variations in Q values. We are using a similar approach to isolate the effect of source depth on the variations in Lg propagation.

Subsurface Structure of Yatsushiro Plain, Japan Inferred From the Observed H/V Spectral Ratio of Microtremors

MATSUSHIMA, S., Disaster Prevention Research Institute, Kyoto University, Uji, Japan, matsushima@sds.dpri.kyoto-u.ac.jp

As part of a project "Integrated active fault survey considering the 2016 Kumamoto Earthquake", survey of the subsurface structure was conducted in the Yatsushiro plain, Kumamoto, Japan where there is high risk of strong ground shaking during an earthquake to occur on the Hinagu fault zone. The 2016 Kumamoto Earthquake occurred on the northern part of the Hingau fault zone, and it is accepted apprehensively that the southern part may rupture in the near future. We observed microtremors along four survey lines intersecting the boundary between the plain and the mountainous area. The microtremor horizontal-to-vertical spectral ratios (MHVRs) showed different characteristics from survey line to survey line, so it is suggested that the lateral heterogeneity of the subsurface structure of Yatsushiro plain is complex. We attempt to estimate the conditions of the lateral heterogeneity of the subsurface structure from the characteristics of the MHVRs.

Cascadia 3D P- and S-Wave Velocity Model for Ground Motion Simulations: Past, Present and Future

STEPHENSON, W. J., U.S. Geological Survey, Colorado, USA, wstephens@usgs.gov

I review the Cascadia three-dimensional (3D) P- and S-wave velocity (*Vp* and *Vs*, respectively) model developed in support of ground motion simulations and earthquake hazards studies in the Pacific Northwest. I discuss the philosophy behind the model's development, present the history and evolution of the model, describe its use and what I perceive as its key limitations. This model, which incorporates the Cascadia subduction zone, encompasses the region from about 40.2°N to 50°N latitude, and from about 122°W to 129°W longitude from mean sea level to 60 km depth. Development of the Cascadia model began in 2003 and evolved into the version described in Stephenson (2007). This presentation describes the updated version of Stephenson *et al.* (2017). EarthVision® modeling software was used throughout model development. The backbone of the velocity property volumes is a simplified geologic model consisting of: (1) continental sedimentary basins, (2) continental crust, (3) continental mantle, (4) oceanic sediments, (5) oceanic crust (including the subducting slab), and (6) oceanic mantle. The model volume incorporates bathymetry as part of the oceanic crust and oceanic sediments but does not incorporate topography. *Vp* and *Vs* within each of the geologic units are derived from published values. Currently, the model can support a subduction zone rupture in excess of 1000 km. I envision key updates to this Cascadia model will include full topography, a geotechnical (weathered) layer, and improved shallow *Vs* in basins that are not constrained by the needs of legacy software and hardware for 3D ground motion simulations. With the current development of the National Crustal Model (Boyd and Shah, 2016), it is plausible that future versions of this model may be directly integrated with that effort. In its current form, the existing Cascadia model can be considered to be a template for a community velocity model of the Cascadia region.

Updating the USGS San Francisco Bay Area 3D Seismic Velocity Model to Improve Ground Motion Estimates

HIRAKAWA, E. T., U.S. Geological Survey, California, USA, ehirakawa@usgs.gov; AAGAARD, B., U.S. Geological Survey, California, USA, baagaard@usgs.gov

Numerical simulations of earthquake ground motions are important for seismic hazard evaluation, as they provide more insight into complex attributes of seismic motions than empirical regressions. We focus on improving the accuracy of ground motion estimates for a region east of the Hayward fault, which previous studies have identified as needing adjustment. We update the empirical rules used to assign elastic properties to the Great Valley Sequence and Cenozoic sedimentary rocks in the USGS San Francisco Bay Area 3D geologic model using ground motion simulations of local earthquakes. The current work is part of an ongoing effort to improve this model by more closely reproducing observed ground motions.

We simulate motions from five Mw 3.0-4.4 earthquakes on the Hayward Fault. The data we use to compare with our synthetics are obtained from broadband stations in local networks within ~25 km of the earthquake epicenters. Some stations lie to the west of the fault zone above Franciscan Complex rocks, while others like to the east of the fault zone above more compliant Great Valley Sequence and Cenozoic sedimentary rocks. In addition to the high seismic hazard associated with the Hayward Fault, this bimaterial contrast makes the study area particularly interesting. The current empirical rules assign seismic properties to geologic units as functions of depth; however, this methodology neglects other factors such as complex deformation or uplift, which is a prevalent feature of the local geology. In this study, we will adjust the rules to more carefully consider the geologic history of rock units. The goal is to show improvements to synthetic waveforms at frequencies up to ~1 Hz based on comparisons with observed motions. We address adjustment uniqueness by considering the best-fitting model over all earthquake simulations.

Complicated Crustal Structure Beneath Northeast China Revealed by Receiver Function Analyses

CHEN, Q., Institute of Geology and Geophysics, Chinese Academy of Sciences, Beijing, China, chenqf@mail.iggcas.ac.cn; LI, T., Institute of Geology and Geophysics, Chinese Academy of Sciences, Beijing, China, tianjueli@163.com

Northeast China locates between the Siberian Craton and the North China Craton. Complicated but episodic evolution shapes the basic geological settings in present NE China. Based on our broadband NECsaids Array stations' records from July 2010 to June 2017, as well as CEA permanent stations' records from July 2008 to June 2017 and NECESSArray records from September 2009 to August 2011, we acquired 33752 P-wave receiver functions in total with high quality. And then using H-κ and CCP stacking techniques, we obtained the highest-resolution crustal structure in central-south part of NE China, which consists of 231 measurements of crustal thickness and Vp/Vs ratio (including 89 measurements from former studies) and 3 CCP stacking profiles. The five micro-continental blocks in our study region show different crustal structure distinctly. The south-central part of the Zhangguangcai Ranges owns the similar crustal thickness and Vp/Vs ratio as the northeastern part of the North China Craton. The southeastern part of the Songliao Block has the thinnest crust and highest crustal Vp/Vs ratio. As for the western Khanka Block, it keeps a slightly thicker crustal thickness while with the lowest crustal Vp/Vs ratio. The southwestern part of the Jiamusi Massif owns an ordinary crustal Vp/Vs ratio but its crust is the thickest. The northern segment of the Tanlu Fault Zone appears to have different crustal structure in its northern and southern parts, though its Moho interface has been cut across along the whole fault zone. For its northern part (44.4°N-47°N), the Moho interface between the two main branches appears to drop down. While for the southern part (41.5°N-43.3°N), the Moho interface changes into being uplifted under the fault zone. Around the Changbaishan Tianchi volcano, the Moho interface under the caldera subsides and the measurements at 3 stations with high Vp/Vs ratio located at the north and east of the caldera within 10 km may indicate the present crustal magma.

Regionalized Properties of the Lowermost Mantle From Spherical Slepian Analysis

OLUGBOJI, T. M., University of Rochester, New York, USA, tolulope.olugboji@rochester.edu; MOULIK, P., University of Maryland, Maryland, USA, moulik@umd.edu; PLATTNER, A., University of Alabama, Alabama, USA, amplattner@ua.edu; LEKIC, V., University of Maryland, Maryland, USA, ved@umd.edu

Lower mantle structure is dominated by a pair of large, antipodal, low shear velocity provinces (LLSVPs) located beneath Africa and the Pacific Ocean. Though LLSVPs are dominantly long-wavelength (degree 2) features imaged in earliest tomographic models, their nature and origin remain enigmatic. A number of hypotheses have been proposed to address their origin, summarized by two end-member scenarios: (1) they represent thermochemical piles that are either primordial or have grown over time, such as by the accumulation of subducted oceanic lithosphere, (2) they are purely thermal features, seen through the lens of tomographic imaging.

Characterizing smaller-scale structures within and outside the LLSVPs may yield insights allowing us to distinguish between these two interpretations. Therefore, we compare the amplitude and length-scales of velocity heterogeneities within and outside the LLSVPs and analyze their variation with height above the core-mantle boundary. This requires estimating the wavenumber spectrum of heterogeneity by localizing it from a global tomographic model. Using spatially abrupt windowing functions leads to unreliable spectral estimates due to their non-compact spatiospectral concentration. We adopt a spherical Slepian approach that balances the trade-off between spatial localization and spectral leakage. For an optimal Slepian taper, the useful bandwidth is controlled by a trade-off between tomographic-model resolution, taper-bandwidth, and LLSVP surface-area. We divide the lower mantle into 6 regions enabling us to extend the useful spectral bandwidth and compare heterogeneity across LLSVP and non-LLSVP regions. We identify robust features by quantitatively assessing the similarities and differences in the spectrum of heterogeneity across a collection of global tomographic models. We show that structure within the African LLSVP is more vertically continuous that in the Pacific.

Sensitivity Tests of Topographic Effects on 3D Simulated Ground Motions in Reno, Nevada

ECKERT, E., University of Nevada Reno, Nevada, USA, eeckert@nevada.unr.edu; DUNN, M., University of Nevada Reno, Nevada, USA, michelledunn@nevada.unr.edu; LOUIE, J. N., University of Nevada Reno, Nevada, USA, louie@seismo.unr.edu; SMITH, K., University of Nevada Reno, Nevada, USA, ken@unr.edu

The availability of cheap computational power has enabled the construction of 3d physics-based models that facilitate the exploration of geologic basins effects on the duration and destructiveness of earthquake shaking. As the resolution of these simulations improves, surface topography may have increasingly pronounced effects on ground motion. In order to examine the consequences of topographic features in a real basin, we have constructed two material property models of the Reno basin in Northern Nevada. A framework using Python, pySW4, Dask, HDF5,and sklearn streamlines the construction of these material models as binary rfiles at 25m resolution. While both models include basin geometry determined by gravimetry, one contains topographic extent while the other is an flat earth model with the same basin thicknesses. Our previous work has explored this basin using recorded events and 3 Hz synthetics generated with SW4. Even at these frequencies many of the synthetic seismograms showed significant mismatches when compared to recordings. This new work examines the role of topography in explaining some of these effects.

Three-Dimensional Tomography of the Crust and Uppermost Mantle of Eastern Nepal

HO, T., University of Cambridge, Cambridge, United Kingdom, th332@cam.ac.uk; PRIESTLEY, K., University of Cambridge, Cambridge, United Kingdom, kfp10@cam.ac.uk; ROECKER, S., Rensselaer Polytechnic Institute, New York, USA, roecks@rpi.edu; GUPTA, R., National Seismological Center, Kathmandu, Nepal, crystal.ratna@gmail.com

The continent-continent collision of the Indian Plate with southern Eurasia has produced the highest mountains— the Himalaya— and the largest and highest plateau— Tibet— on Earth today. The youthful nature of the Himalayan orogen makes it the paramount locality for studying mountain-building, and studies of the Himalaya have shaped much of what is known about the rheology of the continental lithosphere We build a high-resolution wavespeed models of eastern Nepal using data from ~200 seismic stations extending from western Nepal to the Indian state of Sikkim. We employ an inversion procedure that simultaneously models absolute local and regional earthquake P and S arrival times, relative teleseismic arrival times and surface wave group delay times from ambient noise and regional earthquakes to obtain 3-D velocity structure beneath the region. Including local earthquake allows for higher-resolution imaging of structure, as both the higher frequency content of local earthquake seismograms and the presence of the earthquake sources within the model volume generally allow for finer spatial sampling. A key feature of the inversion procedure is that the travel times are generated using a finite difference solution to the eikonal equation providing increased accuracy in the highly heterogeneous medium expected for the Himalaya. The teleseismic body waves recorded by large aperture seismic arrays allow illumination of the deeper structure of the mantle. The earthquakes within the volume are relocated in the heterogeneous structure Much of the seismicity is clustered to the west of Kathmandu at depths < 30 km. There is a clear image of the Main Himalayan thrust extending from a depth of ~5 km beneath the Himalayan foothills to ~12 km depth beneath the Lesser Himalaya. Small areas of strong fast wavespeeds exist in the center of the region in the upper 30 km of the crust. At depths of 40-50 km, large areas of slow wavespeeds are present which track along the plate boundary.

High Resolution 3D Wavespeed Model of the Iranian Plateau Lithosphere

IRANDOUST, M., Institute for Advanced Studies in Basic Sciences, Zanjan, Iran, Islamic Republic Of, ma824@cam.ac.uk; PRIESTLEY, K., University of Cambridge, Cambridge, United Kingdom, kfp10@cam.ac.uk; SOBOUTI, F., Institute for Advanced Studies in Basic Sciences, Zanjan, United Kingdom, farhads@iasbs.ac.ir

The Iranian Plateau forms a broad zone of deformation located between the Arabian and Eurasian Plates. The Arabian-Eurasian collision is similar to the Indo-Eurasian which formed the Himalaya and Tibet but is much younger. Studies of the Iranian Plateau can provide clues to understanding the earlier stages of the continent-continent collision process. To determine the lithospheric structure of this region we determine fundamental mode Rayleigh wave group velocity for 5-70 s periods using large regional earthquake and ambient noise data sets. We build Rayleigh wave tomographic maps including both isotropic and azimuthal anisotropic terms for group velocity. At short periods (<20s) there is no clear anisortopic pattern; at longer periods (>20s) the azimuthal anisotropy trends are more uniform. The southern Zagros, central and eastern Iran and Kopeh-dagh show NE-SW anisotropic trends which are close to reported GPS velocity vectors; the northern part of Zagros shows NW-SE trend and an E-W orientation is dominant in the Alborz and northwest Iran. To achieve a more detailed 3D Vsv models we jointly inverted the group velocity dispersion with P-wave receiver functions at more than 200 seismograph sites in the Zagros Mountains and Iranian Plateau obtaining a high resolution wavespeed model for the crust and uppermost mantle. The crust is as great as 60 km thick below the Zagros Mountains and 50 km thick beneath the Alborz Mountains but thinner (35-45 km) below the central Iranian Plateau. The low shear velocity anomalies of the upper crust correspond to the regions of thick sediments such as Caspian Basin, Zagros fold and thrust belt, Makran accretionary zone, and central Iran basin. The Sanandaj-Sirjan metamorphic zone and the Lut block show higher velocities for the upper crust. In the lower crust there is a boundary separating low-velocity Zagros from the rest of Iran, the deeper parts, representing the uppermost mantle, show higher velocities for Zagros which we interpreted as a thick lithospheric Zagros root compared to a thin lithosphere beneath central Iran

Building a Three Dimensional Model of Plio-Quaternary Basin of Argostoli (Cephalonia Island, Greece) From an Integrated Geophysical and Geological Approach to Perform Numerical Simulations of Seismic Motion

CUSHING, E. M., Institut de Radioprotection et de Sûreté Nucléaire, Fontenay-aux-Roses, France, edward.cushing@irsn.fr; TOUHAMI, S., SSMat,CNRS, CentraleSupélec, Gif-sur-Yvette, France, sara.touhami@centralesupelec.fr; HOLLENDER, F., CEA Cadarache, St Paul-lez-Durance, France, fabrice.hollender@cea.fr; LOPEZ-CABALLERO, F., SSMat,CNRS, CentraleSupélec, Gif-sur-Yvette, France, fernando.lopez-caballero@centralesupelec.fr; MOIRIAT, D., IRSN, Fontenay-aux-Roses, France, denis.moiriat@irsn.fr; GUYONNET-BENAIZE, C., Setec International, Vitrolles, France, cedric.guyonnet@setec.com; THEODOULIDIS, N., ITSAK, Thessaloniki, Greece, ntheo@itsak.gr; PONS-BRANCHU, E., LSCE/IPSL, CEA-CNRS-UVSQ, Université Paris-Saclay, Gif-sur-Yvette, France, edwige.pons-branchu@lsce.ipsl.fr; SEPULCRE, S., GEOPS, Université Paris-Saclay, Orsay, France, sophie.sepulcre@u-psud.fr; BARD, P., University Grenoble Alpes, ISTerre / IRD, Grenoble, France, pierre-yves.bard@univ-grenoble-alpes.fr; CORNOU, C., University Grenoble Alpes, ISTerre / IRD, Grenoble, France, cecile.cornou@univ-grenoble-alpes.fr; DECHAMP, A., CEA, DIF, Bruyeres-le-Chatel, France, aline.dechamp@cea.fr; MARSICAL, A., University Grenoble Alpes, ISTerre / IRD, Grenoble, France, armand.mariscal@ird.fr; ROUMELIOTI, Z., Aristotle University, Thessaloniki, France, zroum@auth.gr

The Cephalonia Island (Greece) area is located in the north-western end of the Aegean subduction frontal thrust that is linked to the dextral Cephalonia Transform Fault (west of Cephalonia). As the mean slip rate and the length of the Cephalonia Transform Fault are large, the seismic hazard is high in terms of earthquake frequency and magnitude. The Plio-Quaternary Koutavos-Argostoli basin site was selected within the French Research Agency PIA SINAPS@ project (www.institut-seism.fr/projets/sinaps/) to host a vertical accelerometer array. The long-term goal is to validate three-dimensional nonlinear numerical simulation codes to assess the site-specific amplification and nonlinearity in the framework of seismic hazard assessment. Geological and geophysical surveys were carried out from 2011 to 2017. The aim of this work is to present i) the geological and structural context, ii) the complementary geological, geotechnical, and iii) the geophysical investigations that led to the identification of the main geotechnical bodies and their structures. The characterization of the three-dimensional structure of the stratigraphic units was achieved by coupling geological cross-sections (*i.e.*, depth geometry) and HVSR/AVA geophysical surveys that were designed to identify the sedimentary body thickness. The data gathered allowed to build a three-dimensional geological model of the Argostoli basin. Starting from this point, a 3D numerical model on the same area was constructed using spectral element code known as SEM3D. Several simulations of seismic scenarios were performed, for the purpose of highlighting the importance of the use a representative model of the complexity of the wave path on the hazard assessment.

Ambient Noise Empirical Green's Function Full Waveform Tomography for the Northern Mississippi Embayment

YANG, Y., Center for Earthquake Research and Information, University of Memphis, Tennessee, USA, yyang14@memphis.edu; LIU, C., Center for Earthquake Research and Information, University of Memphis, Tennessee, USA, cliu5@memphis.edu; LANGSTON, C. A., Center for Earthquake Research and Information, University of Memphis, Tennessee, USA, clangstn@memphis.edu

Ambient noise data recorded by 244 broadband seismic stations within the Northern Mississippi Embayment (NME, 86ºW-94ºW, 33ºN-38ºN) over the time period of 1990 to 2018 are used to extract empirical Green's functions (EGFs) by seismic noise interferometry. The EGFs between pairs of seismographs are estimated from the long-time cross-correlation of ambient noise. With the traditional time-domain normalization to remove transient noise and earthquakes, the signals in the cross-correlation will inevitably loose amplitude information and small earthquakes could get through the procedure and hide in the data. However, the amplitude of signals in the cross-correlations are useful for direct source location, attenuation analysis, differentiating sources and small earthquakes in the data could cause confused high amplitude signals around 0 delay time in the cross-correlations. To avoid these flaws of the time-domain normalization method, we apply a new hybrid seismic de-noising method using wavelet block thresholding to remove earthquakes and other signals. Rayleigh wave group velocity dispersion curves are then estimated from the EGFs using frequency-time analysis and used to invert for a 1D velocity model at each station. Starting with this initial model, the EGFs are next utilized as waveform data for 3D full waveform tomography to acquire the final 3D model for NME. A CUDA-enable collocated grid finite difference code is used to do the waveform modeling and inversion. The final 3D model illuminates several geological and tectonic features such as Reelfoot Rift and is useful for future seismic hazard analysis and seismic source determinations.

Updates to the Regional Seismic Travel Time (RSTT) Tomography Model

BEGNAUD, M., Los Alamos National Laboratory, New Mexico, USA, mbegnaud@lanl.gov; MYERS, S., Lawrence Livermore National Laboratory, California, USA, myers30@llnl.gov; YOUNG, B. A., Sandia National Laboratories, New Mexico, USA, byoung@sandia.gov

The Regional Seismic Travel Time (RSTT) tomography model has been developed to improve travel time predictions for regional phases (Pn, Sn, Pg, Lg) in order to increase seismic location accuracy, especially for explosion monitoring. The RSTT model is specifically designed to exploit regional phases for location, especially when combined with teleseismic arrivals. The latest RSTT model (version 201404um) is located on the Sandia National Laboratories web site (http://www.sandia.gov/rstt). We are in the process of updating the RSTT model to include new features. The original model used CRUST2.0 combined with an a priori model in Eurasia from US National Laboratories. The newest crustal update will use the CRUST1.0 version that includes more detailed and realistic structures. New event data are also being compiled that include global ground-truth (GT) information from local, regional, and teleseismic bulletins as well as data obtained through various RSTT workshops in South America, Latin America, Asia, and Africa. Using the new crust and available data, the tomography will be updated for improved coverage and accuracy. Another new feature is the addition of path-dependent uncertainty estimates for all regional phases in RSTT. For a 2/2.5D model like RSTT, we want to have a path-dependent uncertainty determination with a similar dimension as the model itself. This accounts for spatial variations in empirical data which could lead to bias in the model depending on the specific ray path. The goal for RSTT is to have the general user be able to estimate a path-dependent travel time prediction uncertainty on-the-fly using the available software just like users do for actual travel time itself. We also demonstrate validation of the new model and uncertainty estimates using the International Monitoring System stations and Reviewed Event Bulletin events.

A Bayesian Approach to Regional Phase Blockage Imputation at the Iranian Plateau

HUI, H., University of Missouri, Missouri, USA, hhdhf@mail.missouri.edu; SANDVOL, E. A., University of Missouri, Missouri, USA, sandvole@missouri.edu; ALDOSSARY, H., University of Missouri, Missouri, USA, hnab84@mail.missouri.edu; HOLAN, S. H., University of Missouri, Missouri, USA, holans@missouri.edu

The presence of systematically censoring data can seriously undermine the ability to correctly predict model parameters. Sn is partially or completely blocked (left censored) when travelling through hot or absent lithospheric mantle, which is observed frequently at Iranian Plateau. To estimate the left censored amplitude in the Iranian Plateau, we have investigated the problem of measuring Sn Q in regions with large amounts of Sn blockage. We first developed two codes to simulate a left censored Sn amplitude reduction dataset and to impute the left censored amplitude reduction and Q, respectively. This simulation generates a synthetic dataset with both blocked Sn amplitude reduction and efficient Sn amplitude reduction. Then we take a Bayesian approach to impute the censored amplitude reduction data. We also applied our approach on real Sn amplitude data from stations throughout the northern Middle East where Sn blockage is very commonly observed. Comparing Sn Q models with a censored dataset and models that use both observed and imputed Sn amplitudes, we find the inclusion of imputed amplitude reduction results in a Q model with increased accuracy and resolution. To better understanding high frequency pahse blockage, we are also working on different dataset with a more physically realistic model generated by the software SW4. We have generated a large number of synthetic regional seismograms that we then used to estimate Sn Q as well as data blockage. We will then use these simulated seismograms to better understand the process and effect of phase blockage.

Recent Improvements to the SCEC Unified Community Velocity Model (UCVM) Software Framework

MAECHLING, P. J., University of Southern California, California, USA, maechlin@usc.edu; SU, M., University of Southern California, California, USA, mei@usc.edu; PLESCH, A., Harvard University, Massachusetts, USA, andreas_plesch@harvard.edu; SHAW, J., Harvard University, Massachusetts, USA, shaw@eps.harvard.edu; TABORDA, R., Universidad EAFIT, Medellin, Colombia, rtaborda@eafit.edu.co

The Southern California Earthquake Center (SCEC) has developed the open-source Unified Community Velocity Model (UCVM) software framework to facilitate the registration and distribution of existing and future seismic velocity models to the SCEC community. The UCVM software framework is designed to provide a standard query interface to multiple, alternative velocity models, even if the underlying velocity models are defined in different formats or use different geographic projections. The UCVM framework provides a comprehensive set of software tools for querying seismic velocity model properties, combining regional 3D models and 1D background models, visualizing 3D models, and generating computational models in the form of regular grids or unstructured meshes that can be used as input for ground-motion simulations. The UCVM framework helps researchers compare seismic velocity models and build equivalent simulation meshes from alternative velocity models. These capabilities enable researchers to evaluate the impact of alternative velocity models in ground-motion simulations and seismic hazard analysis applications. Over the last year, we added several new capabilities into UCVM. Using the most recent version of UCVM, researchers can now add an optional Ely-Jordan geotechnical layer into several UCVM-supported velocity models that lack low Vs values in near-surface areas, making these models more useful in ground motion simulations. We updated UCVM to use the 2015 Wills Vs30 map, integrated the latest Proj.5 projection library into the software, and improved UCVM's multi-models tiling mechanism. In addition, UCVM users can now query a central California velocity model that includes an updated San Joaquin Basin model and a Santa Maria Basin model developed by the Harvard Structural Geology and Earth Resources group. We also used UCVM to export several existing California seismic velocity models into netCDF format that can be visualized using IRIS EMC visualization tools.

Injection-Induced Seismicity

Oral Session · Friday · 8:30 AM · 26 April · Cascade I
Session Chairs: Sepideh Karimi, Zia Zafir, Dario Baturan, David Shorey.

Seismicity Induced by Waste Water Injection in Complex Fault Systems

SZAFRANSKI, D., Texas A&M University, Texas, USA, dawid.szafranski@tamu.edu; DUAN, B., Texas A&M University, Texas, USA, bduan@tamu.edu; MENG, Q., Texas A&M University, Texas, USA, qimeng@tamu.edu

In recent years there was an increase in the seismicity level in several areas across the United States. It is believed that this increase is caused by the human activities, mainly injection of the waste water coming from the unconventional hydrocarbons production. Some of these induced earthquakes exceeded magnitude 5.0 which in combination with the shallow depths of their hypocenters makes them potentially dangerous to the surface structures. These earthquakes can be triggered not only solely due to the fluid flow but also because of the stress perturbations caused by the rupture propagation on nearby faults (or other segments of the same fault). These interactions can lead to either increased size of the single earthquakes or the sequence of several significant seismic events. Moreover, seismic hazard estimation with classical methods is difficult to be assessed. For example, the earthquake sequence near Cushing (OK) from 2015 to 2016 occurred on a previously unmapped fault. Moreover, there are multiple strike-slip faults in the region that are close to one another and can be potentially activated in the future. Therefore, in this study we use physics-based, integrated modeling of fluid flow in deformable media with dynamic rupture propagation to investigate this kind of interactions and their impact on seismic hazard assessment. We performed a series of simulations on step-over strike-slip faults. We found that depending on the geometry (including relative position) of faults and injection wells the main causative factor could be the perturbation of pore pressure and/or stress caused by fluid flow, or the transfer of stress from one fault to another due to dynamic rupturing process. They also produce different patterns of ground motion, potentially allowing to distinguish them on seismograms. These results can be useful for regulatory agencies and oil and gas companies.

The Effect of Aseismic Slip on the Timing and Size of Induced Seismicity

LUI, S. K. Y., University of Toronto Mississauga, Mississauga, Canada, semechah.lui@utoronto.ca; HUANG, Y., University of Michigan, Michigan, USA, yiheh@umich.edu; YOUNG, R., University of Toronto, Toronto, Canada, paul.young@utoronto.ca

The key to effective hazard mitigation of induced seismicity is a thorough understanding of the triggering mechanisms of induced earthquakes. Apart from the direct effect of fluid present on the fault and the change in loading due to poroelastic stresses, recent studies also suggested complex driving forces that involve aseismic motion on the fault. The interplay of seismic and aseismic motion in the context of induced seismicity is particularly intriguing because of the complex interaction among fluid, frictional fault interface and the evolving state of stress during and after the injection.

In this study, we simulate the aseismic motion on a fault that is subjected to fluid-induced stress perturbation. The fault is subjected to various levels of poroelastic-stress or pore-pressure perturbations that occur at different times during a selected seismic cycle. We consider the effects of aseismic slip on both the timing and size of the induced seismic events. One observation from our numerical results is that the induced aseismic response on the fault can either advance and delay the next seismic event, *i.e.* it is capable of both stabilizing and destabilizing the fault. In particular, the delaying in triggering tends to happen when the level of stress perturbation is low (0.1 – 0.2 MPa) and when the perturbation occurs late in the interseismic period. Our model shows that the state of stress of the fault at the moment of perturbation and the critical nucleation size of the fault are important factors that control the extent of aseismic response on the fault and timing of the triggered event.

Our ongoing work is to better quantify the aseismic response caused by different types of induced stress perturbation and to investigate the aseismic response of faults in subsequent earthquake cycles. We aim to better constrain the range and timing of stress perturbations that are favorable for inducing earthquakes. The subsequent step is then to incorporate specific fluid injection histories and fault frictional properties to model field observations.

Hydraulic Properties of Injection Formations in Eastern Texas Constrained by Surface Deformation

SHIRZAEI, M., Arizona State University, Arizona, USA, shirzaei@asu.edu; MANGA, M., University of California, Berkeley, California, USA, manga@seismo.berkeley.edu; ZHAI, G., Arizona State University, Arizona, USA, gzhai@asu.edu

Wastewater injection over the past decade has increased seismicity in the central USA, in some cases accompanied by detectable surface uplift. Here, we show that the uplift rate is controlled by the hydraulic diffusivity of the injection medium and thus we can use this uplift to constrain subsurface properties and pore pressure evolution. We apply an advanced multitemporal interferometric algorithm to 35 synthetic aperture radar images acquired by ALOS satellite over a 4-year period before the 2012 earthquake sequence in east Texas, where large volumes of wastewater are disposed at depths of ~800 m and ~1800 m. To solve for the hydraulic diffusivity of the injection layers, we jointly inverted the injected volume and uplift data, considering a poroelastic layered half space. We find diffusivity values of 0.3+-0.1 m^2/s and 0.7+-0.15 m^2/s for shallow and deep injection layers, respectively, which combined with seismicity-derived bulk modulii yields permeability values of 5.5x10^-14 m^2 and 1.9x10^-14 m^2 for these layers, consistent with permeability range reported for Rodessa formation and well test values. Hydraulic conductivity determines the evolution of pore pressure and thus the origin and location of induced seismicity. This study highlights the importance of geodetic observations to constrain key hydrogeological properties of injection layers and to monitor the evolution of the subsurface pressure change.

Increased Detections Through Array Design and Processing

WITTEN, B., Nanometrics Inc., Ottawa, Canada, bwitten@gmail.com; BOOTERBAUGH, A., Nanometrics Inc., Ottawa, Canada, aaronbooterbaugh@nanometrics.ca; SEGSTRO, R., Repsol, Calgary, Canada, rsegstro@repsol.com

Induced and microseismic monitoring is often hindered by the low signal-to-noise ratio (SNR) of the arrivals. This is due to both the often weak source and strong surface noise. Within the oil and gas industry it has become common practice to deploy very large numbers of geophones to allow for the detection of the weak seismic events, primarily through stacking techniques. The cost of acquiring and processing such large datasets can be prohibitive, particularly for academic and government institutions. Therefore, this may not be a practical design for all applications. While more sensors will theoretically improve the signal-to-noise ratio by √N, where, N is the number of measurements, this assumes prior removal of coherent noise sources. Large densely sampled patches remove coherent surface wave noise through application of an F-K, or similar, filter. This approach is only valid when the wavefield is well sampled, often requiring a prohibitive number of instruments. We demonstrate that using a small array and semblance-weighted stacking we can achieve similar results to the large dense patch design.

Our data set consists of two arrays that recorded a hydraulic fracture treatment in western Canada. The first consists of 25 dense patches with 96 recorded channels in a grid. Each channel is comprised of a string of 12 1C geophones. The second array has eight hexagonal subarrays of 3C geophones. Using subsets of the large patch data, we show that semblance-weighted stacking can achieve a √N increase in SNR. This suggests that the coherent noise within the data has been successfully attenuated. We also show that applying semblance-weighted stacking on the hexagonal subarrays falls on the √N from the patch data. We conclude that we can attenuate the coherent noise using only a six-station hexagonal array and semblance-weighted stacking. Thus, a limited number of sensors in an easily acquired array design and intelligent processing can increase detections to provide a more complete catalog.

Hide and Seek: Identification and Analysis of Operational Micro-Seismicity Below the Noise Level During a Hydraulic Stimulation Experiment

SALVAGE, R. O., University of Calgary, Calgary, Canada, beckysalvage@gmail.com; EATON, D. W., University of Calgary, Calgary, Canada, eatond@ucalgary.ca

The Tony Creek Dual Microseismic Experiment (ToC2ME) dataset provides a unique opportunity to investigate operational micro- and induced-seismicity in relation to a hydraulic fracturing experiment in western Alberta. Previous work by researchers at the University of Calgary has identified ~25,000 microseismic events within this dataset and located up to ~18,500 of these using a combination of a stacked amplitude-envelope methodology, template matching using 15 master events, and beam-forming techniques. However, most of the events identified are not thought to be directly associated with the operational fracturing procedure. In this case, operational microseismicity is believed to occur below the noise level leading to an incomplete catalog of detections.

Here, we use an STA/LTA algorithm and coincident trigger methodology to identify microseismicity across a network of 68 geophones. Our thresholds for detection are set reasonably low in order to detect as many events as possible, whilst minimising false alarms. We find many events with clear phase arrivals which have not been identified in previous catalogs of this dataset, but that are locatable. The amplitudes, inter-event times and frequency contents of the waveforms identified are investigated for temporal and spatial changes, indicative of changing conditions at depth. Furthermore, we use the events identified by the STA/LTA algorithm in a template matching procedure to further populate the catalog with low amplitude events that may be hidden by noise or temporal spacing. Our results suggest that a number of families of repeating seismicity occurred during this experiment, and subtle changes in parameters relating to these families, including the similarity of events within the family as identified by a cross correlation co-efficient, can reflect small but important changes in the subsurface. A thorough understanding of these changes relating to the updated catalog of microseismicity is important, in particular in relation to hazard analysis for hydraulic fracturing experiments.

Seismicity Induced by Hydraulic Fracturing in the Central and Eastern United States

BRUDZINSKI, M. R., Miami University, Ohio, USA, brudzimr@miamioh.edu; SKOUMAL, R. J., U.S. Geological Survey, California, USA, skoumarj@gmail.com; RIES, R., Miami University, Ohio, USA, riesr@miamioh.edu; FASOLA, S., Miami University, Ohio, USA, fasolasl@miamioh.edu; FRIBERG, P., ISTI, New

York, USA, p.friberg@isti.com; CURRIE, B., Miami University, Ohio, USA, curriebs@miamioh.edu

We have investigated seismicity potentially associated with hydraulic fracturing (HF) in several areas of the Central and Eastern United States to improve our understanding of the phenomena. In our study we utilized multi-station template matching to lower the detection threshold and improve the completeness of seismicity catalogs. We also collected all publicly available information on timing and location of HF-related well stimulations to evaluate relationships with recorded seismicity. While rare, we find that HF induces seismicity with magnitudes greater than 2.0 more often than generally assumed and is the dominant source of seismicity in some areas. In over a dozen regions, >90% of the seismicity was correlated with reported HF wells, and in a few cases >30% of the HF wells were correlated with seismicity. In the states of Ohio, Oklahoma, and Texas, we have identified >600 earthquakes with M 2.0-3.8 that are best explained by being induced by HF. These findings imply regulations that require operators to modify completion strategies if a M > 2.0 earthquake occurs are likely to have an impact on future operations. Detailed investigations of seismicity induced by HF indicate that the maturity of nearby faults plays a key role in the types of seismicity that are produced. In addition, we find several trends that suggest the likelihood of induced seismicity is influenced by the injected volume, number of laterals on the well pad, stratigraphic interval stimulated, depth of the stimulation, and viscosity of the injected fluid.

Identifying and Forecasting Induced Seismicity Due to Wastewater Injection

GRIGORATOS, I., The University of Texas at Austin, Texas, USA, i.grigoratos@utexas.edu; RATHJE, E., The University of Texas at Austin, Texas, USA, e.rathje@utexas.edu; BAZZURRO, P., School of Advanced Studies IUSS Pavia, Pavia, Italy, paolo.bazzurro@iusspavia.it; SAVVAIDIS, A., Bureau of Economic Geology, University of Texas at Austin, Texas, USA, alexandros.savvaidis@utexas.edu

Wastewater disposal has been related to increases in seismicity in several parts of the Central United States. The vast majority of events have occurred in Oklahoma, which in 2015 experienced an almost 200-fold increase compared to the average annual seismicity rate before 2009, with the largest magnitudes reaching 5.8. In an attempt to quantify the extent of the problem, we develop a framework for seismic hazard assessment in regions with potentially induced seismicity. We developed a physics-based, semi-empirical model that simulates the observed seismicity given the injection time-history and can be used to distinguish the expected tectonic seismicity from disposal-induced seismicity with a certain degree of confidence. The model is also capable of forecasting seismicity rates in terms of space, time and magnitude distribution, given injection forecasts. Our proposed model is a modified version of the Gutenberg-Richter law, building upon the Seismogenic Index model that predicts a linear relationship between the number of induced events and the injected volume. We have allowed the injected volumes to diffuse in space and time and have introduced a time-lag that is dependent on injection rate and derived from rate-and-state friction concepts. The results show that most of the seismicity in Oklahoma is statistically identified as induced by wastewater injection (p-value < 0.1) and that the model is able to forecast both the peak and the decrease in seismicity, even when its calibration is limited to as early as late 2012.

The Application of High-Quality Seismic Catalogs in Forecasting Induced Seismicity: A Risk Management System

KARIMI, S., Nanometrics Inc., Ottawa, Canada, sepidehkarimi@nanometrics.ca; BATURAN, D., Nanometrics Inc., Ottawa, Canada, dariobaturan@nanometrics.ca

In this study, we discuss different published seismicity forecasting models and present the learnings from a practical implementation of three published forecasting models in a risk management system for hydraulic fracturing operations. The seismicity prediction performance of the system is validated via real-time monitoring and playback of over 30 diverse datasets. The results show that the estimated seismicity agrees well with observed seismicity in the majority of cases, that multiple models produce very similar results, and that the injected volume has limited impact on seismicity forecasts. The study also highlights the limitations of this approach when a large event occurs early in the sequence. One of the most important takeaways is the impact that the quality of seismic data has on the system performance. High-quality data recorded by a local array combined with advanced processing techniques designed to generate "research grade" seismic catalogues automatically in near real-time is a key requirement. This development also serves as an excellent example of collaboration between industry (data acquisition and array deployment), academia (model development), and service providers (data processing advancements and implementation) to understand and manage the induced seismicity phenomenon.

Seismic Network Development for Monitoring an Engineered Geothermal System in Finland

MALIN, P. E. A., Southern Methodist University, Texas, USA, pem@asirseismic.com; PASSMORE, K., ASIR Advanced Seismic Instrumentation and Research, Colorado, USA, kp@asirseismic.com; HEIKKINEN, P., ST1 Deep Heat Oy, Helsinki, Finland, pekka.j.heikkinen@helsinki.fi; ADER, T., Arup, London, United Kingdom, thomas.ader@arup.com; KWIATEK, G., GFZ German Research Centre for Geosciences, Potsdam, Germany, grzegorz.kwiatek@gfz-potsdam.de; SAARNO, T., ST1 Deep Heat Oy, Helsinki, Finland, tero.saarno@st1.fi

We introduce here the development of a 3-tier seismic monitoring network around an EGS project a few km from the center of Helsinki, Finland. This network telemetered seismicity data back to a central processing system in near real-time for regulatory and industrial purposes. We describe the network's design, special features, and use in meeting government-set Traffic Light System limits. As described in a subsequent talk, this system was to keep a ~ 6 km deep, 18,160 cubic meter hydraulic stimulation from producing a TLS limit M2.1 earthquake.

Somewhat paradoxically, in Finland's seismically quiet south, special instruments and installations are needed to observe both hazardous and industrially useful seismicity. The paradox arises from the fact that each day there are hundreds of manufactured events each day – from construction of a metro to housing, shopping, and roadways. The resulting Gutenberg-Richter statistics suggested that the network's sensitivity needed to be between -1 < M < 0 to be useful to the TLS system.

This sensitivity can be reached with borehole seismometers. A depth of 350 m was selected for a 1st tier, 8-station net of 4.5 Hz 3-C sensors. Data from this net revealed an even more overwhelming stream of construction noise. Moreover, the detection threshold at 350 m was noticeably higher than expected. Consequently, 4 new ones were added, 3 were place at greater depths: 666 m, 1133 m, and 1148 m. A 2nd tier, 12-level, array of seismometers was installed between 2200-2650 m in a borehole ~10 m from the stimulation well. The network was completed with a 3rd -tier of 17 ground-motion stations in buildings and outcrops around the stimulation site.

This monitoring system met its goals, automatically detecting and locating 5,806 ~ -1 < M < 2 events over 49 days of pumping a net volume of 18,160 m3 of drinking quality water.

Impacts of Induced Seismicity on Geotechnical Aspects of Infrastructure Systems

ZAFIR, Z., Kleinfelder, California, USA, zzafir@kleinfelder.com

Extraction of oil and gas through hydraulic fracturing and re-injection of waste water have caused increased seismicity in many parts of US and Canada, especially in Oklahoma and Northern Texas. Most of the oil and gas induced seismicity resulted in earthquakes with magnitudes less than 3 and 4. However, a few of those earthquakes resulted in events with magnitudes greater than 5.5 resulting in some damages to infrastructure and other properties. This presentation will focus on some of the impacts or potential impacts of these earthquakes on the geotechnical aspects of the infrastructure systems. These aspects include estimating ground motions, assessing liquefaction, lateral spreading, site amplification, and infrastructure damage.

Recently, an effort was undertaken for Oklahoma DOT to develop a protocol for bridge inspections immediately after a seismic event. The protocol includes guidelines for inspecting bridges and developing inspection radii based on the earthquake magnitude and location. As part of that effort, geotechnical assessments for three of the state bridge foundation were performed. This presentation will show results of those assessments in terms of observed and anticipated ground motions and their comparison with the design values, assessment of liquefaction potential at these sites, and response of foundation to the seismic loads

Advances, Developments and Future Research into Seismicity in Natural and Anthropogenic Fluid-Driven Environments

Oral Session · Friday · 1:30 PM · 26 April · Cascade I

Session Chairs: Rebecca O. Salvage, Megan Zecevic, Ruijia Wang.

Controlling Induced Seismicity During Hydraulic Stimulation of a 6 km Deep Enhanced Geothermal System in Finland

KWIATEK, G., GFZ German Research Centre for Geosciences, Potsdam, Germany, kwiatek@gfz-potsdam.de; SAARNO, T., ST1 Deep Heat Oy, Helsinki, Finland, tero.saarno@st1.fi; ADER, T., Arup, London, United Kingdom, thomas.ader@arup.com; BLUEMLE, F., GFZ German Research Centre for Geosciences, Potsdam, Germany, bluemle@gfz-potsdam.de; BOHNHOFF, M., GFZ German Research Centre for Geosciences, Potsdam, Germany, bohnhoff@gfz-potsdam.de; CHENDORAIN, M., Arup, London, United Kingdom, michael.chendorain@arup.com; DRESEN, G., GFZ German Research Centre for Geosciences, Potsdam, Germany, dre@gfz-potsdam.de; HEIKKINEN, P., University of Helsinki, Helsinki, Finland, pekka.j.heikkinen@helsinki.fi; KUKKONEN, I., University of Helsinki, Helsinki, Finland, ilmo.kukkonen@helsinki.fi; LEARY, P., ASIR Advanced Seismic Instrumentation and Research, Texas, USA, pcl@asirseismic.com; LEONHARDT, M., GFZ German Research Centre for Geosciences, Potsdam, Germany, leonhard@gfz-potsdam.de; MALIN, P. E. A., ASIR Advanced Seismic Instrumentation and Research, Texas, USA, pem@asirseismic.com; MARTINEZ-GARZON, P., GFZ German Research Centre for Geosciences, Potsdam, Germany, patricia@gfz-potsdam.de; PASSMORE, P., ASIR Advanced Seismic Instrumentation and Research, Texas, USA, prp@asirseismic.com; PASSMORE, K., ASIR Advanced Seismic Instrumentation and Research, Texas, USA, kp@asirseismic.com; WOLLIN, C., GFZ German Research Centre for Geosciences, Potsdam, Germany, wollin@gfz-potsdam.de; VALENZUELA, S., ASIR Advanced Seismic Instrumentation and Research, Texas, USA, sgv@asirseismic.com

We show that near-realtime seismic monitoring of fluid injection allowed control of induced earthquakes during the stimulation of a geothermal well near Helsinki, Finland. The OTN3 injection well was drilled down to 6.1 km-depth into crystalline rocks. Its open-hole section was deviated 45° from vertical and divided into several injection intervals. A total of 18,159 m^3 of fresh water was pumped during 49 days in summer 2018. The stimulation was monitored in near-real time using (1) a 12-level seismometer array at 2.20-2.65 km depth in an observation well located ~10 m from OTN3 and (2) a 12-station network installed in 0.3-1.15 km deep boreholes surrounding the project site. Earthquakes were processed within a few minutes and results informed a Traffic Light System (TLS). Using near-realtime information on induced-earthquake rates, locations, magnitudes, and evolution of seismic and hydraulic energy, pumping was either stopped or varied between wellhead-pressures of 60-90 MPa and flow rates of 400-800 l/min. This procedure avoided the nucleation of a project-stopping red alert at magnitude M2.1 induced earthquake, a limit set by the TLS and local authorities.

The stimulation resulted in detection of >43,000 earthquakes with -1.2<ML<1.9. The 4032 events were double-difference relocated and used to investigate the spatio-temporal evolution of seismicity, seismic energy release, and maximum magnitude in response to injection. The Gutenberg-Richter (GR) distribution and relation between hydraulic and radiated energy suggest (re-)activation of size-limited network of distributed fractures. The temporal behavior of GR b-value, as well as a lack of temporal (Omori-type) correlations in a presence of spatial localization of earthquakes suggest very limited earthquake triggering and stress transfer. The maximum observed magnitudes scale with stored elastic (~hydraulic) energy, following a fracture-mechanics based model of Galis *et al.* (2017). Our results suggest a possible physics-based approach to controlling stimulation induced seismicity in geothermal projects.

Investigating the Origin of the Mw 5.4 Pohang, Korea, Earthquake of 15 November, 2017: The Investigations and Conclusions of the Overseas Research Advisory Committee (ORAC)

ELLSWORTH, W., Stanford University, California, USA, wellsworth@stanford.edu; GE, S., University of Colorado, Colorado, USA, ges@colorado.edu; GIARDINI, D., ETH Zurich, Zurich, Switzerland, domenico.giardini@erdw.ethz.ch; SHIMAMOTO, T., Institute of Geology, China Earthquake Administration, Beijing, China, shima_kyoto@yahoo.co.jp; TOWNEND, J., Victoria University of Wellington, Wellington, New Zealand, john.townend@vuw.ac.nz

On November 15, 2017 a Mw 5.4 earthquake struck the city of Pohang, Republic of Korea, causing numerous injuries and in excess of $50 million in damage. Initial estimates of the location of the earthquake placed it near an enhanced geothermal systems (EGS) project that was still under development. The proximity of the earthquake to the project raised question about the possible association between industrial activities and the earthquake, and also led to the termination of the project. The Pohang EGS project was developing a geothermal reservoir by high-pressure hydraulic injection into a pair of wells at depths in excess of 4 km in the crystalline basement. The goal was to create a permeable pathway between the boreholes for the extraction of heat for the production of electricity. As part of the official government investigation into the earthquake, the Geological Society of Korea (GSK) formed an Overseas Research Advisory Committee (ORAC) charged with conducting a comprehensive investigation of the earthquake and any potential involvement of the Pohang EGS project in its origin. Investigations included the analysis of both natural seismicity and earthquakes induced during stimulation of the wells, development of mechanical and hydrogeologic models of the stimulations and comprehensive review of relevant drilling and stimulation data. As part of their investigation, the ORAC has been working closely with university researchers and with the full cooperation of government agencies and the EGS project. The summary report by the GSK and the ORAC will be released in March 2017. This presentation will summarize the findings of the ORAC investigation.

Microseismicity Recorded in the Geothermal Areas of Mt. Amiata (Italy)

BRAUN, T., Istituto Nazionale di Geofisica e Vulcanologia, Arezzo, Italy, thomas.braun@ingv.it; CESCA, S., Helmholtz-Zentrum, Potsdam, Germany, simone.cesca@gfz-potsdam.de; CACIAGLI, M., Istituto Nazionale di Geofisica e Vulcanologia, Bologna, Italy, marco.caciagli@ingv.it; FAMIANI, D., Istituto Nazionale di Geofisica e Vulcanologia, Roma, Italy, daniela.famiani@ingv.it; DAHM, T., Helmholtz-Zentrum, Potsdam, Germany, torsten.dahm@gfz-potsdam.de

Mt. Amiata (Tuscany, Italy) is an extinct volcano whose last eruptive activity was dated about 200 ky ago. Today, its underlying crustal volume is still characterized by a high geothermal gradient, which makes the area particularly suitable for geothermal exploitation. Seismicity in the Tuscan Geothermal Areas is generally observed within the upper crust and is confined in depth by the so called K-horizon, a strong seismic reflector located in between 4-8 km b.s.l., often interpreted as the 400°C isotherme. The overlaying structure presents permeable layers of highly fractured volcanic rocks, saturated with hot water and steam. Geothermal exploitation from these layers started in the 1960's. Since then, shallow earthquakes have been occasionally observed close to the geothermal wells, and the question is whether these event are of natural origin or related to the exploitation of heat.

To monitor the seismic activity inside the geothermal field of Mt. Amiata, we installed in 2015 a dedicated 8-station seismic network in the vicinity of the productive geothermal power plants for a 3-years recording period. The main challenges of our experiment are to automatically detect and locate the local microseismicity, trying to discriminate from natural seismicity those events caused by human operations. Due to the strong regional seismic activity of the 2016 Central Italy sequence, the automatic detection of local seismic events resulted challenging. We therefore use a waveform based detector (Lassie, developed at GFZ) to quickly scan the large dataset and automatically detect weak events in the target volume. Lassie provides preliminary event locations, which are then refined in a second step, using standard and waveform based techniques. For those hypocenters that are located close to the geothermal power plants, at a similar depth as the production level (3500 m b.s.l.), it remains very challenging to discriminate between natural and anthropogenic events.

Rapid Tremor Migration and Pore-Pressure Waves in Subduction Zones

CRUZ-ATIENZA, V. M., Universidad Nacional Autónoma de México, Mexico City, Mexico, cruz@geofisica.unam.mx; VILLAFUERTE, C., Universidad Nacional Autónoma de México, Mexico City, Mexico, villafuerte.cd@gmail.com; BHAT, H., Ecole Normale Supérieur de Paris, Paris, France, harshasbhat@gmail.com

Rapid tremor migration (RTM) in subduction zones is a manifestation of complex fault-zone processes on the plate interface. Recent observations have revealed a large diversity of RTM patterns that are always associated with aseismic, shear strain at the interface. Small unstable asperities embedded in the stable shear zone are thus believed to originate tremor radiation during migration. Tectonic tremors have been recognized to occur where overpressured fluids exist. Spatial variations of fluid pressure may lead to non-linear diffusion processes with potentially large implications in tremor generation. Here, we show that pore-pressure waves are likely to exist in the plate interface, propagating with speeds and pathways similar to RTMs observed in different subduction zones including Guerrero, Mexico, where we introduce new high-resolution tremor locations and a RTM source physical model. These waves may explain the whole hierarchy of RTM patterns by producing transient reductions of the fault strength and thus secondary slip fronts triggering tremor during slow earthquakes. The model we propose opens a new area of research that may help to better understand the fault system in different geophysical conditions such as volcanic systems, geothermal fields, and production wells with induced seismicity, where the seismic hazard is high and should be assessed by means of physics-based modeling considerations.

Reference: Cruz-Atienza, V. M., C. D. Villafuerte and H. S. Bhat. Rapid tremor migration and pore-pressure waves in subduction zones. Nature Communications, doi:10.1038/s41467-018-05150-3, 2018.

Untangling the Web of Fluids and Faulting in Earthquake Swarms

SHELLY, D. R., U.S. Geological Survey, Colorado, USA, dshelly@usgs.gov

Earthquake swarms are common signatures of unrest in both volcanic and tectonic environments. Their interpretation in the broader system depends upon determining the underlying physical processes driving the swarm, which can be difficult. Seismic recordings of earthquakes provide the most direct constraints on active processes in the source region, yet the limited resolution of routine processing obscures much of this valuable information. Using large-scale waveform cross-correlation between cataloged events and the continuous data stream, it's possible to detect and precisely locate many times more events than are included in standard catalogs. We have recently extended this technique to estimate relative polarities between events, facilitating robust focal mechanism estimation for large populations of tiny earthquakes, addressing a common shortcoming in microseismicity analyses (Shelly *et al.*, JGR, 2016). Here, I explore high resolution views of recent earthquake swarms at Yellowstone and Long Valley Calderas and consider their implications for source zone physics. This analysis reveals a dramatic migration of earthquake activity with time, with complex faulting geometries. Together, these patterns imply strong interactions between fluid diffusion and faulting processes in the crust.

Hydraulic-Fracturing, Induced Seismicity and the Characteristic Earthquake Hypothesis: Observations and Implications

IGONIN, N., University of Calgary, Calgary, Canada, naigonin@ucalgary.ca; ZECEVIC, M., University of Calgary, Calgary, Canada, megan.zecevic@ucalgary.ca; EATON, D. W., University of Calgary, Calgary, Canada, eatond@ucalgary.ca

The characteristic earthquake hypothesis posits that, over a single complete earthquake cycle, fault systems generate an event with a magnitude near the largest possible for the system. According to this hypothesis, episodic characteristic earthquakes occur more frequently than would be expected based on a Gutenberg-Richter relationship derived from the magnitude-frequency distribution during the interseismic period. Over one or more earthquake cycles, characteristic earthquakes are therefore marked by robust occurrence (*i.e.* exceeding some level of statistical confidence, such as 95%) of large-magnitude event(s) above the expectation of the maximum-likelihood Gutenberg-Richter distribution. Another hypothesis posits that, within a given region, the observed magnitude-frequency relationship for induced seismicity represents a rate-accelerated version of natural background seismicity. According to this model, the seismic moment release over a given time interval corresponds to the expected seismic moment release that would have occurred naturally, over a much longer time window. In the case of a Gutenberg-Richter relationship, log $N=a-bM$, this would correspond with a shift in the activity parameter, a, with no change in the $b$value. By analyzing a set of local induced seismicity catalogs acquired during hydraulic-fracturing operations in western Canada, we observe evidence in support of the characteristic earthquake model. If validated, this model has important implications for hazard analysis, since it implies that the frequency of large events may be underestimated by the Gutenberg-Richter relationship derived from low-magnitude seismicity. More generally, if the characteristic earthquake model is more widely applicable to induced earthquake sequences in previously quiescent intraplate settings than active fault systems, it may be that this could provide important clues about the nature of fault nucleation and rupture on well healed faults.

Source Parameters of the Nov 30, 2018, ML 4.5 Hydraulic Fracturing Induced Earthquake and Aftershock Sequence in Northeast BC, Canada

ONWUEMEKA, J., McGill University, Montreal, Canada, john.onwuemeka@mail.mcgill.ca; PEÑA-CASTRO, A., McGill University, Montreal, Canada, andres.penacastro@mail.mcgill.ca; ROTH, M. P., Ruhr University, Bochum, Germany, marco.roth@ruhr-uni-bochum.de; LIU, Y., McGill University, Montreal, Canada, yajing.liu@mcgill.ca; HARRINGTON, R. M., Ruhr University, Bochum, Germany, rebecca.harrington@rub.de; KAO, H., Pacific Geoscience Centre, Natural Resources Canada, Victoria, Canada, honn.kao@canada.ca

Seismicity related to fluid injection in the exploration of unconventional oil and gas resources has increased dramatically in the Western Canada Sedimentary Basin in the last decade. Hydraulic fracturing is considered to be the main cause of several M4+ events in the Montney Play, including the ML 4.5 mainshock on November 30, 2018 (November 29, local time), in the Dawson-Septimus area. It is the second largest hydraulic fracturing induced event in northeast BC. In order to understand the underlying source physics, we conduct a comprehensive source parameter study of the mainshock and its aftershock sequence, using waveform data from 15 broadband seismic stations (9 McGill, 6 Natural Resources Canada) deployed at distances ranging from ~1 to 50 km from the mainshock epicenter. We first enhance the seismicity catalog for the period of 2018/11/20 to 2018/12/10 from 16 (NRCan reported) to 212 events using a multi-station matched-filter (MMF) method. Preliminary locations of the MMF detected events highlight a NW-SE trending structure, which is, in general, consistent with the fault plane solutions of both the 2018/11/30 ML 4.5 and 2015/08/17 ML 4.6 hydraulic fracturing induced events. The latter event was ~ 100 km north of Fort St John, suggesting the influence of the regional principal stress. The spectral ratio analyses suggest a stress drop value of ~0.1 MPa for the mainshock, compared to values of ~ 10 MPa for the two largest aftershocks, possibly reflecting different rupture mechanisms of the mainshock from the aftershocks. Results from high-precision hypocenter relocation using the MMF catalog will be presented to better illustrate the spatiotemporal migration of seismicity. Once the industrial injection data becomes available, we will model the solid matrix stress and fluid pressure changes due to injection using a coupled poroelasticity model and correlate the modeling results with seismicity.

Controls of Structural Complexity and Earthquake Rupture Process on Spatiotemporal Evolution of Induced Earthquake Sequences

CHEN, X., University of Oklahoma, Oklahoma, USA, xiaowei.chen@ou.edu; QIN, Y., University of Oklahoma, Oklahoma, USA, yan.qin-1@ou.edu; WU, Q., University of Oklahoma, Oklahoma, USA, wqimin86@ou.edu; KOLAWOLE, F., University of Oklahoma, Oklahoma, USA, folarin@ou.edu; DANGWAL, D., University of Oklahoma, Oklahoma, USA, deepankar.s.dangwal-1@ou.edu

It is well known that most of the recent seismicity in Oklahoma are induced due to wastewater disposal and hydraulic fracturing. However, the control factors that control of the initiation and spatiotemporal evolution of individual earthquake sequences still remain unclear. In this study, we focus on a few well well-recorded earthquake sequences in Oklahoma, perform detailed analysis on the spatiotemporal evolution of seismicity and earthquake source parameters analysis, in order to understand the roles of geological structures and earthquake rupture processes on induced earthquake sequences. For the Guthrie sequence in central Oklahoma, we interpret a complex conjugate fault mesh network based on high-resolution earthquake catalog and focal mechanism solutions. Detailed source parameter analysis suggests that the sequence initiated along weaker fault patches in the central shallower portion of the fault. Rapid fault activation of a low stress drop region is accompanied with low b-value and high seismicity rate. Although the entire sequence exhibits diffusion-type spatial migration, embedded slow slip episodes and earthquake-to-earthquake triggering are identified for selected larger earthquakes. For the Cushing sequence, detailed relocation and focal mechanism solutions suggest predominanting NE- oriented right-lateral strike-slip faulting, and show diverse faulting types are found along the portion where the M5 mainshock occurred. The association betweencoincidence of mainshock occurrence and diverse faulting types suggestss that structural complexity may play a role in the rupture initiation process of larger mainshocks. Further analysis of source parameters of small earthquakes, and aeromagnetic datasets will unravel the roles of basement structure and earthquake rupture processes on the Cushing earthquake sequence.

Rainwater and Aquifer Factors of Seasonally Induced Seismicity in Southeast Brazil

CONVERS, J., Universidade de São Paulo, São Paulo, Brazil, jaime.convers@gmail.com; ASSUMPÇÃO, M., Universidade de São Paulo, São Paulo, Brazil, marcelo.assumpcao@iag.usp.br; BARBOSA, J. R., Universidade de São Paulo, São Paulo, Brazil, jroberto@iag.usp.br

While seasonal rainwater is normally not considered as a determining factor in cases of induced seismicity, it has been identified in southeastern Brazil as the driving factor behind seasonally induced seismicity in Jurupema, located in the interior of the state of Sao Paulo. While induced seismicity occurs mostly as a by-product of particular man-made practices and structures, induced seismicity from rainwater is one of the less documented phenomena of this type. Even though this type of seismicity is still scarce and underreported worldwide, this seismicity already has a precedent in Brazil, in Bebedouro, about 50 km away from our study area.

We have been monitoring the seasonality of this phenomenon since 2016, where the trends in the regional precipitation data coincide with trends of seismicity increase of the more than 1300 seismic events between 2016 and 2018. We follow the seismicity variations and perform full moment tensor analysis when possible, to identify two main regions where events are more frequently occurring and have mostly horizontal nodal planes, the very shallow events between 100 and 200 m and from 600 to 700 m depth.

We find that the significant similarities of the seismicity to that of the previously recorded earthquake sequences in Bebedouro, not only correlate to the seasonal precipitation changes, but the seismicity also correlates with the location of water wells used for irrigation drilled contemporary to the onset of seismicity, and the type of underlying rock that hosts the confined and unconfined aquifers.

The behavior and characteristics of this seismicity seems to be promoted by the type of rock hosting the aquifers in this region, where the stress conditions of the fractured basaltic rock inside shallow confined aquifers can be affected by the intrusion and percolation, coming from the addition of rainwater affecting the pore-pressure conditions, given the facilitating factor of water wells that permit permeation of water from upper to lower aquifers.

Snowmelt-Triggered Earthquake Swarms at the Margin of Long Valley Caldera, California

MONTGOMERY-BROWN, E., U.S. Geological Survey, California, USA, emilymb1@gmail.com; SHELLY, D. R., U.S. Geological Survey, Colorado, USA, dshelly@usgs.gov; HSIEH, P., U.S. Geological Survey, California, USA, pahsieh@usgs.gov; SILVERII, F., Scripps Institution of Oceanography, University of California, San Diego, California, USA, fsilverii@ucsd.edu

Fluids are known to influence earthquakes, yet rarely are earthquakes convincingly linked to precipitation. Weak modulation or limited data often leads to ambiguous interpretations. In contrast, we found that shallow seismicity in the Sierra Nevada range near Long Valley Caldera is strongly modulated. Over 33 years, shallow seismicity rates were ~37 times higher during very wet periods versus very dry periods. Precise earthquake locations from a swarm in 2017 reveal downward migration from ~1-3 km depth along a steeply inclined plane. Steeply dipping strata may provide high-permeability pathways and faulting plane. Here we combine the correlated seismicity and hydrologic time series with the propagation observed in the relocated earthquakes. From this combined evidence, we infer that pressure diffusion from groundwater recharge dramatically accelerated shallow seismicity rates, causing seismic swarms unrelated to volcanic processes. The observed deformation helps differentiate timing and effects solely due to the load of the winter snowfall, from those of the later infiltration of meltwater.

Large Intraslab Earthquakes

Oral Session · Friday · 8:30 AM · 26 April · Cascade II
Session Chairs: Zhongwen Zhan, Wenyuan Fan, Linda M. Warren.

A Tale of Two Earthquakes: Two Mw 7.1 Earthquakes in Alaska Reveal the Importance of Deep Earth Structure on Ground Motion

MANN, M., Cornell University, New York, USA, mem533@cornell.edu; ABERS, G. A., Cornell University, New York, USA, abers@cornell.edu

Two Mw 7.1 intraslab earthquakes occurred in Alaska within the subducting Pacific plate in 2016 and 2018 and were well recorded on the Transportable Array broadband seismometers and accelerometers. The January 24, 2016 Mw 7.1 Iniskin earthquake occurred at 125 km depth, 250 km southwest of Anchorage. Unexpectedly, accelerations exceed 0.2 g at 250 km distance from this earthquake. The near-Anchorage earthquake of November 30, 2018 occurred at 45 km depth, 14 km northwest of Anchorage, and generated high accelerations nearby. Conventional models for ground motion captured the variation with distance of the near-Anchorage earthquake across the region, while the same models underpredict accelerations from the intermediate-depth Iniskin earthquake by at least an order of magnitude in greater Anchorage and across the Kenai peninsula. Peak amplitudes of weak-motion signals show similar amplification patterns for 227 intermediate-depth earthquakes (IDEs) near the Iniskin hypocenter (M=3-6), indicating that the acceleration pattern from the Iniskin earthquake is due to path effects and not source effects. All show a sharp transition between low amplitudes in the arc and back-arc and high amplitudes over the forearc, a hallmark of variable seismic attenuation. We measure >10x variation in Q between forearc and backarc paths from IDEs near the Iniskin earthquake hypocenter. Teleseismic body-wave attenuation varies with a similar pattern as regional earthquakes. The pattern resembles predictions from thermal models featuring a hot sub-arc mantle and a cold slab and forearc, which predict similar variations in attenuation. Thus, mantle thermal structure has a major effect on earthquake hazard.

Deep Embrittlement and Complete Rupture of the Lithosphere During the M8.2 Tehuantepec, Mexico Earthquake

MELGAR, D., University of Oregon, Oregon, USA, dmelgarm@uoregon.edu; RUIZ-ANGULO, A., Icelandic Meteorological Office, Reykjavik, Iceland, angel@vedur.is; GARICA, E. S., Kyoto University, Disaster Prevention Research Institute, Kyoto, Japan, garcia.soliman.2x@kyoto-u.ac.jp; MANEA, M., Universidad Nacional Autónoma de México, Queretaro, Mexico, marina@geociencias.unam.mx; MANEA, V. C., Universidad Nacional Autónoma de México, Queretaro, Mexico, vlad@geociencias.unam.mx; XU, X., University of California, San Diego, Scripps Institution of Oceanography, California, USA, xix016@ucsd.edu; RAMIREZ-HERRERA, M. T., Universidad Nacional Autónoma de México, Mexico City, Mexico, ramirez@igg.unam.mx; ZAVALA-HIDALGO, J., Universidad Nacional Autónoma de México, Mexico City, Mexico, jzavala@atmosfera.unam.mx; GENG, J., GNSS Center, Wuhan University, Wuhan, China, jgeng@whu.edu.cn; CORONA, N., Colegio de Michoacán, Centro de Estudios en Geografía Humana, La Piedad, Mexico, corona@colmich.edu.mx; PEREZ-CAMPOS, X., Universidad Nacional Autónoma de México, Mexico City, Mexico, xyolipc@sismologico.unam.mx; CABRAL-CANO, E., Universidad Nacional Autónoma de México, Mexico City, Mexico, ecabral@geofisica.unam.mx; RAMÍREZ-GUZMÁN, L., Universidad Nacional Autónoma de México, Mexico City, Mexico, lramirezg@iingen.unam.mx

Subduction zones, where two tectonic plates converge, are generally dominated by large thrust earthquakes. Nonetheless, normal faulting from extensional stresses can occur as well. Rare large events of this kind in the instrumental record have typically nucleated in and ruptured the top half of old and cold lithosphere that is in a state of extension driven by flexure from plate bending. Such earthquakes are limited to regions of the subducting slab cooler than ~650°C and can be highly tsunamigenic, producing tsunamis similar in amplitude to those observed during large megathrust events. Here we show from analyses of regional geophysical observations that normal faulting during the 2017 M8.2 Tehuantepec, Mexico earthquake ruptured the entire Cocos slab beneath the megathrust region. We find that the faulting most likely reactivated a bend fault fabric and ruptured to a depth well below the predicted brittle-ductile transition for the Cocos slab, including regions where temperature is expected exceed 1000°C. Our findings suggest that young oceanic lithosphere is brittle to greater depths than previously assumed and that rupture is facilitated by wholesale deviatoric tension within the subducted slab possibly due to fluid infiltration or other unknown processes. We conclude that in this region lithosphere can sustain brittle behavior and fail in a large earthquake at greater P-T conditions than previously considered. Finally we show that should such intraslab events be possible oceanward of the trench there is significant cause for concern. The modest (3m) tsunami generated during the 2017 earthquake revealed a host of resonant phenomena associated with the long and flat Tehuantepec shelf which significantly protracts the duration of hazardous tsunami waves.

Complex and Diverse Rupture Processes of the 2018 Mw 8.2 and Mw 7.9 Tonga-Fiji Deep Earthquakes

FAN, W., Florida State University, Florida, USA, wfan@fsu.edu; WEI, S., Michigan State University, Michigan, USA, swei@msu.edu; TIAN, D., Michigan State University, Michigan, USA, tiandong@msu.edu; MCGUIRE, J. J., Woods Hole Oceanographic Institution, Massachusetts, USA, jmcguire@whoi.edu; WIENS, D. A., Washington University in St. Louis, Missouri, USA, doug@wustl.edu

Deep earthquakes exhibit strong variabilities in their rupture and aftershock characteristics, yet their physical failure mechanisms remain elusive. The 2018 Mw 8.2 and Mw 7.9 Tonga-Fiji deep earthquakes, the two largest ever recorded in this subduction zone, occurred within days of each other. We investigate these events by performing waveform analysis, teleseismic P-wave back-projection, and aftershock relocation. Our results show that the Mw 8.2 earthquake ruptured fast (4.1 km/s) and excited frequency dependent seismic radiation, whereas the Mw~7.9 earthquake ruptured slowly (2.5 km/s). Both events lasted ~35 s. The Mw 8.2 earthquake initiated in highly seismogenic, cold core of the slab and likely ruptured into the surrounding warmer materials, whereas the Mw 7.9 earthquake likely ruptured through a dissipative process in a relatively aseismic region. The contrasts in earthquake kinematics and aftershock productivity argue for a combination of at least two primary mechanisms enabling rupture in the region.

Seismogenic Characteristics and Dynamic Triggering in the Slab Penumbra

WIENS, D. A., Washington University in St. Louis, Missouri, USA, doug@wustl.edu; LUO, Y., Washington University in St. Louis, Missouri, USA, yluo24@wustl.edu

Observations from recent earthquakes, such as the 2018 Tonga-Fiji deep events, provide crucial insight into the mechanics of slab earthquakes. The 19 August (M_w 8.2) earthquake represents a larger repeat of the 1994 Tonga (M_w 7.6) event, located 30 km away, with similar mechanism and rupture characteristics (McGuire *et al.*, 1997; Fan *et al.*, in press). Both events initiated near the center of the active slab, occurred along near-vertical faults at high angles to the slab, and ruptured into a region with no previous seismicity. This demonstrates that deep earthquake rupture can propagate well into the aseismic region surrounding the active slab.

The 6 September (Mw 7.9) event, in a previously aseismic region 270 km away, illustrates the dynamic triggering of deep earthquakes. We conduct a systematic study of dynamic triggering of slab earthquakes worldwide since 1964. The seismicity rates at distances of 80-400 km from earthquakes with M_w>6.5 greatly exceeds the background rates for the first 5 hours following the mainshock, and continues at an elevated rate for about 4 days, demonstrating dynamic triggering in that time period. Dynamic triggering is much more common for deep earthquakes than for intermediate depth earthquakes, particularly at depths greater than 600 km. Statistically, dynamically triggered earthquakes are much more likely than background events to occur in areas that are otherwise aseismic, generally deeper or laterally displaced from the active slab. Triggered events follow an Omori's Law decay with time, but there is no triggered seismicity during the passage of waves. Thus, there must be a delay mechanism that stores the transient energy and triggers earthquakes with delays of minutes to a few days. Slabs in the transition zone must be surrounded by material that is critically stressed and warm enough to inhibit nucleation, but which can sustain rupture if a large shear failure propagates into the region. The passage of strong seismic waves can also initiate a runaway shear failure, which nucleates over a period of minutes to days.

Source Variations in Intraslab Earthquakes From Data and Modelling

CHU, S., Stanford University, California, USA, schu3@stanford.edu; BEROZA, G. C., Stanford University, California, USA, beroza@stanford.edu; ELLSWORTH, W., Stanford University, California, USA, wellsworth@stanford.edu

The mechanism of intraslab earthquakes are still incompletely understood. In particular, the relative importance of dehydration embrittlement, thermal shear runaway, hybrid dehydration-induced stress transfer, or some combination, and how these influences might vary in different subduction zones is unclear. To understand the contribution from these mechanisms, we investigate earthquake source parameters from data in the two subduction zones in Japan: the older and colder Pacific Plate east of Hokkaido, and the younger and warmer Philippine Plate south of Kyushu.

We estimate stress drops, radiated energies, and radiated efficiencies of earthquakes greater than M3.6 over a 12-year period using the method of empirical Green's functions (eGfs). Because intraslab earthquakes produce few aftershocks and because the signal-to-noise-ratio is low for small events, special attention must be given to eGf selection. We also consider the variation in high frequency fall-off rate between different events, noting that the standard omega-2 models used in such studies may be inappropriate for intraslab events. We find, in addition to the generally agreed-upon results of a higher stress drop and lower radiated efficiency for intraslab earthquakes, that there appears to be a break in self-similarity in the source parameters for the Hokkaido region, which suggests that different mechanisms may be important in the two subduction zones. However, we note that the observable magnitudes of the earthquakes in each region is limited by the cropped bandwidth at which data has good signal quality. We hence supplement our study by performing source inversions of larger events in each region, to better understand what possible differences in the source model can be observed in the data.

The M7 Anchorage Earthquake: Testing the Resiliency of South-Central Alaska

Oral Session · Friday · 10:45 AM · 26 April · Cascade II

Session Chairs: Michael West, Robert C. Witter.

Aftershock Analysis of the Mw 7 November 30, 2018 Anchorage Earthquake: Locations and Regional Moment Tensors

RUPPERT, N., University of Alaska Fairbanks, Alaska, USA, naruppert@alaska.edu; RICHARDS, C., University of Alaska Fairbanks, Alaska, USA, csrichards2@alaska.edu; TAPE, C., University of Alaska Fairbanks, Alaska, USA, ctape@alaska.edu; WEST, M. E., University of Alaska Fairbanks, Alaska, USA, mewest@alaska.edu

The magnitude 7 Anchorage earthquake occurred in the morning hours of November 30, 2018 and generated intense ground shaking resulting in significant damage to the private property and public infrastructure. It was followed by a vigorous aftershock sequence with nearly 7,000 aftershocks reported through the end of December, 2018. Dozens of aftershocks were felt in the greater Anchorage area further increasing anxiety and keeping heightened public interest in the aftershock sequence updates. The Alaska Earthquake Center produced reviewed aftershock catalog with the magnitude of completeness of 1.6. When available, picks from temporary aftershock monitoring stations installed by the USGS in early December were used. This well recorded sequence provides additional constraints on the mainshock rupture process. The relocated hypocenters spread over a 25-km-long and 15-km-wide zone between 35-50 km depth confined to the subducting slab and indicate two aftershock clusters, a more diffuse shallow-dipping southern cluster and a more clearly-defined and steeply dipping northern cluster. However, regional moment tensor solutions for the aftershocks do not exhibit significant variability and, on average, agree well with the mainshock focal plane parameters, thus not necessarily supporting a multi-plane rupture. We use long-period regional seismic waveforms to estimate a point-source moment tensor for the mainshock. We grid search over the moment tensor space (double couple vs full moment tensor) and a range of depths. This presentation will address the M7 source geometry and rupture characteristics through the aftershock relocation analysis combined with the detailed investigations of the moment tensors.

Preliminary Geodetic Analysis of 2018 M7 Anchorage Earthquake

ELLIOTT, J., Purdue University, Indiana, USA, julieelliott@purdue.edu; GRAPENTHIN, R., New Mexico Institute of Mining and Technology, New Mexico, USA, rg@nmt.edu; FREYMUELLER, J. T., Michigan State University, Michigan, USA, freymuel@msu.edu; ROLLINS, C., Michigan State University, Michigan, USA, john.c.rollins@gmail.com; KAUFMAN, A. M., University of Alaska Fairbanks, Alaska, USA, amkaufman@alaska.edu; WITTER, R. C., U.S. Geological Survey, Alaska Science Center, Alaska, USA, rwitter@usgs.gov; WECH, A., U.S. Geological Survey, Alaska Volcano Observatory, Alaska, USA, awech@usgs.gov

On November 30, 2018, an M7 normal-faulting earthquake struck just north of Anchorage, Alaska at a depth of ~47 km. Based on its location and mechanism, the earthquake appears to have occurred within the downgoing Yakutat slab and may be related to slab bending. The earthquake took place in a particularly complex section of the Alaska subduction zone. South of the epicenter, the Yakutat slab, an oceanic plateau shallowly subducting beneath southern Alaska, transitions to more steeply dipping Pacific plate crust. The earthquake occurred beneath and adjacent to a part of the subduction interface that appears to be partially locked (based on geodetic data) and has experienced multiple large, multi-year slow slip events. Surface displacements generated from the initial USGS finite fault model (based on seismic data) show a fairly smoothly varying coseismic deformation field with maximum values of ~2 cm east of the epicenter. Observations at real-time, high-rate GPS stations suggest a more complex picture, with coseismic displacements west of the epicenter reaching values almost double those predicted by the model.

We present an updated and expanded analysis of available GPS data and examine deformation processes related to the Anchorage earthquake. Specifically, we use available high-rate data to infer the temporal evolution of rupture propagation and combine these data with coseismic displacements from other continuous and campaign GPS sites to constrain a static picture of the final slip distribution. We also assess the first few months of postseismic deformation using data from continuous sites and several campaigns conducted after the earthquake. Furthermore, we examine how other transient processes such as postseismic deformation from the 1964 M9.2 earthquake and previous slow-slip events in the region may have influenced the occurrence of the 2018 earthquake and how the earthquake may have affected the state of stress on the adjacent subduction interface.

Impact of Flat Slab Subduction on Earthquake Ground Motions in South Central Alaska Including the 2018 M7.0 Anchorage Inslab Earthquake

CRAMER, C. H., Center for Earthquake Research and Information, University of Memphis, Tennessee, USA, ccramer@memphis.edu; JAMBO, E., Center for Earthquake Research and Information, University of Memphis, Tennessee, USA, ejambo@memphis.edu

The attenuation of subduction zone earthquake ground motions can be affected by flat slab subduction beneath a region as well as directivity and site conditions. Recent crustal and subduction earthquakes in south central Alaska, including the 2018 M7.0 Anchorage event, demonstrates these effects. Flat slab subduction puts oceanic crust beneath continental crust with little or no intervening hotter mantle material. Such a condition occurs beneath the Cook Inlet and Kenai Peninsula region of Alaska and allows seismic waves to propagate through less attenuating crusts to the surface causing an increase in observed ground motions. The 2015 heat flow map of Alaska shows reduced heat flow in this same region. Ground motion observations from the 2018 M7.0 Anchorage AK earthquake show significantly higher ground motions than current subduction ground motion prediction equations within 50-100 km of the epicenter. At short periods ground motions show reduced amplitudes (PGA ~0.2g, 0.2s ~0.6g) due to sediment nonlinear effects in the Anchorage area, reducing the damage potential of the earthquake. Duration of shaking was too short for widespread liquefaction effects unlike during the 1964 M9.2 earthquake. At long periods ground motions are little affected by sediment nonlinearity and remain higher than expected (up to 0.5g at 1s). Other earthquakes show similar increases in ground motions in the Cook Inlet and Kenai Peninsula region. Ground motions from the 2016 Iniskin M7.1 inslab earthquake show higher than normal ground motions in the Cook Inlet region, in part due to directivity. The 2015 Redoubt M6.3 inslab earthquake also shows increased ground motions in the Cook Inlet region without directivity effects. Crustal Q estimates from Lg waves also show less attenuation (higher Q) in south central Alaska. In the larger south central Alaska region crustal $Q(f) = 336f^{0.34}$ compared to $Q(f) = 200f^{0.8}$ in other portions of Alaska.

Ground Failures Induced by Seismic Shaking During the 2018 Anchorage, Alaska M7 Earthquake

WITTER, R. C., U.S. Geological Survey, Alaska, USA, rwitter@usgs.gov; ALLSTADT, K. E., U.S. Geological Survey, Colorado, USA, kallstadt@usgs.gov; BENDER, A. M., U.S. Geological Survey, Alaska, USA, abender@usgs.gov; GRANT, A., U.S. Geological Survey, California, USA, agrant@usgs.gov; JIBSON, R. W., U.S. Geological Survey, Colorado, USA, jibson@usgs.gov; THOMPSON, E. M., U.S. Geological Survey, Colorado, USA, emthompson@usgs.gov

Strong ground motions during the November 30, 2018 M7 Anchorage, Alaska earthquake triggered numerous ground failures in artificial fill and natural materials over a >5000 km^2 area in south-central Alaska. Shaking generated by the intraslab earthquake (40 km deep) produced peak ground accelerations of 0.3-0.8 g throughout much of the greater Anchorage Metropolitan area. Post-earthquake aerial and ground surveys, spanning December 1–10, focused on coseismic ground failures (liquefaction, lateral spreads, and landslides) in natural materials. The costliest failures occurred in artificial fill, which damaged engineered road and rail embankments and buildings, particularly residential homes. Ground failures in natural materials occurred where landslides were triggered by prior earthquakes, including the 1964 M9.2 Great Alaska earthquake and the 1954 M6.4 Kenai Peninsula earthquake. For example, landslides threatened but did not damage the Alaska Railroad at Potter Hill in 2018, adjacent to an area where landslides destroyed the railroad in 1954 and 1964. Liquefaction-related lateral spreading and sand boils occurred in tidal and deltaic environments along upper Cook Inlet and in areas of Anchorage underlain by sandy, wet soils. We also observed debris avalanches on steep slopes underlain by glacial outwash and rockfalls and snow avalanches in steeper terrain of the Chugach Mountains. Field surveys of translational landslides triggered by the 1964 earthquake identified minor cracking (≤0.01 m wide, ~32 m long) along the margins of landslide blocks and grabens, but no evidence for significant net displacement. We speculate that the 20–40 sec of shaking in the 2018 Anchorage earthquake stopped short of reactivating large translational landslides that failed during much longer (4 to 5 min) shaking in 1964. Our observations will be used to empirically check the USGS ground-failure products that depict areas prone to coseismic liquefaction and landsliding.

USGS Near-Real-Time Ground Failure Product for the 2018 Anchorage Earthquake

THOMPSON, E. M., U.S. Geological Survey, Colorado, USA, emthompson@usgs.gov; ALLSTADT, K. E., U.S. Geological Survey, Colorado, USA, kallstadt@usgs.gov; GRANT, A., U.S. Geological Survey, California, USA, agrant@usgs.gov; JIBSON, R. W., U.S. Geological Survey, Colorado, USA, jibson@usgs.gov; BENDER, A. M., U.S. Geological Survey, Alaska, USA, abender@usgs.gov; WITTER, R. C., U.S. Geological Survey, Alaska, USA, rwitter@usgs.gov; HEARNE, M., U.S. Geological Survey, Colorado, USA, mhearne@usgs.gov; WALD, D. J., U.S. Geological Survey, Colorado, USA, wald@usgs.gov; MCBRIDE, S. K., U.S. Geological Survey, Colorado, USA, skmcbride@usgs.gov

The 2018 M7 Anchorage, Alaska, earthquake is the first earthquake to cause significant damage in the United States since the U.S. Geological Survey (USGS) began providing ground failure hazard information on the earthquake event webpages in May of 2018. These automated ground failure reports provide qualitative alert levels and quantitative summary information. The quantitative information includes aggregate hazard and population exposure statistics for earthquake-induced landslides and liquefaction, as well as maps of the locations of highest probable hazard. The Anchorage earthquake provides a timely, critical test of the accuracy, design, and utility of the ground failure product. To assess model accuracy, we documented the presence or absence of liquefaction and landsliding in the field, targeting zones of both high and low hazard as predicted by the ground failure models. The modeled distributions of landslide and liquefaction hazards, however, did not perfectly match the observed pattern of ground deformation. We primarily observed liquefaction in areas of moderate to high modeled hazard (*e.g.*, Matanuska Valley) while also noting the absence of evidence for liquefaction in some high-hazard zones (*e.g.*, Chickaloon Bay). The landslide model correctly identified heightened hazard in the Chugach Mountains, but did not identify the hazard on coastal bluffs. The observations of ground failure in this earthquake will be used to improve the existing models and in the development of new models. We also summarize how the product was covered by the media and how communication and product usefulness can be improved in the future. Both media reports and USGS field observations generally support the alert statements automatically issued following the earthquake.

Initial Observations From the GEER Reconnaissance Evaluation of the 2018 M7.0 Anchorage Alaska Earthquake

KOEHLER, R. D., University of Nevada Reno, Nevada, USA, rkoehler@unr.edu; FRANKE, K. W., Brigham Young University, Utah, USA, kevin_franke@byu.edu; BEYZAEI, C. Z., SAGE Engineers, California, USA, zeebeyzaei@gmail.com; CABAS, A., North Carolina State University, North Carolina, USA, amcabasm@ncsu.edu; PIERCE, I. K. D., University of Nevada Reno, Nevada, USA, ian@nevada.unr.edu; STUEDLEIN, A. W., Oregon State University, Oregon, USA, armin.stuedlein@oregonstate.edu; YANG, Z., University of Alaska Anchorage, Alaska, USA, zyang2@alaska.edu

The 2018 M7.0 Anchorage Alaska earthquake occurred on November 30th and was located 11.3 km north of the city at a hypocentral depth of 40 km. Widespread damage reported in the media prompted the Geotechnical Extreme Events Reconnaissance Association (GEER) to rapidly mobilize a team to the affected area to assess general patterns of damage to better understand earthquake effects. The main objectives were to document perishable geotechnical and geologic data and evaluate lessons learned from the event. Close collaboration with municipal, state, and federal officials, as well as the local geotechnical engineering community greatly assisted the GEER team's efforts and highlights the importance of open communication during the immediate post-event response and recovery period.

Here we present the GEER team's initial observations from reconnaissance surveys conducted between December 8 and 15, 2018. Damage was characterized based on field mapping and aerial drone photogrammetry at sites within the affected area. We assessed damage to highway embankment slopes and bridges, sites with geotechnical ground improvements, sites with nearby ground motion recording stations, sites of critical infrastructure (*e.g.*, Port of Alaska, Port Mackenzie rail expansion project), and sites impacted by settlement, liquefaction and/or slope failure. The observations indicate that the majority of the infrastructure damage was related to localized liquefaction in granular fills beneath structures, slope instabilities in native slopes and anthropogenic fills, and bearing capacity failures in organic soil deposits due to cyclic softening. Within a week of the event, highway and road bridges had been inspected, major highway embankment damage had been repaired, utility services had been mostly restored, and structural repairs to many residences were underway highlighting the effectiveness of the engineering response and the resiliency of the Anchorage region.

Ground Motion and Hazard Context for the Anchorage Earthquake

WEST, M. E., University of Alaska Fairbanks, Alaska, USA, mewest@alaska.edu; RUPPERT, N., University of Alaska Fairbanks, Alaska, USA, naruppert@

alaska.edu; GARDINE, M., University of Alaska Fairbanks, Alaska, USA, mgardin2@alaska.edu

The 2018 Anchorage earthquake was the most significant earthquake in Alaska in a half century. While neither the source nor the magnitude are tectonically unusual, the close proximity to urban areas make this earthquake exceptional. Compared to most quakes along the Alaska-Aleutian arc, this event caused far more damage and triggered the first federal disaster declaration for an earthquake in Alaska since 1964. However, the earthquake also occurred in one of the most densely instrumented parts of Alaska. As a result, there are excellent ground motion records of the mainshock and the prodigious aftershocks (likely to eclipse 10,000 by the time of the SSA meeting). The combination of good ground motion records and well-documented damage from the earthquake make for a dataset without precedent in Alaska. This presentation will examine a few of the issues and topics raised thus far. The hypocenter was just 12 km north of Anchorage, but was 47 km below the surface. The area was spared the most violent shaking that would have accompanied a similar earthquake at shallow depth. But the depth, together with predominant soil types and topography, created a notably large area of strong shaking. Mercalli Intensities of 7 or higher spanned more than 150 km. Though this earthquake is likely to stimulate considerable discussion of early warning systems, the depth and proximity to Anchorage make this a particularly challenging test case. From a hazards perspective, the earthquake highlights the difficulty of quantifying future intraslab earthquakes. The absence of geologic and geodetic constraints remove some of the primary tools for seismic hazard evaluation. The statistical seismic record is a valid tool but is compromised by the short historical record. A final issue highlighted by this event is the very different styles of ground motion (frequency content and duration) from proximal earthquakes and the much larger but more distant great earthquakes on subduction interface.

Using the M7.0 Anchorage Earthquake to Validate Ground Response Modeling at the Delaney Park Downhole Array in Anchorage, Alaska

THORNLEY, J., Golder Associates, University of Strathclyde Glasgow, Alaska, USA, john_thornley@golder.com; DUTTA, U., University of Alaska Anchorage, Alaska, USA, udutta2@alaska.edu; YANG, Z., University of Alaska Anchorage, Alaska, USA, zyang2@alaska.edu; DOUGLAS, J., University of Strathclyde Glasgow, Glasgow, United Kingdom, john.douglas@strath.ac.uk

On November 30, 2018 Anchorage, Alaska was struck by a M7.0 earthquake, the largest earthquake since the 1964 Great Alaska Earthquake to shake Anchorage. Numerous strong motion instruments recorded the earthquake, including the Delaney Park Downhole Array (DPDA). The DPDA consists of seven strong motion three-component accelerometers at depths ranging from the surface to 61 meters below ground. It is located in downtown Anchorage, near where significant ground failure occurred in 1964. Significant improvements related to modeling ground response at the DPDA have been achieved by the authors over recent years to better estimate ground shaking at high intensities despite the absence of observations from such events. Thanks to the data collected during the 2018 earthquake at the DPDA a comparison can now be made between the model, calibrated with earthquakes of lower intensity, and the observations in the 2018 event. The largest ground motion measured at DPDA prior to November 30, 2018 was from the M7.1 Iniskin Earthquake on January 24, 2016, which was over 200km from Anchorage. Comparisons in site response among the Anchorage, Iniskin and other recent earthquakes is presented with consideration to site response modeling, with a focus on the transfer function.

The DPDA site model leads to a good fit of the large earthquake ground motion response and gives greater confidence in the analysis of site response within downtown Anchorage. There are some limitations to the equivalent-linear model with respect to nonlinear behavior of soil in large earthquakes where larger shear strains are developed. An evaluation of the modeled response with respect to estimation methods for nonlinear effects utilizing recent strain proxies is presented. The results of these evaluations create the groundwork for changes proposed to local building codes related to slope stability analysis within Anchorage.

A Twenty-Story Instrumented Building Response to M7 Anchorage, Alaska Earthquake

WEN, W., Key Lab of Structures Dynamic Behavior and Control of the Ministry of Education, Harbin Institute of Technology, Harbin, China, wenweiping.hit@gmail.com; KALKAN, E., U.S. Geological Survey, California, USA, ekalkan@usgs.gov

We examined the dynamic responses of a twenty-story steel moment-resisting frame building in downtown Anchorage, Alaska, during and after the moment magnitude 7 Anchorage earthquake. This regular-plan mid-rise structure (Atwood Building) is instrumented by the USGS with a 32-channel accelerometer array at ten levels. We computed impulse response functions (IRFs) based on waveforms recorded from the main shock and six aftershocks. The aftershocks have moment magnitudes ranging from 4.2 to 5.7. We determined the building's fundamental frequencies and mode shapes by using a singular-value decomposition of multiple reference frequency-response functions. The traveling waves, identified in IRFs with a virtual source at the roof, are used to estimate the shear-wave velocity (V_S) in the building. The median V_S from the IRFs of the seven earthquakes is 179 m/s for the east-west (EW), 200 m/s for the north-south (NS), and 165 m/s for the torsional responses. The intrinsic attenuation associated with the fundamental modes are identified by the IRFs with a virtual source at the ground. The building's average intrinsic-damping ratio is estimated to be 4.6% and 3.9% in the 0.2–1 Hz band for the EW and NS directions, respectively. These results are generally in agreement with our previous findings, which were based on earthquakes between 2005 and 2014 (Wen and Kalkan, 2017), indicating that the response of the building to the mainshock remained in linear-elastic range—a conclusion, also confirmed by visual inspections after the earthquake.

The M7.0 November 30, 2018, Anchorage, Alaska, Earthquake and Response of the USGS Earthquake Hazards Program

KNUDSEN, K. L., U.S. Geological Survey, California, USA, keithlknudsen@gmail.com; HAEUSSLER, P. J., U.S. Geological Survey, Alaska, USA, pheuslr@usgs.gov; WITTER, R. C., U.S. Geological Survey, Alaska, USA, rwitter@usgs.gov; THOMPSON, E. M., U.S. Geological Survey, Colorado, USA, emthompson@usgs.gov; BLANPIED, M. L., U.S. Geological Survey, Virginia, USA, mblanpied@usgs.gov; HAYES, G. P., U.S. Geological Survey, Colorado, USA, ghayes@usgs.gov

The November 30, 2018, Mw 7.0 earthquake near Anchorage, Alaska, occurred as the result of normal faulting at a depth of about 40 km. The locations and mechanisms of the mainshock and its aftershocks indicate that rupture occurred on an intraslab fault within the subducting Pacific slab, rather than on the shallower subduction interface between the Pacific and North American plates. Descriptions of the mainshock and associated hazards were quickly posted to the Earthquake Hazards Program event page, including two new products: aftershock forecasts and ground failure forecasts. The Anchorage area is relatively well instrumented with seismometers and accelerometers, including in a number of tall buildings and other structures. These seismic sensors generally performed well, recording a maximum acceleration of about 0.55g. Additional temporary seismic stations were deployed in the days following the mainshock in an attempt to better understand the effects of the Anchorage basin on ground motions from the robust aftershock sequence. The USGS loss estimation tool PAGER issued a green alert for fatalities and an orange alert for economic losses, in accord with the observed impacts from the mainshock. About 700 people provided Did You Feel It (DYFI) reports, and the maximum reported shaking intensity was MMI VIII. PGAs in the Anchorage area were generally higher than 0.3 g, and PGVs were on the order of 30 cm/s. As of the end of January 2019, there were >350 magnitude 3 or larger earthquakes, and seven magnitude 5 or larger aftershocks. The aftershock forecasts have been updated multiple times and have been well received by the public and emergency managers. A team of USGS ground failure experts visited the impacted area, along with local geologists and engineers, to map ground failure (liquefaction and landsliding – no surface rupture occurred) and evaluate the performance of the new, rapid ground failure forecasting products. In our presentation, we will summarize the earthquake, results of the new USGS products, and lessons learned during our response to this earthquake.

Emerging Science from the EarthScope Transportable Array in Alaska and Western Canada

Oral Session · Friday · 3:45 PM · 26 April · Cascade II

Session Chairs: Natalia A. Ruppert, Kevin M. Ward, Meghan S. Miller.

The Future of the Alaska Transportable Array

BUSBY, R., Incorporated Research Institutions for Seismology, District of Columbia, USA, busby@iris.edu; ADERHOLD, K., Incorporated Research Institutions for Seismology, District of Columbia, USA, kasey@iris.edu; ENDERS, M., Incorporated Research Institutions for Seismology, Alaska, USA, enders@iris.edu

EarthScope's Alaska Transportable Array (Alaska TA) continues to collect high quality seismic data toward fulfilling its primary objective: to image earth structure beneath the North American continent. The 280-station network has high data delivery completeness, dipping somewhat in the cold, dark winters. The network installation was completed in 2017, and attention recently has been directed toward the durability and power-resilience of the stations.

We continue to engage with numerous collaborators (UAF Alaska Earthquake Center, USGS Alaska Volcano Observatory, NOAA Tsunami Warning Center, UNAVCO Plate Boundary Observatory, Canadia Hazards Information Service, UCSD, Yukon Geological Survey and Wildland Fire Management, NOAA National Weather Service, NASA Arctic Boreal Vulnerability Experiment, U of Utah MesoWest, BLM) in supporting supplemental environmental sensing to help address the sparse coverage of ground-based observations in the U.S. and Canadian Arctic. Through these partnerships, additional sensors have been added to Alaska TA stations to collect meteorological, strong-motion, soil temperature, and infrasound observations with plans to collect soil samples on future visits to stations.

As with the successful Lower48 TA, we expect a profusion of publications and dissertations that will carve and distill the rich Alaska TA dataset over the years to come. The additional diversity in sensors helps to correlate observations and generally leads to greater diversity in science results. As an installed and operating network of autonomous, telemetered stations, the Alaska TA is an opportunity for multi-disciplinary observations collected across a remote, rugged, and rapidly changing region.

Updates regarding the schedule for stations to be removed and plans for stations to remain will be presented.

Contributions of USArray Stations to Regional Earthquake Monitoring in Alaska

RUPPERT, N., University of Alaska Fairbanks, Alaska, USA, naruppert@alaska.edu; WEST, M. E., University of Alaska Fairbanks, Alaska, USA, mewest@alaska.edu

Alaska is the most seismically active state in the nation with earthquakes spanning tectonic regimes, including transform faulting in the southeast Alaska, collision in the St. Elias region, subduction in southern Alaska and along the Aleutian Island Arc, and complex crustal faulting extending north to the Beaufort Sea. As a result of this tectonic complexity, earthquake detection in Alaska is non-trivial. Automatic earthquake detection and review procedures have existed at the Alaska Earthquake Center for decades. The procedures have been calibrated to measure as much seismicity as feasible while minimizing errors and workload. In the last three years, the seismic station coverage in Alaska has grown significantly with the presence of the USArray TA stations. The TA stations have provided an unprecedented opportunity to expand earthquake reporting in areas of Alaska that have never been instrumented. The Alaska Earthquake Center has been incorporating all TA data into its routine earthquake analysis. Recent increases in the number of reported earthquakes (over 50,000 in 2018) can be correlated with additional TA stations, especially those installed in the northeast Brooks Range, Bristol Bay region and interior Alaska. As a result, the magnitude detection threshold in these regions has decreased from M~3.0 to M~1.5. In recent months, phase picks from TA stations totaled about 30,000 per month (or about 30% of the total picks). The only region of Alaska that lacks earthquake detections despite TA station presence is north of the central and western Brooks Range, or so called North Slope region. This presentation will assess the quantitative changes in earthquake reporting that have occurred because of the inclusion of data from the TA stations and highlight recent notable Alaskan earthqukes.

Toward a Community Seismic Velocity Model for Alaska

THURBER, C. H., University of Wisconsin–Madison, Wisconsin, USA, cthurber@wisc.edu; EBERHART-PHILLIPS, D., GNS Science, Dunedin, New Zealand, donnaep.seis@gmail.com; NAYAK, A., University of Wisconsin–Madison, Wisconsin, USA, anayak5@wisc.edu; RUPPERT, N., Alaska Earthquake Center, Alaska, USA, naruppert@alaska.edu; DRISKELL, M., University of North Alabama, Alabama, USA, mmmoore@una.edu; FANG, H., Massachusetts Institute of Technology, Massachusetts, USA, hfang@mit.edu

We have initiated an effort to develop a community seismic velocity model for Alaska. The current goal is to produce a tomographic model based on the best available body-wave and surface-wave data that is useful for obtaining accurate earthquake locations and can be refined via full waveform tomography for purposes of waveform simulations. We are extending the 3D south-central Alaska model of Eberhart-Phillips *et al.* (2006; EP06) to a region with twice the area, adding more earthquake data, in particular taking advantage of data from the USArray Transportable Array, incorporating Rayleigh wave group velocity data from ambient noise, and carrying out joint inversions of body-wave and surface-wave data. Our current model covers a 1400 km by 100 km region with corners near (53° 20' N, 145° 20'W), (56° N, 161°W), (68° 10'N, 156° W), and (64° 45'N, 135° 20'W). The dataset includes approximately 260,000 P arrivals, 60,000 S arrivals, and Rayleigh wave group velocity maps for frequencies of 6.6 to 15.1 seconds. The surface-wave data used so far only cover the central part of the study region. A progressive inversion strategy was used, starting with body-wave only inversions for Vp and Vp/Vs structure with ~50 km grid spacing, followed by body-wave only inversions with ~25 km grid spacing, and finally the joint body-wave and surface-wave inversion, using the method of Eberhart-Phillips and Fry (2017). The area of good resolution is enlarged compared to EP06 in the overlapping area, especially for Vp/Vs thanks to the addition of the surface-wave data. In addition to providing generally minor refinement of the main features present in the EP06 model, we also confirm the deep horizontal velocity contrast across the Denali fault inferred by Allam *et al.* (2017) to represent a 10 km offset in the Moho. Our subsequent work will focus on improving the body-wave dataset, incorporating a larger set of surface-wave data, expanding the model area to cover more of continental Alaska, and comparing inversion results to that obtained using the method of Fang *et al.* (2019).

Alaska Amphibious Community Seismic Experiment: Update and Outlook

ROLAND, E., University of Washington, Washington, USA, eroland@uw.edu; ABERS, G. A., Cornell University, New York, USA, abers@cornell.edu; ADAMS, A. N., Colgate University, New York, USA, aadams@colgate.edu; BÉCEL, A., Lamont-Doherty Earth Observatory, New York, USA, annebcl@ldeo.columbia.edu; HAEUSSLER, P. J., U.S. Geological Survey, Alaska, USA, pheuslr@usgs.gov; SHORE, P. J., Washington University in St. Louis, Missouri, USA, patrick@wustl.edu; SCHWARTZ, S. Y., University of California, Santa Cruz, California, USA, susan@pmc.ucsc.edu; SHEEHAN, A. F., University of Colorado Boulder, Colorado, USA, anne.sheehan@colorado.edu; SHILLINGTON, D. J., Lamont-Doherty Earth Observatory, New York, USA, djs@ldeo.columbia.edu; WEBB, S., Lamont-Doherty Earth Observatory, New York, USA, scw@ldeo.columbia.edu; WIENS, D. A., Washington University in St. Louis, Missouri, USA, doug@wustl.edu; WORTHINGTON, L. L., University of New Mexico, New Mexico, USA, lworthington@unm.edu

The Alaska Amphibious Community Seismic Experiment (AACSE) represents one of the first shoreline-crossing seismic arrays of its kind focused on a subduction zone with prolific earthquakes and a complex volcanic arc. The 105 seismic instruments (75 OBS and 30 land broadband seismometers) associated with the AACSE are currently deployed along the Alaska Peninsula for a period of approximately 15 months, beginning in Spring 2018. This comprises an array that extends from the source region of the January 2018 M 7.9 earthquake east of Kodiak Island, west through the Shumagin Islands, and from the backarc to more than 200 km outboard of the trench. The AACSE array is complemented by EarthScope TA, Alaska network, and AVO stations on land. This effort represents an unprecedented deployment of seismic sensors over the seismogenic zone, sampling a region that that spans a hypothesized change in interseismic coupling along the subduction plate boundary, as well as a systematic change in chemical compositions of arc volcanoes. Better understanding structure and seismic behavior across these kinds of transitional boundaries helped to motivate this community effort, and should be made possible by analysis efforts currently being planned across the seismic community using this open-access data. Here we will provide an overview of the current state of the AACSE following the land and ocean-bottom instrument deployments, and servicing of land stations. We will summarize instrument performance across the land portion of the array, including noise levels and data return-rates, and also provide some initial assessments of recorded seismicity rates. Many complementary and add-on experiments have been coordinated in the final year of the experiment, and we will also provide an update on those opportunities and forthcoming datasets.

Nature and Thermal State of the Cordilleran Lithosphere in Northwestern Canada From a Compilation of Broadband Seismic Studies

AUDET, P., University of Ottawa, Ottawa, Canada, pascal.audet@uottawa.ca; SCHAEFFER, A. J., Geological Survey of Canada, Sidney, Canada, andrew.schaeffer@canada.ca; CURRIE, C., University of Alberta, Edmonton, Canada, claire.currie@ualberta.ca; CLEMENT, E., University of Ottawa, Ottawa, Canada, ceste044@uottawa.ca; SCHUTT, D., Colorado State University, Colorado, USA, derek.schutt@colostate.edu; ASTER, R., Colorado State University, Colorado, USA, rick.aster@colostate.edu; FREYMUELLER, J. T., Michigan State University, Michigan, USA, freymuel@msu.edu; CUBLEY, J., Yukon College, Whitehorse, Canada, jcubley@yukoncollege.yk.ca; KHARE, A., Colorado State University, Colorado, USA, adi.khare@colostate.edu

Various geophysical and geological data indicate that the lithosphere in the northern Canadian Cordillera (NCC) is thin and hot due to its position in a former arc and back arc setting. However, models of the origin and nature of the lithospheric mantle and persistence of the heat source beneath the NCC are debated and direct constraints on lithospheric mantle structure are sparse. The deployment of various broadband seismic networks in the area, including the USArray Transportable Array, is now affording a new opportunity to study the structure of the Cordilleran crust and mantle. In this work we co-examine recent seismic structural models that constrain various components of the NCC lithosphere at different resolution, including receiver functions, teleseismic shear-wave splitting, surface-wave tomography, and teleseismic body-wave tomography. These models indicate that: the Moho has low topography and lies at ~30-35 km depth; the seismic lithosphere-asthenosphere boundary is located at ~50-60 km; and the Cordillera-Craton (CC) boundary at lithospheric depth extends beneath the Cordillera. Toward the south of the NCC, we also identify a structure dipping toward the NCC that is anchored west of the Cordilleran Deformation Front. We examine end-member tectonic models that explain these observations: 1) the thin lithosphere is long-lived; or 2) the lower lithosphere was recently removed and is being rejuvenated. In the long-lived model, steady-state thermal calculations indicate that the Moho is ~950°C; in the lithosphere removal model, time-dependent thermal calculations suggest that an event occurring 10-20 My ago can reproduce the thermal and structural constraints. Finally, we discuss the tectonic and geophysical consequences of both end-member models combined with geologic evidence and favor models where the lithosphere of the NCC is either exotic or the result of progressive thickening and cooling since the Miocene.

Next Generation Seismic Detection

Oral Session · Friday · 8:30 AM · 26 April · Elliott Bay
Session Chairs: Timothy Melbourne, Richard M. Allen, Gavin P. Hayes, Raymond J. Willemann, G. Eli Baker.

A Deep Learning Pipeline for Earthquake Detection

ROSS, Z. E., California Institute of Technology, California, USA, zross@gps.caltech.edu; HAUKSSON, E., California Institute of Technology, California, USA, hauksson@gps.caltech.edu

Deep learning has led to significant recent advances in earthquake detection, phase picking, and association. Here, we discuss an end-to-end detection pipeline suitable for producing seismicity catalogs from raw continuous data. First, continuous data is processed with a deep convolutional network designed for generalized detection of body waves. Next, the resulting phase detections are examined by a recurrent neural network that is trained to link together phases that originate from the same earthquake. The final clusters of phase picks can then be used with a formal hypocenter inversion. We demonstrate the performance of the complete pipeline on datasets from southern California and Japan, and compare the results with that of template matching.

Cone Detectors That Operate at IMS Arrays Screen Background Seismicity at the DPRK Test Site

CARMICHAEL, J. D., Los Alamos National Laboratory, New Mexico, USA, josh.carmichael@gmail.com; WAGNER, G., Air Force Technical Application Center, Florida, USA, gwagner@aftac.gov

We derive a template-based, nonlinear convex cone-type waveform detector that demonstrably reduces nuisance alarms on background seismicity. Our detector is more discriminating than a correlation detector, and screens out signals that partially correlate with the detector's waveform template. We quantify this discrimination power with physical parameters that depend on source and background seismicity, that include the relative magnitude between ``template'' and ``target'' sources. We then use seismic records of several events that locate at or near the North Korean test site from an IMS array (USRK) to quantify the capability of this detector to screen non-target explosion-sources that spatially separate from the template source. By applying source-receiver reciprocity, we thereby calculate values for screening capability improvement versus template-target explosion source separation. Our results show a demonstrable improvement in both the observed and predictive capability, over that of the correlation detector, for explosion-triggered target signals contaminated by background seismicity.

Analyzing Data From MyShake Smartphone Seismic Network

KONG, Q., Berkeley Seismological Laboratory, California, USA, kongqk@berkeley.edu; INBAL, A., Tel Aviv University, Tel Aviv, Israel, asafinbal@tauex.tau.ac.il; ALLEN, R. M., Berkeley Seismological Laboratory, California, USA, rallen@berkeley.edu

MyShake is a global smartphone seismic network that harnesses the power of crowdsourcing. The deployment of a seismometer becomes a simple download of MyShake application in the app store that turns the smartphone into a portable seismometer. The accelerometers inside the phones can be used to monitor the ground motions during the earthquakes and using the onboard communication unit to send the data to the central data center. After the release of MyShake in Feb 2016, more than 900 earthquakes were recorded by the citizen scientists globally, with some of the earthquakes recorded by many users nearby. Even though the quality of the sensors inside a smartphone is low compared with the traditional sensors, the large number of users will compensate on the quality. In this presentation, I will report the recent analysis on the data we collected globally from the consumer devices and show that the MyShake global smartphone seismic network can do many useful applications in seismology and engineering, such as detect the earthquakes, and estimate the earthquake parameters, such as magnitude, location, and origin time, and potential structural health monitoring. This will be really useful for places where they can not afford traditional seismometers and used as a stand-alone seismic network to monitor earthquakes in the region.

Smartphone App Earthquake Detections: How Combined Analysis of Crowdsourced and Seismic Data Can Improve Performance of Existing Seismic Networks

BOSSU, R., European-Mediterranean Seismological Centre, Arpajon, France, bossu@emsc-csem.org; STEED, R., European-Mediterranean Seismological Centre, Arpajon, France, robert.steed@emsc-csem.org; LANDES, M., European-Mediterranean Seismological Centre, Arpajon, France, matthieu.landes@emsc-csem.org; ROCH, J., European-Mediterranean Seismological Centre, Arpajon, France, julien.roch@emsc-csem.org; ROUSSEL, F., European-Mediterranean Seismological Centre, Arpajon, France, roussel@emsc-csem.org

App earthquake detection is the latest crowdsourced-earthquake-detection method implemented at the EMSC to automatically identify felt events. It simply monitors concomitant LastQuake smartphone app launches. Compared to the 2 other methods in operation - Twitter earthquake detection and website traffic monitoring - it offers much more accurate geographical information and faster detections respectively. In practice, detections can be as fast as 20 sec and felt area be automatically mapped within tens of seconds of the propagation time to reach the most distant eyewitnesses, independently of any seismic data. Similarly to seismic networks, detection times are shown to depend on the number of users at close epicentral distances. App earthquake detections are exploited to reduce the latency of publishable seismic locations by combining their analysis with seismic data, a method named CrowdSeeded earthquake Location (CSLoc). Picks are automatically retrieved through a messaging system from GEOFON stations in a time and space window centered on the app detection, picks are then selected for consistency with seismic wave propagation before a seismic location is performed using the barycenter of app launches as seed. The process iterates until location is reliable. Reliable locations are available at global scale within 100s (median time), with a pick extraction delay of 30s, performance depending on the actual station coverage in the epicentral region. Beyond the presentation of the methods and its performances, we will outline future work in collaboration with the EarthquakeNetwork, an app that detects shaking on the internal sensors of smartphones.

Global Seismic Monitoring With Real-Time GNSS

SZELIGA, W., Central Washington University, Washington, USA, walter@geology.cwu.edu; MELBOURNE, T. I., Central Washington University, Washington, USA, tim@geology.cwu.edu; SCRIVNER, C., Central Washington University, Washington, USA, scrivner@geology.cwu.edu; SANTILLAN, V. M., Central Washington University, Washington, USA, marcelo@geology.cwu.edu

The ongoing, global proliferation of real-time GNSS networks has blanketed many of Earth's tectonically active regions with receivers that straddle active crustal faults, tsunamigenic subduction zones, volcanoes, landslides, and many other sources of natural hazards. In some seismically active regions such as Japan and the western US, the number of GNSS receivers now rivals seismometers available for earthquake and tsunami monitoring. Steady improvements in the accuracy and stability of real-time positioning has encouraged integration of GNSS into existing monitoring and hazards mitigation systems. GNSS positions computed in real-time are now utilized by the USGS and NOAA because they offer nearly instant quantification of coseismic deformation, a direct constraint on moment magnitude, while coseismic slip unfolds. Where station density allows, real-time positions can also map the accumulation of fault slip as rupture propagates, which is particularly valuable during extended, complex earthquakes whose rupture may last minutes and span multiple fault systems. For these most damaging events, traditional seismic centroid solutions fail to accurately characterize either slip. Additionally, the delay required to obtain accurate centroids severely limits many emergency response mechanisms. Real-time GNSS offers dramatic improvements for these types of events. Improvements in real-time positioning and downstream product generation are expected to continue. The incipient launch of new constellations transmitting on distinctive frequencies will enable higher-order corrections to signal propagation delays that will result in stable, sub-centimeter real-time point positioning. The development of high-quality ancillary models required for positioning will also improve delivery and rate of adoption of new hazard mitigation products. These products include time-dependent atmospheric delay, satellite orbit and clock perturbations, and earth orientation, increasing the stability and accuracy of positioning and downstream hazard mitigation products to those who need them quickly.

New Frontiers in Global Seismic Monitoring and Earthquake Research

Oral Session · Friday · 10:45 AM · 26 April · Elliott Bay
Session Chairs: Gavin P. Hayes, Paul Earle, Kristine Pankow, Alberto Michelini.

Semi-Supervised Learning for Seismic Monitoring Applications

LINVILLE, L., Sandia National Laboratories, New Mexico, USA, llinvil@sandia.gov; ANDERSON, D., Sandia National Laboratories, New Mexico, USA, dzander@sandia.gov; MICHALENKO, J., Rice University, Texas, USA, jjmich@sandia.gov; GALASSO, J., Sandia National Laboratories, New Mexico, USA, jgalass@sandia.gov; DRAELOS, T., Sandia National Laboratories, New Mexico, USA, jdrael@sandia.gov

The impressive performance that Deep Neural Networks demonstrate on a range of seismic monitoring tasks is largely due to the availability of event catalogs that have been manually curated over many years or decades. However, the quality, duration, and availability of seismic event catalogs varies significantly across the range of monitoring operations, regions, and objectives. Semi-Supervised Learning (SSL) methods provide a framework to leverage the abundance of unreviewed seismic data, that would otherwise go unused for learning a variety of target tasks. We apply two recently published SSL algorithms (Mean-Teacher and Virtual Adversarial Training) on seismic event classification to examine how unlabeled data can enhance model performance. We explore how SSL techniques can close the generalization gap when the input and target distributions differ as well as when they are approximately equivalent, the intended use case of SSL. We provide discussion for when these techniques work well and cautions for when using SSL for monitoring in regions where no ground truth is available.

Comparison of Pick-Based and Waveform-Based Event Detectors for Local to Near-Regional Distance Data From Utah

HECK, S., Sandia National Laboratories, New Mexico, USA, sheck@sandia.gov; YOUNG, C. J., Sandia National Laboratories, New Mexico, USA, cjyoung@sandia.gov; BROGAN, R., ENSCO, Inc., New Mexico, USA, brogan.ronald@ensco.com

In this presentation, we compare a pick-based event detector, the Probabilistic Event Detection Association and Location (PEDAL) algorithm, to a waveform-based detector, the Waveform Correlation Event Detection System (WCEDS). Both algorithms were tested on 3-component data from stations in the University of Utah Seismic Station (UUSS) network. We chose to focus on Utah because the region is tectonically complex and includes both regularly occurring earthquakes from the north-south trending Intermountain Seismicity Belt (ISB) as well as various types of anthropogenic events (quarry blasts and mining induced seismicity), hence it presents a variety of challenges for event detection. The interval of time processed (January 1-14, 2011) was chosen because of the occurrence of a significant aftershock sequence (several hundred events) near the town of Circleville in southern Utah. The data set also includes a huge number of mining induced events from a coal mining region in central Utah. The events built by our two methods are scored against a master catalog, carefully built by an expert analyst who attempted to find all events with observable signals at 3 or more stations (resulting in a total of 7883 events for the 14 days). Comparison of the 3 catalogs is done using a Venn diagram, to investigate areas of overlap and isolation. Our results suggest that when tuned to achieve a comparable level of recall, the waveform-based method has better precision (*i.e.* fewer false events). We also found the waveform-based method to be more stable and easy to configure due to the lack of an additional processing step to generate signal detections.

Regional Earthquake Relocation Using Multiple Seismic Arrays: Case Examples From Offshore Eastern Taiwan and Yellow Sea Between China and South Korea

CHIU, J., University of Memphis, Tennessee, USA, jerchiu@memphis.edu; KIM, K., Pusan National University, Busan, Korea, Republic of, kwanghee@pusan.ac.kr; CHIU, S. C., University of Memphis, Tennessee, USA, scchi168@gmail.com; KANG, S., Pusan National University, Busan, Korea, Republic of, sukang@gmail.com; HAN, J., Pusan National University, Busan, Korea, Republic of, handy0718@gmail.com; HWANG, B., Institute of Earth Sciences, Academia Sinica, Taipei, Taiwan, hwbs@earth.sinica.edu.tw; CHEN, K., Institute of Earth Sciences, Academia Sinica, Taipei, Taiwan, chenkc@earth.sinica.edu.tw

Regional earthquake locations using local seismic network are always subjecting to large uncertainties due to poor spatial coverage of seismic stations, discrepancies on velocity models, and limitations on traditional location technologies. For instance, it is not uncommon that the same earthquake within Yellow Sea may be reported more than tens to hundreds of km apart independently in Chinese and Korean catalogs while there is no mechanism for earthquake data exchange between two countries. Integrating seismic stations into multiple arrays, apparent azimuths and apparent velocities of incoming seismic waves (mainly Pn) from a regional earthquake to each array can be reliably determined. Epicenter of a regional earthquake can thus be reasonably located by tracing seismic rays following the back azimuths derived from multiple arrays. This method has been applied to relocate earthquakes in offshore region of eastern Taiwan using CWB island-wide network data and in Yellow Sea region using KMA network data. In the Taiwan case, relocated epicenters are consistent with that reported by JMA and NEIC. While the apparent velocity ~6.8 km/sec is found for all arrays that implies the propagation of oceanic Pn waves across the ocean-continent transition region into land stations along a path of minimum travel time. In the Yellow Sea case, the apparent velocity ~8.0 km/sec for all arrays suggests a typical continental Pn waves propagating across the continent-continent transition region into Korean Peninsula. The significance of relocated epicenters in the Yellow Sea region is yet to be explored.

Rapid Characterisation of Large Earthquakes in New Zealand

FRY, B., GNS Science, Wellington, New Zealand, b.fry@gns.cri.nz; GLEDHILL, K., GNS Science, Wellington, New Zealand, k.gledhill@gns.cri.nz; KAISER, A. E., GNS Science, Wellington, New Zealand, a.kaiser@gns.cri.nz; HOLDEN, C., GNS Science, Wellington, New Zealand, c.holden@gns.cri.nz

New Zealand GeoNet, a facility operated by GNS Science, monitors earthquakes and tsunami in New Zealand. GNS Science are a government owned research institute and provide information directly to the Ministry of Civil Defense during crises. GeoNet recently opened a 24/7 operations centre, which provides a robust pathway for delivering rapid event information directly to government decision makers. However, current information available to the operations center in the first minutes after an event is primarily limited to earthquake magnitude and hypocenter from automated processing using traditional association of sta/lta seismic triggers and amplitude-based magnitudes. To improve on this and provide a better first estimate of potential impacts to affected communities including strong shaking and tsunami potential, as well as support rapid decision making, we are aggressively prototyping better ways to use available strong motion data. These include better estimates of magnitude and spatial mapping of impacts through locating the strong motion centroid and mapping the rupture area with back-projection based approaches. We aim to provide these results within the first 5 minutes after the event. We are exploring options to integrate geodetic analysis with seismic techniques through further upgrade our geodetic network to provide real-time high-rate GPS data for rapid finite fault inversion. Lastly, we have identified a class of offshore earthquakes that are capable of generating significant tsunami with coastal travel times under 1 hour that may not be strongly felt by vulnerable coastal communities, thus limiting natural warning coastal evacuation. The necessity of developing instrumental warning for these near-regional events has prompted an update of our procedures and the national tsunami response plan and a scoping of integrated seismic and ocean observation options and tools to underpin local and regional tsunami early warning.

Update From the Powell Center Working Group on Future Opportunities in Regional and Global Seismic Network Monitoring and Science

HAYES, G. P., U.S. Geological Survey, Colorado, USA, ghayes@usgs.gov; EARLE, P., U.S. Geological Survey, Colorado, USA, pearle@usgs.gov

In September 2018, the USGS Powell Center hosted a multi-day international meeting on "*Future Opportunities in Regional and Global Earthquake Monitoring and Science.*" The meeting brought together domestic and international researchers and network representatives interested in improving earthquake monitoring and characterization. The primary goals were to build a list of priorities for earthquake monitoring, to begin outlining how these changes will be implemented, and to improve communication and coordination among regional and international earthquake monitoring agencies.

Areas of focus identified by the group included use of machine learning techniques to improve the reliability of source characterization, leveraging insights from the nuclear monitoring community in processing array data for

earthquake detection and association, compressing the timeline of rapid source characterization, and improving our use of social media and crowd-sourced data. This presentation will provide an update on the progress of the working group, and the next steps towards implementing the goals raised at the 2018 meeting at earthquake monitoring agencies.

Using Repeating Seismicity to Probe Active Faults

Oral Session · Friday · 1:30 PM · 26 April · Elliott Bay
Session Chairs: Calum J. Chamberlain, Amanda M. Thomas, William B. Frank.

The Initiation of Dynamic Rupture on a 3-m Laboratory Earthquake Experiment

MCLASKEY, G., Cornell University, New York, USA, gcm8ster@gmail.com

Repeating earthquakes and low-frequency tremor-like signals have been observed prior to the initiation of some earthquakes suggesting an extended nucleation process. I describe sequences of laboratory earthquakes generated on a 3-meter laboratory rock experiment that provide insights into how earthquakes can initiate and have implications for variability in repeating earthquake sequences. The granite sample was loaded to 2-12 MPa stress levels and then sheared, while slip on the laboratory fault was measured at 16 locations along its 3-m length. If the initial along-fault stress distribution was sufficiently heterogeneous, stick-slip events that ruptured the entire fault were preceded by a sequence of smaller, M -2.5 earthquakes that repeatedly ruptured the same subsection of the fault, with successive events increasing in rupture length and stress drop. More uniform stress distributions produced stick-slip events that initiated more abruptly, often with a meter-sized zone of slow slip (nucleation zone) that expanded and accelerated until reaching seismic slip speeds (>0.1 m/s). The effects of fault strength heterogeneity and fault healing can cause variations in the size and speed of the nucleation process. When continuously loaded at a steady rate, the sample produced sequences of complete-rupture stick-slip events which might be analogous to repeating earthquake sequences observed in nature. The laboratory experiments show that the largest events in these sequences are the result of a smaller and more abrupt nucleation process, whereas weaker events nucleated more slowly and over a larger fault area. Finally I discuss different models for scaling up the laboratory results to larger, rougher natural faults, and describe which aspects are supported by laboratory and field observations.

Spatial and Temporal Evolution of Microseismicity of the Rattlesnake Ridge Landslide

THOMAS, A. M., University of Oregon, Oregon, USA, amt.seismo@gmail.com; TOOMEY, D., University of Oregon, Oregon, USA, drt@uoregon.edu; CHAMBERLAIN, C. J., Victoria University of Wellington, Wellington, New Zealand, calum.chamberlain@vuw.ac.nz; NEWTON, T. J., University of Oregon, Oregon, USA, tnewton@uoregon.edu; MALONE, S., University of Washington, Washington, USA, smalone@uw.edu

In October of 2017, a 3 million cubic meter translational landslide, known as the Rattlesnake Ridge rockslide, developed over the course of two months on the Rattlesnake Hills anticline outside Union Gap, WA. Acceleration of the slide mass raised concern over the stability of the ridge resulting in road closures, mandatory evacuation of a nearby residential area, and placement of concrete filled shipping containers to block rockfall onto Interstate 82. The slide accelerated until early April reaching a peak slip rate of 74 cm/day, approximately two orders of magnitude faster than "typical" plate boundary faults, and then has gradually slow down to half that rate by the end of 2018. To study microseismicity associated with slide motion, we deployed 40 3C Nodal seismometers around the Rattlesnake Ridge landslide body for a four-month period between March and July of 2018. Initial analysis reveals frequently occurring, very small magnitude earthquakes with dominant frequencies of 30-40 Hz. Because these events often exceed background noise levels, and have impulsive arrivals, we use STA/LTA on 118 days of seismic data to compile an initial set of earthquake detections. We then use these events as waveform templates and cross-correlate them through the remaining dataset to search for repeating earthquakes. After summing the daily cross correlations for a particular template, we consider anything with a summed network cross correlation of greater than eight times the median absolute deviation as a repeater. The resulting families of repeating events are subsequently culled such that no family shares more than 20% of detections with any other family. This process results in 30,000+ repeating earthquakes per day constituting 60+ families. Crude location estimates suggest that these events occur both along the bounding, left-lateral oblique fault on the slide margin and within the slide body itself. Here we report on the locations, occurrence patterns, and evolution of waveform character of this repeating earthquake dataset.

Modeling High Stress Drops, Scaling, Interaction and Irregularity of Repeating Earthquake Sequences Near Parkfield

LUI, S. K. Y., University of Toronto, Mississauga, Canada, semechah.lui@utoronto.ca; LAPUSTA, N., California Institute of Technology, California, USA, lapusta@caltech.edu

Repeating earthquake sequences have been actively investigated to clarify many aspects of earthquake physics and mechanics. In particular, small repeating earthquakes present a rare predictable opportunity for detailed observation and study because of their short recurrence times and known location. For example, two well-studied sequences along the San Andreas Fault, known as the Los Angeles and San Francisco repeaters, have several intriguing observations: (1) long (for the seismic moment) recurrence times that would suggest stress drops of 300 MPa based on typical assumptions, (2) near-synchronized timing prior to 2004, and (3) higher than typical inferred stress drops (of 25 to 65 MPa, up to 90 MPa locally), but not as high as the recurrence times suggest.

Our study shows that all these observations are self-consistent, *i.e.* they can be reproduced in a single fault model. The suitable models build on the standard rate-and-state fault models, with velocity-weakening patches imbedded into a velocity-strengthening region. To allow for the higher stress drops, either enhanced dynamic weakening during seismic slip or elevated normal stress, or both, are added to the velocity-weakening patches. Such models are able to match the observed average source properties of the San Francisco and Los Angeles repeaters, as well as the overall nontrivial scaling between the recurrence time and seismic moment exhibited by many repeating sequences as a whole, for reasonable parameter choices based on experiments and theoretical studies. One key finding is the substantial and variable occurrence of aseismic slip at the locations of the repeating sources among these models, which explains their atypical relation between recurrence interval and seismic moment, induces variability in the repeating source properties as observed, and results in their neither slip- nor time-predictable behavior.

Slow Slip Happens Every Day

FRANK, W. B., University of Southern California, California, USA, wbfrank@usc.edu; BRODSKY, E. E., University of California, Santa Cruz, California, USA, brodsky@ucsc.edu

Slow slip plays a major role in accommodating the relative motion at the boundaries between tectonic plates. Lasting from seconds to months, no single geophysical instrument is able to observe the full continuum of slow slip. Here, we jointly analyze seismic and geodetic data from the Mexican subduction zone to explore this instrumental blind spot, and report on the first observations of hours-long slow transients that occur daily. We find that these slow transients scale like ordinary earthquakes, suggesting that slow and fast slip are different constituents of a broad spectrum of transient slip.

Aseismic Slip at the Mendocino Triple Junction From Repeating Earthquakes

MATERNA, K., University of California, Berkeley, California, USA, kmaterna@berkeley.edu; TAIRA, T., University of California, Berkeley, California, USA, taira@berkeley.edu; BÜRGMANN, R., University of California, Berkeley, California, USA, burgmann@seismo.berkeley.edu

The Mendocino Triple Junction (MTJ) is a seismically active region at the transition between the San Andreas Fault system, the Mendocino Transform Fault, and the Cascadia Subduction Zone. The triple junction itself is located offshore, making it especially difficult to study using land-based methods. In this work, we document the occurrence of aseismic creep near the MTJ using characteristically repeating earthquakes (CREs) as indicators of creep rate. Using seismic data from 2008-2018, we identify CREs as recorded by an array of seismometers, including eight 100-Hz borehole instruments in the Cape Mendocino area. We apply a repeating earthquake detection criterion to the waveforms, and identify several dozen sequences of repeating earthquakes. The CRE data implies a creep rate of ~3 cm/yr on the downgoing extension of the Mendocino Transform Fault, consistent with other estimates of coupling on oceanic transform faults. We also find repeating earthquakes on the southern margin of the North American accretionary wedge. The creep rates are mostly steady over the study period, although we investigate the potential for small transients due to stress interactions between moderate-sized earthquakes and the CRE sequences. This project demonstrates the ability of CREs to monitor aseismic creep and its time-dependent features in a plate boundary region outside the coverage of current geodetic networks.

Non-Traditional Application of Seismo-Acoustics for Non-Traditional Monitoring

Oral Session · Friday · 3:45 PM · 26 April · Elliott Bay
Session Chairs: Monica Maceira, Chengping Chai, Omar Marcillo.

Mapping the Harmonic Tonal Noise in the Continental U.S.

MARCILLO, O., Los Alamos National Laboratory, New Mexico, USA, omarcillo@lanl.gov; MACCARTHY, J. K., Los Alamos National Laboratory, New Mexico, USA, jkmacc@lanl.gov

Industry has a significant impact in the local seismic background noise. The repetitive nature of industrial processes generates persistent mechanical energy that can be observed at distances of several 10's of kilometers in the ground and air, its spectral signature is usually characterized by broadband and discrete features. Using a dense seismic sensor network that scanned the contiguous US between 2003 and 2014 with broadband sensors with inter-sensor distance of around 75 km we identified areas affected by persistent industrial noise with very similar characteristics that we argue are related to similar physiographic characteristics in the US territory, such as, favorable winds or abundance of water. We will show preliminary results of our efforts to map Harmonic Tonal Noise (industrial noise) for the contiguous US.

The 2016 Infrasound Wanaka Balloon Flight: What Have We Learned?

LEES, J. M., University of North Carolina at Chapel Hill, North Carolina, USA, jonathan.lees@unc.edu; BOWMAN, D. C., Sandia National Laboratories, New Mexico, USA, dbowma@sandia.gov; LAMB, O., University of North Carolina at Chapel Hill, North Carolina, USA, olamb@email.unc.edu; TRAPHAGAN, J. W., University of North Carolina at Chapel Hill, North Carolina, USA, juliant@live.unc.edu

The spectacular 20 day balloon flight of a high altitude balloon, circumnavigating Antarctic in 2016 has produced a series of critical, new observations. A fortuitous hover over the source of the microbarom south of New Zealand can be used to estimate the heat flux into the upper atmosphere, testing early estimates by (Rind *et al.*, 1977). Initial projections in the Southern Ocean suggest a flux of 0.05 mW/m^2 maximum acoustic energy generated from the ocean microbarom. Thermospheric heating calculations indicate a temperature rise of several degrees Kelvin per day while the source is active, agreeing with earlier estimates made in the 1970's. Estimates of spatial kernels of the ocean surface source indicate that crude integration is adequate to determine a response in the stratosphere. Lightning strikes have been observed off the coast of New Zealand, observed at IMS arrays and the floating observatory. Balloon borne platforms and associated harsh environment technology is currently being proposed for extra-terrestrial seismological exploration of planets where ground installations are prohibitive (Venus and Jupiter).

Unconventional Seismic Monitoring in the Built Environment, From Canal Integrity to Coal Seam Fires

LEVANDOWSKI, W., Tetra Tech, Inc., Colorado, USA, will.levandowski@tetratech.com; O'CONNELL, D. R., Tetra Tech, Inc., Colorado, USA, dan.oconnell@tetratech.com; STEELE, L., Tetra Tech, Inc., Colorado, USA, lincoln.steele@tetratech.com; JOHNSON, M., Tetra Tech, Inc., Colorado, USA, max.johnson@tetratech.com; NUTTALL, J., Tetra Tech, Inc., Colorado, USA, jeff.nuttall@tetratech.com; ISAACSON, M., Tetra Tech, Inc., Colorado, USA, mitch.isaacson@tetratech.com; TURNER, J., Tetra Tech, Inc., Colorado, USA, jamey.turner@tetratech.com

Seismic approaches can be used in a wide variety of geotechnical applications, but the exact needs of any specific project defy any uniform methodology. With a bit of creativity, however, a diverse array of applications can be realized. Here, we present a few examples of unconventional uses of seismic data in anthropogenic environments. In a pilot study, we deployed a passive seismometer overnight at a highly active coal seam fire in Colorado. In addition to migrating elk, the instrument recorded intermittent, repeating impulsive events and distinct, unfamiliar long-period signals. We hypothesize that these signals are spalling of roof material or propagation of roof-subsidence fractures and air intake or slow flexure of the roof material, respectively. To test these hypotheses and to assess the utility of passive seismic monitoring of abandoned coal mine fires, a small array of six instruments has been deployed for a one-month trial. We will discuss the results of that monitoring. In a separate project, we were tasked with determining the location, geometry, and integrity of the wood-crib frame structure at a polluted, urban canal site. We used a horizontally polarized shear source to produce scattered Rayleigh and P wave responses on vertical-component geophones (finite-element simulations demonstrated that coupled S-Love-Rayleigh responses on horizontal components would be too complicated to use efficiently), which very clearly delineate the cross-beams and inner crib walls. Vertical sources elicit strong P and Rayleigh responses within the wood-crib itself, allowing for the determination of the full geometry of the frame and moduli and density of timbers and other geotechnical material.

Detecting and Monitoring Operational Events Around a Nuclear Reactor Using Seismo-Acoustic Signals

CHAI, C., Oak Ridge National Laboratory, Tennessee, USA, chaic@ornl.gov; MARCILLO, O., Los Alamos National Laboratory, New Mexico, USA, omarcillo@lanl.gov; RAMIREZ, C. A., Oak Ridge National Laboratory, Tennessee, USA, ramirezca@ornl.gov; MACEIRA, M., Oak Ridge National Laboratory, Tennessee, USA, maceiram@ornl.gov

There are more than one hundred nuclear reactors operating in the United States, making it the world's largest producer of nuclear energy. Around two-thirds of these reactors generate 20 percent of the total electricity in the country and the rest are used for research or training purposes. Operating a nuclear reactor involves multiple procedures and complex systems of interrelated machines. If we consider as an operational event any change in status (initiation, interruption, and termination) or configuration (change in power, speed, or frequency) of said machines, then many of these events are characterized seismically and/or acoustically by transient or permanent changes in the spectral distribution of energy. In particular, recorded seismo-acoustic signals can be used to detect and monitor these operational events. To demonstrate this idea, we have deployed a three-component seismic station with three acoustic sensors close to the High Flux Isotope Reactor (HFIR) at Oak Ridge National Laboratory (ORNL) for more than a year.

We developed an approach for the automatic detection of operational events based on identifying statistical changes in the spectral distribution of energy compared to a spectral baseline. We applied the power spectral density (PSD) based detection algorithm to continuous seismo-acoustic data and compare the results with operational ground truth logs. The algorithm not only finds the timing of detectable operational events but also the frequencies of the associated seismic/acoustic signal. Furthermore, we developed interactive visualization tools to examine the results in detail. Preliminary results show a good agreement between the PSD detections and ground truth for several operational events.

Monitoring a Nuclear Research Reactor with Traditional and Non-Traditional Vibration Measurements

PARIKH, N. K., Los Alamos National Laboratory, New Mexico, USA, nidhip@lanl.gov; FLYNN, G. S., Los Alamos National Laboratory, New Mexico, USA, garrison@lanl.gov; CASLETON, E., Los Alamos National Laboratory, New Mexico, USA, ecasleton@lanl.gov; RAY, W., Oak Ridge National Laboratory, Tennessee, USA, raywr@ornl.gov

Distributed Acoustic Sensors (DAS) with fiber optics presents new opportunities for monitoring vibrational signals by allowing for closely spaced sensors to be placed over large distances to collect data in the kilohertz range and potentially resolve spatial locations of sources. However, the fiber optic sensors tend to have higher sensitivity to environmental conditions relative to traditional seismo-acoustic (SA) sensors as well as coupling of acoustic and seismic signals together in an unknown manner. Ground-based DAS sensors, as well as traditional SA sensors, have measured multiple power-up events of the High Flux Isotope Reactor (HFIR), a research reactor at Oak Ridge National Laboratory that operates at a power of 85 MW. Vibrations from cooling towers associated with the reactor's secondary cooling loop produce unique seismic and acoustic signatures during different stages of reactor operations. Statistical analysis is used to compare features extracted from the DAS measurements and traditional SA measurements to determine coupling of seismic and acoustic signatures, in addition to identifying sensitivities to DAS deployment configuration and environmental effects.

Seismology BC(d)E: Seismology Before the Current (digital) Era

Oral Session · Friday · 8:30 AM · 26 April · Pike
Session Chairs: Susan E. Hough, Lorraine Hwang, Allison L. Bent, Maurice Lamontagne, Emile Okal, Brian Young, Graziano Ferrari.

From Historical Seismology to Seismogenic Source Models to Seismic Risk: 20 Years On, Results and Challenges

VALENSISE, G., Istituto Nazionale di Geofisica e Vulcanologia, Rome, Italy, gianluca.valensise@ingv.it

Over the past two decades Historical Seismology has experienced a silent revolution that turned it from purely descriptive to fully quantitative, transformed its outcomes from vaguely subjective to solidly reproducible, and – unbeknown to many – increased its relevance far beyond the mere computation of "activity rates" in the SHA practice.

In Italy this revolution was largely spawned by the inception of the Catalogue of Strong Earthquakes in Italy, or CFTI (see Ferrari *et al.* in this session): a large databases providing for each earthquake all felt intensities along with the precise identification of the reported sites and a description of the earthquake effects. CFTI allowed automatic processing of intensity data to derive the epicentral parameters, an equivalent magnitude and the geometric parameters of the prospective causative fault through a Fortran code termed Boxer (Gasperini *et al.*, BSSA, 1999).

The improved data manageability and resolution allowed large Italian earthquake sequences to be investigated in depth, often revealing an unexpected source complexity and setting new constraints on the location and magnitude of the most significant shocks. This evidence contributed to unraveling the arrangement and behavior of large seismogenic fault systems, greatly supporting seismotectonic interpretations in areas dominated by tectonic complexity and blind faulting. Historical data have been used for calculating earthquake budgets to be compared with geodetically-determined tectonic strains, which allowed crucial investigations on the variability of seismic coupling and on earthquake recurrence models devised for seismic hazard assessment. Finally, the availability of the seismic history of all Italian municipalities served as a basis for a first-cut estimation of their vulnerability, thus contributing to the definition of priorities for seismic risk mitigation countrywide.

Little or none of all this would have been possible without Historical Seismology data, an often overlooked treasure that still awaits to be exploited in many seismogenic areas worldwide.

Himalaya – A Present-Day Evaluation of Its Thousand-Year Seismic Slip Potential

BILHAM, R., University of Colorado Boulder, Colorado, USA, roger.bilham@colorado.edu

Seismic, geodetic and felt-intensity observations from the 2015 Mw=7.8 Gorkha earthquake provide a template for the interpretation of pre-1960 earthquakes in the Himalaya. Four Mw>7.0 earthquakes since 1800 show striking similarities to the Nepal event and, as in 2015, are each inferred to have incremented elastic strain tens of km short of the frontal thrusts. Since no nearby major earthquakes have followed historical earthquakes, the resulting accumulating reservoir of elastic strain (invisible to geodesy once emplaced), is apparently impotent at nucleating spontaneous up-dip or along-strike contiguous ruptures. If this is a universal feature of M<8 Himalayan earthquakes it is obviously good news for the Kathmandu region where concerns have been expressed about the destiny and future evolution of the 2015 co-seismic strain-field. However, this latent strain, and reservoirs of relict strain energy elsewhere in the Himalaya, cannot persist indefinitely and are destined to be liberated in future great earthquakes. The ≥10 m of slip inferred for some paleoseismic surface ruptures may in large part be attributable to these Mw>8.5 earthquakes being fueled by inherited latent up-dip strain. The past 1000 years of earthquakes within 15 Himalayan segments between Kashmir and Assam are evaluated in the context of these new insights. In some places the current slip potential exceeds 10 m, and depending whether contiguous segments rupture individually or in parallel, a hierarchy of pending 8.0<Mw<8.7 scenario earthquakes can be envisaged. Two of these scenarios are for Mw=8.7 earthquakes. Alternatively, partial rupture of these regions could nucleate as many as seven Mw≥8.4 earthquakes. The current convergence rate is sufficient to generate a great (Mw=8) earthquake in every 180-km-long segment of the Himalaya once per century, *i.e.* one somewhere roughly every decade. History records just two great earthquakes in the past five centuries, signifying that the rupture of the Himalaya in one or more of these scenario ruptures must be considered overdue.

Whither the Big One: Dynamic Rupture Modeling of Large Historic San Andreas-System Earthquakes

LOZOS, J., California State University, Northridge, California, USA, julian.lozos@csun.edu

The San Andreas fault system is responsible for many of California's most damaging historic earthquakes. Understanding the specific causative faults and rupture behaviors for these events is therefore critical for assessing seismic hazard in California. However, most of these events occurred early in, or entirely before the age of instrumental seismology. Firsthand accounts of shaking intensity and damage, as well as paleoseismic records, can pin specific earthquakes to likely faults, but this does not inherently address the rupture process or even the physical plausibility of a given interpretation of an event. Dynamic rupture modeling can add the aspect of rupture physics to the question of deciphering the historic earthquake record. Here, I will discuss how dynamic models with observation-based inputs can be compared to paleoseismic and historic intensity records to better understand the processes of several historic San Andreas system earthquakes, including the 1812 Wrightwood and 1857 Fort Tejon events.

A Bayesian Approach to Estimating the Source of Historical Earthquakes From Intensity Data: Application to the Eastern Sunda Arc, Indonesia, 1681-1877

GRIFFIN, J. D., University of Otago, Dunedin, New Zealand, jonathan.griffin@postgrad.otago.ac.nz; NGUYEN, N., Australian National University, Canberra, Australia, ngoc.nguyen1@uqconnect.edu.au; CUMMINS, P., Australian National University, Canberra, Australia, phil.cummins@anu.edu.au; CIPTA, A., Geology Agency of Indonesia, Bandung, Indonesia, wamditanka_santee@yahoo.com

Historical reports of earthquake effects from the period 1681 to 1877 from Java, Bali and Nusa Tenggara, Indonesia, are used to estimate the source mechanisms of some of the most significant earthquakes. After assigning intensity values based on original historical reports, the source is estimated by undertaking a grid search of source parameters (magnitude, location, depth, strike and dip). For each parameter combination, we use ground-motion models and ground motion to intensity conversion equations to forward model intensity at each intensity data point. Due to limitations in the spatial coverage of intensity data inherent in reports from the archipelago, which predominantly focus on impacts to Dutch colonial economic interests, a range of parameter combinations is possible for each event. Bayesian inference is therefore used to calculate the distribution of source parameters given the historical intensity data. A Bayesian approach allows us to include our prior beliefs about the source; most significantly by applying a Gutenberg-Richter distribution to the prior magnitude distribution, we account for that fact that smaller earthquakes occur more frequently than larger earthquakes. The approach also allows us to account for uncertainty in the choice of ground motion model. The results demonstrate that large intraslab earthquakes have been responsible for major earthquake disasters in Java, including an Mw ~ 7:4 intraslab earthquake near Jakarta in 1699 and an Mw ~ 7:8 event in 1867 in Central Java. The results also highlight the potential for large earthquakes to occur on the Flores thrust, with a cluster of large earthquakes rupturing the Flores thrust in 1815, 1818, and 1820. We do not find conclusive evidence for the occurrence of large earthquakes on the Java megathrust during the time period, although smaller events may have occurred.

Toward a Database of Consistently Reinterpreted Intensities in California

SALDITCH, L., Northwestern University, Illinois, USA, leah.salditch@gmail.com; HOUGH, S. E., U.S. Geological Survey, California, USA, hough@usgs.gov; STEIN, S., Northwestern University, Illinois, USA, s-stein@northwestern.edu; SPENCER, B., Northwestern University, Illinois, USA, bspencer@northwestern.edu; BROOKS, E. M., Northwestern University, Illinois, USA, eddie@earth.northwestern.edu; NEELY, J. S., Northwestern University, Illinois, USA, james@earth.northwestern.edu; GALLAHUE, M., Northwestern University, Illinois, USA, molly@earth.northwestern.edu

Historical seismic intensity data spanning long time intervals have been used to assess the performance of probabilistic seismic hazard assessments (PSHA). The short time since hazard maps began to be made is a challenge for assessing how well they work. Hindcasts offer long records, but are not true tests, as they compare maps to data that were available when the map was made. Historical intensity data are somewhat independent of the PSHA models because they were often not considered directly in the map's creation, so hindsights give useful insight into the strengths and weaknesses of PSHA maps. As part of an effort to create a consistently reinterpreted maximum observed seismic intensity database for California with which to asses PSHA performance, we investigate the 1952 Kern County, California earthquake. Intensity data provide a measure of ground motion through first-hand accounts of shaking during an earthquake. These data reveal the distribution of ground motions in detail. Practices for assigning intensity values have changed over time, warranting reinterpretation of the intensity distributions of historic earthquakes. Although intensity interpretations have several sources of uncertainty, they are often the primary data available for historic and early instrumental earthquakes. For the Kern County earthquake we use the data and intensity prediction equations to arrive at an intensity magnitude of M_I 7.2 ± 0.2. This estimate is on the lower end of previously published instrumental estimates.

The Potential of Analogue Seismograms for Science and Education

ISHII, M., Harvard University, Massachusetts, USA, ishii@eps.harvard.edu; MORINAGA, T., School Innovation Forum & Kyoto University, Kyoto, Japan, school.innovation.forum@gmail.com; LEE, T. A., Harvard University, Massachusetts, USA, thomasandrewlee@college.harvard.edu

In contrast to about 40 years of digital data collection, analogue recording of seismograms occurred for nearly 100 years. The duration of seismic data availability is thus increased more than twofold if the analogue data can be accessed. This longer time span provides unique opportunities to study unusual events and time-dependent phenomena that are too gradual to be constrained by the 40-year digital data availability. This presentation reviews some of the research questions that can be asked using analogue data, and the potential for engaging the public in building the required database.

With advances in our understanding of data and computational resources, our use of seismograms has moved from limited segments of earthquake recordings to continuous waveforms of ground motion. These approaches allow us to investigate non-traditional targets such as subsurface changes, glacial calving events, and tracking storm systems. The vast majority of analogue recordings are dominated by these types of signal, portions that were once considered noise. However, the analyses of these data are built upon a fundamental stipulation that the input are digital time series. In order to utilize the analogue seismograms, they must be converted to the digital format.

The analogue recordings of non-earthquake seismograms are easiest to digitize from the perspectives of trace crossings and associations. These are the types of recordings that citizen scientists can, with some training, digitize using the DigitSeis software. To explore the potential of such a citizen science project, we have been working with nearly 200 students from 14 high schools in Japan. The students learn to use the DigitSeis software with an example image, and once their analysis have been reviewed and passed, they move on to digitize images that have never been digitized. The project produces digital data for seismologists to use, but is also a great opportunity to engage students in science and research at an early stage.

The Large Andaman Islands Earthquake of 26 June 1941: Why No Significant Tsunami?

OKAL, E. A., Northwestern University, Illinois, USA, emile@earth.northwestern.edu

We present a modern seismological study of the earthquake of 26 June 1941 in the Andaman Islands, the largest pre-2004 event along that section of the India-Burma plate boundary. Despite a large conventional magnitude (#M sub PAS ^=^8.1#), it generated at best a mediocre tsunami for which no definitive quantitative reports are available. We show that the 1941 earthquake took place under the Andaman accretionary prism, and consisted of a composite event, whose nucleating phase had a strike-slip mechanism incompatible with a dataset of spectral amplitudes of mantle Rayleigh and Love waves. Combining this initial phase with a larger normal faulting mechanism can reconcile them with P-wave first motions, reports of subsidence on the Eastern coast of the Andaman Islands, and with the small amplitudes of any putative tsunami. The small tsunami results from a combination of that mechanism and of a source located under the islands themselves and in shallow water, implying a reduction in amplitude under Green's law when transitioning to a deeper basin.

Comparison of Three Mw ~7 Pre-Digital Era Intraplate Alaska Earthquakes to the November 30, 2018 Anchorage Event

DOSER, D. I., The University of Texas at El Paso, Texas, USA, doser@utep.edu

The occurrence of the November 30, 2018 Anchorage earthquake (~ 50 km from Anchorage) allows us to compare the waveforms and effects of this well recorded intraplate earthquake to three pre-digital era intraplate events of similar magnitudes that occurred on April 27, 1933 (Mw~6.9), November 3, 1943 (Mw~7) and October 3, 1954 (Mw~6.8) within 100 km of Anchorage. The 1933 earthquake (~75 km from Anchorage) occurred within Upper Cook Inlet at a depth of 9±4 km, likely along one of the numerous offshore faults mapped within the Cook Inlet basin. The 1943 earthquake (~100 km from Anchorage) occurred at a depth of 27±4 km. Its relationship to the regional tectonics is not well understood. The 1954 earthquake (~100 km from Anchorage, depth 60±10 km) occurred within the subducting Pacific plate. Initial comparisons of intensity data for the 1933 and 2018 events suggest a lower intensity of shaking in 1933 for communities located northeast of the 1933 epicenter, although intensities in Anchorage (VI to VII) were comparable. Intensities reported in Anchorage in 1943 were considerably lower (IV) than in 2018, however the 1954 event caused intensities of VIII from Anchorage to the southern Kenai Peninsula. Waveform comparisons indicate that neither the 1933 or 1943 events had focal mechanisms similar to the 2018 event. The 1954 event has similar waveforms to the 2018 event at some stations, suggesting there may be larger component of normal faulting involved in 1954 that previously estimated.

Source Processes of the Complex 1932 M7.6 Changma Earthquake in Gansu, China, From Early Seismic Records and Modern Photogrammetric Geomorphology

ELLIOTT, A. J., University of Oxford, Oxford, United Kingdom, ajelliott@ucdavis.edu; KULIKOVA, G., University of Potsdam, Potsdam, Germany, galina.kulikova@geo.uni-potsdam.de; OU, Q., University of Oxford, Oxford, United Kingdom, ouqi1005@gmail.com; WALKER, R. T., University of Oxford, Oxford, United Kingdom, richard.walker@earth.ox.ac.uk; PARSONS, B., University of Oxford, Oxford, United Kingdom, barry.parsons@earth.ox.ac.uk

Contemporary earthquake ruptures continue to surprise us with their variety and complexity, exceeding anticipated lengths or involving more faults than expected from inadequate recurrence models. The inadequacy of these models stems from the limited span of our observational period. However, the level of detail captured by modern remote sensing is now sufficient to map and measure complete earthquake ruptures that were originally only sparsely mapped, overlooked entirely, or not specifically documented. Examples of early complex earthquakes warrant deeper seismological investigation than was conducted in the predigital era. Through modern computational analysis of analog seismograms from 1932, we investigate the source process of a M7.6 earthquake in western China that ruptured 5–6 "different" fault segments. We have documented the surface ruptures of this earthquake in unprecedented detail using high resolution photogrammetric topography and field investigations. We calculate 3D slip vectors from offset landforms in order to track the spatial variation of kinematics along the rupture, showing how separate faults with different slip senses partitioned oblique slip during this earthquake. To evaluate how the rupture propagated through this array of faults with differing kinematics, we perform waveform analysis on the analog seismograms of this event. From archives around the globe we locate, collect, and digitize 62 seismic records from 40 stations and correct them for clock and mechanical errors. We analyze source duration versus azimuth to identify rupture directivity, and we measure body wave amplitude ratios to redetermine the focal mechanism. Despite exceptionally challenging timing errors throughout the waveform due to inconsistent recording on early mechanical drums, salient source parameters can still be extracted. Combining historical seismology with modern high-res fault mapping, we can add to our observations and understanding of complex rupture behavior among fault systems.

Examining Taiwanese Historical Earthquakes From Literature Intensity to Synthetics for the Understanding of Fault System, Multiple Fault Segments Rupture and Seismic Hazard Analysis

MA, K., Earthquake- Disaster & Risk Evaluation and Management (E-DREaM) Center, National Central University, ChungLi, Taiwan, fong@earth.ncu.edu.tw; YEN, M., Earthquake- Disaster & Risk Evaluation and Management (E-DREaM) Center, National Central University, ChungLi, Taiwan, mingshen108@gmail.com; LIAO, Y., Earthquake- Disaster & Risk Evaluation and Management (E-DREaM) Center, National Central University, ChungLi, Taiwan, ryoaimika@gmail.com

Taiwan Earthquake Model (TEM) published the first public PSHA map of Taiwan in late 2015, which adopt the source parameters of 38 seismogenic structures under a single fault segment basis, and shallow areal source for crustal events, and, intraplate, and interplate subduction events. The occreence of moderate, but, damaging 20160206 M6.4 Meinong and 20180206 M6.5 Hualiean earthquake brought the attention on the notes of the seismic hazard potential addressed in TEM PSHA2015. Historically, significant crustal damaging earthquakes in Taiwan mostly were from complicated fault system rather than from a single fault segment, which was not yet incorporated in the seismic hazard analysis. The 1906 M7.1 Meishan earthquake, recently, had been resolved to be from a fault system of blind NE strike thrust with EW surface breaching fault (one of the identified seismogenic structures). And, the 1935 M7.1 was occurred with bilateral rupture from a blind fault to strike-slip mechanism to the south and thrusting mechanism to the north. We employed the rupture kinematic modeling to the historical geodetic data with comaprison to the intensity pattern to understand the possible involement of the fault system. These historical and past events suggest that a single fault segment evaluation for seismic hazard might be inadequate. But, we have not yet had solution to solve this inadequacy. We examined the effect of the hazard assessment from the fault rupture system from kinematic and dynamic modeling of the historical events. In addition to the damaging earthquakes from seismic active region, an ancient 1604 M7.5-M8.0 Quanchao damaging Earthquake in southeastern coast China region was also explored from literature intensity to understand the seismic potential of less seismic active regime. We hope the effort we had made in past several years in studying the historical earthquakes could shred a light on the importance of resolving historical damaging earthquakes from modern developed seismology to seismic hazard assessment and risk management.

Status and Future of Macroseismic Information in Canada

LAMONTAGNE, M., Geological Survey of Canada, Ottawa, Canada, maurice.lamontagne@canada.ca; BURKE, K. B. S., University of New Brunswick, Fredericton, Canada, kbsb@unb.ca

Our project is aimed at gathering existing felt information of Canadian earthquakes ("macroseismic observations") in a digital repository. This repository will insure preservation of existing and future information in a homogeneous format and eventually, ease of access through a web-platform. The macroseismic information exists in a variety of forms (books, reports, digital tables (only a few), felt reports on paper, isoseismal maps, Did-you-feel-it text files). For many earthquakes, the felt reports on paper are lost. For those that are available, systematic scanning was started for the significant earthquakes. For only a few earthquakes, the Modified Mercalli intensity (MMI) ratings existed in a digital format. Although the data for most post-1970 earthquakes existed, much digital information was lost through retirements of seismologists or conversions to newer computer systems. Some MMIs also existed in books, most notably for earthquakes in the provinces of Quebec (Gouin, 2001) and New Brunswick (Burke, 2009). Our task is now to gather the latter information and format it in a computer table. To gain experience and evaluate the level of effort required, we used a few earthquakes as pilot projects: 1929 Grand Banks; 1855 Moncton, New Brunswick; 1870 Charlevoix and 1988 Saguenay. Each one presented some special issues but we are in the process of releasing the information as GSC Open File reports. Our experience with these suggests the following points. The macroseismic information needs to be better preserved and this can only be done though digitizing of all existing information. To preserve the macroseismic information, organizations have to take measures to face: the retirement of personnel who keep their data 'local', the discarding of paper material that takes up too much space, the lack of a central and web-accessible repository and finally, the lack of interest for data that may appear old-fashioned.

The New Version of the Catalogue of Strong Earthquakes in Italy and in the Extended Mediterranean Area (CFTI5Med): A Fundamental Seismological Tool for Learning, Discovering and Predicting

FERRARI, G., Istituto Nazionale di Geofisica e Vulcanologia, Bologna, Italy, graziano.ferrari@ingv.it; GUIDOBONI, E., Centro Euro-Mediterraneo di Documentazione Eventi Estremi e Disastri, Bologna, Italy, eguidoboni@gmail.com; MARIOTTI, D., Istituto Nazionale di Geofisica e Vulcanologia, Bologna, Italy, dante.mariotti@ingv.it; COMASTRI, A., Istituto Nazionale di Geofisica e Vulcanologia, Bologna, Italy, alberto.comastri@ingv.it; TARABUSI, G., Istituto Nazionale di Geofisica e Vulcanologia, Bologna, Italy, gabriele.tarabusi@ingv.it; SGATTONI, G., Istituto Nazionale di Geofisica e Vulcanologia, Bologna, Italy, giulia.sgattoni@ingv.it; VALENSISE, G., Istituto Nazionale di Geofisica e Vulcanologia, Rome, Italy, gianluca.valensise@ingv.it

In spring 2018 Guidoboni *et al.* published CFTI5Med, a new, largely revised and updated version of the Catalogue of Strong Earthquakes in Italy and in the extended Mediterranean area (http://storing.ingv.it/cfti/cfti5/). CFTI5Med collects the results of over three decades of research and comprises the reference study for most damaging earthquakes in the Italian parametric earthquake catalogue (https://emidius.mi.ingv.it/CPTI15-DBMI15/).

CFTI5Med supplies not only parametric data, but also 42,663 macroseismic intensities assigned to individual localities, plus a set of 39,924 historical-critical comments providing general descriptions for each earthquake sequence and for each affected locality. CFTI5Med hence provides a synthetic account of the territorial impact of the earthquake and of the resulting social and economic upheaval. This information is complemented by 2,337 descriptions of earthquake-induced effects on the natural environment.

For every investigated earthquake sequence CFTI5Med supplies the relevant bibliography in an organized form, allowing the reader to navigate upstream from the parameters of a specific earthquake to the original sources used to investigate it. Overall CFTI5Med makes available as searchable PDF files 23,538 of the 47,211 witnesses used for compiling it, many of which are extremely rare or kept in rather inaccessible repositories.

A totally re-designed, more efficient web-GIS interface allows both expert and inexperienced users to fully appreciate the information stored on over 1,259 Italian and 475 Mediterranean damaging earthquakes. The new CFTI5Med website is in fact an advanced e-infrastructure that was designed to navigate its diverse contents at different levels and that can be replicated in any country endowed with a rich pre-instrumental earthquake history.

Finally, starting from CFTI5Med we developed CFTILab, a virtual historical seismology lab offering recently developed tools for locating historical earthquakes, comparing different events or investigating complex earthquake sequences in space and time.

A Discussion of Efforts Needed to Extract Key Information From Important Old Seismograms

RICHARDS, P., Columbia University, New York, USA, richards@ldeo.columbia.edu; KIM, W., Columbia University, New York, USA, wykim@ldeo.columbia.edu; WILDING, J. D., Columbia University, New York, USA, wilding@ldeo.columbia.edu

We begin with practical issues arising from analysis of the Tucson Observatory (TUO) Benioff SP seismogram on 1945 July 16, recorded 437 km from the first nuclear explosion, TRINITY, conducted in Southern New Mexico in the atmosphere. It includes clearly-identifiable regional seismic phases, plus arrivals apparently due to ground motion from energy along two different infrasound paths.

We review the challenges in finding such records, and discuss what level of scanning is required for: assessing S/N and for phase identification; for measuring arrival times and maximum amplitudes; for coda studies; and for spectral analysis. We ask: what can be achieved at different levels of scanning quality, and with different digitizing packages; what are the potential audiences, present and future; and what consensus can be developed, to make progress on data rescues?

We note some successful efforts in countries other than the USA, to make archives of analog seismograms amenable to use with modern analytical tools; and we suggest some priorities, such as the need to search for the most important records before they are lost, to scan them with adequate quality, and to develop an information center on activities related to making old records useful once again.

Historical (Pre-Digital) Earthquake Information at the UC Berkeley Seismological Lab

HELLWEG, M., University of California, Berkeley, California, USA, peggy@seismo.berkeley.edu

What is now the University of California's (UC) Berkeley Seismological Laboratory (BSL) was founded in 1887 with the installation of Ewing Seismographs at Mt. Hamilton (MTC) and at Student Observatory Hill (BRK) on UC's Campus. The first earthquakes were recorded in April 1887. Since then, the archives at the BSL have continued to grow. From 1887-1910, the earthquake records consist almost solely of log-books from the observers at MHC and UC. The exception are seismic records from the 1906 earthquake recorded in the Bay Area and collected in the Lawson Report, along with seismograms from all over the world. In 1910, the BSL purchased a Wiechert Seismograph, which operated into the 1950s, and continued to upgrade instrumentation over time. Only a few seismic records from 1910 to the early 1920s are available in the BSL's archives, however. With the arrival of Perry Byerly in the 1920s, the BSL took on responsibility for earthquake reporting in Northern California. The Bolt-Miller Catalog (https://berkeley.app.box.com/s/iy6nz14k47uy0h571fuc6na64jyumtuu) summarizes earthquakes recorded from 1910-1972 and covers equipment from contributing stations. Original readings sheets are also still available. Paper and film records from the mid-1920s to the early 1990s are still archived and available at the BSL. We continue to explore ways to make them more easily available. The BSL also has a variety of other resources describing earthquakes, including original felt and newspaper reports. The Byerly Collection includes seismic records from all over the world for some earthquakes such as the Fairweather quake in 1958, and the 1923 Great Kanto earthquake. Records from the BSL's historical collection have been used to study predigital earthquakes (Parkfield earthquakes, Fairweather earthquake, 1960 Chile earthquake), nuclear explosions, as well as wave formation and climate in the Pacific Ocean, and for other applications.

Preserving Ohio's Historic Seismogram Collection: 83 Years of Global Seismology: 1909 – 1992

FOX, J., Ohio Seismic Network, Ohio, USA, jeffrey.fox@dnr.state.oh.us

The Ohio Geological Survey (OGS) is the current proprietor of eighty-three years' worth of analog seismic records of the Jesuit Seismological Association, recorded at the John Carroll University (JCU) near Cleveland Ohio. The collection contains records from the 80-kg Wiechert seismograph spanning the years 1909 to 1947. JCU then installed two long-period horizontal and one short-period vertical Sprengnether instruments. The Sprengnether instrument records contain traces from July 1947 to 1986. In 1986 a multi-station network of short-period L4 seismometers were used until the end of operations in 1992. The Ohio Seismic Network saved these paper recordings from destruction and has housed them at the H.R. Collins Laboratory in Delaware, OH since 1999. Recent preservation grants have been obtained by OGS through which the archiving, detailed cataloging and preservation work has begun. Phase-I was completed in mid-2018 and it is anticipated that two more phases will be required to complete the project. Over 100,000 seismograms are currently in the inventory and are nearly complete. The records have not been inventoried in detail but appear to be continuous from the early 1920's through 1931. From 1931 – 1936 JCU was in the process of moving locations, so no records exist during this time. Work has begun listing the significant global, regional and local earthquakes contained in the collection, which are recognized in the traces. Digital scanning has begun on select seismograms and the entire collection is available in-person to interested researchers. This presentation covers the history, current inventory, progress and plans for this rare collection.

Environmental Seismology: Glaciers, Rivers, Landslides and Beyond

Oral Session · Friday · 3:45 PM · 26 April · Pike
Session Chairs: Bradley Paul Lipovsky, Marine A. Denolle, Rick Aster.

Glacial Dynamics From Sequences of Long-Lived Repeating Glacial Stick-Slip Events

WINBERRY, J. P., Central Washington University, Washington, USA, winberry@geology.cwu.edu; HUERTA, A., Central Washington University, Washington, USA, huertaa@geology.cwu.edu; ANANDAKRISHNAN, S., Pennsylvania State University, Pennsylvania, USA, sxa17@psu.edu; ASTER, R., Colorado State University, Colorado, USA, rick.aster@colostate.edu; CONWAY, H., University of Washington, Washington, USA, hcon@uw.edu; KOUTNIK, M., University of Washington, Washington, USA, mkoutnik@uw.edu; NYBLADE, A., Pennsylvania State University, Pennsylvania, USA, andy@geosc.psu.edu; WIENS, D. A., Washington University in St. Louis, Missouri, USA, doug@wustl.edu

Many glaciers primarily dissipate their gravitational potential energy by sliding along the ice-bedrock interface. In such cases, a glacier's driving stress is often balanced by regions of enhanced basal traction known as sticky-spots. While the role of sticky-spots in the force budget of glaciers and ice streams has long been recognized, their temporal beahvior and formation remains less well understood. In this presentation, we leverage recent advances in seismograph coverage in the Transantarctic Mountains (TAM) to study relatively large glacial seismic events (> M2) that can be observed at regional distances. We report on 5 newly discovered sequences of repeating glacial earthquakes. These new sequences reveal that repeating families of glacial earthquakes can be long-lived, remaining active for up to 9 years. We show how the pattern and magnitude of these repeating events can be used to study temporal variations in glacier behavior. Additionally, by tracking subtle changes in relative arrival times as well as waveform similarity, we deduce that these sticky-spots originate from migrating bands of basal debris.

Multiple Constituents of Solid Earth Tides Observed With Ambient Seismic Noise

SENS-SCHÖNFELDER, C., GFZ German Research Centre for Geosciences, Potsdam, Germany, sens-schoenfelder@gfz-potsdam.de; EULENFELD, T., University Jena, Jena, Germany, tom.eulenfeld@uni-jena.de

Elastic moduli of geological materials are not constant. Due to the elastic nonlinearity of heterogeneous materials they change with the applied strain. This makes the seismic waves whose velocity depends on the elastic moduli an ideal tool for remote monitoring of subsurface strain variations – an observation that is of fundamental importance in underground operations from construction to mining, and for the monitoring of geological processes in volcanoes and fault zones. However, the strain sensitivity of the seismic wave velocity is a parameter that is hard to measure in-situ. The laboratory approach to probe the sensitivity in an active deformation test cannot be transferred to the field where controlled strain cannot be applied. Using the laboratory estimates for interpretation on the field scale requires access to representative samples and involves significant uncertainty in the upscaling. Here we show that improved processing of data from a single seismic station allows to measure the strain sensitivity of the seismic wave velocity in a natural experiment that uses the deformation induced by tidal forces as perturbations and the ambient seismic noise to measure the velocity response. We observe multiple tidal constituents, a thermal strain signal and nonlinear coupling between tidal and thermal strain perturbations.

Simulation of Asteroids Impacting Earth: Tsunami Generation and Consequences on U.S. Major Cities for Disaster Response and Management Preparedness

EZZEDINE, S. M., Lawrence Livermore National Laboratory, California, USA, ezzedine1@llnl.gov

A hypothetical asteroid-impact scenario (https://cneos.jpl.nasa.gov/pd/cs/pdc19/) designed by the International Academy of Astronautics (IAA) is used as the basis for discussion and analyses of the table-top exercise. The asteroid is classified as a potentially hazardous asteroid with a diameter initially estimated between 100-300 meters. The large size uncertainty is due to uncertainties in both albedo and absolute-magnitude values. As the object is tracked over subsequent months, its impact-risk region is estimated to be much longer than the diameter of the Earth, but its width is only about 70 kilometers. The intersection of the uncertainty region with the Earth creates a risk corridor across the surface of the Earth. The corridor wraps more than halfway around the globe, spanning from the Hawaii on the western end, across the U.S. and Atlantic Ocean, and all the way to central and southern Africa on the eastern end. Given the significant water-impact probability, and because most of the potentially affected coastal regions are heavily populated, we focused our simulation efforts on modeling water impacts at several locations along the asteroid risk corridor. We have simulated the problem from asteroid entry, to ocean impact, to wave/tsunami generation, propagation, interaction with the shoreline and the flooding of the coastline major US cities. We have simulated three different asteroid diameters (100, 200 and 300m) and we have delimited the zones of inundation for each scenario for risk assessment and disaster management & response. The interaction of the asteroid with the ocean are simulated using the hydrocode GEODYN, creating a hydroacoustic signal, and also generating water wave source for the Boussinesq-based water-wave-propagation code, WWP. Run-up and flooding were simulated using WAST – water/structure – a CFD code for urban flooding assessment. Results are displayed with high resolution in Google Earth for all major coastal US cities. We will demonstrate these new capabilities and we illustrate the consequences at the local and global scales.

Seismic Detection of Internal Gravity Waves at the Dongsha Atoll, South China Sea

SHADDOX, H. R., University of California, Santa Cruz, California, USA, hshaddox@ucsc.edu; BRODSKY, E. E., University of California, Santa Cruz, California, USA, brodsky@ucsc.edu; DAVIS, K., University of California, Irvine, California, USA, davis@uci.edu

Oceanic internal waves are gravity waves localized on density stratifications in the water column and are ubiquitous. They can propagate thousands of kilometers before breaking and the ensuing turbulent mixing affects coastal processes and climate feedbacks. The need for global detection and long time series of internal waves motivates a search for geophysical detection methods. The pressure coupling of a propagating internal wave with the sloping seafloor provides a potential mechanism to generate seismically observable signals. Here we use data from the South China Sea where the world's largest internal waves occur to identify internal wave signals in an onshore passive seismic dataset for the first time. The key data comes from the Dongsha Atoll where temporary (October 15, 2013 – May 31, 2014) 15-minute temperature mooring measurements in the water column at the eastern forereef directly detect the passage of internal waves by a sudden drop in temperature, and are complemented by a long-term seismic observatory on the western side of the atoll. Our goal is to correlate the established internal wave signal in the oceanic (temperature) data with a signal in the seismic. We produce a time series of internal waves in the oceanic data by taking the 2-hour smoothed envelope squared of a 50-minute zero phase high-pass. In the seismic, we take the 4-hour smoothed envelope of a 200-1000 second (expected period of internal waves) zero phase band-pass. We find a high-power signal in the seismic that consistently lags behind the oceanic internal wave signal. We find that the daily activity rates (fraction of day with detections) are similarly high at times we expect internal waves (fall, spring) and low at times we do not expect internal waves (winter). The seismic and oceanic activity rates are correlated at a 99.5% significance. It appears that we have successfully developed a technique to detect internal waves that opens up the possibility of utilizing the global seismic network to construct broad spatial maps and long-term timeseries of oceanic internal waves.

Seismic Recordings Reveal the Timing and Extent of Subglacial Water Pressurization

BARTHOLOMAUS, T. C., University of Idaho, Idaho, USA, tbartholomaus@uidaho.edu; LABEDZ, C., California Institute of Technology, California, USA, clabedz@caltech.edu; AMUNDSON, J. M., University of Alaska Southeast, Alaska, USA, jmamundson@alaska.edu; GIMBERT, F., Université Grenoble Alpes, Grenoble, France, flo.gimbert1754@gmail.com; VEITCH, S. A., The University of Texas at El Paso, Texas, USA, saveitch@utep.edu; TSAI, V. C., California Institute of Technology, California, USA, tsai@caltech.edu; KARPLUS, M., The University of Texas at El Paso, Texas, USA, mkarplus@utep.edu

The evolving state of the subglacial hydrologic system is of fundamental importance for the regulation of fast glacier flow, subglacial bedrock erosion, and, in the case of marine-terminating glaciers, submarine melt of glacier termini by warm ocean water. However, the state of this subglacial hydrologic system is notoriously difficult to assess. Here we report on the use of broadband seismic recordings to reveal subglacial water pressurization and track subglacial discharge over three months of the melt season at Lemon Creek Glacier, in Southeast Alaska, USA. Simultaneous Global Positioning System (GPS), meteorological, proglacial runoff, and active-source seismic measurements, as well as glaciohydraulic modeling, support and inform our interpretations.

We find that, over the significant majority of the summer (approximately 90%), water flow beneath 190 m-thick Lemon Creek Glacier is likely unpressurized, since the relationship between 1.5 – 10 Hz glaciohydraulic tremor and proglacial runoff follows a 5/4th power relationship predicted theoretically. However, during storms in which at least 4 cm of rain fall in day-long periods, the subglacial hydrologic system appears to pressurize and drive increased basal motion. During these apparently pressurized time periods, we observe broadband seismic power increases, an increase in power spectral slopes, and nonlinearity between tremor power and proglacial runoff consistent with theoretically-predicted power relationships near 14/3rds. This nonlinearity, and the observation of high frequency seismic signals produced from flowing, turbulent water, indicates that hysteresis between tremor and discharge is necessarily the result of bedload sediment transport. These results expand our understanding of melt-season glacier hydrology (often assumed to include continuously-pressurized, full subglacial conduits), provide empirical support for theoretical predictions in seismology, and represent a new tool for the validation of subglacial hydrologic models.

Methods for Site Response Estimation

Oral Session · Friday · 8:30 AM · 26 April · Pine

Session Chairs: Thomas L. Pratt, Lisa S. Schleicher, Lee M. Liberty.

Common Best Practice Procedures for Site and Seismic Station Characterization: A European Initiative

DI GIULIO, G., Istituto Nazionale di Geofisica e Vulcanologia, Roma, Italy, giuseppe.digiulio@ingv.it; CORNOU, C., Université Grenoble Alpes, Univ. Savoie Mont Blanc, CNRS, IRD, IFSTTAR, ISTerre, Grenoble, France, cecile.cornou@univ-grenoble-alpes.fr; CULTRERA, G., Istituto Nazionale di Geofisica e Vulcanologia, Roma, Italy, giovanna.cultrera@ingv.it; BARD, P., Université Grenoble Alpes, Univ. Savoie Mont Blanc, CNRS, IRD, IFSTTAR, ISTerre, Grenoble, France, pierre-yves.bard@univ-grenoble-alpes.fr

Site characterization is a key input in seismic hazard, risk assessment and seismic design. Although the number of strong-motion stations in free-field and engineered structures has largely increased in the last twenty years, only a limited number of instrumented sites includes site condition indicators: mostly geology and EC8 soil class, more rarely measured Vs30 and Vs profiles, without any quality assessment in most cases. This lack of information is a critical issue, *e.g.* for deriving reference-rock or soil velocity profiles for region-specific GMPEs, site-specific hazard assessment, Vs-kappa adjustments, seismic response of engineering infrastructures, risk modeling at urban or regional scale. Within the framework of the SERA "Seismology and Earthquake Engineering Research Infrastructure Alliance for Europe" Horizon 2020 Project, a networking activity has been set up to propose a comprehensive European strategy and standards fostering site characterization of seismic stations in Europe.

We will present the main outcomes regarding common best practice procedures for site and seismic station characterization. In order to evaluate the most relevant site characterization scalar, depth- and frequency-dependant indicators for site response purposes (*e.g.* Vs30, resonance period, velocity profiles, kappa, etc.), we sent an international questionnaire to the broad seismological and engineering community. Aside prioritizing the most critical set of indicators to be measured at a given site, it also allowed estimating the level of difficulty and the related cost for estimating each single indicator. We defined an overall quantitative quality metric scheme for site characterization that combines quality of single indicator, combination and overall compatibility of various indicators. We finally propose recommendation guidelines for the necessary information to allow a reliable description of the seismic characterization of single site and associated quality index. The outcome has been shared within a broad scientific community in Europe and worldwide.

Resolving S-Wave Velocity Structure from Weak-Motion S-Wave HVSR

CARPENTER, S., Kentucky Geological Survey, University of Kentucky, Kentucky, USA, seth.carpenter@uky.edu; WANG, Z., Kentucky Geological Survey, University of Kentucky, Kentucky, USA, zhenming.wang@uky.edu; WOOLERY, E. W., University of Kentucky, Kentucky, USA, ewoolery@uky.edu

Quantifying the response of sediments to incident waves is needed for predicting the effects of strong earthquake shaking, which requires determination of the S-wave velocity structure. The importance of accounting for site response increases when the impedance contrast between the sediment overburden and underlying bedrock is strong, which can result in seismic waves being trapped, yielding amplification in excess of that due to the sediment-bedrock impedance contrast alone. The horizontal-to-vertical spectral ratio (HVSR) of weak-motion S-waves can estimate empirical site transfer functions (TF) for frequencies up to a site-dependent frequency, f_{max}. As determined from several deep-soil borehole sites, f_{max} is approximately five times the fundamental frequency of vertically propagating SH-waves. Amplification of vertical motions reduces the spectral ratio with respect to TF for frequencies greater than f_{max}.

We evaluated inversion of S-wave HVSR for S-wave structure at both deep-soil vertical seismic arrays in the northern Mississippi Embayment, USA—VSAP (100 m) and CUSSO (585 m)—at a nearby shallow-soil site, and at a deep-soil KiK-net borehole station. We used a guided Monte Carlo algorithm to optimize the fit between mean S-wave HVSRs and the theoretical responses from Thompson-Haskell propagator matrices for incident SH-waves, for frequencies below f_{max}, to obtain the best-fitting family of models. We found that (1) a reasonable initial sediment-column thickness is needed, (2) the ensemble median structures from multiple trials are consistent with published velocity models at the deep-soil sites, (3) for these sites, structures are resolvable from simple initial models consisting of uniform layers over a half-space, and (4) in contrast, best-fitting models at the shallow-soil site are inconsistent with the published structure, in part due to the absence of resonance modes above the fundamental mode. Therefore, S-wave HVSR is useful for constraining or resolving shear-wave models of thick, unlithified sediments overlying stiff bedrock.

Quantifying Site Response of the Atlantic Coastal Plain Strata in the Eastern United States Using Horizontal to Vertical Spectral Ratios

SCHLEICHER, L. S., Independent Researcher, Maryland, USA, lisasschleicher@gmail.com; PRATT, T. L., U.S. Geological Survey, Tennessee, USA, tpratt@usgs.gov

Ground motion intensities measured during the 2011 magnitude 5.7 Virginia earthquake exceeded expected ground motions in Washington, DC, leading to surprising damage to the Washington Monument and National Cathedral. The larger-than-estimated site response caused by the unconsolidated sediments of the Atlantic Coastal Plain (ACP) during the Virginia earthquake highlights the need to improve earthquake site response estimates in the eastern United States. The horizontal-to-vertical spectral ratio (HVSR) method, using either earthquake signals or ambient noise as input, offers an appealing method for measuring site response because it uses only a single seismometer rather than requiring two or more seismometers traditionally used to compute a horizontal sediment-to-bedrock spectral ratio (SBSR). We compared site response estimates on the ACP strata using the HVSR and SBSR methods. We find a close match in the frequencies of the first primary resonance peaks (f_{peak}) with both the SBSR and HVSR methods using teleseismic signals recorded by regional arrays. The HVSR method estimates the amplitude of f_{peak} within a factor of 2 for ACP strata up to about 200 m thick, but consistently underestimates by a factor of ~5 the amplitude for ACP strata with thicknesses above about 200 m. Although previous studies show mixed results when comparing HVSR with SBSR methods, many of these studies were carried out on confined sedimentary basins that can generate substantial 3D basin surface wave effects. The strong bedrock reflector underlying ACP strata causes 1D resonance effects to dominate the site response estimates, with the amplitudes of the resonance peaks determined largely by the reflection coefficient at the base of the sediments. These preliminary results suggest that the HVSR method may successfully estimate regional site response amplifications from the ACP, or similar geologic environments, if appropriate amplitude correction factors are used. [This abstract represents the views of the authors and does not necessarily represent the views of the DNFSB.]

Direct Evaluation of Horizontal Amplification Factor HHbR From Earthquake HVR and Empirical Vertical Amplification Factor VHbR

KAWASE, H., Disaster Prevention Research Institute, Kyoto University, Uji, Japan, kawase@sere.dpri.kyoto-u.ac.jp; NAKANO, K., HAZAMA ANDO CORPORATION,, Tsukuba, Japan, nakano.kenichi@ad-hzm.co.jp; NAGASHIMA, F., DPRI, Kyoto University, Uji, Japan, nagashima@sere.dpri.kyoto-u.ac.jp; ITO, E., DPRI, Kyoto University, Uji, Japan, ito@sere.dpri.kyoto-u.ac.jp

We have been discussing on how to obtain velocity structures below the target sites and what is the best proxy for site characterization for long time. But what we really need is not the velocity but the horizontal amplification factor (HHbR) relative to the reference bedrock spectrum Hb, since it controls the ground motion characteristics.

As an empirical tool, the Horizontal-to-Vertical ratios of earthquakes (EHVRs) or microtremors (MHVRs) have been utilized to extract ground motion characteristics. The so-called "Nakamura" method assumes that MHVR provides us directly HHbR. However, we need to validate two main assumptions; 1) EHVR and MHVR should be the same and 2) the vertical amplification factor (VHbR) should be unity.

As for the difference of EHVR and MHVR, the diffuse field concept (Sánchez-Sesma *et al.*, 2011; Kawase *et al.*, 2011) lead us to see the systematic difference between EHVRs and MHVRs and therefore we have proposed empirical correction factors, EMRs, the ratios of EHVR to MHVR (Mori *et al.*, 2018). We can use these EMRs to transform MHVR into pseudo EHVR (pEHVR).

As for VHbR we have used generalized spectral inversion technique (Nakano *et al.*, 2015) to separate HHbR and VHbR from S-wave part of weak-motions observed in Japan. We used YMGH01 with small site correction to obtain amplification relative to the seismological bedrock spectrum Hb. We found that VHbR is much similar to each other than HHbR because P-wave velocity contrasts would be smaller than S-wave velocity contrasts in general. We calculated the averaged VHbRs for eight categorized sites with different predominant frequencies in EHVR. Then we can obtain pseudo HHbR as EHVR*VHbR. Since the site-specific variation in VHbR is relatively small, the pseudo HHbR can be conveniently and precisely derived from EHVR in the frequency range from 0.1 to 15 Hz without any velocity structures, as long as we have small numbers (~10) of weak-motion records at the target site. If we have only MHVR, we need first transform it to pEHVR then get pseudo HHbR as EMR*MHVR*VHbR.

Estimation of EMR Correction Factor in the Grenoble Basin; an Attempt to Establish a Simple Method to Get Earthquake HVR From Microtremors

ITO, E., Disaster Prevention Research Institute, Kyoto University, Uji, Japan, ito.eri.4x@kyoto-u.ac.jp; KAWASE, H., Disaster Prevention Research Institute, Kyoto University, Uji, Japan, kawase.hiroshi.6x@kyoto-u.ac.jp; CORNOU, C., Université Grenoble Alpes, Grenoble, France, cecile.cornou@univ-grenoble-alpes.fr; NAGASHIMA, F., Disaster Prevention Research Institute, Kyoto University, Uji, Japan, nagashima.fumiaki.6v@kyoto-u.ac.jp

It is quite important to get velocity structures for site amplification evaluation. Kawase *et al.* (2018) proposed a method to calculate pEHVR (pseudo earthquake horizontal-to-vertical spectral ratios) from HVR of microtremors (MHVR) and EMR, which is the spectral amplitude ratio between HVR from earthquakes (EHVR) and MHVR at one hundred sites in Japan. They calculated EMRs for five categories based on their fundamental peak frequencies in MHVR. They found that pEHVR is much closer to EHVR than MHVR. They used their inversion code to invert one-dimensional S-wave velocity structures from EHVR based on the diffuse field theory (Nagashima *et al.*, 2014). They found that velocity structures by pEHVR are much more similar to those by EHVR in comparison to those by MHVR.

However, when we apply this method to the data in other countries, EMR in Japan may not be directly applicable, because EMR should be a function of the velocity structures from the bedrock to the surface which may not be the same. If we want to calculate EMR in other countries in the same way as Kawase *et al.* (2018) did, we need to collect sufficient amount of data, which would not be easy in seismically not so active regions. This study is the first step to establish an easier way to get EMR correction factors outside Japan.

We calculated pEHVR at the earthquake observation sites in the Grenoble basin using the observed MHVR and EMR in Japan to check the difference between pEHVR and observed EHVR. We found that pEHVR seemed to be overestimated in almost all the frequency higher than the fundamental peak frequency.

In order to make pEHVR closer to the observed EHVR, we assumed EMR specific for the Grenoble basin depends on EMR in Japan and a modification factor α. Then we found α so that the logarithmic residuals of amplitude between pEHVR and observed EHVR became the minimum value at each station. After we got the optimal α to be around 0.3, new pEHVR with the optimal α have quite good match with the observed EHVR in a wide frequency range.

Shallow Shear Wave Velocities for Downtown Salt Lake City: Relationships With Surface Topography, Basin Depth and Earthquake Site Amplifications

LIBERTY, L. M., Boise State University, Idaho, USA, lliberty@boisestate.edu; ST CLAIR, J., Boise State University, Idaho, USA, jamesstclair@boisestate.edu; GRIBLER, G., Boise State University, Idaho, USA, gabegribler@u.boisestate.edu; MCDONALD, G. N., Utah Geological Survey, Utah, USA, gregmcdonald@utah.gov; PECHMANN, J. C., University of Utah, Utah, USA, pechmann@seis.utah.edu

As part of an earthquake hazards assessment, we acquired more than 10,000 shear wave velocity (Vs) measurements along the city streets of Salt Lake City (SLC), Utah. From these data, we produce Vs and near-surface site amplification maps. We compare time-averaged measurements for the upper 30 m (Vs30) from this ~15 sq km area with: 1) mapped geology and active fault locations; 2) lidar-derived surface elevation and slope; 3) seismic reflection-derived structure and stratigraphy; and 4) Bouguer gravity measurements and modeled layer boundary depths. We show the slowest Vs30 values (site class D1 soils) at the lowest elevations, with velocities consistent with modern marine silts, clays and sands. We observe a linear increase of 4.6 m/s increase per meter of elevation gain within latest Pleistocene and Holocene lacustrine deposits. Where fan alluvium was mapped, we measure Vs30 between 230 to 420 m/s (site class D2 to C1 soils) with a poor correlation with surface elevation. We compare slope to Vs30 and observe a linear relationship in log-log space, with slower Vs30 values relative to slope when compared to global averages. We attribute slower Vs30 values in SLC to the latest Pleistocene and Holocene lacustrine sediments that fill the valley. We show a high correlation between Vs30 and Bouguer gravity values, suggesting that Vs30 is a reasonable proxy for basin depth for the SLC area. When comparing Vs30 to Vs20 or shallower measurements, we identify shallow hard boundary regions that may produce local changes in site response. We estimate site amplification relative to bedrock sites using our Vs30 measurements and physical property estimates from previous studies. We suggest that slow Vs Holocene lacustrine deposits mapped to the south and west of downtown may produce increased site amplifications when compared to sites that host higher Vs fan alluvium.

Evaluation of Vs30 at Southern California Edison Substations Using S-Wave Refraction Tomography and Multichannel Analysis of Surface Waves

CHAN, J. H., U.S. Geological Survey, California, USA, jchan@usgs.gov; CATCHINGS, R. D., U.S. Geological Survey, California, USA, catching@usgs.gov; GOLDMAN, M. R., U.S. Geological Survey, California, USA, goldman@usgs.gov; CRILEY, C. J., U.S. Geological Survey, California, USA, ccriley@usgs.gov; SICKLER, R. R., U.S. Geological Survey, California, USA, rsickler@usgs.gov; STRAYER, L. M., California State University, East Bay, California, USA, luther.strayer@csueastbay.edu

Southern California Edison (SCE) provides electricity to more than 15 million people in 15 southern California counties by maintaining a vast network of transmission lines and substations, many of which are susceptible to strong ground shaking from earthquakes. To better understand the potential for amplified ground shaking at several of those sites with co-located strong motion recording stations, we evaluated V_{S30}, the time-averaged shear-wave velocity in the upper 30 m of the subsurface. Ground motion models and ground motion prediction equations (GMPEs) use V_{S30} as a parameter to account for site amplification and site conditions; the parameter is also used to classify soil stiffness, which is widely used in building codes. To evaluate lateral variability in V_{S30} at each site, we conducted 2-D active-source seismic surveys, recording body and surface waves along linear profiles (118 to 174 m long) near the strong motion recording stations. We used sledgehammer (3.5-kg) and accelerated weight-drops (45-kg angled and 226-kg vertical) at each shot point co-located with 4.5-Hz (vertical- and horizontal-component) geophones at 2-m spacing along the profiles. We used 2-D refraction tomography and Multichannel Analysis of Surface Waves (MASW) methods to evaluate shear-wave velocities, from which we calculated V_{S30} at every meter along the seismic profiles. Our results show that V_{S30} varies by as little as 30 to as much as ~ 200 m/s along individual seismic profiles. We also found that V_{S30} nearest to strong motion stations can be up to 46% lower or 41% higher than V_{S30} within 50 m of the strong motion stations, suggesting 1-D V_{S30} may not accurately capture true site conditions at many strong motion sites due to lateral changes in subsurface materials and structures, which imply SCE substations may experience greater or smaller shaking than indicated by the co-located strong motion stations.

New Geotechnical Maps and 3D Basin Velocity Model for Central Wellington, New Zealand, Following the Mw 7.8 Kaikoura Earthquake: Explaining Site Effects in a Shallow, Steep-Sided Sedimentary Basin

KAISER, A. E., GNS Science, Lower Hutt, New Zealand, a.kaiser@gns.cri.nz; HILL, M., GNS Science, Lower Hutt, New Zealand, m.hill@gns.cri.nz; WOTHERSPOON, L., University of Auckland, Auckland, New Zealand, l.wotherspoon@uoa.ac.nz; BOURGUIGNON, S., GNS Science, Lower Hutt, New Zealand, s.bourguignon@gns.cri.nz; BRUCE, Z., GNS Science, Lower Hutt, New Zealand, z.bruce@gns.cri.nz; MCVERRY, G., GNS Science, Lower Hutt, New Zealand, g.mcverry@gns.cri.nz; MORGENSTERN, R., GNS Science, Lower Hutt, New Zealand, r.morgenstern@gns.cri.nz; GIALLINI, S., Italian National Research Council, Rome, Italy, s.giallini@gmail.com

Wellington's shallow steep-sided 3D basin structure has a critical influence on the spatial patterns of ground motion observed in major earthquakes (*e.g.* Mw 7.8 Kaikoura). Detailed modelling of the subsurface and geotechnical mapping can guide efforts to mitigate future damage and risk.

We compile a new 3D basin model and updated geotechnical maps for central Wellington, including parameters of site period, basin depth and New Zealand site classification. Our contribution extends the previous work of Semmens *et al.* (2010) by using modern modelling techniques to integrate complementary new geophysical and geological data throughout the central city. Specifically we have incorporated 1400+ borelogs and 400+ new geophysical site period measurements and associated uncertainty, as well as new LiDAR elevation information. These measurements have allowed us to better define both the shallow subsurface layers (based largely on borehole and CPT/SPT logs) and the deeper basin response (based largely on the geophysical measurements).

This compilation provides an overview of spatial variations and key features within the Wellington basin on a block-by-block scale. We also investigate the role of site and 2D/3D basin effects through correlation of key geotechnical parameters with observed ground motion amplification in Wellington during major events such as the 2016 Mw 7.8 Kaikoura earthquake.

Estimation of Bedrock Depth in the Kathmandu Valley, Nepal, Using Long-Term Ambient Noise and Teleseismic Data

HAYASHIDA, T., Building Research Institute, Tsukuba, Japan, takumi-h@kenken.go.jp; YOKOI, T., Building Research Institute, Tsukuba, Japan, tyokoi@kenken.go.jp; BHATTARAI, M., Department of Mines and Geology, Kathmandu, Nepal, mb2058@yahoo.com; DHAKAL, S., University of Canterbury, Christchurch, New Zealand, santoshdkl@yahoo.com; SHRESTHA, S., Department of Mines and Geology, Kathmandu, Nepal, suresh-shrestha@hotmail.com; POKHAREL, T., Department of Mines and Geology, Kathmandu, Nepal, tara_geo@yahoo.com; MAHARJAN, N., Department of Mines and Geology, Kathmandu, Nepal, nrshmhrjn72@gmail.com; TIMSINA, C., Department of Mines and Geology, Kathmandu, Nepal, chintan1119@gmail.com

Long-period strong ground motions were predominantly observed in the Kathmandu Valley, Nepal during the 2015 Gorkha earthquake (Dixit *et al.*, 2015; Bhattarai *et al.*, 2015; Takai et al, 2016). Analysis of aftershocks and gravity data indicated that there is a strong S-wave velocity contrast between sedimentary layers and bedrock in the valley (*e.g.*, Dhakal *et al.*, 2016; Bijukchhen *et al.*, 2017; Pradhan *et al.*, 2018). We have conducted microtremor array explorations with broadband seismometers and determined phase velocities of Rayleigh wave in the lower frequency range (< 1 Hz) to estimate the depth to bedrock (Bhattarai *et al.*, 2017; Yokoi *et al.*, 2018), but the dispersion characteristics below 0.2 Hz were unclear due to weak power of ambient noise. In order to explore the surface-wave phase velocity below 0.2 Hz for better estimation of bedrock depth, we deployed temporary continuous seismic observation stations (totally eight broadband stations) in the valley from February 2018 to present. The station-to-station intervals are 4.6 - 14.7 km. During the observation period, signals from shallow local (M > 4) and teleseismic events (M > 6) were clearly detected and we used surface-wave component of the recordings for the estimation of Rayleigh-wave phase velocities in the lower frequencies. The estimated phase velocities show dispersive characteristics between 0.01 and 0.13 Hz and the phase velocity at higher frequency side can be connected with the estimated ones from our microtremor explorations (> 0.2 Hz). We confirmed that the estimated phase velocities are comparable with those derived from the newly proposed seismic velocity structure model of Nepal (Yamada *et al.*, 2018). We also examined dominant frequencies of ambient noise H/V peaks as well as site amplifications at our target sites, and estimated surface-wave group velocities inside Kathmandu Valley using seismic interferometry. Our results indicate that the maximum depth to the bedrock could be 700 - 800 m.

Bias and Uncertainty of Depth Parameters Extracted From a Regional Velocity Model and Its Implications on Ground Motion Prediction

ZHU, C., GFZ German Research Centre for Geosciences, Potsdam, Germany, chuanbin.zhu@hdr.qut.edu.au; COTTON, F., GFZ German Research Centre for Geosciences, Potsdam, Germany, fabrice.cotton@gfz-potsdam.de; PILZ, M., GFZ German Research Centre for Geosciences, Potsdam, Germany, marco.pilz@gfz-potsdam.de

Site depth is utilized as a site proxy, in addition to the shear-wave velocities averaged over the first 30 m, VS30, to parameterize a site in ground motion models and seismic regulations, *e.g.*, Next Generation Attenuation of Ground Motions models and the revised European building code EC8. However, site-specific depth measurements are often unavailable at sites of interest. Considering that subsurface velocity models have been developed for some regions, *e.g.*, Japan and California, can site depth extracted from these structural models be utilized instead? To address this issue, we examine a subsurface model for Japan, the J-SHSIS model, proposed by the National Research Institute for Earth Science and Disaster Prevention (NIED). We firstly identity KiK-net sites with reliable velocity profiles of which empirically-derived site periods are consistent with theoretical ones calculated from the velocity profile. Then we establish site-specific depth measurements from these reliable velocity profiles, and then we compare these depth measurements with depth data extracted from the J-SHIS model. The comparison indicates that the J-SHIS depths are fraught with large bias and uncertainty. The J-SHIS model underestimates site depths at shallow sites and overestimates depths at deep sites, which can have a potentially significant impact on ground-motion prediction, *e.g.*, overestimation of ground motion by a factor up to 1.4. Besides, our results also show that correlation models for estimating depth parameters from VS30 have considerably large scatter. Therefore, one needs to be cautious about inferring site depth from a regional velocity model or from a known VS30.

Shallow Vs Structure Imaged With the Ambient Noise Recorded by a Telecommunication Fiber-Optic Cable in Urban Area

ZENG, X., Institute of Geodesy and Geophysics, Chinese Academy of Sciences, Wuhan, China, zengxf_whigg@outlook.com; WANG, B., University of Science and Technology of China, Hefei, China, bwgeo@ustc.edu.cn; LI, X., Earthquake Administration of Yunnan Province, Kunming, China, 17920082@qq.com; XU, W., Institute of Geophysics, China Earthquake Administration, Beijing, China, wwxu@cea-igp.ac.cn; XU, S., Institute of Geophysics, China Earthquake Administration, Beijing, China, xushanhuia@126.com; SONG, Z., University of Science and Technology of China, Hefei, China, song_zhenghong@163.com

The shear wave velocity structure is a key parameter in site response estimation and it is imaged with various methods. The ambient noise tomography (ANT) has been successfully used to image Vs structure at shallow depths. In previous studies, short-period surface wave signal is extracted from the continuous ambient noise recorded by the Distributed Acoustic Sensing (DAS) technique with fiber-optic cables buried in shallow trenches, which is employed to construct Vs model in test sites. A 5.2 km long telecommunication fiber-optic cable buried at about 30-cm depth in urban area is used to record more than 10-hours continuous ambient noise. The high-frequency (~ 10 Hz) Rayleigh wave signal emerges on the noise cross-correlation functions. The dispersion information of Rayleigh wave is inverted for Vs at the top 30 m and construct a 2D profile, which helps to assess ground shaking in this area.

Imaging and Monitoring Temporal Changes of Shallow Seismic Velocities at the Garner Valley Near Anza, California, in Relation to the M7.2 2010 El Mayor – Cucapah Earthquake

QIN, L., University of Southern California, California, USA, qinl@usc.edu; BEN-ZION, Y., University of Southern California, California, USA, benzion@usc.edu; BONILLA, L., Universite Paris Est, Marne-la-Vallée, France, luis-fabian.bonilla-hidalgo@ifsttar.fr; STEIDL, J. H., University of California, Santa Barbara, California, USA, steidl@eri.ucsb.edu; VERNON, F. L., Scripps Institution of Oceanography, California, USA, flvernon@ucsd.edu

We investigate temporal changes of seismic velocities after the M7.2 2010 El Mayor – Cucapah (EMC) earthquake, as well as the shallow velocity structure at the Garner Valley site northeast of ANZA, CA, with data from the Garner Valley Downhole Array (GVDA). The analyzed data include all events recorded by GVDA stations at various depths (0 m, *i.e.* surface, 6 m, 15 m, 22 m, 50 m and 150 m) in 2010. The local shallow velocity structure is first analyzed using travel times of direct arrivals between the surface and borehole stations. We observe extremely low shear wave velocity (~160 m/s) and high VP/VS ratio (~8) in the top 15 m and large variations of seismic velocities, especially the shear wave velocities, in the top 150 m (VS from ~160 m/s to ~1000 m/s and VP from 2000 m/s to 2800 m/s). The temporal changes of velocities in relation to the EMC earthquake are estimated from evolving autocorrelation functions at the two shallow stations (surface and 6 m borehole) and seismic interferometry between the surface station and borehole stations at 15 m, 22 m, 50 m and 150 m. The obtained average SH wave velocity reductions decrease with depth (~4.5% in the top 150 m, ~6.3 % in top 50 m, ~9.6% in top 22 m, ~10.9% in top 15 m, and ~13.2% in top 6-8 m). Based on the travel time and average velocity drops between different stations, the results imply that the velocity changes are concentrated in the top 22 m. The velocity reductions occur at the passage of large amplitude surface waves (~39 Gal) and the highest pore pressure variation of ~7 kPa, and are followed by rapid recovery in about 100-300 seconds. More than 10% of S wave velocity reductions in the top 15 m are produced by peak ground accelerations (PGA) smaller than 40 Gal, indicating that nonlinear site behavior may be more common and prominent than previously thought.

Soil Seismic Non-Linear Behavior Inferred by Analysis of Vertical Arrays Recordings

CASTRO CRUZ, D., CEREMA, Sophia Antipolis, France, david.castro@cerema.fr; BERTRAND, E., CEREMA, Sophia Antipolis, France, etienne.bertrand@cerema.fr; RÉGNIER, J., CEREMA, Sophia Antipolis, France, julie.regnier@cerema.fr; COURBOULEX, F., Géoazur, Sophia Antipolis, France, francoise.courboulex@geoazur.unice.fr

Seismic ground motion is strongly dependent on the subsurface layers mechanical characteristics and geometry. This phenomenon must be considered in hazard assessment through the evaluation of the seismic soil response. This response is not only depending on the soil parameters but also on the level of the seismic solicitation. The non-linear behavior is especially important to consider when modeling strong ground motion. We analyzed this effect using seismological data recorded by the Japanese Kiban Kyoshin Network (Kik-net). We use recordings from boreholes instrumented with two 3-components accelerometers, one located at surface and the other in depth. From these data, we are estimating the transfer functions by the computation of borehole spectral ratios (*BSR*) and are taking the advantage of the large database to study the variability of these*BSR*-with the level of seismic solicitation.

The main effect of the soil non-linear behavior on the transfer function is a shift of the amplification peaks towards lower frequencies and a decrease of the amplification level. We propose thus to characterize this non-linear behavior by quantifying those changes in the *BSR*. This work results in site-dependent relationships between the intensity of the ground motion and the modifications in the *BSR*. The presentation will show the procedure used for correcting surface ground motion of the non-linear behavior of the soil. The results obtained on several cases demonstrates that this procedure better predict strong motion and thus an attempt to take it into account in semi-empirical ground motion prediction is presented.

Site Characterization Based Upon Body-Wave Polarization

PARK, S., California Institute of Technology, California, USA, sunnyp@caltech.edu; ISHII, M., Harvard University, Massachusetts, USA, ishii@eps.harvard.edu; TSAI, V. C., California Institute of Technology, California, USA, tsai@caltech.edu

Body-wave polarization is sensitive to properties immediately beneath a seismic instrument, and has been demonstrated to be effective at estimating the near-surface P- and S-wave speeds (Park & Ishii, 2018). In this presentation, we extend the technique to consider the frequency dependence of body-wave polarization. Since lower frequency waves have longer wavelengths and sample deeper than higher frequency waves, examining the body-wave polarization at various frequencies provides insights into the depth-dependent wave speed beneath a station. Depending on the available frequency range, wave speeds near the surface to the upper crust and beyond can be explored. These results provide invaluable knowledge of the local 1-D structure beyond Vs^{30}, which helps with seismic hazard assessment.

We apply the frequency-dependent analysis to explore near-surface and upper-crustal structure of the continental United States. Our preliminary results show correlation with the geological features and prominent basins, with depth-dependent features that suggest complex subsurface processes at some sites. This versatile technique requires minimal computational resources and can be applied to any single three-component seismograph. It can also provide a means of monitoring changes that occur within the very upper crust caused by volcanic or hydrological processes. It opens a new path to a reliable, non-invasive, and inexpensive way of performing hazard assessment even for locations where drilling or field experiments using vibro-trucks or explosives are not practical options, and reduces uncertainties and ambiguities in resolving near-surface seismic structure.

Mapping Near-Surface Rigidity Structure Using Co-Located Pressure and Seismic Sensors From the Earthscope Transportable Array

WANG, J., University of California, Santa Barbara, California, USA, jiongwang@ucsb.edu; TANIMOTO, T., University of California, Santa Barbara, California, USA, toshirotanimoto@ucsb.edu

The coupling between the atmosphere and the solid Earth is strong for frequencies between 0.01 Hz and 0.05 Hz. In this frequency band, when the surface pressure is large, the atmosphere-generated seismic noise completely dominates the ocean-generated noise. By adopting the homogeneous half-space model by Sorrells (1971) and following the theoretical work by Tanimoto and Wang (2018), we estimated rigidity at 801 stations in the EarthScope Transportable Array (TA) by studying the atmosphere-ground coupling. We compute the ratio between the horizontal seismic power spectral density (PSD) and the (co-located) pressure PSD at 0.02 Hz, and this ratio reflects how much the ground responds to the surface pressure. Soft medium has higher seismic PSD amplitude in comparison to hard medium under the same pressure, thus has higher ratios; from this ratio, we can determine the shallow elastic structure.

We select one-hour-long horizontal seismic and pressure data with coherence higher than 0.7, and thus obtain robust estimates for rigidity. Our approach in this study focuses on the analysis of the horizontal-component seismic data, which differs from our previous work (Tanimoto and Wang, 2018).

We determined rigidity at 801 TA stations that are available since 2012. The resulting rigidity on the dense station map shows good spatial agreement with large-scale surface geology. Among them, 31 most rigid stations are in Alaska; many other high rigidity stations are in the Appalachian Mountains area. Both regions are known for having hard rocks. Low rigidity stations are located along the Mississippi Alluvial Plain, where soft sediments are found. Our method provides a simple and cost-effective way to retrieve near-surface structure by using stations with co-located seismic and pressure sensors.

Metamaterials, Resonances and Seismic Wave Mitigation, an Emerging Trend in Seismology

Oral Session · Friday · 3:45 PM · 26 April · Pine

Session Chairs: Andrea Colombi, Philippe Gueguen, Antonio Palermo.

3D Finite Difference Simulation for Evaluating the Possibility of Buildings as Metastructures

JOSHI, L., Indian Institute of Technology, Roorkee, India, ljoshi@eq.iitr.ac.in; NARAYAN, J. P., Indian Institute of Technology, Roorkee, India, jaypnfeq@iitr.ac.in

The concept of metamaterials has been effectively developed for various fields of physics like electromagnetism, optics and acoustics since their advent, but their application is relatively recent in the field of seismology and earthquake engineering. Although seismic metamaterials impart an exceptional solution for seismic hazard mitigation, till now very few studies have been conducted in which the actual frequency of interest (0-10 Hz) has been the primary focus due to lack of their practical applications. In the present study we investigate whether the existing structures of a city can act as metastuctures for other structures within the city on rayleigh wave to create a band gap on earthquake engineering scale. For this purpose, several 3D simulations using visco-elastic finite difference algorithm have been performed, while varying the height and the arrangements of the structures of the city. After the analysis of the results obtained through the simulations it is concluded that structures of the city act as sub-wavelength resonators which pluck the energy from the rayleigh wave at their fundamental and higher modes of vibrations, for both longitudinal as well as their flexural modes. Finally, an ideal arrangement of structures in a city is given for which the aforementioned effect is maximum. This arrangement although ideal could act as an aid for urban planners and earthquake engineers in planning and development of new cities as well as better estimation of design parameters for earthquake resistant design of structures in the epicentral zone of a shallow damaging earthquake.

Passive Redirection of Seismic Waves Through the Use of Gradient Index Metamaterial Barriers

SHAKALIS, A. J., Thornton Tomasetti, New York, USA, ashakalis@thorntontomasetti.com; GHISBAIN, P., Thornton Tomasetti, New York, USA, pghisbain@thorntontomasetti.com; MILNER, D., Thornton Tomasetti, California, USA, dmilner@thorntontomasetti.com; CIPOLLA, J. L., Thornton Tomasetti, District of Columbia, USA, jcipolla@thorntontomasetti.com

Conventional methods of dissipating or absorbing seismic energy come in the form of inertial or resonance-based approaches, such as tuned-mass dampers. This concept has extended to more complex metamaterial designs exploiting the same kinetic-energy physics, such as the 'Metaforet' and related soil-mounted approaches. However, in order to dissipate the extraordinary amount of energy present in seismic waves effectively, in the frequency band of interest, very large masses and/or oscillation amplitudes are required.

An alternative passive metamaterial approach would instead redirect the incident waves, rather than absorbing them, using internal energy physics to optimize the elastic properties of the metamaterial design. Optical Gradient index lenses (GRIN lenses) provide a means to redirect light, using regions of differing refractive index. Borrowing this concept, an analogous approach for wave propagation in solids, the acoustic or dilatational GRIN lens can be employed. Acoustic Metamaterial theory provides a design methodology for creating GRIN lenses; such metamaterial lenses redirect seismic waves away from structures of interest, reducing ground vibration levels considerably.

Mitigation of various solid waves and the design concepts behind geoscale acoustic metamaterials is discussed, with numerical experiments effected through the finite element software PZFlex. Discussion of some current mitigation technologies that would be augmented / supplanted by a notional metamaterial, if successful, will be provided to establish context for the development of a practical metamaterial-based solution.

Experimental Analysis of the Concept of Meta-City Considering a Geophysical Scale Analog City-Like Environment

GUÉGUEN, P., ISTerre, Université Grenoble Alpes/Université Savoie Mont-Blanc/CNRS/IRD/IFSTTAR, Grenoble, France, philippe.gueguen@univ-grenoble-alpes.fr; TOUMA, R., ISTerre, Université Grenoble Alpes/Université Savoie Mont-Blanc/CNRS/IRD/IFSTTAR, Grenoble, France, rita.touma@univ-grenoble-alpes.fr

At the city scale, the seismic vibration of the buildings induce a complexity in the ground motion due to Site-City interaction phenomenon: buildings act like secondary sources contaminating the free field and influencing the wave propagation. The aim of this study is to extend current knowledge of the site-city interaction to meta-city concept using a very dense network experiment deployed in a analog city-like environment constituted by resonators: the METAFOREST experiment. Experimental data retrieved from a pine-tree forest were analyzed in order to understand the impact of such as resonators on the seismic ground motion. We proved the concept that considers trees acting like resonant meta-materials at the geophysical scale. Buildings like trees can be considered as meta-resonators. We investigated the ambient noise and seismic ground motion recorded by 3-components geophones through two configurations: a square and a line seismic deployment of 100 receivers each, crossing the open field-forest boundary. The spatial variability between the field and the forest is studied. Significant differences are highlighted through ground motion intensity measures (Aria intensity, Fourier Amplitude Spectra, Spatial Coherency, etc.), wide band-gaps are identified proving that Rayleigh waves interact naturally with the trees resulting in a strong attenuation of the seismic ambient energy within the forest.

Resonant Metasurfaces for Surface Shear Horizontal Wave Attenuation in Unconsolidated Granular Media

ZACCHERINI, R., ETH Zurich, Zürich, Switzerland, zaccherini@ibk.baug.ethz.ch; COLOMBI, A., ETH Zurich, Zürich, Switzerland, colombi@ibk.baug.ethz.ch; PALERMO, A., California Institute of Technology, California, USA, palerman@caltech.edu; DERTIMANIS, V. K., ETH Zurich, Zürich, Switzerland, v.derti@ibk.baug.ethz.ch; MARZANI, A., University of Bologna, Bologna, Italy, alessandro.marzani@unibo.it; CHATZI, E. N., ETH Zurich, Zürich, Switzerland, chatzi@ibk.baug.ethz.ch

Arrays of mechanical resonators, referred to as metasurfaces, have proven capable of controlling in-plane polarized surface waves across multiple length scales, *i.e.*, from the micrometer scale, for the design of devices for sensing applications, up to the metric scale, for the attenuation of mechanical and seismic vibrations. In the context of seismic waves and groundborne vibration mitigation, researchers have recently proposed metasurfaces composed of meter-size resonators arranged around the foundation of critical infrastructures as innovative seismic isolation systems. While diverse studies on metasurfaces for Rayleigh wave attenuation are present in literature, investigations over the interaction between metasurfaces and surface shear waves are scarcely reported thus far. A recent numerical study demonstrated that it is possible to extend the concept of metasurfaces to anti-plane surface waves existing in semi-infinite layered media, the so-called Love waves. Furthermore, by varying the mechanical parameters of the resonators, the target frequency to control the wave propagation can be controlled.

Initiating from the aforementioned works, we experimentally investigate the potential of resonant metasurfaces for the mitigation of surface shear waves propagating in an inhomogeneous material. An unconsolidated granular medium is considered, featuring a 1D power-law velocity profile, mimicking waves in a scaled sedimentary basin. In particular, we first design and fabricate a small-scale resonant metasurface consisting of an array of mechanical horizontal oscillators buried under the surface of the unconsolidated granular substrate. Then, we study the interaction between the metasurface and the horizontal shear waves originating at the surface of the granular medium. Our findings demonstrate wave attenuation around the horizontal frequency of the resonators, revealing the potential of realizing seismic resonant metamaterials for shear surface waves.

Periodic Excavations, Hills and Inclusions as Seismic Metamaterials: Can They Be Used as Wave Barriers Protecting Structures From Seismic and Anthropogenic Sources of Vibrations?

TODOROVSKA, M. I., Tianjin University, Tianjin, China, maria.todorovska@yahoo.com; BA, Z., Tianjin University, Tianjin, China, bazhenning_001@163.com; OZMUTLU, A., Namik Kemal University, Tekirdag, Turkey, aozmutlu@nku.edu.tr; GAO, X., Tianjin University, Tianjin, China, 191990951@qq.com

It has been long known that features of surface topography and near surface geology, such as excavations, hills and inclusions, act as barriers for seismic waves. A periodic arrangement of such features would constitute a seismic metamaterial, acting as a selective filter for horizontally propagating seismic waves. We study the characteristics and effectiveness of such filters by numerical simulation of SH-wave propagation in a homogeneous and layered half-space with infinite and finite periodic clusters of elliptic "canyons", "hills" and "valleys". We use an Indirect Boundary Element Method (IBEM) to compute the motions on the ground surface, and simple 1D approximations, such as binary periodic beams, to compute the dispersion. The results show that periodic barriers are more effective shields than single barriers, and that the periodic "valleys" reduce more the motions on the ground surface than the periodic "canyons" and "hills". We discuss possible use of such periodic barriers as shields for earthquake and ground born vibrations.

The 2018 Eruption of Kīlauea Volcano, Hawai`i

Oral Session · Friday · 8:30 AM · 26 April · Puget Sound

Session Chairs: Charlotte A. Rowe, Jefferson C. Chang, Ellen M. Syracuse.

Evolution of Seismicity During the 2018 Kīlauea Volcano Eruption

CHANG, J. C., U.S. Geological Survey, Hawaii, USA, jchang@usgs.gov; SHIRO, B., U.S. Geological Survey, Hawaii, USA, bshiro@usgs.gov; DOTRAY, P. J., U.S. Geological Survey, Hawaii, USA, pdotray@usgs.gov; BURGESS, M., U.S. Geological Survey, Hawaii, USA, mburgess@usgs.gov; OKUBO, P., U.S. Geological Survey, Hawaii, USA, pokubo@usgs.gov; ANTOLIK, L., U.S. Geological Survey, Hawaii, USA, lantolik@usgs.gov; THELEN, W., U.S. Geological Survey, Hawaii, USA, wthelen@usgs.gov; WAITE, G. P., Michigan Tech, Michigan, USA, gpwaite@mtu.edu

The 2018 eruption of Kīlauea Volcano began on April 30th, as Pu`u `Ō`ō vent collapsed and a trail of earthquakes marched towards the Lower East Rift Zone (LERZ). The subsequent withdrawal of the lava lake at Halema`uma`u began on May 1st, and the first of 24 eruptive fissures in the LERZ opened-up half a day before the M6.9 tectonic earthquake on May 4th.

Seismicity on the LERZ subsided when Fissure 8 became the dominant source of lava after May 27th, while a dozen explosive, very long period (VLPe) events with moment magnitudes of M4.7-5.1 occurred at Kīlauea summit at 8-45 hour intervals from May 16-26th. By the end of May, these explosive events transitioned into VLP collapse (VLPc) events, with moment magnitudes of M5.2-5.4 at almost-daily occurrences until August 5th. A total of 62 VLP events, and the swarms of smaller earthquakes in between, chronicle the largest collapse of the Kīlauea summit caldera in at least 200 years.

Bounding these keystone seismic events, from April 30th to August 5th, are unprecedented rates of seismicity that signal the migration of magma in conduits and/or failure of asperities on faults. The interplay between the volcanoseismic and tectonic events during the 2018 Kīlauea eruption sequence is poorly understood. In this preliminary work, we look at hypocentral locations, timing, and frequency content of over 60k detected events at this time period to better elucidate their source processes and triggering mechanisms, and ultimately, future hazard mitigation.

Seismic Velocity Changes Associated With the 2018 Collapse of Kīlauea's Summit

HOTOVEC-ELLIS, A. J., U.S. Geological Survey, California Volcano Observatory, California, USA, ahotovec-ellis@usgs.gov; SHIRO, B., U.S. Geological Survey, Hawaiian Volcano Observatory, Hawaii, USA, bshiro@usgs.gov; HANEY, M., U.S. Geological Survey, Alaska Volcano Observatory, Alaska, USA, mhaney@usgs.gov; SHELLY, D. R., U.S. Geological Survey, Geologic Hazards Science Center, Colorado, USA, dshelly@usgs.gov; THELEN, W., U.S. Geological Survey, Cascades Volcano Observatory, Washington, USA, wthelen@usgs.gov; MONTGOMERY-BROWN, E., U.S. Geological Survey, California Volcano Observatory, California, USA, emontgomery-brown@usgs.gov; ANDERSON, K. R., U.S. Geological Survey, California Volcano Observatory, California, USA, kranderson@usgs.gov; JOHANSON, I., U.S. Geological Survey, Hawaiian Volcano Observatory, Hawaii, USA, ijohanson@usgs.gov

Several weeks after the eruption of lava began in the lower east rift zone of Kīlauea volcano in 2018, seismicity at the summit settled into a remarkably cyclic pattern: increase in number and size of earthquakes, culminate in a ~M5 collapse event, quiescence, then increase and repeat again. Deformation at the summit was also similarly cyclic. Overprinted on a general trend of deflation as magma exited the shallow reservoir, steps of inflation occurred at the times of the large collapse events. Using a repeating earthquake catalog, we solved for changes in seismic velocity in the shallow subsurface with half-hourly temporal resolution using coda wave interferometry. To first order, seismic velocity changes as a function of volumetric strain, where velocity decreases as cracks open in dilatation. We also solved for temporal changes in mean free path related to crack formation with a similar technique.

We find that over the duration of a single cycle, velocity decreased prior to the collapse event and immediately increased afterwards. These changes likely reflect the opening and closing of cracks due to volumetric strain caused by elastic rebound from slip on the newly formed caldera walls and/or changes in pressure in the shallow magmatic system. Over the course of the last two months of the eruption, long-term trends in the seismic velocity timeseries can be divided into two linear segments: a decrease in velocity of ~5% from early to late June, and then roughly constant velocities in July through the end of the eruption in early August. We interpret the long-term velocity decrease was related to crack formation and opening during the creation of the ring fault outlining the roof block above the shallow magmatic system. Then, the constant velocities were due to a stable configuration of the system where the episodic sliding and down-dropping of the roof along that established margin did not further open cracks.

Anatomy of a Caldera Collapse: Kilauea 2018 Summit Seismicity Sequence in High Resolution

SHELLY, D. R., U.S. Geological Survey, Colorado, USA, dshelly@usgs.gov; THELEN, W., U.S. Geological Survey, Cascades Volcano Observatory, Washington, USA, thelen@usgs.gov; OKUBO, P., U.S. Geological Survey, Hawaii Volcano Observatory, Hawaii, USA, pokubo@usgs.gov

The Kilauea eruption and caldera collapse of 2018 was an incredibly dynamic sequence, observed at close distances by a dense, modern, multi-faceted network. The seismic sequence associated with summit caldera collapse was especially rich, with cycles of seismicity closely tracking cycles of large (typically M_w 5.2-5.4) collapse events associated with magma withdrawal from the summit area. To gain further insight into the summit sequence, we applied waveform-based earthquake detection, double-difference relocation, and correlation-based focal mechanism analyses. Using ~2800 earthquakes cataloged by the Hawaiian Volcano Observatory from April 29 to August 6, 2018, we detected and relocated ~44,000 events. Event hypocenters form complex structures in space and time. The vast majority of seismicity concentrated just east of Halema'uma'u crater, at shallow depths of 2.5 km or less below Kilauea summit, and roughly outlined the eastern extent of caldera collapse. We note changes in event distributions at different stages of the repeated collapse cycles, with events early in each cycle concentrating near the center of the seismic zone, with activity moving to the perimeter later in the cycle. Using cross-correlations to measure relative P and S polarities, we cluster events by similarity of polarity patterns observed across the network. Some mechanism clusters are formed by earthquakes with primarily double-couple slip, while others are composed of distinctly non-double-couple events dominated by dilatational first motions. In total, these events illuminate complex kinematics and dynamics associated with the 2018 Kilauea caldera collapse. The double-couple mechanisms likely reflect slip on faults accommodating caldera subsidence; the implosive events may reflect sudden closure of cracks or dikes.

Understanding Summit Failure Processes During the 2018 Kilauea Eruption Through Analysis of Earthquake Swarms

TEPP, G., U.S. Geological Survey, Alaska, USA, gtepp@usgs.gov; HOTOVEC-ELLIS, A. J., U.S. Geological Survey, California Volcano Observatory, California, USA, ahotovec-ellis@usgs.gov; SHIRO, B., U.S. Geological Survey, Hawaiian Volcano Observatory, Hawaii, USA, bshiro@usgs.gov; HANEY, M., U.S. Geological Survey, Alaska Volcano Observatory, Alaska, USA, mhaney@usgs.gov; THELEN, W., U.S. Geological Survey, Cascades Volcano Observatory, Washington, USA, wthelen@usgs.gov

In early May 2018, Kilauea's summit lava lake began to quickly drain after a rift zone intrusion and subsequent collapse at the Pu'u 'O'o vent, marking the start of a major eruption. As fissures opened and magma poured out in the Lower East Rift Zone, the summit crater began to collapse. Major summit collapse events occurred roughly every 1-2 days between May 16 (local time) and August 2 and were each preceded by swarms of earthquakes. The rate of earthquakes in each swarm increased leading up to the collapse events and dropped significantly after a collapse event occurred. Along with the increases in earthquake rate, the earthquake magnitudes also increased on average with more large earthquakes occurring in the latter stages of the swarms.

We examine the characteristics of the summit swarms to improve understanding of the failure processes involved in the summit collapse events. In particular, we focus on the inverse moment rate, which is a measure of seismic energy release over time. When all earthquakes are considered as part of the swarms, the character of the inverse moment rate of each swarm appears to change over the duration of the eruption, with major changes occurring concurrently with changes in the collapse event waveforms. This suggests that the failure processes may have evolved over time. We also consider sub-swarms of repeating earthquakes. Each family of repeating earthquakes can be assumed to come from one fault or area around the crater. Thus, the inverse moment rate of each family provides more detailed information about how the failure during each collapse event proceeded. Over the duration of the eruption, swarm families and the character of their inverse moment rates changed over time, providing more insight into the progression of the summit failure. We compare these results with other information about the collapse events to further understand the processes involved in the summit crater collapse.

How Did the 2018 Kilauea Eruption Affect the Volcano's Submarine South Flank? Preliminary Results From an Ocean Bottom Seismometer Deployment Offshore Kilauea

CAPLAN-AUERBACH, J., Western Washington University, Washington, USA, caplanj@wwu.edu; SHEN, Y., University of Rhode Island, Rhode Island, USA, yshen@uri.edu; MORGAN, J. K., Rice University, Texas, USA, morganj@rice.edu; SOULE, S. A., Woods Hole Oceanographic Institution, Massachusetts, USA, ssoule@whoi.edu

The south flank of Kilauea moves to the southeast as a consequence of gravitational and magmatic stresses. This motion is punctuated by episodic slow or seismic slip events on the decollement or shallow thrust faults underlying the island, generating extension in the East Rift Zone. On May 4 2018, following injection of magma into the Lower East Rift Zone (LERZ), a M6.9 earthquake occurred beneath the south flank. Aftershocks were recorded along the western and southern boundaries of the submarine flank in areas that had not previously experienced significant seismicity. These epicenters suggest a broad change in the flank stress field, triggered by the LERZ intrusion, the M6.9 earthquake, or a combination thereof. This has implications for seismic, landslide, and tsunami hazards associated with slip of the submarine flank.

In July 2018, we deployed a network of 12 short-period ocean-bottom seismometers (OBSs) on the Kilauea submarine south flank; data were recovered from 10. Recording was continuous until recovery in mid-September 2018, spanning the termination of the active eruption. The objectives of the project were threefold: (1) to record aftershocks of the M6.9 event, determine faults that slipped, and identify phases traveling within the decollement, (2) to better constrain the locations of earthquakes occurring beneath and within the south flank to identify other active structures and associated changes in the stress state, and (3) to capture acoustic signals associated with the active ocean entry to better understand the delivery and downslope transport of eruptive products.

Preliminary analysis suggests that many more earthquakes occurred offshore than were detected by the land-based seismic network. The OBS data allow substantially improved hypocentral constraint for offshore earthquakes. Many submarine landslides were recorded, and the relative strength of the acoustic signals allows us to constrain their source locations.

Interseismic Quiescence and Triggered Slip of Active Normal Faults of Kīlauea Volcano's South Flank During 2001-2018

WANG, K., University of California, Berkeley, California, USA, kwang@seismo.berkeley.edu; MACARTHUR, H., California Institute of Technology, California, USA, hmacarth@caltech.edu; JOHANSON, I., U.S. Geological Survey, Hawaiian Volcano Observatory, Hawaii, USA, ijohanson@usgs.gov; MONTGOMERY-BROWN, E., U.S. Geological Survey, California Volcano Observatory, California, USA, emontgomery-brown@usgs.gov; POLAND, M., U.S. Geological Survey, Cascades Volcano Observatory, Washington, USA, mpoland@usgs.gov; CANNON, E. C., Golder Associates, Alaska, USA, eccannon@gmail.com; D'ALESSIO, M., California State University, Northridge, California, USA, matthew.dalessio@csun.edu; BÜRGMANN, R., University of California, Berkeley, California, USA, burgmann@seismo.berkeley.edu

The mobile south flank of Kīlauea Volcano on the Island of Hawai`i has generated a number of large earthquakes on its basal detachment, with the most recent being the May 4, 2018 M6.9 earthquake. The south-dipping Hilina fault system (HFS) appears to represent the headscarp of a large-scale gravitationally driven landslide complex. This series of faults is known to have slipped coseismically by several meters during large detachment earthquakes, including the 1975 quake. The Koa`e fault system (KFS) consists of north-dipping normal faults bounding the summit region of Kīlauea Volcano to the north. These shallow faults slip slowly during interseismic periods and are triggered by volcano-tectonic episodes. To date, geodetic monitoring has been unsuccessful in conclusively detecting interseismic motion of the HFS, which might in part stem from the lack of sufficient geodetic coverage. We analyze kinematic GPS data collected between 2001 and 2017. Our results indicate that the faults did not significantly slip during this time. The lack of interseismic slip is possibly due to the south flank having been in compression from two major intrusive events in 2007 and 2011. Despite its substantial magnitude, space-based radar interferograms show that the May 4, 2018, M6.9 earthquake only triggered sub-cm level slip along sections of the mapped HFS surface trace. Up to 20 cm of offset occurred on what appears to be a newly formed (or previously unknown) fault near the eastern end of the HFS. During the 3 months following the M6.9 earthquake, up to tens of cm of slip occurred along the KFS, helping accommodate rapid large-scale subsidence of Kīlauea's summit region as large volumes of summit reservoir magma fed the lower East Rift Zone eruption. The HFS appears to activate only in concert with large earthquakes on the basal detachment, while the KFS displaces by aseismic creep during small seismic events and in response to substantial subsurface magma redistribution, including rift zone intrusions and volume loss of the summit magma chamber.

Inter-Event Seismicity Statistics Associated With the 2018 Quasi-Periodic Collapse Events at Kīlauea, HI, USA

FILDES, R. A., University of California, Davis, California, USA, rfildes@ucdavis.edu; KELLOGG, L. H., University of California, Davis, California, USA, lhkellogg@ucdavis.edu; TURCOTTE, D. L., University of California, Davis, California, USA, dlturcotte@ucdavis.edu; RUNDLE, J. B., University of California, Davis, California, USA, jbrundle@ucdavis.edu

Following the Mw 6.9 Hawaiian earthquake on May 4, 2018 and the decay of its aftershock sequence, a remarkable quasi-periodic sequence of collapse events began at Halema'uma'u Crater at the summit of Kīlauea Volcano. The collapse events were associated with the drainage of magma from beneath the summit to the Lower East Rift Zone where fissure eruptions occurred. From June 4, 2018 through August 2, 2018 the collapse events, each releasing the energy equivalent of a Mw 5.3 ± 0.1 earthquake, occurred every 1.30 ± 0.32 days. This study focuses on the smaller seismicity (magnitudes ≥ 2.5, based on the fit of the data to Gutenberg-Richter scaling) occurring between collapse events at the summit. Between sequential pairs of collapses, the same temporal pattern of seismicity occurred. Following a large collapse event, there was a relatively quiescent period typically lasting 0.53 ± 0.16 days. Following this quiescent period, there was a sudden onset of seismicity at a nearly constant rate of 397 ± 96 earthquakes per day. These seismically active periods, lasting 0.77 ± 0.33 days, with linear rates of seismicity, lasted until the next collapse event occurred. The temporal pattern then repeated itself beginning again with post-collapse quiescence. The pattern occurred 46 times between the 47 collapse events in our study period. A large shift in the rates of seismicity during the active times occurred around June 15th. There were also significant changes in the lengths of the quiescent times and the number of earthquakes during the total inter-event times that occurred around this date. Building on our preliminary study we are further investigating these trends and changes in the behavior of the smaller seismicity. Further statistical breakdown of the quiescent time behavior compared to the active time may give insight to the pre- and post-collapse volcanic and tectonic dynamics through-out the sequence.

Six Axis Measurements at Kilauea – More Riddles to Be Solved?

WASSERMANN, J. M., Ludwig Maximilian University of Munich, Munich, Germany, j.wassermann@lmu.de; BERNAUER, F., Ludwig Maximilian University of Munich, Munich, Germany, fbernauer@geophysik.uni-muenchen.de; SHIRO, B., U.S. Geological Survey, Hawaiian Volcano Observatory, Hawaii, USA, bshiro@usgs.gov; JOHANSON, I., U.S. Geological Survey, Hawaiian Volcano Observatory, Hawaii, USA, ijohanson@usgs.gov; IGEL, H., Ludwig Maximilian University of Munich, Munich, Germany, igel@geophysik.uni-muenchen.de; GUATTARI, F., iXblue, Saint-Germain-en-Laye, France, frederic.guattari@ixblue.com

Near field recordings and thus finite source inversions of large earthquakes and volcano-induced events very often suffer from unaccounted effects of local tilt, saturation of classical instrumentation, unknown shallow velocity structure and doubtful orientation of the instruments. Recent advances in hardware and software development made it possible to install a very broadband, high sensitive rotational motion sensor based on fibre optical gyroscope technology in very close distance of only two kilometres to the area of activate slumping at the Halema'uma'u pit of Kilauea's summit apparatus. Using this new instrument together with permanent deployed classical instrumentation (*i.e.*, translational seismometer. accelerometer and tilt meter) we were able to record three magnitude Mw5 earthquakes during the 2018 Kilauea summit eruption. The resulting six axis measurement reveals clear rotations around all three coordinate axis. Outstanding is hereby the observation of rotation around the vertical axis, a motion which will not be detectable using classical instrumentation only. We are furthermore able to demonstrate how this six axis measurements can help to improve the location procedure due to its property to act as a physical wave polariser. We also demonstrate the application of a single site shallow velocity estimation using volcanic background noise only which further will improve the estimation of the source mechanism.

In parts the surprisingly clear static rotations and translations can be verified by simulations using computed moment tensor solution inverted from the local to regional network data as well as with data from a local installed borehole tilt meter. Discrepancies between classical instrumentation can be explained in parts by the near field observation of a finite source and very localised near fault effects.

Hindcasting May 2018 Kīlauea Summit Explosions With Atmospheric Remote Sensing, Geophysical Monitoring and 3D Eruptive Plume Simulations

CROZIER, J. A., University of Oregon, Oregon, USA, crozierjosh1@gmail.com; KARLSTROM, L., University of Oregon, Oregon, USA, leif@uoregon.edu; THELEN, W., U.S. Geological Survey, Washington, USA, wthelen@usgs.gov; ANDERSON, K. R., U.S. Geological Survey, California, USA, kranderson@usgs.gov; DUFEK, J., University of Oregon, Oregon, USA, jdufek@uoregon.edu; LIANG, C., Stanford University, California, USA, chao2@stanford.edu; BENAGE, M., U.S. Geological Survey, California, USA, mbenage@usgs.gov

Between May 17- 24, 2018, a series of eruptions at the summit of Kīlauea Volcano, HI, produced ash plumes as high as 30 km which were monitored by visual, radar, and infrasonic data. Co-eruptive ground deformation was recorded by nearby broadband seismometers. Eruptions manifested as 40 s long M4-5 seismic impulses, coincident with increased high frequency seismicity and infrasonic signals. 20-30 s later, eruptive plumes surfaced that persisted for tens of minutes, and very-long-period seismic oscillations occurred. After May 24, M5 events continued but with different high-frequency seismicity and no explosive eruptions. Here we invert seismic data for source parameters that we then use to drive 3D multiphase atmospheric plume models in order to seek a self-consistent explanation for geophysical and atmospheric data.

For all events, we invert >15 s period co-eruptive seismic data with quasi-static source models: moment tensors, tensile cracks, ring faults, spherical reservoirs, and combinations of these models. Moment tensors show primarily isotropic inflation with appreciable double-couple and CLVD components. Ground displacements are best fit by either a shallowly dipping 1 km deep crack or a 1.8 km deep sphere. Source mechanisms are relatively consistent until May 24 when energy at depths <1 km and double-couple motion increase, likely from collapse with signifigant slip along ring faults.

Plume simulations forced by seismically-derived time-varying basal conditions can produce plumes with heights and subsurface ascent times consistent with observations. These suggest (1) inflation accompanies collapse of rock overlying a shallow magma reservoir, (2) a significant fraction of displaced magma enters eruptive plumes, and (3) simulations can place bounds on fragmentation depths. We find that ground deformation was sufficiently well recorded to constrain source dynamics, but that available atmospheric data provides suboptimal constraints on eruptive plume dynamics.

What Lies Ahead for Kilauea? Perhaps Lo`ihi Knows. Remarkable Parallels Between the 1996 Eruption of Lo`ihi Seamount and the 2018 Kilauea Eruption

CAPLAN-AUERBACH, J., Western Washington University, Washington, USA, caplanj@wwu.edu; THURBER, C. H., University of Wisconsin–Madison, Wisconsin, USA, cthurber@wisc.edu

The cessation of eruptive activity at Kilauea in August 2018 marked the end of 35 years of continuous activity and begs the question of what we can expect with regard to the volcano's future. This event exhibits remarkable similarity to the 1996 eruption of Lo`ihi seamount, and suggests that Lo`ihi's long term eruptive behavior may provide insight into future activity at Kilauea.

The 1996 Lo`ihi earthquake swarm was preceded by over a decade of seismic activity. From 1986 to 1996, the seamount experienced several earthquakes per month, as well as near annual earthquake swarms. Although Lo`ihi's location below sea level makes it difficult to determine when it was erupting, there is evidence of eruptive activity in 1990 and in early 1996, well before the earthquake swarm. The 1996 event began with increased seismic activity within Lo`ihi's south rift zone, after which seismicity moved to the summit area. This parallels Kilauea's behavior in April and May of 2018. In both cases summit activity was highly energetic: Lo`ihi experienced over 100 M4+ earthquakes during the event, and Kilauea's activity included >50 M5+ events. Perhaps most striking, both summit swarms were associated with the collapse of a significant portion of the summit, creating Pele's Pit on Lo`ihi and massively enlarging the Halema`uma`u crater on Kilauea. Relocations of Lo`ihi earthquakes confirm a tightly concentrated zone of summit activity that is likely associated with pit crater collapse.

Following the 1996 event, seismicity at Lo`ihi tapered dramatically, and it remained low until 2015. This period included two deployments of instruments directly on the volcano, confirming that the quiescence was real. Seismicity gradually increased, and near-annual swarms initiated again in 2015. If these similarities in behavior between these volcanoes are a guide to the future, we speculate that it may be as much as two decades before Kilauea becomes active again.

Observations of Volcanism in the Three Spheres: Land, Air and Sea

Oral Session · Friday · 1:30 PM · 26 April · Puget Sound

Session Chairs: Alicia J. Hotovec-Ellis, Gabrielle Tepp, Jackie Caplan-Auerbach, Mel Rodgers.

Ancillary Land, Sea and Air Records of the Krakatau Eruption and Tsunami of 22 December 2018

OKAL, E. A., Northwestern University, Illinois, USA, emile@earth.northwestern.edu; HYVERNAUD, O., Laboratoire de Geophysique, Commissariat a l'Energie Atomique, Papeete, French Polynesia, hyvernaud@labogeo.pf; PARIS, A., Laboratoire de Detection et Geophysique, DASE, CEA, Bruyeres-le-Chatel, France, alexandre.paris@cea.fr; HEBERT, H., Laboratoire de Detection et Geophysique, DASE, CEA, Bruyeres-le-Chatel, France, helene.hebert@cea.fr; HEINRICH, P., Laboratoire de Detection et Geophysique, DASE, CEA, Bruyeres-le-Chatel, France, philippe.heinrich@cea.fr

We examine records obtained on "ancillary" instruments not necessarily designed for that purpose, of the catastrophic volcanic landslide and tsunami at Krakatau on 22 December 2018. In particular, in the absence of operational DART-type sensors in that part in the Indian Ocean, we use records on horizontal long-period seismometers at a number of coastal sites: this methodology, pioneered by Yuan *et al*. [2005] has been successfully applied to several tsunamis, both in the far field and more recently at close distance during the 2017 Karrat Fjord, Greenland landslide. Using records at Cocos Island (COCO; 1160 km), we reconstruct an equivalent amplitude in deep water of 0.15 mm peak-to-peak, with energy peaked around 2.5 mHz. On the other hand, we fail to observe hydroacoustic T phases on hydrophones of the IMS off Diego Garcia, but a weak signal is present on the seismic records at COCO and at one of the two stations of the Australian network on Christmas Island (490 km), the latter featuring energy in the 7-t0-20 Hz band. Finally, the eruption is recorded as an exceptionally crisp signal by the infrasound array I06 of the IMS at Cocos Islands, with a signal peaked around 0.25 Hz. Quantified modeling of these various signals will be presented, based in particular on a combined dynamic model of the landslide and tsunami, coupled to a simulation of the water waves using a Boussinesq approximation, whose results will be compared to the deconvolved seismic record at COCO.

Explosion Volume Flux Comparison Using Seismically Derived Tilt, Infrasound and Gas Data at Stromboli Volcano, Italy

MCKEE, K. F., Carnegie Institution for Science, District of Columbia, USA, kfmckee@carnegiescience.edu; FEE, D., Alaska Volcano Observatory, Geophysical Institute, University of Alaska Fairbanks, Alaska, USA, dfee1@alaska.edu; WAITE, G. P., Michigan Technological University, Michigan, USA, gpwaite@mtu.edu; ROMAN, D. C., Carnegie Institution for Science, District of Columbia, USA, droman@carnegiescience.edu; RIPEPE, M., University of Florence, Florence, Italy, maurizio.ripepe@unifi.it; AIUPPA, A., University of Palermo, Palermo, Italy, alessandro.aiuppa@unipa.it; CARN, S., Michigan Technological University, Michigan, USA, scarn@mtu.edu; LE MÉVEL, H., Carnegie Institution for Science, District of Columbia, USA, hlemevel@carnegiescience.edu; DELLE DONNE, D., University of Palermo, Palermo, Italy, dario.delledonne@unipa.it; BITETTO, M., University of Palermo, Palermo, Italy, marcello.bitetto@unipa.it; LACANNA, G., University of Florence, Florence, Italy, giorgio.lacanna@unifi.it; SEALING, C., Drexel University, Pennsylvania, USA, christine.sealing@gmail.com; CIGALA, V., Ludwig Maximilian University of Munich, Munich, Germany, valeria.cigala@min.uni-muenchen.de; TAMBURELLO, G., Istituto Nazionale di Geofisica e Vulcanologia, Bologna, Italy, giancarlo.tamburello@ingv.it

Basaltic volcanoes are characterized by low-level explosions and lava fountaining, but are capable of violent subplinian to plinian eruptions. Stromboli Volcano has been observed with seismometers and tiltmeters to deform prior to explosion [Genco and Ripepe, 2010]. Quantitatively linking this precursory deformation, often interpreted as inflation due to an influx of magma and gas, with the volume of subsequent erupted material (gas and tephra) will be helpful for understanding eruption dynamics and in hazard mitigation, as we can better constrain expected volatile output from monitored volume input.

To these aims, we temporarily deployed 7 seismometers, 7 infrasonic microphones, an FTIR, FLIR, gravimeter, and MultiGAS at Stromboli Volcano, Italy in May 2018. We use these data in combination with data from permanently installed seismometers, infrasound sensors, tiltmeters, and a UV camera to examine the volatile budget of Stromboli by comparing shallow volume input derived from broadband, tilt-affected seismic and tilt data with volume output from infrasound and gas data. First, we characterize and locate the seismically-derived tilt source using a nonlinear moment tensor inversion method [Tape and Tape, 2012; Waite and Lanza, 2016] and use the result to quantify the volatile volume input. Initial inversion results place the tilt-affected source ~300 m below the active craters. We will attempt to characterize the input volume density using gravity data. Independently, we characterize and locate the infrasonic explosion source and quantify the output volume using an infrasonic waveform inversion technique that accounts for the influence of topography by computing numerical Green's functions by way of a 3-D finite difference time domain method [Kim *et al*., 2015]. The seismically estimated volume input and infrasonically estimated volume output will then be validated with volume output estimated from gas observations. This quantitative examination of tilt, infrasound and gas data aims to advance our ability to determine the size of eruption prior to its occurrence.

Seismic Imaging of Magmatic- and Subduction-Related Structures Beneath Arc Volcanoes: A Case Study at Mount Cleveland, Alaska

JANISZEWSKI, H. A., DTM, Carnegie Science, District of Columbia, USA, hjaniszewski@carnegiescience.edu; WAGNER, L. S., DTM, Carnegie Science, District of Columbia, USA, lwagner@carnegiescience.edu; ROMAN, D. C., DTM, Carnegie Science, District of Columbia, USA, droman@carnegiescience.edu

Cleveland Volcano is one of the most active volcanoes in the central-Aleutian island arc and represents one of the shallow-end members of depth to subducting slab at only ~ 65 km below the volcano. It was the site of a temporary deployment of twelve broadband seismometers from August 2015 – July 2016. We calculate P-to-s receiver functions using these as well as two permanent Alaska Volcano Observatory stations, which have operated since 2014, to determine new seismic constraints on the crustal structure beneath Cleveland Volcano and the depth to the subducting crust. At Cleveland Volcano we image a clear P-to-s conversion from the Moho discontinuity. However, its arrival time relative to the initial P-wave typically varies up to two seconds at a given station with later arrivals systematically corresponding to ray paths that have passed through crust directly beneath the volcano. The most likely explanation is that slow shear-wave velocities associated with the magmatic system beneath Cleveland Volcano contribute to the travel time variability, with perhaps a secondary contribution from smaller variations in Moho topography.

Combining Active- and Passive-Source Seismic Observations to Image Magma Storage Beneath Mount St. Helens

ULBERG, C. W., University of Washington, Washington, USA, ulbergc@uw.edu; KISER, E., University of Arizona, Arizona, USA, ekiser@email.arizona.edu; CREAGER, K. C., University of Washington, Washington, USA, kcc@uw.edu; LEVANDER, A., Rice University, Texas, USA, alan@rice.edu; SCHMANDT, B., University of New Mexico, New Mexico, USA, bschmandt@unm.edu; HANSEN, S., Macquarie University, Sydney, Australia, steven.hansen@mq.edu.au; ABERS, G. A., Cornell University, New York, USA, abers@cornell.edu

In the summer of 2014 we initiated passive and active seismic tomography experiments at Mount St. Helens (MSH), Washington, as part of the collaborative imaging Magma Under St. Helens (iMUSH) project. The passive experiment used local earthquake data from 70 broadband seismometers that were deployed in a 100-km aperture array around MSH from 2014 to 2016, and the active experiment used recordings of 23 explosions in the summer of 2014 at ~6000 locations using Texan and Nodal seismometers. The passive and active data sets were inverted separately to obtain 3-D velocity models of the upper crust around MSH, yielding many similar features and interpretations. These include: (1) High P- and S-wave velocities near the surface corresponding to surface-mapped plutons; (2) Low velocities near the surface corresponding to the Chehalis sedimentary basin and the Indian Heaven volcanic field; (3) Low velocities along the St. Helens seismic zone, striking NNW-SSE north of MSH from near the surface to at least 10 km depth; (4) Low P- and S-wave velocities beneath MSH at depths of 6-15 km below sea level, probably indicating a magma storage region. However, there remain some areas which differ between the two models, including the details of the MSH magma storage region. In this work, we present the results of a joint inversion of the active and passive data sets, evaluate the reasons for any differences in the separate inversions, and make further interpretations using results of iMUSH magnetotelluric inversions and petrologic/tectonic models of the area.

Insights Into Shallow Submarine Explosion Dynamics at Bogoslof Volcano From Infrasound, Hydroacoustic and Seismic Data

LYONS, J. J., U.S. Geological Survey, Alaska, USA, jlyons@usgs.gov; WECH, A., U.S. Geological Survey, Alaska, USA, awech@usgs.gov; TEPP, G., U.S. Geological Survey, Alaska, USA, gtepp@usgs.gov; HANEY, M., U.S. Geological Survey, Alaska, USA, mhaney@usgs.gov; FEE, D., Geophysical Institute, University of Alaska Fairbanks, Alaska, USA, dfee1@alaska.edu; WAYTHOMAS, C., U.S. Geological Survey, Alaska Volcano Observatory, Alaska, USA, cwaythomas@usgs.gov

Shallow submarine volcanoes pose unique scientific and monitoring challenges. The interaction between water and magma creates violent explosions just below the surface, but the inaccessibility of submerged volcanoes means they are typically not instrumented. This both increases the risk to marine and aviation traffic and leaves the underlying eruption physics poorly understood. The 2016-2017 submarine eruption of Bogoslof volcano, Alaska, is a unique example of a shallow submarine eruption that produced more than 70 explosive events over 9 months, many of which were captured on infrasound, seismic, and hydroacoustic stations. The nearest infrasonic and seismic monitoring stations are on islands more than 50 km from Bogoslof, making detection and characterization of eruptive events challenging. A campaign hydrophone was installed in May of 2017 near the volcano and captured the second half of the eruption sequence. The eruption infrasound is dominated by low frequency energy, and modeling of discrete low frequency signals associated with many of the explosions indicate large magmatic gas bubbles expanding at the water-air interface were responsible for generating these signals. Seismic signals recorded during unrest on nearby islands showed varying T phase amplitudes, which are used as a proxy for source depth. The single hydrophone recorded a wide variety of events, including high-amplitude signals during explosions. Some of the strongest explosions produced clear signals on all three sensors. Travel-time corrected onsets for some of the strongest explosions show a surprising result: infrasound signals arrive first, followed by hydroacoustic and then seismic. These data support the development of a new, top-down explosion model in cases where gas-rich magmas are erupted from shallow submarine vents.

Causes and Consequences of the Columbia River Flood Basalts

Oral Session · Friday · 3:45 PM · 26 April · Puget Sound

Session Chairs: A. Christian Stanciu, YoungHee Kim, Eugene D. Humphreys, Robert W. Clayton.

Origin of the Columbia River Flood Basalts: Geochemical Evidence

WOLFF, J. A., Washington State University, Washington, USA, jawolff@wsu.edu; STEINER, A. R., Washington State University, Washington, USA, arron@wsu.edu; RAMOS, F. C., New Mexico State University, Washington, USA, framos@nmsu.edu

The Columbia River Basalt Group (CRBG) consists of 210,000 km^3 of basalt and basaltic andesite lava. Recent age estimates constrain 99% of this volume to have erupted between ~16.7 and 15.9 Ma for an overall magma flux of 0.26 km^3/y; this value may have been exceeded by x5 during the peak eruptive periods. All CRBG lavas were processed through and evolved in crustal magma system(s); Grande Ronde magmas, in particular, experienced crustal contamination in these plumbing systems. Restoration to primitive compositions approximately doubles the total volume to ~0.5M km^3 of mantle-derived magma, requiring 5M km^3 of mantle source at nominal 10% melting. Hypotheses for the origin of the province fall into two broad groups: dominantly "bottom-up", that is, driven by a deep-seated mantle plume; or "top-down", fundamentally plate-driven. Geochemical support for a bottom-up origin is supplied by the following observations: 1. The basalts are derived from both enriched and depleted mantle, as expected for a rising plume entraining ambient depleted upper mantle. 2. The enriched component has high $^3He/^4He$ and bears isotopic affinities with the sources for some Pacific Ocean island groups. The following observations militate in favor of top-down mechanisms: 3. Highly magnesian melt compositions, which would provide clear evidence for derivation from deep-seated upwelling mantle with anomalously high potential temperature, are absent. 4. All CRB lavas, including those with the least isotopic evidence for crustal contamination, have elevated LILE/HFSE ratios expected from subduction-related processes. 5. In addition to overall LILE enrichment, all CRBG formations exhibit the strong additional Ba enrichment that characterises many mid-late Cenozoic magmatic provinces in the inland western U.S., arguing for a source component that is shared throughout the Cordillera. The geochemical features of the CRBG can best be reconciled by a compromise model, where lithospheric instabilities affected regional upper mantle which was simultaneously being invaded by a rising plume.

Crustal Seismic Structure Beneath the Source Area of the Columbia River Flood Basalt: Bifurcation of the Moho Driven by Lithosphere Delamination

GAO, H., University of Massachusetts Amherst, Massachusetts, USA, haiyinggao@geo.umass.edu

The source area of the ~16 Ma Columbia River flood basalt eruptions originated beneath the Wallowa Mountains in northeast Oregon, with a distinct circular pattern of topographic uplift. Teleseismic receiver functions reveal two layers between latitude 45.5° and 46.5° beneath north of the Wallowas, one at 25 km depth and the other one at 45 km depth. A new full-wave ambient noise tomography model shows a circular anomaly, which is seismically fast in the upper crust and slow from lower crust to uppermost mantle in comparison with the surroundings, coincident with the circular pattern of the Wallowas. The seismic structures suggest that delamination of the Farallon lithosphere initiated the basalt eruptions and consequently modified the lowermost crust, forming a new shallow Moho. The Farallon slab is probably detached directly beneath the Wallowas, while being maintained at the northern edge of the Wallowas, corresponding to the deeper interface.

Wallowa Seismic Anomaly: Lithospheric Delamination and Northward Rollback Triggered by the Yellowstone Plume, Along the Western Edge of Precambrian North America

STANCIU, A., University of Oregon, Oregon, USA, cstanciu@uoregon.edu; HUMPHREYS, E. D., University of Oregon, Oregon, USA, genehumphreys@gmail.com; CLAYTON, R. W., California Institute of Technology, California, USA, clay@gps.caltech.edu

Three main phases of volcanism are generally associated with the 16.7 Ma Columbia River flood basalt event: Steens, Imnaha, and Grande Ronde, with the latter being the largest. Geochemical data shows a time and space progression from south to north, and a change in the geochemical signature likely related to the northward propagation of part of the Yellowstone plume beneath the lithosphere underlying the Blue Mountains terranes and Precambrian North America

(Wolff and Ramos, 2013). We use new and previously acquired teleseismic data from the region of the Columbia River basalts, western Snake River Plain, and Idaho batholith, with an improved seismic tomography algorithm, to characterize the upper mantle seismic structure. Our P and S tomography models better resolve the geometries of the high-velocity anomalies beneath the source region of the Columbia River basalts. In NE Oregon, the Wallowa high-amplitude, high-velocity anomaly extends to depths of ~350 km. This anomaly is separate from the large, slab-like "Siletzia" anomaly located beneath central Idaho, and from a shallower high-velocity anomaly. We image a southward dip for the Wallowa seismic body consistent with a northward delamination triggered by the arrival of the Yellowstone plume at the base of North America at 17 Ma. The south-to-north rollback along the Precambrian margin of North America coincides with the temporal and spatial progression of the Miocene volcanism west of the major continental boundary as defined by the $^{87}Sr/^{86}Sr$ 0.706 isopleth. The northern end of the rollback is located today along the east-west segment of the 0.706 isopleth west of Orofino, Idaho. The separation between the Wallowa and Siletzia upper mantle anomalies and their different amplitudes and geometries are thought to result from their different tectonic histories. While the correlation between the geometries of the mantle anomalies and fundamental lithospheric boundaries is not understood, the lithospheric structure appears to be expressing significant control.

Imaging the Crust and Upper Mantle Beneath Columbia River Flood Basalts With Ambient Seismic Noise, Regional and Teleseismic Events and Converted Phases

CASTELLANOS, J. C., California Institute of Technology, California, USA, jacastil@caltech.edu; CLAYTON, R. W., California Institute of Technology, California, USA, rclayton@gmail.com; KIM, Y., Seoul National University, Seoul, Korea, Republic of, yh1230@gmail.com; HUMPHREYS, E. D., University of Oregon, Oregon, USA, genehumphreys@gmail.com

The dynamics of flood basalt events are not well understood. The latest flood basalt eruption is the Columbia River Basalts (CRB), which initiates of the Yellowstone hotspot track. This event initiated near the southern Oregon state line and propagated north, possibly due to the foundering and sinking of large portions of the lithosphere into the asthenosphere. In the process, geochemical evidence suggest a large crustal magma chamber was established in east-central Oregon. To investigate the link between the CRB and the lithospheric foundering, we use data of from 380 stations, including the newly completed Wallowa experiment, to generate a detailed 3D shear-wave velocity model of the region by inverting waveform data of regional and teleseismic events and surface wave data extracted from the ambient seismic noise. In addition, we use the discrepancy between horizontally and vertically polarized shear wave velocities in the crust to quantify radial anisotropy and illuminate any structural fabric that might be related with the areal extent of the magma chamber and the existence of a descending pluton beneath it. To further refine our model, we use an array-based receiver function (RF) deconvolution method to generate a sharp and coherent image of the structure beneath the CRBs. Our study provides new insights into the role of lithospheric foundering on flood basalt magmatism.

Deep Seismic Crustal Structure Beneath Wallowa, Columbia River Flood Basalt Province

KIM, Y., Seoul National University, Seoul, Korea, Republic of, younghkim@snu.ac.kr; CLAYTON, R. W., California Institute of Technology, California, USA, clay@gps.caltech.edu; KANG, H., Seoul National University, Seoul, Korea, Republic of, hyunsun91@snu.ac.kr; HUMPHREYS, E. D., University of Oregon, Oregon, USA, ghump@uoregon.edu

The Columbia River basalts (CRB) represent the largest volume of flood basalts associated with the Yellowstone hotspot, yet their source appears to be near the Wallowa Mountains, about 500 km north of the projected hotspot track (Hales *et al*., 2005). We extract teleseismic *P*-to-*S* converted phases from the temporary seismic linear-array to constrain deep seismic crustal structure in the source area of CRB eruptions. The dense, 160-km-long, N-S linear array covers an upper-mantle high-velocity anomaly that extends to ~225 km depth (Darold & Humphreys, 2013), and also a post-CRB bullseye pattern of topographic uplift with the Wallowa Mountains at the center. Receiver functions (RFs) and teleseismic migration provide enhanced sensitivity at localized velocity gradients across the lithospheric discontinuities. Preliminary images reveal a clear crust-mantle boundary shown as a single positive-polarity amplitude at 30-35 km depth at the southern and northern end of the seismic line. In the middle of the profile, where the seismic line crosses the bullseye topographic uplift (at 45.5°-46.5° latitude), we observe complex RF waveforms but mostly two positive-polarity amplitudes (at ~25 km and ~45 km depth), suggesting multi-layer structure interlaced with high and low velocities. The complexity in the waveforms indicates structural heterogeneities and/or anisotropy reflecting lithospheric interactions with the deep CRB magmatism.

Building, Using and Validating 3D Geophysical Models

Oral Session · Friday · 8:30 AM · 26 April · Vashon
Session Chairs: Oliver Boyd, William J. Stephenson, Brad Aagaard.

The Western Australia Modeling (WAMo) Project: Geomodel Building and Seismic Validation

SHRAGGE, J. C., Colorado School of Mines, Colorado, USA, jshragge@mines.edu; LUMLEY, D., The University of Texas at Dallas, Texas, USA, david.lumley@utdallas.edu; BOURGET, J., Total E&P, Pau, France, julien.bourget@total.com

A key goal in industry and academic seismic research is overcoming long-standing imaging, inversion and interpretation challenges. One way to address these challenges is to develop a realistic 3D geomodel constrained by local-to-regional geological, petrophysical and seismic data. Such a geomodel can serve as a benchmark for numerical experiments to facilitate understanding of the key factors underlying - and devise novel solutions to - these challenges. We present a case study on the Western Australia Modeling (WAMo) project, which discusses the development of a detailed large-scale 3D geomodel of part of the Northern Carnarvon Basin (NCB) located on Australia's Northwest Shelf. Based on existing regional geological, petrophysical and 3D seismic data, we detail our procedure for: developing the geomodel's tectono-stratigraphic surfaces; populating the intervening volumes with representative geological facies, lithologies and layering as well as complex modular 3D geobodies; and generating petrophysical realizations well matched to borehole observations. The resulting WAMo geomodel is geologically and petrophysically realistic, representative of common NCB short- and long-wavefield features, and is well-suited for high-resolution seismic modeling studies. We validated model realizations using seismic finite-difference modeling and imaging. Near-surface calibration proved to be challenging due to the limited well data within the top 500m below mudline. We addressed this issue by incorporating additional information (geotechnical data, analog studies) and using soft constraints of matching the character of nearby NWS seismic data with modeled shot gathers. Overall, the WAMo geomodel, modeled shot gathers and imaging results reproduce the complex full-wavefield character of NWS marine seismic data. Thus, the WAMo model is well calibrated for use in geologic and geophysical scenario testing to address common NWS seismic imaging, inversion and interpretation challenges.

Progress on Building a USGS National Crustal Model for Seismic Hazard Studies

BOYD, O. S., U.S. Geological Survey, Colorado, USA, olboyd@usgs.gov; SHAH, A. K., U.S. Geological Survey, Colorado, USA, ashah@usgs.gov; SOWERS, T., California State University, Sacramento, California, USA, nichollesowers@csus.edu

The USGS National Crustal Model (NCM) is being developed to assist in the modeling of seismic hazards across the conterminous United States by improving estimates of site response in the USGS National Seismic Hazard Model. Improved hazard assessments may also be used for planning and risk assessments but are not intended for site-specific engineering applications. We are currently in Phase 1 of the project, which covers the western United States west of -100 degrees longitude. In Phase 2, we will complete the NCM in the central and eastern U.S.

The NCM is composed of geophysical attribute-depth profiles on a 1-km grid from which can be extracted metrics needed for ground motion models. Quantities of immediate interest are the time-averaged shear-wave velocity in the upper 30 meters and the depths to 1.0 and 2.5 km/s shear-wave velocity. The NCM has the flexibility to provide additional metrics such as fundamental frequency, a fully frequency-dependent site response function derived from 1D, 2D, or 3D analyses, or 3D geophysical volumes for wavefield simulations. The NCM may also benefit other aspects of seismic hazard analysis including better accounting for path-dependent attenuation and geometric spreading and more accurate estimation of earthquake source properties such as hypocentral location and stress drop.

Each geophysical profile within the NCM is based on subsurface geology, pressure, and temperature coupled with mineral and rock physics theory and porosity and attenuation models. The primary elements used to construct the NCM are: 1) depth to bedrock and basement; 2) 3D geologic framework; 3) petrologic and mineral physics database; 4) 3D temperature model; 5) calibration of a porosity and attenuation model; and 6) validation. These elements make use of a host of geology, borehole, gravity, and seismic datasets and are detailed in separate reports. The first primary element of the NCM is published as a USGS Open-File Report. Elements 2 through 4 are in review, and the methods for calibration and validation are in development.

Validation of Seismic Crustal and Mantle Models of the Contiguous U.S.

CHEN, M., Michigan State University, Michigan, USA, chenmi22@msu.edu; ZHOU, T., Michigan State University, Michigan, USA, zhouton3@msu.edu; XI, Z., Michigan State University, Michigan, USA, xiziyi@msu.edu

Since the completion of the Transportable Array deployment across the contiguous US, there have been various seismic models with improved image resolution inferred for the crust and (mostly) mantle beneath US (*e.g.*, DNA13, US-SL-2014, and US.2016). However, discrepancies exist between these models due to the differences in both data sets and tomographic methods. In order to build a unified seismic model for the contiguous US, it is an essential (often missing) step to validate these models and to find out which model achieves the optimal predictability, *i.e.*, best predicting complex wave propagation phenomena at higher frequencies. In this study we systematically compared a total of eight (regional and global) models publically available through the IRIS EMC-EarthModels, in terms of the waveform fitting between data and synthetics. The criteria for model predictive capability include waveform similarities and travel time misfits for different phases (P, S, and surface waves) for different epicentral distances using USArray stations. The synthetics are calculated based on the spectral-element method with grid spacing of about 5 km in the crust and 10 km in the mantle within a model region of 36 by 48 degrees, which includes the western, central, and part of eastern US. Both synthetics and data are filtered between 10 and 40 seconds and low signal-to-noise-ratio (SNR < 10) data traces are excluded from the comparison. All the 3-D models without good crustal imaging resolution are implemented in the simulation region with CRUST1.0 embedded except US.2016, which instead is combined with model AK135 for the mantle below the depth of 150 km. The results of the model predictive capabilities will be presented along with the proposed solution toward a unified model of the contiguous US.

Evaluation of the USGS 3D Seismic Model of the San Francisco Bay Area From Moderate Earthquake Waveform Modeling

RODGERS, A. J., Lawrence Livermore National Laboratory, California, USA, rodgers7@llnl.gov; KOTTKE, A. R., Pacific Gas and Electric Company, California, USA, arkk@pge.com; ABRAHAMSON, N., University of California, Berkeley, California, USA, abrahamson@berkeley.edu

The United States Geological Survey (USGS) three-dimensional (3D) model of the geology and seismic material properties in San Francisco Bay Area (SFBA) has been used for ground motion simulations of past large and moderate earthquakes as well as possible damaging scenario events (including simulations to 5 Hz and higher). Simulated intensities reveal significant variability caused by known geologic structure. In order to evaluate the USGS 3D model, we are modeling waveforms from recent moderate earthquakes. These events are appealing because they are well recorded by permanent seismic stations in the region, especially as station coverage has improved in the last few years, and permit sampling diverse propagation paths. We use routine source parameters: double-difference locations (Waldhauser, 2009) and point double couple focal mechanisms or moment tensors (Dreger and Romanowicz, 1994). We evaluate source parameters by modeling waveforms at the closest stations (within 10 km). This helps identify candidate events and problems with source parameters. We have modeled a few well-characterized events for paths sampling the broader SFBA to investigate path-dependent performance of simulated motions using the USGS 3D model and an average plane-layered (one-dimensional, 1D) model of the region. Motions are simulated with the SW4 finite difference code resolving frequencies up to 5 Hz and including surface topography with the 3D model. We have found that 3D effects are clearly seen, especially for longer paths (> 30 km) even at relatively low-frequencies (< 0.5 Hz). Matching waveforms is difficult for frequencies above about 0.5 Hz because of large phase errors that complicate waveform alignment. We are quantifying goodness-of-fit using several metrics including delay times, correlation coefficient, duration, peak motions and spectral measurements. Maps of path-specific goodness-of-fit can inform which areas in the model need improvement.

Combining Geotechnical and Geophysical Data to Build a 3D Model of the Var Valley, Nice (France)

OPHÉLIE, R., CEREMA, Sophia Antipolis, France, ophelie.rohmer@cerema.fr; BERTRAND, E., CEREMA, Sophia Antipolis, France, etienne.bertrand@cerema.fr; MERCERAT, D., CEREMA, Sophia-Antipolis, France, diego.mercerat@cerema.fr; LANGLAUDE, P., CEREMA, Sophia Antipolis, France, philippe.langalude@cerema.fr; RÉGNIER, J., CEREMA, Sophia-Antipolis, France, julie.regnier@cerema.fr

In seismic risk studies, the assessment of lithologic site effect is based on an accurate knowledge of mechanical properties and geometry of superficial geological formations. Therefore, we currently work on improving a 3D subsurface model of the lower Var valley, an economically developing zone of the city of Nice, southeastern France.

Using punctual and ambient vibration array measurements, the alluvial deposits of the lower Var valley close to Nice (France) are investigated. In particular, the S waves velocity profile and the bedrock depth are estimated. These data are included together with geotechnical observations (more than 200 boreholes though only few of them reaching the bedrock) in a commercial software (GDM, BRGM) allowing to model, represent and visualize geoscientific data and geological models in 3D. From the geophysical data, the fundamental resonance frequency pointed on H/V curves indicates the basin/bedrock interface with the help of the well known fo=Vs/4H relationship . The contribution of these constraints in the 3D model are analyzed by comparing the model derived exclusively from the geophysical data analysis and the one derived from the borehole database. The result shows that the nature of the bedrock, found between 20 m and 80 m depth underneath the recent alluvial sediments is laterally varying. Furthermore, the average S wave velocity in these deposits is found to be close to 410 m/s.

The 3D model of the lower Var valley will be used to simulate strong ground motions in order to evaluate and prevent the seismic risk in the area in the frame of the Ritmica project supported by Université Côte d'Azur through one of its JEDI transdisciplinary programs.

Structural Seismology: From Crust to Core

Oral Session · Friday · 10:45 AM · 26 April · Vashon

Session Chairs: Vedran Lekic, Jessica C. E. Irving, Andrew J. Schaeffer, Meghan S. Miller.

Seismic Images of the North American Upper Mantle From S-to-P Converted Waves

MOONEY, W. D., U.S. Geological Survey, California, USA, mooney@usgs.gov; KIND, R., GFZ German Research Centre for Geosciences, Potsdam, Germany, kind@gfz-potsdam.de; YUAN, X., GFZ German Research Centre for Geosciences, Potsdam, Germany, yuan@gfz-potsdam.de

We present new seismic images of the key structural elements of the upper mantle beneath the continuous USA and southern Canada. Our method is based on the well-established S-to-P seismic converted wave technique, but with the important difference that we do not used seismic deconvolution, as is conventionally done. We avoid deconvolution because this processing step can introduce strong artifacts into the resultant seismic images. We present comparisons of our preferred plain stacking method versus deconvolution methods. Our imaging results are significantly different from previous studies that use deconvolution. We image the lithosphere-asthenosphere boundary (LAB), but without a mid-lithospheric discontinuity (MLD). This suggests that the MLD may be an artifact introduced by seismic deconvolution. Other prominent features are the Lehmann discontinuity and the 410-discontinuity with a low velocity layer above it. Two newly-discovered features in our seismic images are: (1) a northwest dipping boundary in the uppermost mantle beneath the Archean Superior craton that we interpret as early Proterozoic subducted oceanic lithosphere, and (2) a southeast dipping boundary just below the Moho beneath eastern Texas that we interpret as the Paleozoic suture between Laurentia and Gondwana, marking the formation of Pangea.

Teleseismic Traveltime Tomography of the Crust and Upper Mantle Beneath the Southern U.S. Continental Margin

NETTO, A., Baylor University, Texas, USA, alden_netto1@baylor.edu

The southern U.S. continental margin records a rich tectonic history spanning over 1.2 Ga, including two complete Wilson cycles. However, due to a thick sediment cover, the paucity of significant local seismicity, and sparse instrumentation in place to record seismicity, details of the tectonomagmatic evolution of this passive margin remain poorly understood. These issues include the amount, pattern, and direction of continental extension, the influence of pre-existing tectonic features during rifting, and the location and extent of allochthonous terranes and their associated suture zones. The advent of USArray's Transportable Array, a temporary network of seismic stations, offers the unique opportunity to address these issues, which are vital to better understand the lithospheric structure and tectonic history of this scientifically and economically significant continental margin. This study incorporates broadband seismic data from 1,640 stations collected during the interval 2008-2017. Arrival times of direct P and S phases are picked, using a multi-channel cross-correlation method, for teleseismic earthquakes with magnitudes > 5.0 located at epicentral distances of 30° to 90° and PKIKP phases from earthquakes with magnitudes > 6.0 at epicentral distances of 125°-180°. An iterated, nonlinear solution technique is used in which raypaths and travel times are re-computed and Frechet derivatives are recalculated between inversions.

Imaging Terranes and Structure of the Southern South Island, New Zealand, With Joint Earthquake Travel-Time and Ambient-Noise Tomography

EBERHART-PHILLIPS, D., GNS Science, University of California, Davis, Dunedin North, New Zealand, eberhartphillips@ucdavis.edu; UPTON, P., GNS Science, Lower Hutt, New Zealand, p.upton@gns.cri.nz; REYNERS, M., GNS Science, Lower Hutt, New Zealand, m.reyners@gns.cri.nz; FRY, B., GNS Science, Lower Hutt, New Zealand, b.fry@gns.cri.nz; BOURGUIGNON, S., GNS Science, Lower Hutt, New Zealand, s.bourguignon@gns.cri.nz

The South Island lithosphere consists of multiple terranes that were amalgamated during previous periods of subduction. Currently oblique collision produces major faulting, crustal thickening and subduction along the western South Island, with decreased deformation and seismicity towards the east. Local earthquake travel-time tomography has provided South Island seismic structure, and illustrated most transitions between terranes, but the sparse seismicity only allows coarse imaging in some key areas. In this study, we combine surface wave group velocity with the travel-time data to increase the resolution. We use ambient noise data from the permanent network and 47 portable broadband stations. This enhances spatial resolution in low seismicity areas, and improves resolution of shallow features. The Haast schist has distinct variation in seismic properties across the region, from a zone of ductile deformation and crustal thickening in the western South Island to a thick dry unit in the east. Although the eastern seismicity is sparse, there are numerous distributed potentially active fault structures, as well as basins which include active faults. The Matai terrane and Median batholith, which acted as backstops to Cretaceous accretion and schist development, are shown in the eastern South Island. In southwestern South Island, there is a sharp change in seismic properties and structure where the Fiordland block of Median batholith was emplaced.

Receiver Function HV Ratio: A New Single Station Seismic Measurement for Imaging Crustal Structure

CHONG, J., Institute of Geodesy and Geophysics, Chinese Academy of Sciences, Wuhan, China, jiajunchong@whigg.ac.cn; NI, S., Institute of Geodesy and Geophysics, Chinese Academy of Sciences, Wuha, China, sdni@whigg.ac.cn; CHU, R., Institute of Geodesy and Geophysics, Chinese Academy of Sciences, Wuhan, China, chur@asch.whigg.ac.cn

We have developed a single station seimic measurement with localized sensitivity, which can be applied to image curstal structure of extraterrestrial bodies with a single seismic station.

As we know, receiver function (RF) is a single station seismic meaurement with lcoalized sensitivity, however it may fail to constrain the absolute shear wave velocity, thus joint inversion of RF and surface wave dispersion are usually suggested. The newly proposed Receiver function HV ratio (RFHV), which takes advantage of the amplitude ratio between the radial and vertical receiver functions, is able to constrain the shear-wave velocity, hence, make it possible to constrain the crustal structure with a single station. A joint inversion of RF and RFHV has been developed, and both synthetic tests and real data application proved the feasibility of the joint inversion. The method has been applied to a linear array which is a part of the dense seismic array of ChinArray program in SE Tibet during the time period from August 2011 to August 2012 in SE Tibet (ChinArray-Himalaya, 2011). The crustal structure obtained with this newly developed technique is consistent with previous study with RF and surface wave dispersion in major features, such as the crustal low velocity layer and low velocity feature of the basins in the SE Tibet.

This method can be applied to image curstal structure of extraterrestrial bodies with a single seismic station or Earth structure with sparse network or dense array. It can also be combined with other single station measurements such as Rayleigh wave ZH ratio to improve resolution of the structure beneath the seismic station.

Reference:

ChinArray-Himalaya. 2011. China Seismic Array waveform data of Himalaya Project. Institute of Geophysics, China Earthquake Administration. doi:10.12001/ChinArray.Data. Himalaya.

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Direct Observations of Surface-Wave Eigenfunctions at the Homestake 3D Array

MEYERS, P., University of Melbourne, Parkville, Australia, pat.meyers@unimelb.edu.au; TSAI, V. C., California Institute of Technology, California, USA, tsai@caltech.edu; BOWDEN, D. C., ETH Zurich, Zurich, Switzerland, daniel.bowden@erdw.ethz.ch; PRESTEGARD, T., University of Minnesota, Minnesota, USA, tprestegard@gmail.com; MANDIC, V., University of Minnesota, Minnesota, USA, vuk@umn.edu; PAVLIS, G. L., University of Indiana, Indiana, USA, pavlis@indiana.edu; CATON, R., University of Indiana, Indiana, USA, rccaton@umail.iu.edu

Ever since 1885, when Lord Rayleigh first predicted the existence of waves that travel along a free surface, observations interpreted to be surface waves have been remarkably useful for helping determine Earth structure and earthquake source properties. Yet despite the theory for both Rayleigh and Love waves being well accepted, and the theoretical predictions accurately matching observations, the observation of their quantifiable decay with depth has never been measured in the Earth's crust. The primary difficulty of confirming this decay of motion with depth is that nearly all seismometers are placed at or near the Earth's surface, or in isolated borehole installations. In this work, we address this gap in observations by making direct observations of both Rayleigh-wave and Love-wave eigenfunction amplitudes over a range of depths, using data collected at the three-dimensional Homestake Array for a suite of nearby mine blasts. Observations of amplitudes over a range of frequencies from 0.4-1.2 Hz are consistent with theoretical eigenfunction predictions, with clear exponential decay of amplitudes with depth, and a reversal in sign of the radial-component Rayleigh-wave eigenfunction at large depths, as predicted for fundamental-mode Rayleigh waves. Minor discrepancies between the observed eigenfunctions and those predicted using estimates of the local velocity structure suggest that the observed eigenfunctions could be used to improve the velocity model. Our results confirm that both Rayleigh and Love waves have the depth dependence that they have long been assumed to have. This is an important direct validation of a classic theoretical result in geophysics, and provides new observational evidence that classical seismological surface-wave theory can be used to accurately infer properties of Earth structure and earthquake sources.

State of Stress and Strain in the Crust and Implications for Fault Slip Based on Observational, Numerical and Experimental Analysis

Oral Session · Friday · 1:30 PM · 26 April · Vashon

Session Chairs: Niloufar Abolfathian, Patricia Martinez-Garzon, Thomas H. W. Goebel.

Heterogeneity of Shallow Crustal Stress Estimated From Borehole Breakouts and Local Earthquake Focal Mechanism Inversions in the Los Angeles Basin

LUTTRELL, K., Louisiana State University, Louisiana, USA, kluttrell@lsu.edu; HARDEBECK, J., U.S. Geological Survey, California, USA, jhardebeck@usgs.gov

Many models of stress state rely heavily on the observations of stress field orientation provided by earthquake focal mechanisms and borehole breakouts to constrain their estimates. However, these two types of observations necessarily sample different locations within the 3-D crust, and it is unclear how they should be jointly interpreted and incorporated into ongoing modeling efforts. The goal of this research is to constrain the conditions over which borehole breakouts and earthquake focal mechanisms indicate consistent stress field orientations. We consider 60 published observations of SHmax from borehole breakouts throughout the Los Angeles basin area. We identified subsets of earthquakes nearby each borehole, using a range of maximum depth criteria and maximum distance criteria, and inverted each subset of earthquake focal mechanisms for the orientation of the local stress state. Focal mechanisms in each subset are derived from the YSH catalog [*Yang et al.*, 2012] and independently inverted using the method of *Michael* [1984, 1987]. The nodal plane with the greater instability in the stress field is selected as the preferred plane, and the uncertainty is determined by bootstrap resampling. We then compared the SHmax from each local subset with SHmax from each borehole to identify the optimal length scale of earthquakes consistent with borehole observations. Preliminary results suggest stress field orientation is most consistent when considering earthquakes that are shallow (< 5 km depth) and nearby the borehole breakout (< 10 km horizontal distance).

Spatial variation in misfit between subregions suggests that underlying crustal structure may mitigate the characteristic length scale of stress field heterogeneity within the region. Overall, the results indicate that stress orientations from borehole breakouts are primarily representative of very nearfield stresses and should not in general be interpreted to represent the broader tectonic crustal stresses.

Influence of Coseismic and Postseismic Stress Induced by the 2011 M9.0 Tohoku-Oki Earthquake on Regional Medium Properties and Seismicity

HONG, T., Yonsei University, Seoul, Korea, Republic of, tkhong@yonsei.ac.kr; LEE, J., Yonsei University, Seoul, Korea, Republic of, aqualung@yonsei.ac.kr; KIM, I., Yonsei University, Seoul, Korea, Republic of, ilgoo@yonsei.ac.kr; PARK, S., Yonsei University, Seoul, Korea, Republic of, seongjunpark@yonsei.ac.kr; KIM, W., Gyeongsang National University, Jinju, Korea, Republic of, wookim@gnu.ac.kr

Megathrust earthquakes produce large coseismic and postseismic lithospheric displacements that induce changes in static stress and medium properties in regional distances. The 2011 M9.0 Tohoku-Oki megathrust earthquakes produced large displacements up to regional distances. The lithospheric displacements directing to the epicenter on the convergent plate boundary developed transient uniaxial tension field over the backarc lithospheres. We observed Vp/Vs changes between -0.0458 and 0.0422 in the upper crust of Japanese islands. The medium-property changes appeared to recover to the original state in a couple of years to a decade. The upper crust presents complicated deformation in short distances from the epicenter. The Vp/Vs changes display a 2 theta azimuthal variation, suggesting azimuthal-anisotropic deformation. The lower crust of the Korean Peninsula in distances of ~1300 km displayed coseismic velocity changes of 3 % after the megathrust earthquake, which recovered gradually with time for several years. A series of moderate-sized earthquakes occurred as a consequence of medium response to the temporal evolution of stress field.

Spectral and Temporal Evolution of Surface Creep Events in Parkfield, 1990-Present

MENCIN, D., UNAVCO, Colorado, USA, mencin@unavco.org; BILHAM, R., University of Colorado Boulder, Colorado, USA, roger.bilham@colorado.edu; HODGKINSON, K., UNAVCO, Colorado, USA, hodgkinson@unavco.org; MATTIOLI, G., UNAVCO, Colorado, USA, mattioli@unavco.org

Creepmeters and strainmeters permit the depth evolution of shallow creep events to be quantified as they propagate along strike. To complete describe a transient episodic creep event requires constraints on depth, area, and velocity and the evolution of all these three parameters with time. In recent work we have found it possible to define the properties of an aseismic slip event using just three parameters - an initiation time (t0), a time constant (w) and a slip velocity (vp). This combination, constrained from observations of multiple events at known locations and invoking simple assumptions about planar fault geometry, allows for the characterization of static and dynamic spatial-temporal behavior of creep events. We develop a quasi-dynamic model and code to exploit this and to apply it successfully to observed creep events. Detection of creep events has hitherto been accomplished by visual inspection. Our new method permits us to use these parameters and machine learning methods to detect creep events. Our previous investigations have been confined to studies where creep events were simultaneously observed on strainmeters and creepmeters allowing for constraints on area and average depth, here we apply this analysis to using surface creep data alone. We demonstrate the method on a catalog of ~6000 creep events observed on three creepmeters (XMM1,XMD1,XVA1), located near Parkfield on the creeping section of the San Andreas Fault, between 1984-2018 including the September 28, 2004, M6.0 Parkfield event. We show that while the total creep rate on creepmeters near Parkfield is similar before and after the 2004 earthquake (excluding a four year period of afterslip), that there is a evolution and change of the dynamic behaviour of creep events, in particular the time constant (w), during the observation period.

Nonlinear Rheology of the Shallow Crust Inferred From Multi-Year Borehole Strain Time Series

ROELOFFS, E., U.S. Geological Survey, Washington, USA, evelynr@usgs.gov

The largest strains that borehole strainmeters record are caused by slow creep of the formation around the borehole and grouted-in strainmeter. These strains, which are amplified by the stress concentration around the borehole, dwarf most signals of tectonic or magmatic origin, so are usually removed and ignored. However, these long-term strains can be interpreted to characterize the nonlinear rheology of the shallow crust at the borehole depths of 150-200 m. Long-term (10-13 year) records from four-component Gladwin Tensor Strainmeters (GTSMs) of the Earthscope Plate Boundary Observatory (PBO) yield horizontal strain tensors whose principal strain rates decrease with time toward non-zero steady rates, often with superimposed seasonal signals. After 10-13 years of operation, typical strain rates are several microstrain/year, one to two orders of magnitude higher than strain rates inferred from GNSS. The azimuths of the principal strains and maximum shear are approximately constant in time except for seasonal variation. For a large subset of the PBO strainmeters, the long-term strains can be closely fit by the sum of a secular strain rate plus a fractional-power dependence on time. Such a time history is consistent with a fractional Maxwell rheology, a generalization of a Maxwell material whose viscous component is replaced by a component in which stress is a fractional derivative of strain rate. This characterization can provide rock mass parameters of interest to geotechnical engineers who are concerned with long-term stability of underground structures such as tunnels or fractures in unconventional hydrocarbon reservoirs. The nonlinear, inelastic rheology is not apparent in strain recordings of earth tides, but may influence measured time histories of deformation in response to large tectonic stress steps, such as those imposed by earthquakes, and therefore may need to be taken into account in interpreting post-seismic geodetic information.

Stress From Plate Bending in the Nankai Trough

HARDEBECK, J., U.S. Geological Survey, California, USA, jhardebeck@usgs.gov; LOVELESS, J. P., Smith College, Massachusetts, USA, jloveles@smith.edu

Earthquakes in the crust of the downgoing plate of a subduction zone can be destructive, for example the 2018 M7.0 Anchorage, 2017 M7.1 Puebla, and 2001 M6.8 Nisqually earthquakes. These intraplate events often have normal-faulting mechanisms associated with stresses from bending of the downgoing plate. Prior studies have inverted earthquake moment tensors for stress orientations in the downgoing plate, and interpreted the stress orientations in terms of plate bending or unbending. However, this approach can't separate the plate bending stresses from the stresses associated with the loading of the coupled plate interface. In this study, we isolate the intraplate bending stress by modeling the total stress as a combination of the intraplate stress and the stress due to loading. We compute the loading stress from a geodetically-determined model of plate coupling. We then invert for the intraplate stress such that the total stress best fits the moment tensors of earthquakes occurring in the subducting crust. The inversion constrains the orientations and the sign of the principal stress axes of the intraplate stress. The absolute stress amplitudes can be estimated relative to the amplitude of the modeled loading stress, given some assumptions. We focus on the Nankai Trough because of the abundance of well-recorded earthquakes in the crust of the downgoing plate, and the existence of dense geodetic data to constrain the interface coupling. We find that most of the downgoing plate is in along-strike tension, consistent with prior results. The down-dip stress, in contrast, shows alternating zones of tension and compression. We find a statistically significant correlation between the intraplate absolute stress and the plate curvature, in both the along-strike and down-dip directions. The sign of the correlation is consistent with the intraplate stress being controlled by the bending of an initially-planar plate to its current curvature. These results suggest that plate geometry can be used to infer the stresses driving intraplate earthquakes.

Post-Large Earthquake Seismic Activities Mediated by Aseismic Deformation Processes

GUALANDI, A., Jet Propulsion Laboratory, California Institute of Technology, California, USA, adriano.geolandi@gmail.com; LIU, Z., Jet Propulsion Laboratory, California Institute of Technology, California, USA, zhen.liu@jpl.nasa.gov; ROLLINS, C., Michigan State University, Michigan, USA, john.c.rollins@gmail.com

Two aseismic deformation processes are commonly invoked to explain the transient geodetic surface displacements that follow a major earthquake: afterslip and viscoelastic relaxation. Both induce time dependent stress variations in the crust, potentially affecting aftershock occurrence. However, the two mechanisms' relative impacts on crustal deformation and seismicity remain unclear, and discriminating between the two is challenging. We achieve this result by applying a variational Bayesian Independent Component Analysis to the position time series from 125 GPS stations following the Mw 7.2 El Mayor-Cucapah earthquake, 2010 (Mexico). Among the retrieved Independent Components, two are clearly related to post-seismic activity: one is characterized by long relaxation time and broad spatial signature, while the other is concentrated in space and time near the mainshock and largest aftershock events. This separation helps to resolve the modeling tradeoff between these contributions. We further compare our geodetic results with the seismic activity that followed the mainshock. We find not only that, for the case of the 2010 Mw 7.2 El Mayor-Cucapah (EMC) earthquake, afterslip drove clustered seismicity after the earthquake, but also that long-range earthquake interactions were modulated by viscoelastic relaxation at large scales in space (>5 times the fault rupture length) and time (>7 years). This has important implications for the study of the "seismic cycle" and for seismic hazard estimation, since post-seismic deformation related to a single Mw 7.2 earthquake affects interseismic velocities for more than a decade.

Assimilating Stress and Strain in an Energy-Based PSHA Workflow

ZIEBARTH, M. J., GFZ German Research Centre for Geosciences, Potsdam, Germany, ziebarth@gfz-potsdam.de; HEIDBACH, O., GFZ German Research Centre for Geosciences, Potsdam, Germany, oliver.heidbach@gfz-potsdam.de; COTTON, F., GFZ German Research Centre for Geosciences, Potsdam, Germany, fabrice.cotton@gfz-potsdam.de; ANDERSON, J. G., Nevada Seismological Laboratory, University of Nevada Reno, Nevada, USA, jga@unr.edu; WEATHERILL, G., GFZ German Research Centre for Geosciences, Potsdam, Germany, graeme.weatherill@gfz-potsdam.de; VON SPECHT, S., GFZ German Research Centre for Geosciences, Potsdam, Germany, sebastian.specht@gfz-potsdam.de

The advent of data science augurs complementing catalog-based probabilistic seismic hazard assessment (PSHA) with hitherto unused but relevant geophysical data. Especially in regions of low seismicity, where catalog data acquisition rates are limited by occurrence rates, additional data sources may provide crucial information.

Stress and strain, quantifying the driving physics of seismicity, are obvious candidates to incorporate into seismic hazard assessment. With rapidly growing geodetic data sets and stress data assimilation efforts, their data set quality may rapidly increase in near future.

We demonstrate how energy conservation, elasticity, and the assumption of stationarity can be used to integrate stress and strain data into the existing PSHA workflow, yielding boundary conditions on the magnitude-frequency distribution. The resulting energy-based seismic area source model constitutes a component of an energy-based PSHA framework.

The workflow is demonstrated using the San Andreas Fault as a well-researched and tectonically homogeneous test region. Strengths, limitations, and methods for the assimilation of different geospatial data sets are discussed. Specifically, this includes data processing techniques for the homogenization of differently- sampled strain rate and stress data sets.

Spatial Variations of Stress Patterns Near the South Central Transverse Ranges in Southern California

ABOLFATHIAN, N., University of Southern California, California, USA, niloufar.abolfathian@gmail.com; MARTINEZ-GARZON, P., GFZ German Research Centre for Geosciences, Potsdam, Germany, patricia@gfz-potsdam.de; BEN-ZION, Y., University of Southern California, California, USA, benzion@usc.edu

We analyze high-resolution spatial variations of the stress patterns in South Central Transverse Ranges (SCTR) in southern California and their correlation with topography and the fault system in the area. The analysis is based on the refined stress inversion methodology employing a declustered focal mechanism catalog for the years 1981-2017. The stress inversion provides the orientation of the three principal stress axis, from which we derive the maximum horizontal compressive stress direction (SHmax) and the stress ratio parameter $R = (\sigma 1 - \sigma 2)/(\sigma 1 - \sigma 3)$. The obtained spatial distribution of stress parameters is generally in agreement with the tectonic setting, showing strike-slip faulting type. The SHmax orientation is generally to the north with some variations toward NEN in the eastern and western sections of the SCTR. The SHmax orientation shows a significant clockwise rotation of about ~23° with depth near the Crafton Hills (CH). Over regional scale, the stress ratios R vary from transtensional stress regime in the east towards transpressional in the west. Sharp changes of R are observed near CH with significant transtensional components, and near Cajon Pass and San Gorgonio Pass with transpressional components. The stress patterns estimated from aftershocks amplify the sharp changes in stress ratios relative to those seen with the background seismicity. The seismicity distribution suggests significant variations of seismogenic depth in the region between the San Andreas Fault (SAF) and San Jacinto Fault (SJF). Initial results from separate analyses of focal mechanisms in sub-regions with different seismogenic thicknesses indicate changes of stress patterns between the eastern part of the SAF, the western part of the SJF, and the region between them, where the stress pattern no longer follows the regional stress variations.

Surface-Wave Induced Dynamic Stresses on Arbitrary Faults in a Layered Earth

ROESLER, B., Northwestern University, Illinois, USA, boris@earth.northwestern.edu; VAN DER LEE, S., Northwestern University, Illinois, USA, suzan@northwestern.edu; CHAO, K., Northwestern University, Illinois, USA, kchao@northwestern.edu

Propagating Rayleigh and Love waves from large earthquakes generate considerable dynamic stresses in the Earth's crust, even in the far field. These stresses occasionally exceed empirical triggering thresholds on faults that are presumed to be critically stressed. Both volumetric and deviatoric stress variations in these dynamic stress tensors can affect the normal stress on a given fault, while shear stress variations on the fault are a result from transient deviatoric stresses from both types of surface waves, which often act on the fault at the same time.

Reports of potentially dynamically triggered tremor or earthquakes on a given fault are frequently accompanied by estimates of dynamic stresses on this fault. However, these reports do either not consider vertical variations in surface-wave displacements or assume a homogeneous crust. Estimates of the variations of dynamic stresses with back-azimuth typically do not include the effects of radiation patterns controlled by varying source mechanisms and depths.

To complement these estimates we calculate full dynamic stress tensors from 3-D and 3-C surface-wave displacement fields for a realistic Earth model. We test our approach on simulated data from the September 8, 2017, Mw 8.2 earthquake near the coast of Chiapas in Mexico. We quantify and visualize spatiotemporal variations in the isotropic stresses and principal stresses from the deviatoric stress tensors.

We then project these stresses onto the San Andreas fault and observe that 1) stresses generated at mid- and lower-crustal depths, where triggered events occur, are as large as and occasionally larger than those at the surface, 2) the maximum dynamic stress at these depths is reached at different times than peak ground velocity at the surface, which is used as a proxy for stress, 3) Combined stresses from simultaneous Rayleigh and Love waves create complex dynamic stress histories, 4) The off-shore Chiapas earthquake's Love waves generated larger stresses on the San Andreas fault than its Rayleigh waves.

Contemporary Stress and Strain Field Data in the Mediterranean From Surface to Depth: Resolution, Correlations and Contradictions

MARTINEZ-GARZON, P., GFZ German Research Centre for Geosciences, Potsdam, Germany, patricia@gfz-potsdam.de; HEIDBACH, O., GFZ German Research Centre for Geosciences, Potsdam, Germany, heidbach@gfz-potsdam.de; BOHNHOFF, M., Helmholtz Centre GFZ Potsdam, Potsdam, Germany, bohnhoff@gfz-potsdam.de

Mapping the contemporary stress field orientation in the Mediterranean can provide fundamental insights on the complexity of plate tectonic forces in this region at different depths. Despite increased data availability and methodological improvements, most recent stress field characterization across the entire Mediterranean dates back to 1995. We consistently map stress field orientations and related parameters for the Mediterranean utilizing all focal mechanisms from the World Stress Map database release 2016. Main goals are (1) to resolve the regional stress field orientation at unprecedented finer scale, (2) to evaluate the performance of our stress inversion methodology in one of the most tectonically complex regions on Earth, (3) to compare different types of stress and strain observations covering the entire depth range from surface (*e.g.* GPS data) to mantle (*e.g.* shear wave splitting). The obtained stress distributions generally capture correctly the main seismotectonic features of each area, including tectonically complex settings such as the Alpine Orogeny or the Ionian Sea. S_{HMax} and stress regimes tend to be depth-uniform within uncertainties, but larger stress heterogeneity is resolved for the upper 10 km. Both coseismic elastic strain field from potency tensors and strain field from GPS data are highly consistent with the stress field orientation, indicating that stress and strain maintain a linear relationship in this area and that inelastic strain release is consistent with the elastic stress or strain accumulation. The Italian Peninsula displays the largest discrepancies between these parameters, potentially indicating stress/strain changes with depth, a prominent role of aseismic deformation, and/or a non-linear relation between stress and strain. Increasing discrepancy between stress field orientation and fast shear wave propagation is found from eastern (sub-parallel) to western (sub-perpendicular) Mediterranean, eventually indicating different causes of anisotropy. Implications of these results with respect to seismic hazard will be discussed.

Advances, Developments and Future Research into Seismicity in Natural and Anthropogenic Fluid-Driven Environments

Poster Session · Friday · 26 April · Fifth Avenue

A Wastewater Disposal Reservoir Sensitive to Teleseismic Waves

BARBOUR, A. J., U.S. Geological Survey, California, USA, abarbour@usgs.gov

Faults in areas of injection-induced seismicity, like central Oklahoma, may have an enhanced sensitivity to dynamic triggering because only relatively small changes in stress or pore pressure are needed (van der Elst, *et al.*, 2013). An understanding of how fluid-pressures in the disposal reservoir and the underlying basement rock respond to dynamic strains from seismic waves would help confirm or disprove this idea. While it is now common to find observations of seismically induced water-level oscillations in aquifers or reservoirs across the globe, in Oklahoma we have a limited understanding of the response of the Arbuckle Group – the principal wastewater disposal reservoir. Since April 2017 the USGS has been monitoring fluid-levels in a deep well with high frequency sampling (1/4 Hz), giving a continuous record of fluid-pressure changes in the Arbuckle. We observe a clear response to dynamic strains from the passage of long period surface waves, with peak dynamic fluid-levels appearing to be proportional to the magnitude and distance from the source; there is always a response to Rayleigh waves, as we expect. Radial flow is the expected flow regime because the Arbuckle is thought to be a confined, laterally extensive reservoir, but the seismic response shows evidence of a mixed flow regime modified by hydraulically conductive features. In particular, the transfer function between Arbuckle fluid pressures and broadband velocity seismograms at the wellhead can be modeled at short periods with radial flow models (*e.g.*, Cooper, *et al.*, 1965), but diverges from this at much longer periods, where poroelastic coupling between deformation and fluid flow is strongest. There is also a response to Love waves in some cases, which is unexpected because isotropic, poroelastic media are insensitive to shear stresses. These data suggest an influential role for hydraulically conductive fractures in controlling the hydraulic diffusivity of the reservoir, though it is presently unclear how reservoir permeability responds to strong shaking from local induced earthquakes.

Evolution of Faulting Induced by Deep Fluid Injection, Paradox Valley, Colorado

DENLINGER, R. P., U.S. Geological Survey, Washington, USA, roger@usgs.gov; O'CONNELL, D. R., TetraTech, Inc., Colorado, USA, dan.oconnell@tetratech.com

High pressure fluid injection into a sub-horizontal confined aquifer at 4.3 km to 4.6 km depth induced > 7000 recorded earthquakes between 1991 and 2012 within once seismically-quiescent Paradox Valley in Colorado, with magnitudes ranging up to Mw 3.9. Alignment of earthquake epicenters define trends of nine vertical fault zones near the well that offset left-stepping normal faults of the Wray-Mesa fault system within the Paradox Valley structural basin. Over time earthquake hypocenters expand laterally away from the well and vertically above and below the pressurized aquifer with continued fluid injection. Hypocenters, rakes, and strikes of 2061 well constrained focal mechanisms show that most induced earthquakes occur on steeply-dipping dextral strike-slip faults that begin at acute angles to the strikes of the fault zones, then evolve into faults nearly aligned with the fault zones as deformation continues. A laboratory experiment with similar boundary conditions indicates that these faults are Riedel shears formed to accommodate fault slip. A fully coupled poroelastic analysis of stress from fluid injection shows that Riedel shears first occur when the effective stresses exceeding Coulomb failure conditions are between 0.35 MPa and 0.4 MPa. As they form, the Riedel shear faults affect the local stress state to produce anastomosing fault zone structures that coalesce over time to form horizontally and vertically expanding vertical fault zones. The three largest induced earthquake ruptures occurred along three of the nine vertical fault zones. Among all developing fault zones, seismicity rates were highest in the first decade of injection as fault zones developed, and then substantially declined with time in the second decade of injection.

Rupture Model of the 2016 M5.8 Pawnee Earthquake From Regional and Teleseismic Waveforms: Potential Influence of Pore Pressure Perturbations on Rupture Dynamics

MOSCHETTI, M. P., U.S. Geological Survey, Colorado, USA, mmoschetti@usgs.gov; HARTZELL, S., U.S. Geological Survey, Colorado, USA, shartzell@usgs.gov; HERRMANN, R. B., Saint Louis University, Missouri, USA, rbh@eas.slu.edu

The 2016 M5.8 earthquake near Pawnee, Oklahoma is the largest induced earthquake in Oklahoma and is the largest earthquake induced by wastewater injection in the U.S. We invert regional and teleseismic waveforms and compute apparent source time functions to produce a finite-fault model of earthquake rupture. Use of aftershocks as empirical Green's functions allows us to use waveforms to higher frequencies (0.5–3 Hz) than previous slip models, providing additional information about the evolution of the earthquake rupture and its potential interaction with pore fluids. The rupture model indicates that earthquake rupture occurred in three stages and was confined to disconnected shallow and deep slip patches. Rupture initiated near 5 km depth, with initial rupture towards the surface and confined within the shallow slip patch. About 1 s into the rupture, our model indicates that slip commenced on the deeper part of the fault (>8 km). About one third of the moment of the earthquake rupture occurred at this greater depth. The relation of coseismic slip to the region of pore pressure perturbation is of great interest for understanding the magnitudes of induced-earthquakes. Slip on the deeper part of the fault occurred beneath most of the aftershocks and at greater depths than the vast majority of regional seismicity. Shallow slip largely occurred within zones where previous pore pressure modeling indicates greater perturbations. The correspondence of slip patches on the shallow part of the fault and pore pressure perturbations, as well as the inference of deeper rupture for the M5.8 earthquake than for regional events, suggests a unique rupture process, which may be explained by the influence of perturbed pore pressures. This observation is consistent with recent numerical modeling work and has important consequences for forecasting the size of and hazards associated with injection-induced earthquakes.

The Similarity Between Induced and Natural Earthquakes: A View From the Non-Double-Couple Component

WANG, R., Western University, London, Canada, ruijia.wang@uwo.ca; GU, Y., University of Alberta, Edmonton, Canada, ygu@ualberta.ca; SCHULTZ, R., Alberta Geological Survey, Alberta Energy Regulator, Edmonton, Canada, rjs10@ualberta.ca; CHEN, Y., Future Science Platform, CSIRO, Perth, Australia, yunfeng1@ualberta.ca

Focal mechanisms of induced earthquakes reflect anthropogenic contributions to the pre-existing geological features and fault slippages. In this paper, we examine the fault-related (double-couple, DC) and possibly fluid-related (non-double-couple, non-DC) mechanisms of induced earthquakes at a regional scale (M2-6). We systematically compare the well-resolved focal mechanisms of 35 shallow events in the Western Canada Sedimentary Basin, among which 14 were induced by hydraulic fracturing and one by secondary recovery. Overall, M>4 natural and induced earthquakes show consistent fault plane solutions when located close to each other. Thus, their focal mechanisms are likely pre-determined by event locations, indicating origins that are dominated by tectonic stress release. Limited (but consistent) non-DC components are obtained from the hydraulic-fracturing induced seismicity in central Alberta. We interpret the persistent compensated-linear-vector-dipole (CLVD) components (M2.1-3.8) as reflecting 1) fracture growth during hydraulic-fracturing stimulation and/or 2) co-slipping of the dextral transentional faults. Both explanations are widely adopted to explain the CLVD components observed in volcanic regions. We further expand the moment tensor decomposition analysis to four representative classes of induced seismicity globally and find that the overall contribution of non-DC components is largely comparable between induced and tectonic earthquakes.

Moment Tensors of Waste-Water Disposal Induced Seismicity in Southern Kansas

MARTINEZ-GARZON, P., GFZ German Research Centre for Geosciences, Potsdam, Germany, patricia@gfz-potsdam.de; AMEMOUTOU, A., GFZ German Research Centre for Geosciences, Potsdam, Germany, amandine@gfz-potsdam.de; RUBINSTEIN, J., U.S. Geological Survey, California, USA, jrubinstein@usgs.gov; KWIATEK, G., GFZ German Research Centre for Geosciences, Potsdam, Germany, kwiatek@gfz-potsdam.de; BOHNHOFF, M., GFZ German Research Centre for Geosciences, Potsdam, Germany, bohnhoff@gfz-potsdam.de

Fluid-injection into the subsurface in the frame of reservoir-engineering activities for hydrocarbon and geothermal energy production has resulted in a dramatic increase of induced seismicity during the last 10 years. This includes four M>5 earthquakes in Oklahoma and Kansas (US) through the reactivation of previously unknown critically stressed and thus hazardous faults in the basement. We investigate seismic recordings of relocated events with local magnitudes ML in the range [1.9, 5.2] from a regional seismic network deployed in southern Kansas since 2014 including 19 broadband stations and 5 accelerometers. Determination of seismic moment tensors and subsequent refinement was done employing the hybridMT package (Kwiatek, 2016). HybridMT inversion is based on the P-waves first ground displacement amplitudes from vertical components and provides unconstrained full, deviatoric, and double-couple constrained moment tensors. The results of moment tensor inversion are refined and suppresses the influence of local path, site, and sensor effects. In this study, we also implemented the use of the horizontal components, thereby increasing the input data by a factor of 3. The refined methodology was tested and tuned on synthetic datasets based on the shear-tensile source model (Vavrycuk, 2001). This model describes the source kinematics by four fault plane parameters (strike, dip, rake) and a tensile angle representing the fault opening. We find that focal mechanisms from the 3-component inversion are generally consistent with the generated synthetic fault plane parameters, signifying the correct performance of the new approach. Furthermore, moment tensor inversion of several tens of events with already reported focal mechanisms (Rubinstein, 2018) appear to be generally consistent between applied methods. In this contribution, first results from statistically significant full moment tensors as well as double-couple solutions from initial ~2,300 seismic events are presented and discussed in the context of their spatial and temporal changes within the investigated area.

Tidally Triggered Earthquakes at the Geysers in Northern California

DELOREY, A. A., Los Alamos National Laboratory, New Mexico, USA, andrew.a.delorey@gmail.com; CHEN, T., Los Alamos National Laboratory, New Mexico, USA, tchen@lanl.gov

Seismicity at the Geysers geothermal field in northern California is highly clustered. This clustering is caused by fluid injections and withdrawals, aftershocks, dynamic triggering by seismic waves from distant earthquakes, and possibly other mechanisms. We are investigating whether or not earthquakes are triggered by Earth tides because temporal changes in triggering may reveal evolving stress conditions and help us to forecast behavior. We start with an earthquake catalog that runs from April 2003 to Jun 2016 containing ~470000 earthquakes; using only the ~41000 earthquakes above the magnitude of completeness of 1.75. Because focal mechanisms are unknown, we analyze the relationship between tidally induced volumetric strain with seismicity. Because we know of no way to accurately model and remove all other forms of clustering except for hypothesized clustering by Earth tides, we need an alternative analysis that does not require declustering. We use a likelihood analysis which consists of adding up the tidal stress magnitudes (positive = dilation) for all earthquake times in the catalog. We compare this sum against simulated catalogs that are constructed by segmenting the real catalog using the largest interevent times, then randomly reordering the segments. The number of segments does not significantly affect our results within the range we tested (50-500). This analysis preserves clustering behavior such as aftershock sequences and other forms of clustering that have time scales of several months or less, but randomly shifts them in time. For the entire catalog, less then 1 percent of the simulated catalogs have a higher likelihood value than the real catalog, indicating triggering of the Geysers earthquakes by Earth tides. Further analysis shows that the triggering likelihood during the dry season (May – October) is higher than that during the wet season (November – April).

Hydraulic-Fracturing Induced Seismicity Driven by Accelerated Fault Creep

EYRE, T. S., University of Calgary, Calgary, Canada, thomas.eyre@ucalgary.ca; EATON, D. W., University of Calgary, Calgary, Canada, eatond@ucalgary.ca; GARAGASH, D., Dalhousie University, Halifax, Canada, garagash@dal.ca; VENIERI, M., University of Calgary, Calgary, Canada, marco.venieri@ucalgary.ca; WEIR, R., University of Calgary, Calgary, Canada, ronald.weir@ucalgary.ca; LAWTON, D., University of Calgary, Calgary, Canada, lawton@ucalgary.ca

Models for injection-induced earthquakes typically incorporate effects of poroelastic diffusion and ascribe earthquake fault activation to elevated pore pressure or increased shear stress. In the case of hydraulic fracturing in shale, this paradigm is incompatible with underground experiments and rate-state frictional models, which predict stable sliding (aseismic slip) on faults that penetrate rocks with high total organic content (TOC) or elevated clay content. Here, we present a high-resolution microseismic dataset that monitored a hydraulic-fracturing treatment associated with a M_w4.1 induced earthquake in the Western Canadian Sedimentary Basin. This dataset shows the locations of the fault activated events nucleated above the injection depth, at a timescale that is likely too fast for pore-pressure diffusion, similar to other observations of induced seismicity in the region. Therefore, we develop an alternative model, wherein distal, unstable regions of a fault are progressively loaded by fluid-injection driven aseismic slip, and test it through rate-state modeling based on the real dataset. The rate of expansion of the associated slip front significantly outpaces pore-pressure diffusion and is consistent with observed timescales of earthquake nucleation. Our model predicts that dynamic (earthquake) rupture initiates when the slip front impinges on a fault region where rock composition favors slip-rate-weakening behavior. Dynamic weakening of the fault gouge is essential for a large earthquake to be induced, therefore carbonates are most susceptible. The magnitude of the event produced by the model is a very similar magnitude to the real earthquake, based on a data-derived geomechanical model and realistic input parameters. Improved understanding of fundamental processes of fault activation during hydraulic-fracturing is key to developing effective monitoring and mitigation strategies and could also help to inform models for natural earthquake triggering.

Seismicity of Bull Shoals Lake Area of Missouri and Arkansas

KOPPER, M. T., Arkansas Geological Survey, Arkansas, USA, martha.kopper@arkansas.gov; AUSBROOKS, S. M., Arkansas Geological Survey, Arkansas, USA, scott.ausbrooks@arkansas.gov; HORTON, S. P., Center for Earthquake Research and Information, University of Memphis, Tennessee, USA, shorton@memphis.edu

Northern Arkansas, historically aseismic, has seen an increase in the seismicity in the vicinity of Bull Shoals Lake area of Arkansas and Missouri since 2017. It is hypothesized that: 1) an intense rainfall event, 2) the rate at which the lake filled over a short timeframe, and 3) nearby geologic structural components were the cause this seismicity. Since April, 2017, there have been 61 seismic events. The main event, a M3.6, occurred on June 11, 2017. Prior to this sequence, the area reported only 18 events which have occurred over the past 90 years. The moment tensor indicated a strike slip normal fault earthquake at a depth of 6.0 km. This investigation revealed that the region received over 20 inches of rain over two month period in an area which normally receives an average rainfall of 42 inches and that the lake level increased more than 37 feet over a period of 48 days. The nearby structural component, the Ponca Lineament (northeast-southwest) extension has been projected to run through this seismic cluster. Previous studies (Snow, 1972, Talwani, 1976, Talwani, et al, 2007) have demonstrated that pore pressure diffusion is associated with the buildup of fluid pressures and the onset of seismicity. Talwani's study (90+ induced seismicity case histories) determined that the hydraulic diffusivity ("C") value of fractures associated with seismicity to lie between 0.1 and 10 meters^2 per second (referred to as the seismogenic permeability k_s). For the Bull Shoals study area, based on preliminary calculations, it is proposed that the change in the pore pressure/diffusion (hydraulic diffusivity or "C") is on the order of about 0.2 meters^2 per second.

Stress State Inferred From Moment Tensors of Induced Events Near Fox Creek, Alberta: Implications for Fault Criticality

ZHANG, H., University of Calgary, Calgary, Canada, hongliang.zhang@ucalgary.ca; EATON, D. W., University of Calgary, Calgary, Canada, eatond@ucalgary.ca; RODRIGUEZ PRADILLA, G., University of Calgary, Calgary, Canada, german.rodriguezprad@ucalgary.ca; JIA, S., University of Calgary, Calgary, Canada, qing.jia@ucalgary.ca

Using continuous recordings from the ToC2ME field program acquired by the University of Calgary in Fall 2016, we have computed 530 moment tensors of induced seismic events that took place during hydraulic-fracturing operations near Fox Creek, Alberta. Three distinct groups of source mechanisms were identified based on the best double-couple solutions of the retrieved moment tensors, of which two are characterized by predominantly strike-slip motion on sub-vertical nodal planes. One event cluster is characterized by more complex mechanisms, with slip on a shallow-dipping plane accompanied by significant (>30%) non-double-couple components. Stress inversion of this dataset revealed a predominantly strike-slip regime, with S_{Hmax} in a direction of about N60E. This orientation is in agreement with the nearest available borehole measurement from the World Stress Map but differs from the median regional S_{Hmax} direction by about 15 degrees. Our analysis indicates that a north-south fault system that hosted most of the M_W> 1.5 events is mis-oriented for slip within the inferred background stress field. Based on our analysis, this fault would require a considerable change in effective stress in order to be brought to a state of incipient failure.

Injection-Induced Seismicity

Poster Session · Friday · 26 April · Fifth Avenue

Analysis of the 29 November 2018 ML 4.5 Earthquake Near Fort St. John, BC

EATON, D. W., University of Calgary, Calgary, Canada, eatond@ucalgary.ca; KAO, H., Natural Resources Canada, Sidney, Canada, honn.kao@canada.ca; ESMAEILZADEH, Z., University of Calgary, Calgary, Canada, zahra.esmaeilzadeh@ucalgary.ca

A ML 4.5 earthquake occurred at 18:27 local time on 29 November, 2018, approximately 16 km from Fort St. John, British Columbia. This event occurred in an area of drilling within the Septimus region of the Montney siltstone resource play and it has been linked to active hydraulic fracturing in the Lower Montney, leading to a halt in operations by the B.C. Oil and Gas Commission. The mainshock was felt to a distance of at least 200 km and was followed by two significant aftershocks of ML 4.0 and ML 3.4. The event is located within a region of moderate structural complexity near the southern edge of the Carboniferous-to-Permian Fort St. John graben complex and also near the foreland limit of the Late Cretaceous-Paleocene Rocky Mountain thrust belt. A compilation of data, including seismic profiles, well logs, stress information and waveform data from regional seismograph networks, provide a basis for an integrated interpretation of this induced sequence that incorporates geomechanical analysis, pre-existing faults and structural setting.

Stochastic Modelling of Induced Seismicity Clusters in Central Alberta

WANG, R., Western University, London, Canada, ruijia.wang@uwo.ca; SHCHERBAKOV, R., Western University, London, Canada, rshcherb@uwo.ca; ATKINSON, G. M., Western University, London, Canada, gmatkinson@aol.com; ASSATOURIANS, K., Western University, London, Canada, karenassatourians@yahoo.com

For the past several years, hydraulic fracturing has been associated with the increasing seismicity rate in the Western Canada Sedimentary Basin (WCSB). Despite the high density of injection wells in the WCSB, induced earthquake clusters exhibit 1) large spatial and temporal variability and 2) swarm-like behavior that may not follow traditional recurrence laws. Site-specific statistical analyses of such induced seismicity are further challenged by the limited size and completeness of earthquake catalogs. Taking advantage of on-site industrial monitoring and recently-developed detection methods, thousands of M > 0 events were identified to be associated with two distinct hydraulic fracturing well-pads in central Alberta, Canada. In this study, three catalogs are examined and simulated: 1) the SO2 region where "traffic-light" protocol is in effect, 2) the November 2016 cluster containing multiple sub-clusters of earthquakes and several M ~3 events (Tony Creek Dual Microseismic Experiment, Eaton *et al.*, 2018), and 3) the January 2016 cluster characterised by a mainshock with M 4.1 (Wang *et al.*, 2017). To evaluate and characterize the recurrence patterns of these earthquake clusters, we employ a modified Epidemic Type Aftershock Sequence model, where we approximate the rate of seismicity as a linear superposition of the rate due to past earthquakes and the normalized effect of the operation of hydraulic-fracturing wells. Our results support that both the injection strategies and geological features are the key factors that control the occurrence of induced seismicity. The modeled earthquake rate can be used in the Monte-Carlo based stochastic earthquake simulations for a short-term earthquake hazard assessment accounting for nearby hydraulic-fracturing activities.

The 16 December 2018 Mw 5.3 Earthquake in the Southern Sichuan Basin of China Was Likely Caused by Hydraulic Fracturing

MENG, L., China Earthquake Networks Center, Beijing, China, meng.lingyuan@hotmail.com; MCGARR, A., U.S. Geological Survey, California, USA, mcgarr@usgs.gov

An M_W5.3 (CENC, 2018) earthquake was located at shallow depth near the northeast corner of the shale gas field N201 in the southern Sichuan Basin of China (SBC) on 16 December 2018. From 2015 to 2018, nearly 19,000 earthquakes were recorded by a temporary network with 21 mobile stations. As reported for western Canada, hydraulic fracturing accounts for the majority induced seismicity in the southern SBC. Previously, it was found that seismicity located to the southwest near well pad H7 of shale gas field YS108 was induced by hydraulic fracturing operations from 12 to 19 January 2017, including the M_W4.7 earthquake that occurred on 28 January 2017 (Lei *et al.*, 2017; Meng *et al.*, 2019). The epicenter of M_W5.3 earthquake was located, using a local seismic network, about 2.0 km away from the well pad N201H24. From this pad, there were hydraulic fracturing operations from 4 October until 9 December 2018. During the hydraulic fracturing, there was only one M_L > 3.0 event detected near this well pad, on 12 November 2018. Following completion of the hydraulic fracturing, an event of M_L3.5 was recorded on 16 December 2018, followed 17 sec later by the M_W5.3 earthquake. Another M_W5.0 (CENC, 2019) earthquake occurred in the central area of N201 on the 3 January 2019, nearly 10 km southwest of the M_W5.3 earthquake and 2 km north of an earthquake of M_W4.5 that occurred on 4 May 2017, respectively (Lei *et al.*, 2017). In view of plans for extensive further development of these natural gas resources in the southern SBC, there is clearly a need to continue seismic monitoring in this region using a local network. Additionally, comprehensive information concerning the corresponding injection activities should be accessible in the public domain to enable an improved understanding of how these earthquakes are related to well completion operations.

Seismicity Induced by Hydraulic Fracturing in Ohio in 2016: Case Study of the Conotton Sequence in Harrison County

FRIBERG, P., Instrumental Software Technologies, Inc., New York, USA, p.friberg@isti.com; BRUDZINSKI, M. R., Miami University, Ohio, USA, brudzimr@miamioh.edu; FASOLA, S., Miami University, Ohio, USA, fasolasl@miamioh.edu; RIES, R., Miami University, Ohio, USA, riesr@miamioh.edu; KOZLOWSKA, M., Polish Academy of Sciences, Warsaw, Poland, mkozlow@igf.edu.pl; SKOUMAL, R. J., U.S. Geological Survey, California, USA, rskoumal@usgs.gov

In November of 2016, a sequence of hydraulic fracturing induced seismicity was observed in Harrison County, Ohio. The events in this sequence were ≤ M 2.7 and were spatiotemporally correlated with hydraulic pumping stages from the Conotton horizontal wells. A series of adjacent wells to the west of the Conotton wells also induced seismicity along an east-west trending basement fault system. The fault's east-west trend extended beneath the Conotton horizontals based on seismicity observed in 2015, and the seismicity from the Conotton stimulation is an extension of the same fault system. Using a 5 station seismic network, 129 earthquakes were picked and located using Hypoinverse. Relative locations were obtained using HypoDD and demonstrate that the activity was 800 to 1200 meters below the Utica formation being stimulated and related to the crystalline basement fault system. In addition, cross-correlation template matching techniques were used to observe some ~1200 detections of earthquakes with M > -0.85. Interestingly, the b-value evolved from values > 1 early in the sequence to < 1 when the larger events started happening. During the sequence, the operator took mitigation actions by skipping stages and reduced volume across stages that were closer to the fault. Pressure and volume data were investigated to assess if there was any relationship with specific stimulation parameters to the earthquake rate. Production data from the wells are also examined to investigate how interactions with a fault influence produced oil, gas, and brine.

Comparing Seismicity-Inferred Fault Structures to Local Basement Fault Structures in Oklahoma

TRIPPLEHORN, T. J., The University of Tulsa, Oklahoma, USA, tyler-tripplehorn@utulsa.edu; RUHL, C. J., The University of Tulsa, Oklahoma, USA, cruhl@utulsa.edu; ROCHE, S. L., The University of Tulsa, Oklahoma, USA, slr1725@utulsa.edu

The vast majority of seismicity that north central Oklahoma has experienced since 2009 has occurred in the upper portion of the basement. Basement fault structure, however, remains poorly understood on a regional basis. Recent relocation studies have found that earthquake clusters very rarely correlate with faults mapped in the overlying stratigraphic sequence; this implies a distinct difference in structural style between the sedimentary cover and the basement, and that the most significant seismic hazard currently exists on unknown faults. Given the importance of basement structure to seismic hazard in the region, correlating fault structures inferred from spatiotemporal clustering of seismicity to structures derived from other geophysical techniques (*e.g.*, potential field and subsurface imaging) may prove to be a useful tool for corroborating fault structures. These structures could then be incorporated into seismic hazard maps with more confidence, particularly in areas where seismicity has yet to migrate to. Here, we test this hypothesis by systematically comparing high-precision earthquake relocations to a variety of other basement fault data on a local basis in Oklahoma.

Infrasound Generated by Fluid-Induced Seismicity in Finland

LAMB, O., University of North Carolina at Chapel Hill, North Carolina, USA, olamb@live.unc.edu; LEES, J. M., University of North Carolina at Chapel Hill, North Carolina, USA, leesj@ad.unc.edu; MALIN, P. E. A., ASIR Advanced Seismic Instrumentation and Research, Texas, USA, pem@asirseismic.com; SAARNO, T., St1 Deep Heat Oy, Helsinki, Finland, tero.saarno@st1.fi

Enhanced (or Engineered) Geothermal Systems (EGS) hold a high potential for exploiting the ubiquitous heat energy of the Earth but require stimulation of fluid-flow channels with the common by-product of triggered or induced earthquakes. To reduce the risk of damage from these earthquakes, effective monitoring systems must be deployed around drilling locations and are largely composed of seismic stations. Here we present infrasonic recordings of earthquakes generated during hydraulic-stimulation of the world's deepest EGS located near Helsinki, Finland, in July 2018. Infrasound is defined as atmospheric acoustic waves with frequencies below 20 Hz, the lower threshold of human hearing. In response to public reports of booming noises in the surrounding area, eight infrasound microphones were rapidly deployed across two locations no further than 2.5 km from the drill site. The microphones were deployed for a total of 13 days, during which 342 earthquakes of magnitudes up to Mw 1.9 were recorded and located by the seismic monitoring system already in place. Arrival times of the infrasound waveforms suggests they were generated by stimulation of the atmosphere by seismic waves travelling past the station. This case study highlights how microphones capable of recording infrasound can complement seismic monitoring networks around current or future EGS projects.

Seismology and Drilling, Characterizing and Hydraulic Stimulation of the OtN-3 EGS Well in Finland

MALIN, P. E. A., Southern Methodist University, Texas, USA, pem@asirseismic.com; KWIATEK, G., GFZ German Research Centre for Geosciences, Potsdam, Germany, grzegorz.kwiatek@gfz-potsdam.de; SAARNO, T., ST1 Deep Heat Oy, Helsinki, Finland, tero.saarno@st1.fi

Using hammer drilling for the 1st 4500 m of an Enhanced Geothermal System well, OTN-3, the Finnish company St1 Deep Heat Ltd completed this well in May 2018 to 6400 m measured depth. This district heating EGS well is on Aalto University's Otaniemi campus, a few km from downtown Helsinki. The development included the installation of a 3-tier seismic monitoring and Traffic Light System. This talk sets up the seismological background to the project's drilling, characterization, and hydraulic stimulation, describing the seismological aspect of each stage and operation. Follow-on talks will discuss the TLS and how monitoring of the stimulation was used to limit the induced seismicity to less than an M2.1 event.

In 2015 St1 cored a 2 km OTN-1 pilot hole and logged it, establishing a gradient of ~18oC /km. A 1.8 km, 24-level seismometer chain was installed in OTN-I for Hammer-Drill Seismic Profiling while OTN-2 was drilled to 3.325 km. This profiling effort reveled several geological structures and estimated seismic velocities for use in the stimulation event location effort. During its drilling, OTN-3 intersected and cut through the OTN-1 array. OTN-3 was then mud drilled to 6400 m md. It was deviated ~45o from 4.9 km, normal to the WNW-ESW stress maximum. Temperature profiles revealed numerous m-scale, 0.1oC incursions, decameter-long isothermals, and a remarkable 260 m long isothermal between 4770 and 5030 m.

The bottom of OTN-3's 1260 open-hole section m was completed with an 800 m, 5 stage stimulation assembly. These stages were sequentially pressured during clean water injection program, including hours-to-days long rest periods over 49 days. The net injection was 18,160 cubic meter. Thousands of microearthquakes were detected by the network, none exceeding the M2.1 Red-light. The main public notice resulted not so much from the ground motion of the induced events, but from the thunder-like acoustic signals for events larger than ~M1.

Assessing the Applicability of Ground Motion Models for Induced Seismicity Application in Central and Eastern North America

FARHADI, A., University of Memphis, Tennessee, USA, afarhadi@memphis.edu; PEZESHK, S., The University of Memphis, Tennessee, USA, spezeshk@memphis.edu

This study aims to present a relatively short list of interim induced proxy ground motion models (GMMs) most suitable for induced seismicity application in central and eastern North America (CENA). Induced proxy GMMs are models not established from datasets strictly made of induced events but can be used to predict ground motions from such events. For this purpose, we test the predictive power of a long list of GMMs against a dataset of induced earthquakes using the popular log likelihood (LLH) method of Scherbaum *et al.* (2009) and its natural extension known as the multivariate logarithmic score of Mak *et al.* (2017). Our dataset is a subset of data provided by Rennolet *et al.* (2017) and is composed of 2414 time histories from 384 CENA induced events with hypocentral distances below 50 km and moment magnitudes from 3.5–5.8. Candidate GMMs are from two categories, including purely empirical models developed from the NGA-West2 database and indigenous models of CENA. The NGA-West2 database contains a large number of shallow small-to-moderate magnitude events from California that may approximate characteristic features of induced events in CENA. Some of the CENA models have considered near distance saturation for small-to-moderate magnitude range and/or have explicitly modeled source parameter as a function of focal depth that may make them reasonable induced proxy GMMs. Some models performed better in certain frequencies than others and not a single model performed the best over the entire frequency range. Overall, three models including Atkinson (2015), Chiou and Youngs (2014), and Abrahamson *et al.* (2014) GMMs outperformed other models. These models are not specifically established for CENA but are properly modeled for magnitude and depth scaling. In addition, stochastic models favored in the low seismicity region of CENA, appear not performing better than models developed based on conventional statistical and empirical approaches for induced seismicity applications.

Mapping Temporal Stress Evolution in Pawnee and Cushing Oklahoma Using Ambient Noise

OGWARI, P. O., Oklahoma Geological Survey, Oklahoma, USA, pogwari@ou.edu

Subsurface injection of saltwater into the Arbuckle group in Oklahoma has produced stress changes which have resulted in increased seismicity in the region. We investigate the temporal evolution of stress using seismic interferometry with ambient noise by exploring the temporal evolution of velocity leading up to the 2016 Mw 5.8 Pawnee and Mw 5.0 Cushing earthquakes. We implement a combination of cross-station and single-station autocorrelation ambient noise cross-correlations to provide a robust analysis of the velocity. We analyze continuous seismic data recorded between 2013-2017 on four stations to document the period leading to the largest earthquakes in the study area by computing noise cross-correlation functions using MSNoise software. Waveform analysis is implemented on the 3 components of each station by performing instrument correction and spectral whitening of one-hour long waveforms in the frequency ranges of 0.01–1.0 Hz, 0.5–1.0 Hz, 1.0–2.0 Hz, and 2.0–4.0 Hz then 1-bit normalized. The temporal variability of seismic velocity is evaluated by measuring the time delay between the 5 and 10-day stack of noise correlation functions and a reference defined by the mean velocity of the hourly noise correlation functions for the period analyzed. Preliminary results indicate a velocity increase in 2013-2014 before the beginning of seismic activity leading to the largest events in the area. The temporal velocity variations correlate positively with the seismicity rate in the area in the 2014-2016 period. Both the velocity increase and seismicity rate may be modulated by increased pore pressure in the area.

Observations of Volcanism in the Three Spheres: Land, Air and Sea

Poster Session · Friday · 26 April · Fifth Avenue

Melt Evolution Beneath Axial Volcano Imaged Using Continuous Seafloor Compliance Data

DORAN, A. K., Scripps Institution of Oceanography, University of California, San Diego, California, USA, adoran@ucsd.edu; CRAWFORD, W. C., Institut de Physique du Globe de Paris, Paris, France, crawford@ipgp.fr

We present the first continuous observations of the evolution of the magmatic melt system beneath Axial Volcano. We analyzed data from December 2014 through May 2018 from two cabled broadband ocean-bottom seismometers with collocated absolute pressure sensors to estimate seafloor compliance as a function of both frequency and time. The April 2015 submarine eruption induced dramatic changes in shear structure that were primarily concentrated in the lower crust (deeper than 2.5 km). We propose that the nearly 20% drop in shear velocities in the lower crust over the course of 10-12 weeks following the eruption represents the fracturing of the lower crust and the intrusion of high aspect-ratio melt sills. The subsequent rate of healing suggests that the sills were on the order of 1 meter thick. The absence of a signal on the eastern flank of the caldera indicates that the lower crustal melt pathway is relatively narrow in cross section (<1.2 km2) compared to the overlying melt chamber (≥42 km2). The lower crustal melt must also be concentrated beneath the center or to the west of the surface caldera. We find that the melt chamber and the lower crust contain minimum melt fractions of 14% and 4%, respectively, though the true melt fractions may be significantly higher. Our images demonstrate the promise of using continuous data to understand submarine volcanism and crustal accretion processes.

Repeating Deep Long-Period Earthquakes Beneath Mauna Kea Volcano

WECH, A., U.S. Geological Survey, Alaska, USA, awech@usgs.gov; THELEN, W., U.S. Geological Survey, Washington, USA, wthelen@usgs.gov

Mauna Kea is a large postshield-stage volcano that forms the highest peak on Hawaii Island. The 4,205-meter high volcano erupted most recently between 6,000 and 4,500 years ago and exhibits relatively low rates of seismicity, which are mostly tectonic in origin resulting from lithospheric flexure under the weight of the edifice. Here we identify repeating, deep long-period earthquakes (DLPs) occurring beneath the summit of Mauna Kea. These earthquakes, which are not part of the Hawaiian Volcano Observatory's regional network catalog, were initially detected through a systematic search for coherent seismicity using envelope cross-correlation, and subsequent analysis revealed the presence of a long-term, persistent source. The events have energy concentrated at 2-7 Hz, and can be seen in filtered waveforms dating back to the earliest continuous data from a single station archived at IRIS from November 1999. We use a single-station (horizontal components) match-filter analysis to create a catalog of the repeating earthquakes for the past 18 years. Using templates created through the stacking of thousands of sta/lta-triggers, we find > 1 million earthquakes repeating every 7-12 minutes throughout this time period, in addition to many smaller events occurring in between. The earthquakes occur at 28-31 km within a conspicuous gap in seismicity depth directly beneath the summit that corresponds to a low-velocity anomaly in regional tomography model. Magnitudes (~Ml 1.3-1.6) and periodicity are remarkably stable over time periods of years but do vary slightly on shorter time scales, and the DLPs can be triggered or modified by regional tectonic earthquakes. Based on the events' frequency content and location, we infer a volcanic source distinct from the regional tectonic seismicity responding to the load of the island.

Next-Generation Volcano Monitoring at Mount Rainier, Washington

MORAN, S. C., U.S. Geological Survey, Washington, USA, smoran@usgs.gov; THELEN, W., U.S. Geological Survey, Washington, USA, wthelen@usgs.gov; LOCKHART, A., U.S. Geological Survey, Washington, USA, ablock@usgs.gov; PAUK, B., U.S. Geological Survey, Washington, USA, bpauk@usgs.gov; KRAMER, R., U.S. Geological Survey, Washington, USA, rkramer@usgs.gov; LOCKETT, C., U.S. Geological Survey, Washington, USA, clockett@usgs.gov

Over the last 2,600 years Mount Rainier has produced at least 8 large lahars (most recently ~1500 C.E.) that inundated now heavily populated areas of the Puget Sound Lowland. Many of these lahars occurred during eruptive episodes, but scientists have found no geologic evidence of an eruption at the time of the most recent large lahar. Hydrologic modeling indicates that these flows could reach small communities near Rainier within 20 minutes and larger Puget Sound communities within an hour. Slope-stability analyses suggest that the western flank of Rainier is particularly vulnerable to a future gravity-driven collapse, which could generate a large lahar with little or no warning.

Volcano monitoring systems are a key strategy for lahar-hazard mitigation at Rainier. For the last two decades there have been two separate systems in operation: a real-time seismic-and-GPS-monitoring network, jointly operated by the Pacific Northwest Seismic Network and USGS Cascades Volcano Observatory (CVO); and a lahar-detection system (LDS) with geophones and tripwires installed along two drainages originating at Rainier, designed and installed by CVO in 1998 and operated by Pierce County (Washington) Emergency Management (PCEM) from 1998 to the present. The two systems operate autonomously, with LDS stations transmitting average seismic amplitudes every two minutes.

In 2016 CVO began working with PCEM officials to upgrade volcano monitoring capabilities at Mount Rainier. The first steps have included upgrading LDS sites with modern instruments (broadband seismometers, infrasound, webcams) and real-time telemetry, and integrating these sites with the real-time volcano-monitoring network. Future work includes new sites on the west flank of the volcano and along its other river drainages, and implementing algorithms for detecting and tracking moving flows. When finished, the integrated network will include more than 30 monitoring stations, making it one of the densest volcano-monitoring networks in the world.

Hydroacoustic and Seismic Observations of the 2016-17 Bogoslof Eruption, Alaska

TEPP, G., U.S. Geological Survey, Alaska, USA, gtepp@usgs.gov; POWER, J., U.S. Geological Survey, Alaska Volcano Observatory, Alaska, USA, jpower@usgs.gov; DZIAK, R., National Oceanic and Atmospheric Administration, Pacific Marine Environmental Laboratory, Oregon, USA, robert.p.dziak@noaa.gov; SEARCY, C., U.S. Geological Survey, Alaska Volcano Observatory, Alaska, USA, csearcy@usgs.gov; LYONS, J. J., U.S. Geological Survey, Alaska Volcano Observatory, Alaska, USA, jlyons@usgs.gov; HANEY, M., U.S. Geological Survey, Alaska Volcano Observatory, Alaska, USA, mhaney@usgs.gov; WECH, A., U.S. Geological Survey, Alaska Volcano Observatory, Alaska, USA, awech@usgs.gov; HAXEL, J., Oregon State University, Cooperative Institute for Marine Resources Studies, Oregon, USA, joe.haxel@noaa.gov; MATSUMOTO, H., Oregon State University, Cooperative Institute for Marine Resources Studies, Oregon, USA, haru.matsumoto@noaa.gov

In December 2016, Bogoslof volcano unexpectedly began erupting from a vent just below the ocean's surface. Over the next 8.5 months, Bogoslof produced 70 major explosions with ash plumes up to 13 km, three lava domes that broke the sea surface, around 40 earthquake swarms, and other seismicity. Bogoslof is an unmonitored seamount with a summit that forms a small island. Thus, the eruption was only monitored by seismometers on nearby islands (>45 km away), regional infrasound arrays, satellites, and lightning sensor networks. For the last 3.5 months of the eruption, a campaign hydrophone was moored about 7 km from the summit, allowing for more detailed seismo-acoustic recordings than were possible with the available telemetered networks.

We analyze and compare the seismic and hydroacoustic recordings to outline the seismic story of the eruption, which can be broken into five phases. The Precursory Phase comprised a major earthquake swarm in late September 2016, a smaller swarm a week later, and many sporadic earthquakes. The Opening Phase followed with near-continuous, alternating tremor and earthquakes between 11-15 December. This seismicity led into Explosive Phase I, which included 38 of the major explosions and most of the precursory earthquake swarms. After an explosion on 13 March, the eruption went into a 2-month-long Pause during which the only activity was a single earthquake swarm. On 17 May, an explosion opened Explosive Phase II, which lasted until the eruption ended on 30 August. Additionally, we further examine the characteristics of the eruptive tremor and the earthquake swarms that were common throughout the eruption. We then put the seismic and hydroacoustic observations into context with other observations of the eruption.

Preliminary Earthquake Detections From Seismic Stations Installed on Bioko Island, Equatorial Guinea

LOUGH, A. C., Drexel University, Pennsylvania, USA, alough@drexel.edu; SEALING, C., Drexel University, Pennsylvania, USA, crs358@drexel.edu

Equatorial Guinea's Bioko Island is located in the Atlantic Ocean off the west coast of Cameroon. Bioko is a volcanic island and the first off-shore expression of the Cameroon Volcanic Line. It is home to three shield volcanoes: Pico de Basile, Pico Biao, and San Carlos. Eruptive histories are not known for Pico Biao or San Carlos. Pico de Basile erupted within the past 100 years, and steam vents were observed as recently as 2012. Malabo, the capital city of Equatorial Guinea, sits in the shadow of Pico de Basile. There is no permanent seismic monitoring; the closest seismic stations are in Cameroon and have not reported data since 2015.

In November 2017 Drexel University researchers, supported by the Bioko Biodiversity Protection Program (BBPP) and the Universidad Nacional de Guinea Ecuatorial (UNGE), installed 4 broadband seismometers. In February 2018, the data were retrieved, and stations serviced. Preliminary earthquake detection and location was completed using an automated STA/LTA algorithm. S wave arrivals were added manually. The initial locations use the global IASP91 model and events were relocated using a local model. The events detected cluster into two areas: those near Bioko Island and those near Cameroon.

Between 12-Dec-2017 and 17-Feb-2018, 77 events were recorded. Local magnitudes range between 0.16 and 2.61. Of these events, 49 are located near Cameroon and 28 are near Bioko. Most of the depths are crustal, mostly upper to mid crust. Our preliminary results show there is seismicity associated with Bioko Island as well as Cameroon. The locations match well with events recorded by a local network installed in Cameroon in 2007.

The four stations were serviced again in November 2018. One station failed due to water infiltration and one was vandalized within a week of the previous service. One station was still operational at service with only a few days down and the last station was operational until the height of the rainy season when power failed.

Conjugate Flow, Heat and Chemical Transport Processes in Underground Cavities Partially Filled With Molten Rock: A Numerical Investigation

EZZEDINE, S. M., Lawrence Livermore National Laboratory, California, USA, ezzedine1@llnl.gov; NGUYEN, J. S., Lawrence Livermore National Laboratory, California, USA, nguyen115@llnl.gov; ROSE, T. P., Lawrence Livermore National Laboratory, California, USA, rose23@llnl.gov; CASSATA, W., Lawrence Livermore National Laboratory, California, USA, cassata2@llnl.gov; ANTOUN, T. H., Lawrence Livermore National Laboratory, California, USA, antoun1@llnl.gov; WALTER, W. R., Lawrence Livermore National Laboratory, California, USA, walter5@llnl.gov

A transient numerical study of conjugate flow, heat and mass transfer by natural convection of gases – air, carbon dioxide, noble gases – within an underground cavity partially filled with molten rock is presented. The molten rock is initially considered to be at rest at an initial temperature and concentration. The molten rock is viscous and possesses strength that is temperature, viscosity, and crystal fraction dependent. Under natural conditions, convection cells are developed within the molten rock leading to circulation, mixing and degassing of the initially trapped gases. Furthermore, the molten rock as well the degassing enhances the conjugate convection flow in the air gap above the molten rock within the cavity and promote Bénard-Rayleigh-Taylor instabilities. We illustrate the onset of the different regimes of instabilities and their combined effect of flow, heat and mass transport of different gas species as function of the geometry of the cavity and the fraction of molten rock. The transient governing equations of mass, momentum, heat and chemical species were solved using the finite element method. Several numerical coupling schemes are presented, and numerical stability conditions are illustrated. We also present a sensitivity analysis of the effect of the outer cavity boundary condition on the heat loss and cooling to the adjacent rock formation and its effect on the convective mixing topology with the air gap and the molten rock.

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Seismic Structure of Tanaga and Takawangha Volcanoes, Tanaga Island, Alaska

CAPLAN-AUERBACH, J., Western Washington University, Washington, USA, caplanj@wwu.edu; LALLY, K. F., Western Washington University, Washington, USA, lallyk@wwu.edu; POWER, J., U.S. Geological Survey, Alaska, USA, jpower@usgs.gov

Tanaga Island is located in the Central Aleutian Islands and includes four strato-volcanoes: Sajaka, Tanaga, and East Tanaga in the north, and Takawangha in the central part of the island. Of these volcanoes, only Tanaga has reported eruptive activity in 1914. Over 6000 earthquakes have been recorded beneath the island and the surrounding offshore region since the six-station seismic network was emplaced in 2003. We use cross-correlation and double-difference methods to relocate Tanaga Island earthquakes from the period 2003 – 2017. High precision relative relocations show multiple subsurface faults in the Tanaga area related to volcanism and crustal tectonics. In 2005, a large volcanic swarm of nearly 600 volcano-tectonic (VT) events located below the NW portion of the island culminated with a several minute long episode of volcanic tremor. Although there was no verified eruption associated with this swarm, we suggest that this activity is associated with Takawangha volcano due to the shallowing of events towards Takawangha and the inferred location of the tremor. In 2008, a M6.6 earthquake was recorded 2.5 km east of Tanaga Island, associated with bookshelf faulting and block rotation in the overriding plate. Shortly after the M6.6 event, two regions on Tanaga Island, 20 and 30 km west of the epicenter became seismically active, suggesting triggering by the M6.6. We also examine a variety of smaller swarm episodes in the Tanaga area. From 2006 – 2017, we identify activity along the Delarof Block (Geist *et al.*, 1988), one of five forarc crustal blocks, including a small swarm in 2010. In 2013 and 2014, heightened seismicity suggests brittle rupture possibly accompanied by fluid movement due to the observations of hybrid events 8 km south of Takawangha. In addition, shallow zones of brittle rupture were discovered 6 km south of Takawangha and 25 km southeast of Takawangha. This analysis suggests a complex pattern of earthquake hypocenters that is governed by both volcanic and tectonic processes surrounding Tanaga and Takawangha volcanoes.

Eruption Dynamics and Variations in Earthquake Stress Drop With the 2015 Eruption of Axial Seamount

MOYER, P., University of New Hampshire, New Hampshire, USA, pamela@pamelamoyer.net; BOETTCHER, M. S., University of New Hampshire, New Hampshire, USA, margaret.boettcher@unh.edu; BOHNENSTIEHL, D. R., North Carolina State University, North Carolina, USA, drbohnen@ncsu.edu; ABERCROMBIE, R. E., Boston University, Massachusetts, USA, rea@bu.edu

The Ocean Observatory Initiative Cabled Array at Axial Seamount on the Juan de Fuca Ridge captures an unprecedented amount of geophysical, chemical, and biological data associated with submarine volcanism in real time. The cabled array includes seven ocean bottom seismometers located within and along the caldera that recorded the intense seismicity (including more than 100,000 earthquakes between January 2015 and November 2017) associated with the most recent eruption of Axial in April and May 2015. We use this unique seismic data to investigate how crustal strength, inferred from earthquake stress drop, evolves with seafloor deformation and magmatic processes before, during, and after the 2015 eruption.

We calculate stress drops between 0.07 – 9.4 MPa from corner frequency derived using an empirical Green's function spectral ratio method for 249 earthquakes ($1.1 < M_W < 3.2$) located within the caldera near the cabled array. We use strict pairing and modeling criteria for spectral ratios, and further examine earthquakes with M_W 1.7 – 2.5 to ensure that noise is well-outside the range of observed corner frequencies. We focus on a subset of 79 earthquakes in the northeast caldera where lava flows indicate dike intrusion. We find stress drops between 0.09 – 8.4 MPa for these events and 1.8 times higher average stress drop during inflation than deflation. This difference in stress drop is not statistically significant, and likely reflects increased hydrothermal fluid flow before and during the eruption; with slightly decreased crustal strength during magma ascent and deflation.

Velocity Changes Associated With the Three Year Buildup of Activity at Great Sitkin Volcano, Alaska – Are Precursory Signals Detectable?

BREMNER, P., University of Florida, Florida, USA, pbremner@ufl.edu; TEPP, G., U.S. Geological Survey, Alaska, USA, gtepp@usgs.gov; HANEY, M., U.S. Geological Survey, Alaska Volcano Observatory, Alaska, USA, mhaney@usgs.gov; WOO, H., University of Florida, Florida, USA, hbwoo@ufl.edu; POWER, J., U.S. Geological Survey, Alaska Volcano Observatory, Alaska, USA, jpower@usgs.gov

Great Sitkin volcano is located in the western Aleutian Islands, Alaska near the town of Adak where large explosive eruptions have the potential to impact local and trans-Pacific air traffic and produce ashfall on populated areas. In the spring of 2016, earthquake activity at Great Sitkin began a steady increase over background levels. The heightened activity further increased in the summer of 2018 but has leveled off in early 2019. In January 2017, the first of 9 explosions occurred with 6 of the 9 explosions recorded between Aug-Nov 2018. While the explosions are thought to be phreatic in origin, an explosion in June 2018 is known to have deposited ash, although the ash is thought to be fragmented country rock rather than juvenile material. Identifying potential precursors before explosions could help improve eruption forecasts if the current increase in seismicity continues.

Previous studies have proposed that seismic velocity changes, dv/v, may precede volcanic eruptions via ascent of magmatic material and volatile fluids. Such changes are useful for forecasting possible eruptions. It has been shown that these changes in aquifer depth and pore fluid pressurization have the potential to decrease seismic velocity on the order of 0.1%. In this work, we look for velocity changes over the long buildup of activity at Great Sitkin. To do this, we cross-correlate synchronous seismic data from pairs of stations and calculate dv/v from a moving reference. We also examine the auto-correlations of stations. Of particular interest in our analysis is whether velocity changes are different prior to the June 2018 event compared to the other explosions.

The 2018 Eruption of Kīlauea Volcano, Hawai'i

Poster Session · Friday · 26 April · Fifth Avenue

Verification of Sub-Faults Division in the Numerical Evaluation Precision of Near-Fault Seismic Ground Motions Accompanied by Surface Rupture

NAGANO, M., Tokyo University of Science, Noda, Japan, nagano-m@rs.noda.tus.ac.jp; KIDO, T., Tokyo University of Science, Noda, Japan, 7114034@alumni.tus.ac.jp

Numerical evaluation of near-fault ground motions is of great interest to many earthquake engineers, because the pulse-like ground motions and accompanied surface ruptures are responsible to structure damages in many historic earthquakes. However, in order to estimate amplitudes and spatial variation of near-fault pulse-like ground motions with high precision, the calibration of numerical evaluation methods is indispensable. In this study, as a case study, we applied the seismic fault model of the main shock of the 2016 Kumamoto, Japan, earthquake, to investigate the influence of sub-fault division in the fault plane to evaluat the near-fault strong ground motions. During the 2016 Kumamoto earthquake, surface ruptures along the seismic fault and large-amplitude pulse-like waves with predominant period of 1 second were observed in the vicinity of the seismic fault. These near-fault pulse-like ground motions resulted in devastating damages to wooden houses. For the numerical simulation of ground motions near the seismic fault accompanied by surface ruptures, evaluation of the Green's function is crucial as well as the subsurface structure. We performed a theoretical simulation of the near-fault seismic ground motions, which considered a fine division of the fault plane into several sub faults. Numerical convergence of the spatial integration is examined using the Thin Layer Method, which is addressed as a numerically effective tool for ground motions simulation for the seismic fault with surface ruptures. We found that the permanent displacement and dynamic velocity converge can be well produced using an integration spacing of approximately half of the source distance based on the comparison with results of the rigorous methods. We applied the seismic fault model to the main shock of the 2016 Kumamoto earthquake to investigate the influence of differently divided sub-faults in the fault plane on the evaluation of strong ground motions in the vicinity of the seismic fault.

Interpretation of and Proposed Model for Progressive Decorrelation of Auto-Correlation Functions on the East Rift Zone of Kīlauea during the Volcanic Activity of 2018

LEE, T. A., Harvard University, Massachusetts, USA, thomasandrewlee@college.harvard.edu; ISHII, M., Harvard University, Massachusetts, USA, ishii@eps.harvard.edu

A long-standing goal of volcano monitoring has been to better constrain signals associated with the movement of magma leading up to and during eruptive events. Recently, changes in magma chambers and the presence of magmatic bodies have been examined through ambient seismic noise correlations, for example, single-station auto-correlations. Volcanoes and their eruptions have proven to be an apt application of such techniques. We apply similar techniques to examine the eruptive activity at Kīlauea from May to August 2018. Single-station vertical-vertical ambient noise auto-correlations are calculated from seven stations that span the edge of Halema'uma'u Crater at the summit to the area of active flows and vents in the Lower East Rift Zone. These auto-correlation functions lose their coherence progressively starting from the summit on May 5th and propagating downrift to all stations by May 13th. The stations regain coherence by the end of May. This timing is of interest, because the loss of coherence begins within 48 hours of the May 4th M6.9 flank event, and the timing of stations returning to coherence corresponds well to the beginning of the "regular" collapse events at the summit and significant eruption at Fissure 8 in the Lower East Rift Zone. We interpret this signal as being the result of scattering caused by an intrusion triggered by the May 4th earthquake. The intrusion progresses from the summit area into the Upper East Rift Zone, eventually creating a more definite link between the summit and the Lower East Rift Zone fissures. This model explains the dynamic relationship between the flank earthquake, decorrelation, summit collapse, and eruption from active vents.

Mechanism of the 4 May 2018 East Hawaiian Earthquake and Tsunami: Evidence of Progressive Volcanic Flank Failure?

LIN, J., University of Oregon, Oregon, USA, jiunting@uoregon.edu; MELGAR, D., University of Oregon, Oregon, USA, dmelgarm@uoregon.edu; THOMAS, A. M., University of Oregon, Oregon, USA, amt.seismo@gmail.com

Large earthquakes occur at boundary of the volcanic edifice and the old Pacific Plate in the Hawaii islands. These earthquakes, including the 1868 M8.0 Kau, Hawaii and the 1975 M_w7.7 Kalapana earthquake also generated large tsunamis that caused serious damage and casualties. However, the mechanism of these tsunamis is not well understood. Previous research postulated that the 1975 tsunami was triggered by the combination of faulting and slumping of the weak volcanic flank caused by strong shaking. In this study, we focus on the most recent 4 May 2018 M_w6.9 Kilauea, Hawaii earthquake and its tsunami to understand whether the anomalous tsunamis of these can be explained by ongoing flank collapse.

Thirty-one near-field GPS data and nine strong motion data are used to jointly invert for a source model of the 2018 M_w6.9 earthquake. We then forward model the coseismic seafloor deformation and the ensuing tsunami. Our preliminary results from the joint inversion show that the earthquake-driven component cannot explain the tsunami records completely. This discrepancy is further analyzed by carrying out a tsunami ray tracing analysis, where an additional far-field tide gauge and a Deep-ocean Assessment and Reporting of Tsunami (DART) buoy data are used to constraint the location of the tsunami source using the measured travel times. This suggests that the tsunami is likely, at least in part, driven by a coseismic landslide.

The mechanism of submarine landsliding in Hawaii is of broad interest for the natural hazards community. Geologic evidence shows that at least 15 large landslides associated with volcanic processes have generated megatsunamis with interpreted run up as large as 300 m. Tsunamis in the Hawaiian Islands can cause widespread devastation, so our understanding of the 2018 M_w6.9 earthquake, its tsunami, and the relationship between different tsunamigenic sources is important for understanding and quantifying tsunami hazards in Hawaii.

Source Mechanism of Caldera Collapse Events During the 2018 Kīlauea Volcano Eruption

DAWSON, P., U.S. Geological Survey, California, USA, dawson@usgs.gov.

The 2018 eruption of Kīlauea Volcano produced voluminous lava flows from the Lower East Rift Zone that were accompanied by continuous deflation at the summit of the volcano. Sixty-two semi-regular collapse events at the summit caldera resulted in about 4 km^2 of the caldera dropping between 100–400 m. Total volume loss at the summit over the 3-month-long eruption estimated by differencing pre- to post-eruption digital elevation models was ~825×10^6 m^3. Previous studies of very-long-period (VLP) seismicity at Kīlauea have illuminated the shallow magmatic transport system as a composite of near-vertical dikes featuring an east striking dike intersecting a north striking dike near the northeast corner of the Halema`uma`u pit crater. VLP seismicity from a source centroid positioned on this intersection near sea level has been observed since the deployment of broadband sensors in 1994. The dominant component of motion for each of the collapse events as observed on the horizontal components of the local broadband seismometers is a simple step in ground displacement. Geodetic observations indicate this signal is originating in ground tilt. Waveform inversion of the raw seismic data with Green's functions convolved with both displacement and tilt responses of the broadband instruments illustrates a source mechanism consisting of rapid inflation of the underlying dike system over of period of 5–10 s that overprints the continuous deflation of the dike system. This behavior is similar in character to that observed in previous years when piecemeal collapses of wall rock impacted the lava lake in the Overlook pit crater. Using a simple lumped parameter model of the magmatic system, the mass of each collapse event associated with the inflationary step is estimated to be ~1.6×10^6 m^3 for the first 12 events and ~16×10^6 m^3 for the remaining 50 events. The sum of all collapse events is ~824×10^6 m^3 suggesting a remarkable conservation of mass between the draining of the summit magmatic system and associated collapse events.

Non-Traditional Application of Seismo-Acoustics for Non-Traditional Monitoring

Poster Session · Friday · 26 April · Fifth Avenue

On the Use of Seismo-Acoustic Signatures for Power-Level Classification at an Industrial Facility

RAMIREZ, C. A., Oak Ridge National Laboratory, Tennessee, USA, ramirezca@ornl.gov; CHAI, C., Oak Ridge National Laboratory, Tennessee, USA, chaic@ornl.gov; MACEIRA, M., Oak Ridge National Laboratory, Tennessee, USA, maceiram@ornl.gov; MARCILLO, O., Los Alamos National Laboratory, New Mexico, USA, omarcillo@lanl.gov

In a broad sense, industrial operations may be attributed to the initiation-or-termination of machine processes and changes in operational state configurations (*e.g.* power consumption, speed level, and frequency). These operational activities, within or adjacent to industrial facilities, generate mechanical energy that may propagate into the earth and air as seismic and acoustic waves, respectively. The types and intensities of the seismo-acoustic signals vary according to machinery and their relative location with respect to sensors. For example, seismo-acoustic signals recorded in close-range to a facility display a mixture of multiple harmonics with corresponding overtones embedded in broad band noise.

We have analyzed continuous seismo-acoustic data from a permanent station nearby the High Flux Isotope Reactor (HFIR) at Oak Ridge National Laboratory (ORNL). HFIR is an 85 MW research reactor and runs on an operational cycle of about 24 days, followed by an outage period. For each cycle, the reactor starts with a set of increasing power-levels (10%, 30%, 50%, 70% and 90%) before reaching full capacity. The recorded seismo-acoustic data provide us an opportunity to monitor power-levels using sensors outside the facility. Seismo-acoustic data corresponding to multiple cycle start-ups are extracted and compared to facility-operation ground–truth information. We will present results on the automatic classification of reactor start-up power-levels obtained by training machine learning models on these continuous seismo-acoustic data.

A New Approach for Lightning Infrasound Detection Using Ground and Balloon-Based Instruments

TRAPHAGAN, J. W., University of North Carolina at Chapel Hill, North Carolina, USA, juliant@live.unc.edu; LEES, J. M., University of North Carolina at Chapel Hill, North Carolina, USA, jonathan.lees@unc.edu; LAMB, O., University of North Carolina at Chapel Hill, North Carolina, USA, olamb@email.unc.edu

Infrasound recorded by airborne and ground-based instruments can be used cooperatively to locate and identify acoustic signals generated by events of unknown source location. A linear inversion method for determining the azimuth and source location of an infrasound signal is presented as an alternative to Progressive Multi-Channel Correlation (PMCC) [Cansi, 1995]. This method estimates both azimuth and inclination of incoming plane waves at a sensor array, mitigating some limitations presented by the PMCC algorithm. These methods are applied to events detected (1.4-3.3Pa) during a nearby (30-500km north) storm (data acquired from WWLLN) by the ground-based IMS station IS36 in Chatham Islands, New Zealand on May 24, 2016. Source to receiver raypaths are used to estimate the infrasound travel times at the IS36 array. The travel time estimates correlate to 6 ground station arrivals, suggesting that the detections are storm-generated. Plane wave inversions indicate that the events originate from azimuths ranging -14 to 9 degrees from North with inclinations ranging 43 to 56 degrees from horizontal, further supporting the source locations. A total of 9 events detected by a balloon-borne infrasound microphone (Bowman & Lees, 2016; Lamb *et al.*, 2018) traveling at mid-stratospheric altitudes approximately 445km southwest of the IS36 array will be presented as candidates for secondary lightning detections.

Seismo-Acoustic Responses of Explosions, Mining and Machining in Different Geological Materials: A Parametric Study of Different Emplacements and Different Energy Depositions.

EZZEDINE, S. M., Lawrence Livermore National Laboratory, California, USA, ezzedine1@llnl.gov; VOROBIEV, O. Y., Lawrence Livermore National Laboratory, California, USA, vorobiev1@llnl.gov; YODER, M. K., Lawrence Livermore National Laboratory, California, USA, yoder6@llnl.gov; RODGERS, A. J., Lawrence Livermore National Laboratory, California, USA, rodgers7@llnl.gov; ANTOUN, T. H., Lawrence Livermore National Laboratory, California, USA, antoun1@llnl.gov; WALTER, W. R., Lawrence Livermore National Laboratory, California, USA, walter5@llnl.gov

We have performed quasi-3D high-resolution numerical simulations of surface and underground explosions using LLNL's massively parallel eulerian hydrocode GEODYN to assess the impact of parameters such as, first, yield from explosion sources and noise sources from mining and industrial machining; second, height & depth of burst (HOB and DOB, respectively) of explosions versus mining and industrial machining emplacements; and, third, geological material on the overall source resulting overpressure in air and seismic motions at distance. The material properties span a large spectrum from hard rock, such as granite with low porosity, limestone, sandstone, tuff, salt, and very weak material, such as dry and wet alluvium. Arrival times to surface station are determined by the shock wave propagation and the coupling of ground motion. We show that for explosion overpressures and peak velocities due to the same yield at the same scaled HOB/DOB are functionally very similar regardless the geological fabric and therefore the response can be scaled. Moreover, the impulse is calculated by integrating the initial positive pressure time-history. It was found that the functional form of the impulse as a function of scaled HOB/DOB is also consistent for emplacements above ground, at ground level and down to depths where cratering occurs regardless for all geological materials even though the material properties show drastic geomechanical variations. While the current study used numerical simulation from idealized settings, additional factors can complicate observed seismo-acoustic signals and bias the amplitudes and subsequent source characteristics signatures and emplacements estimates. For example, we show that the emplacement geological uncertainties strongly impact the seismo-acoustic amplitudes and could impede source and source parameters identification.

Monitoring of Industrial Facilities With Telecom Fiber Optics

RAY, W., Oak Ridge National Laboratory, Tennessee, USA, raywr@ornl.gov; RAMIREZ, C. A., Oak Ridge National Laboratory, Tennessee, USA, ramirezca@ornl.gov; POSKA, M., Oak Ridge National Laboratory, Tennessee, USA, poskamj@ornl.gov

Distributed acoustic sensing (DAS) technologies are able to convert a long stretch of optical fiber into a dense array of sequential strain sensors. While routinely used for oil & gas exploration and perimeter monitoring, the spatial diversity of sensors offered by this technology could potentially be leveraged to complement existing suites of sensors deployed in industrial monitoring applications. We report empirical measurements collected with telecommunications fiber infrastructure serving the High Flux Isotope Reactor (HFIR) and the Radiochemical Engineering Development Center (REDC), a research reactor and processing facility complex at the Oak Ridge National Laboratory. Analysis of the collected signals reveals features of distinct subsystems supporting primary operations both inside and outside of these facilities. Algorithms enabling online monitoring of the status of identified systems are being developed to demonstrate the potential of DAS to provide local or global real-time state of health assessments in complex operational environments.

Non-Traditional Application of Seismo-Acoustics for Non-Traditional Monitoring

AHUJA, K. K., Georgia Institute of Technology, Georgia, USA, krish.ahuja@gtri.gatech.edu

This talk discusses on-going research at Georgia Tech Research Institute (GTRI), the applied research arm of Georgia Institute of Technology, in non-traditional application of Seismo-acoustics for Non-traditional Monitoring. In particular it deals with connection between seismic activity related to industrial machinery and Infrasound. In particular, results of a study that compared a number of commercially available infrasound sensors with and without a wind screen loaned to GTRI by NASA Langley will be presented. Sources of producing controlled infrasound under consideration at GTRI will also be discussed. These include a sonic boom simulator, a low frequency acoustic driver, oscillating jets, and door opening and closing. Each source was most effective in a given frequency range. Controlled infrasound at 0.1 Hz was obtained by varying the exit Mach number of exit Mach number of a cold plume from very low Mach number to a high Mach number at a nominal frequency of 0.1 Hz. It is expected that the amplitude of this signal will increase by heating the jet. Preliminary results of successful attempts at removing wind noise using Wavelet methodology are also shown. Characteristics of seismic signals from a fan and a compressor in a building together with related infrasound will be discussed. The implication of such research on monitoring industrial machinery activity will be summarized.

Environmental Seismology: Glaciers, Rivers, Landslides and Beyond

Poster Session · Friday · 26 April · Grand Ballroom

Geochemical Characteristics of Underground Fluid Observation Points in the North Tianshan

GAO, X., Institute of Crustal Dynamics, China Earthquake Administration, Beijing, China, gaoxq06@126.com

In the process of underground fluid observation about earthquake, the characteristics of groundwater recharge sources, circulation and evolution are the basis for earthquake precursor analysis relevant to underground fluid. Currently, the methods of water chemistry, environmental isotopes and groundwater dating are becoming useful tools in the research on the groundwater recharge and evolution. These methods also can be used to both study the hydrogeological environment of underground fluid observation sites and analyze the groundwater recharge sources and circulation of the sites, all of which will provide theoretical evidence and reference information to analyze earthquake precursory.

The groundwater chemistry types, water-rock interaction, groundwater reservoir temperature, circulation depth, recharge sources and height of the underground fluid observation sites in the study areas were analyzed and calculated, as well as groundwater age.

The study on the hydrogeology environment of underground fluid monitoring sites in earthquake belts will contribute to the application of water chemistry, environmental isotopes and groundwater dating in earthquake monitoring field. Although the methods especially groundwater dating have been applied few times in the science and research of earthquake underground fluid, they can be widely used in the near future according to the examples of relevant subjects.

Estimations of Ambient Seismic Noise Sources Around Antarctica From Waveform Inversions of Multi-Component Rayleigh-Wave Crosscorrelations

XU, Z., Boise State University, Idaho, USA, zongboxu@u.boisestate.edu; MIKESELL, T. D., Boise State University, Idaho, USA, dylanmikesell@boisestate.edu; MORDRET, A., Massachusetts Institute of Technology, Massachusetts, USA, mordret@mit.edu; GRIBLER, G., Boise State University, Idaho, USA, gabegribler@u.boisestate.edu

The ambient seismic noise source distribution is a critical, and often under characterized, component of ambient noise imaging and monitoring methods. In practice, seismic sources are non-uniformly distributed around receivers, which leads to errors when the cross-correlation results are interpreted as Green's functions. The cross-correlations themselves contain both source and structure information, and one must unravel the source information if one wants to estimate structure information from noise correlations. Complimentary to the structure information, estimates of the source location(s) are useful to study and monitor source processes. Here we present a source location inversion scheme based on full-waveform inversion of ambient noise cross-correlations to provide an accurate estimation of sources in and around the Antarctic continent. We compare our results with other source imaging methods (*e.g.* matched-field processing). We have implemented a fully elastic waveform inversion, and we will discuss the use of different misfit functions (*e.g.* full waveforms or travel-time) in the source inversion process. We discuss related sensitivities to inversion parameters (*e.g.* the starting model) and explain the physics behind the different types of source kernels derived from the misfit functions. Finally, we discuss the benefits of using the multicomponent cross-correlations during noise estimation as opposed to only the vertical component correlations.

Tidally Induced Cryoseismicity Observed Along the Periphery of the Ross Ice Shelf, Antarctica

COLE, H., Colorado State University, Colorado, USA, hankmcole@gmail.com; ASTER, R., Colorado State University, Colorado, USA, rick.aster@colostate.edu; BAKER, M. G., Colorado State University, Colorado, USA, michael.g.baker@colostate.edu; CHAPUT, J., University of Texas El Paso, Texas, USA, jchaput82@gmail.com; WIENS, D. A., Washington University in St. Louis, Missouri, USA, doug@wustl.edu; STEPHEN, R. A., Woods Hole Oceanographic Institution, Massachusetts, USA, rstephen@whoi.edu; NYBLADE, A., Pennsylvania State University, Pennsylvania, USA, aan2@psu.edu; BROMIRSKI, P. D., Scripps Institution of Oceanography, California, USA, pbromirski@ucsd.edu; GERSTOFT, P., Scripps Institution of Oceanography, California, USA, pgerstoft@ucsd.edu

Repeating swarms of local cryoseismic events were recorded by a broadband seismic network deployed on the Ross Ice Shelf, Antarctica from late 2014 to early 2017. The swarms are observed exclusively at stations near the grounding line. They occur in phase with modeled tidal cycles and produce peak seismicity with an approximate 90° phase lag following high tide. Swarms commonly persist for over 6 hours, gradually increasing in event intensity and frequency before terminating abruptly to pre-swarm background levels. Total swarm intensity correlates with the modeled tide range, which is highly variable in the Ross Sea. Swarm seismicity may also be sensitive to seasonal changes in environmental conditions. Waveforms also show that events originate from multiple distinct source regions. Signals from these regions trigger repeatedly, resulting in families of events with similar seismograms. Our work aims to locate the source regions and determine their seismogenic processes. Particle motion analysis shows that the seismograms are dominated by Rayleigh waves, so we use surface wave analysis to constrain their mechanism and location. Given azimuthal and perhaps range (determined from dispersion) information, source regions can be constrained then evaluated via satellite imagery for association with surface features. Preliminary results suggest a shallow source possibly related to crevassing, but other candidate mechanisms will continue to be explored. Additionally, we will analyze swarm aggregate metrics and statistics to quantitatively examine how mechanisms vary spatially and evolve over time and through tidal variations. We hypothesize that these swarms arise from increasing tensile stresses during falling tide as bending occurs near the grounded margins. We anticipate that these observations will provide further insight into the dynamics and brittle properties of the ice shelf. This should also guide efforts to observe and utilize this phenomenon to improve understanding of other tidally stressed glacial masses.

Glacier Sliding, Seismicity and Sediment Entrainment

LIPOVSKY, B. P., Harvard University, Massachusetts, USA, brad_lipovsky@fas.harvard.edu; MEYER, C. R., University of Oregon, Oregon, USA, colinrmeyer@gmail.com; ZOET, L. K., University of Wisconsin Madison, Wisconsin, USA, lzoet@wisc.edu; HANSEN, D. D., University of Wisconsin Madison, Wisconsin, USA, ddhansen3@wisc.edu; GIMBERT, F., Université Grenoble Alpes, CNRS, IRD, Institut des Geosciences de l'Environnement, Grenoble, France, florent.gimbert@univ-grenoble-alpes.fr; REMPEL, A. W., University of Oregon, Oregon, USA, rempel@uoregon.edu

Ice sheet stability depends on the resistance to ice sliding provided by the subglacial ice—sediment interface. Glacier basal seismicity due to small-scale stick-slip motion provides a window into sliding processes. Stick-slip motion requires an interface with reduced resistance under increased sliding or sliding rate, a property called rate-weakening friction. Experimental studies of ice slip over glacial materials, however, often exhibit rate-strengthening friction. Here, we argue that this apparent paradox may be resolved by invoking rate-weakening rock-on-rock friction between sediments frozen to the bottom of the glacier and the underlying water-saturated sediments. We present laboratory experiments and numerical simulations using a simplified viscoelastic model of small-scale stick-slip motion. We find that sediment freeze-on and stick-slip both require high effective normal stress. Sediment entrainment therefore provides a mechanism by which rock-on-rock friction may occur at glacier beds and produce small-scale stick-slip motion. At extremely high effective normal stress, however, seismicity is suppressed in favor of viscous flow. Stick-slip motion and stagnation at the Whillans Ice Stream, Antarctica may be caused by sediment entrainment due to increasing effective normal stress. Our results suggest that glacier bed seismicity due to stick-slip motion may be used to infer subglacial geomorphic activity.

A Multidisciplinary Study of Shallow Water Microseisms in Yellowstone Lake

KOPER, K. D., University of Utah, Utah, USA, koper@seis.utah.edu; FARRELL, J., University of Utah, Utah, USA, jamie.farrell@utah.edu; BURLACU, R., University of Utah, Utah, USA, burlacu@seis.utah.edu; SOHN, R. A., Woods Hole Oceanographic Institution, Massachusetts, USA, rsohn@whoi.edu

It has recently been observed that wind-driven waves on Yellowstone Lake generate significant microseismic energy at a period of ~1 s. This setting provides a near-ideal laboratory for probing the origin and propagation of shallow water microseisms because it is a relatively small, closed system with a regular diurnal pattern of microseism excitation. In the summer of 2018, we deployed a suite of instruments to monitor Yellowstone Lake microseisms. We deployed 40 5-Hz, three-component, Nodal seismometers around the perimeter of the lake and on three islands within the lake, 4 meteorological stations recording wind speed and direction, and two wave gauges recording wave speed and direction. This instrumentation complemented a separate, ongoing deployment of 10 lake-bottom seismometers (HD-YLAKE project) as well as the 7 permanent land-based seismometers that border on the lake and are part of the Yellowstone Seismic Network. Initial analyses of these datasets illustrate the tightly coupled nature of the processes that generate microseisms, starting with sustained winds that generate gravity waves on the lake surface. The amplitude and period of the lake waves increase until the fetch limited wavefield is saturated with a peak period of ~2 s. Contemporaneously, the amplitude and period of the lake-generated microseisms increase until reaching a peak period of ~1 s. The factor of two difference in peak period suggests that these are double frequency (secondary) microseisms, presumably generated by waves reflected off the shoreline and islands that interact with the primary wavefield.

Sea Ice and the Alaska Transportable Array

ADERHOLD, K., Incorporated Research Institutions for Seismology, District of Columbia, USA, kasey@iris.edu; BRADLEY, A. C., Williams College, Massachusetts, USA, alice.c.bradley@williams.edu; BUSBY, R., Incorporated Research Institutions for Seismology, District of Columbia, USA, busby@iris.edu

The northern coastal seismic stations of the National Science Foundation sponsored EarthScope Alaska Transportable Array are well-positioned to record the seasonal changes in microseism due to the formation and break-up of sea ice. We examine the correlation between noise levels around the 1 Hz frequency band at these stations and sea ice concentration. Power spectral densities and noise spectrograms are requested from the IRIS DMC MUSTANG metric service and sea ice concentrations measurements are obtained from the National Snow and Ice Data Center. Formation of continuous sea ice corresponds to a significant drop in noise at coastal stations, up to a ~25 dB decrease in less than 24 hours. This drop in noise amplitude coincides with the formation of near-shore ice locally, with station A36M exhibiting an earlier drop in noise than A19K which is further to the southwest where sea ice forms later in the season. We can use data from multiple stations recording multiple cycles of sea ice formation and breakup to build on previous investigations both in the Arctic (Tsai and McNamara, 2011) and in the Antarctic (Anthony *et al.*, 2017). Additional datasets for near-shore ice conditions including in-situ observations can also be incorporated to better understand the effect of sea ice on seismic noise.

Monitoring Seismic Velocity Changes in the Coastal and Sinking Sedimentary Basin of Jakarta, Indonesia

DENOLLE, M. A., Harvard University, Massachusetts, USA, mdenolle@fas.harvard.edu; CLEMENTS, T., Harvard University, Massachusetts, USA, thclements@g.harvard.edu; CUMMINS, P., Australian National University, Canberra, Australia, phil.cummins@anu.edu.au

Jakarta exhibits among the fastest subsidence rates on Earth with up to 20 cm/year. It thus exposes over 30 million inhabitants to dramatic flooding due to the rising of ocean levels. Jakarta is also a relatively thick sedimentary basin that is known to amplify ground motions and will likely be prone to intense liquefaction during the next strong earthquake. We use a temporary deployment of broadband seismic stations between 2013 and 2014 to explore the temporal evolution of seismic velocity and seismic attenuation. We use both inter-station and single-station correlation functions in all components of the correlation tensor to map the changes at various spatial scales. We also explore the stability of our results with various methodologies to measure changes in seismic velocities (*e.g.*, moving window cross spectrum, stretching, dynamic time warping, and wavelet cross-spectrum). These changes in velocity and attenuation yield changes in future ground motions, which we quantify using ground motion prediction equation and pseudo-analytical wave modeling. Finally, we correlate our results with remote sensing observation of land subsidence.

Seismic Observations of Precipitation and Recharge-Related Signals in the Floridan Aquifer at Santa Fe River Sink and Rise, Florida

GOCHENOUR, J. A., New Mexico Institute of Mining and Technology, New Mexico, USA, jacob.gochenour@student.nmt.edu; BILEK, S., New Mexico Institute of Mining and Technology, New Mexico, USA, susan.bilek@nmt.edu; GRAPENTHIN, R., New Mexico Institute of Mining and Technology, New Mexico, USA, rg@nmt.edu; LUHMANN, A. J., Wheaton College, Illinois, USA, andrew.luhmann@wheaton.edu; MARTIN, J. B., University of Florida, Florida, USA, jbmartin@ufl.edu; BARBOSA, S. A., New Mexico Institute of Mining and Technology, New Mexico, USA, sergio.barbosa@student.nmt.edu

Environmental seismology encompasses a broad range of Earth surface processes. Such studies have primarily focused on hillslopes to obtain information on landslides, on glaciers to investigate ice movement and subglacial water flow, and on rivers to characterize turbulent flow, discharge, bedload, and sediment transport. However, environmental seismology has not been fully utilized to investigate the unique subsurface processes which occur within a karst aquifer. Monitoring karst systems is of growing concern due to the significant percentage of people who rely on them as a source of fresh water as well as for hazard assessment related to sinkhole formation. In May 2018, we deployed two co-located geophysical arrays to observe recharge-induced responses of subsurface water flow in a karstic conduit network known as the Santa Fe River Sink-Rise system in north-central Florida, which is where the Santa Fe River (average 31 m^3/s) is captured by a sinkhole and flows ~6 km through a network of water-filled caves to River Rise, a first magnitude spring. The first of these arrays is a seismic network consisting of 12 L-22 and two broadband (CMG 3T) seismometers, and the second consists of two platform and four borehole tiltmeters. We also deployed 19 hydrologic sensors (4 level and temperature, 14 level, temperature, and conductivity, and 1 barologger) in 11 wells, five karst windows, and at River Sink and River Rise, and are collecting meteorological data onsite. Based on preliminary review of the seismic data, we find increases in seismic amplitudes and power in frequency bands of 1-150 Hz during and subsequent to significant precipitation events of at least 10 mm over a half-hour span. Given the presence of a signal after precipitation ceases, additional processes beyond simply the precipitation must contribute to the seismic signals, for instance discharge related pressure pulses. Further examination of the seismic data, reinforced through modeling, tilt, hydrologic, and meteorological data, should elucidate the specific processes generating the observed signals.

Towards a Probabilistic Model of Fluid Pressure Changes During Earthquakes

WEAVER, K. C., Victoria University of Wellington, Wellington, New Zealand, konrad.weaver@vuw.ac.nz; ARNOLD, R., Victoria University of Wellington, Wellington, New Zealand, richard.arnold@vuw.ac.nz; TOWNEND, J., Victoria University of Wellington, Wellington, New Zealand, john.townend@vuw.ac.nz; COX, S. C., GNS Science, Dunedin, New Zealand, s.cox@gns.cri.nz

In the last decade, New Zealand has experienced several large earthquakes that have induced widespread hydrological changes in groundwater systems. This provides a rare opportunity to develop a probabilistic model of aquifer susceptibility to earthquake-induced groundwater changes as a function of shaking intensity. Persistent groundwater-level changes, or absences of change, have been quantified in 495 monitoring wells in response to one or more of 11 New Zealand earthquakes larger than Mw 5.4 between 2008 and 2017. We apply a binary logistic regression model with random effects to the dataset and examine the effects of three predictors: earthquake shaking (peak ground velocity), degree of hydrogeological confinement (monitoring well depth), and rock strength (site average shear-wave velocity). The model also accounts for variations in monitoring wells' susceptibilities to earthquake-induced persistent water-level changes. We calculate marginal probabilities as a function of the three predictors and of Modified Mercalli Intensity (MMI). This enables us to quantify the likelihood of persistent water-level changes for MMI levels II–VIII. Our study constitutes a regional-scale, multi-site, multi-earthquake investigation of the occurrence and absence of hydraulic responses to large earthquakes spanning almost a decade of seismic shaking. It is a first attempt at incorporating seismic and hydrogeological factors in a common probabilistic description of earthquake-induced groundwater level changes. Although focused to date solely on New Zealand data, the modeling framework we have developed provides a more generalizable approach to quantifying hydrological responses to earthquakes than alternative metrics based on epicentral distance, magnitude and seismic energy density, and one which we anticipate being of use to both the scientific and engineering communities alike.

Using Ambient-Noise Based Ellipticity and Delay Times to Probe Groundwater Changes in Southern California

SYRACUSE, E. M., Los Alamos National Laboratory, New Mexico, USA, syracuse@lanl.gov; DELOREY, A. A., Los Alamos National Laboratory, New Mexico, USA, andrew.delorey@lanl.gov; GOLDBERG, H., Case Western Reserve University, Ohio, USA, hsg26@case.edu; MUIR, J. B., California Institute of Technology, California, USA, jmuir@caltech.edu

In recent years, a dramatic and unsustainable mining of groundwater, our largest fresh water source, has taken place in the western US, with depletion rates currently at their highest. Paired with periods of drought in as much as a third of the contiguous US, the monitoring of groundwater resources is increasingly important. How do aquifers respond to stresses such as increased withdrawal rates and droughts? What does the end of a drought mean for groundwater availability? We employ temporal monitoring of ambient-noise-based horizontal-to-vertical amplitude measurements (H/V, or ellipticity) and delay times of Rayleigh waves to reflect changing conditions within the shallow subsurface. Both types of measurements are promising for monitoring changes at shallow depths relevant to groundwater, and they are complementary in their relative sensitivities to the near-sensor and integrated-path structure between sensors, respectively. We present results of this analysis for southern California for 2000-present using data from stations in the CalTech Regional Seismic Network. Notable features observed are long-term changes in H/V interpreted to be groundwater signals and seasonal variability in H/V from a variety of sources.

Seismoacoustic Insights From the May 22nd, 2016 Iliamna Volcano Rock and Ice Avalanche

TONEY, L. D., Alaska Volcano Observatory, Geophysical Institute, University of Alaska Fairbanks, Alaska, USA, ldtoney@alaska.edu; FEE, D., Alaska Volcano Observatory, Geophysical Institute, University of Alaska Fairbanks, Alaska, USA, dfee1@alaska.edu; HANEY, M., U.S. Geological Survey, Alaska Volcano Observatory, Alaska, USA, mhaney@usgs.gov; MATOZA, R. S., University of California, Santa Barbara, California, USA, rmatoza@ucsb.edu; ALLSTADT, K. E., U.S. Geological Survey, Geologic Hazards Science Center, Colorado, USA, kallstadt@usgs.gov

Landslides occur around the world and can have devastating impacts in populated areas. Seismoacoustic signals produced by these hazardous events may permit quick landslide location and characterization, even when they occur in remote regions. Such information could enable a more rapid and effective emergency response. Here, we jointly apply seismic and infrasound techniques to characterize a large rock and ice avalanche which occurred on Iliamna volcano, Alaska on May 22nd, 2016. Iliamna is a glacier-mantled composite stratovolcano located ~200 km from Anchorage, Alaska. The subglacial rocks near its summit are weakened by hydrothermal activity, resulting in sporadic catastrophic avalanches. Seismic signals from the May 22nd event were observed out to ~230 km on more than 20 stations in the region. The event also produced energetic acoustic signals recorded on at least 10 stations, including two arrays and six EarthScope Transportable Array (TA) stations. We model infrasound propagation via the AVO-G2S open-source atmospheric specification to separate acoustic source directionality from propagation-biased directionality. We also apply the transverse coherence minimization method (Haney, 2018) to select TA stations to determine the source velocity from backazimuth variation over time. We additionally perform a single-force inversion on very-long-period (20–250 s) seismic data from the event to determine the centroid force vector for the avalanche, which we compare to a traditional moment tensor inversion. Lastly, we relate our findings to independent information derived from remote sensing and land-based imagery. We aim for these analyses to eventually be useful in an operational real-time monitoring context.

Reference:

Haney, M. M. (2018). Volcanic explosion backazimuth from near-surface seismo-acoustic coupling minimization, Abstract NS44A-06 presented at the 2018 AGU Fall Meeting, Washington, D.C., 10–14 Dec.

Seismic Monitoring of Mass Wasting Events Following the 2017 Brian Head Wildfire in Southern Utah

FORBES, N. M., University of Utah, Utah, USA, nicholasforbes95@gmail.com; KOPER, K. D., University of Utah, Utah, USA, koper@seis.utah.edu; BURLACU, R., University of Utah, Utah, USA, burlacu@seis.utah.edu; JEWELL, P., University of Utah, Utah, USA, paul.jewell@utah.edu

During the 2017 Brian Head wildfire in southern Utah, over 63,000 acres of steep terrain was burned, leaving hydrophobic soil and an increased probability of mass wasting, especially during the annual monsoon season of July through September. Following the fire, we began a two-year experiment with the goal of capturing the seismic signature of debris flows and related events. Between 12 August 2017 and 7 October 2017, we deployed ten 3-component, short-period (Sercel L-28) seismometers in a quasi-linear array about 10 km long. The instruments were provided by IRIS/PASSCAL (with the network code ZV) and recorded continuous ground motion at 250 Hz. We applied frequency-dependent

polarization analysis to the continuous data and observed a strong diurnal pattern across a wide frequency range as well as some weather-related transient signals, possibly related to thunder; however, we did not record any signals unambiguously related to mass wasting. We returned to the Brian Head region the following year and between 31 July 2018 and 7 October 2018 we deployed 28, 5-Hz, 3-component Nodal instruments recording continuous ground motion at 500 Hz. We installed a linear, 20-node array with ~275 m spacing along a creek that flowed consistently throughout the experiment and at increased rates during and after rainfall. The remaining eight Nodals followed separate drainages towards a NW-SE running ridge at a gradient of ~30 degrees. Three trail-cameras were also deployed in hopes of having time-stamped evidence of any mass wasting events. We processed the 2018 seismic data with frequency-dependent polarization code and correlated the output with meteorological data from a nearby NOAA station. We tentatively identified ~12 signals related to mass wasting events and are currently characterizing their duration and intensity.

Microseismicity Detection Across the Antarctic Continent

WALTER, J., University of Oklahoma, Oklahoma, USA, jakeiwalter@gmail.com; PENG, Z., Georgia Institute of Technology, Georgia, USA, zpeng@gatech.edu; ROSSON, Z., University of Oklahoma, Oklahoma, USA, zachrosson@ou.edu; HANSEN, S., University of Alabama, Alabama, USA, shansen@ua.edu

Though the Antarctic continent has been vastly unexplored due to obvious constraints, the last decade of scientific investment has yielded numerous regional- and continent-scale seismological experiments carried out by researchers. The public archiving of those data at the IRIS Data Management Center makes unintended discoveries possible. As an example, we utilize broadband seismic data from a recent experiment (TAMNNET), which was originally proposed as a structural seismology experiment across the Transantarctic Mountain area of Victoria and Oates Land, for detecting local seismic events. Most of the seismicity emanates from David Glacier, upstream of the Drygalski Ice Tongue, which has been documented by several other studies; however, additional areas include clusters of activity. In order to improve the catalog completeness for the David Glacier area, we utilize a matched-filter technique (also known as template matching) to detect potential missing earthquakes that may not have been originally detected. We expand this analysis and utilize existing phase picks for machine learning applications and compare the relative effectiveness between template matching and machine learning approaches. We have also downloaded other regional- and continental-scale seismological datasets from Antarctica and preliminary results suggest abundant small-magnitude seismicity that may illuminate interesting ice-dynamic, tectonic, or a combination of both processes. We plan to use machine-learning techniques to automatically classify different types of seismic events recorded around the Antarctic continent. Updated results will be presented at the meeting.

Using Repeating Seismicity to Probe Active Faults

Poster Session · Friday · 26 April · Grand Ballroom

A Repeating Earthquake Catalog for New Zealand

CHAMBERLAIN, C. J., Victoria University of Wellington, Wellington, New Zealand, calum.chamberlain@vuw.ac.nz; TOWNEND, J., Victoria University of Wellington, Wellington, New Zealand, john.townend@vuw.ac.nz; HUGHES, L., Victoria University of Wellington, Wellington, New Zealand, hugs.l.1997@gmail.com; THOMAS, A. M., University of Oregon, Oregon, USA, amt.seismo@gmail.com

Repeating earthquakes have the potential to elucidate dynamic processes at depth on faults. In particular, recent work has shown that repeating earthquakes may provide a means for measuring deformation rates at depth. Furthermore, slip-rates derived from repeating earthquakes appear to change throughout the seismic cycle. New Zealand's diverse tectonics provide an ideal setting to test ideas on how we interpret repeating seismicity. Thanks to the efforts of New Zealand's national seismograph network, GeoNet, New Zealand has an incredible archive of digital data spanning from the late 1980s. This long-duration dataset permits the study of repeating earthquakes over a range of inter-event times and magnitudes.

We have analysed the New Zealand earthquake catalog from 1987 to 2018 to look for repeating earthquakes and are currently building the first nationwide catalog of repeating seismicity for New Zealand. During this period more than 500,000 earthquakes were cataloged, of which we analyse the 391,688 for which digital data and seismograph response information are available. From this initial catalog we cross-correlate all available channels for nearby events to obtain a catalog of possible repeaters. This catalog contains a strong contribution from swarms, aftershock sequences and volcano seismicity as well as classical repeating events. Repeaters cluster on the Fiordland subduction zone, at the transition from southern to central Alpine Fault, and at various locations along the northern Hikurangi subduction margin. Deep repeating seismicity occurs beneath the Taupo volcanic zone, as well as appearing to locate on the deep extent of the southern Hikurangi margin. Further work remains to precisely relocate all events and separate true repeaters from clustered seismicity.

Systematic Search for Repeating Earthquakes Along Haiyuan Fault in Northeast Tibet

DENG, Y., Guangzhou Institute of Geochemistry, Chinese Academy of Sciences, Guangzhou, China, yangfandeng345@gmail.com; PENG, Z., Georgia Institute of Technology, Georgia, USA, zpeng@gatech.edu; YANG, Z., China Earthquake Networks Center, Beijing, China, 308191147@qq.com

The Haiyuan fault is a major left-lateral fault along the northeastern boundary of Tibet Plateau. Since the 20th century, two great earthquakes (1920, Ms8.5; 1927, Ms8.0) have occurred on this fault. The Tianzhu seismic gap was sandwiched between these two earthquake rupture zones. Shallow creep has been observed from geodetic data along some portion of the Haiyuan fault (Jolivet *et al.*, 2013). However, it is still not clear the depth extent of shallow creep, and whether it is capable of driving repeating microearthquakes that occur virtually at the same location at different times. Here we conduct a systematic search for repeating earthquakes along the Haiyuan fault based on the 10 years seismic data. Specifically, first, we compute cross-correlations (CCs) among all events listed in the regional earthquake catalogue, and identify all repeating event pairs with median (or mean) CC value above 0.90. We then group repeating pairs into clusters using an Equivalency Class (EC) algorithm. Finally we extract differential times for P and S waves and use hypoDD program to relocate them in each cluster. Our next step is to recompute their stress drops and average slips, and use them to estimate the aseismic creep at depth. We also plan to use them to measure temporal changes of seismic velocity at depth. Updated results will be presented at the meeting.

State of Stress and Strain in the Crust and Implications for Fault Slip Based on Observational, Numerical and Experimental Analysis

Poster Session · Friday · 26 April · Grand Ballroom

Uppermost Mantle Velocity and Anisotropy Beneath Mongolia and Its Adjacent Regions

HE, J., Institute of Crustal Dynamics, China Earthquake Administration, Beijing, China, hejing11@163.com

In order to image the lateral variations of seismic velocity and anisotropy within the uppermost mantle underneath Mongolia and the adjacent regions, travel times of 198,390 Pn arrivals from earthquake at regional distances are inverted. Our model resolution width of 2°×2° are achieved in the study region, with the capacity of distinguishing small-scale geological features. The average velocity of the mantle lid is 8.18 km/s, substantially faster than the global average. We also measured azimuthal anisotropy in the upper and lower mantle lid by grouping the travel time data into two different epicentral distance ranges. Strong lateral variations in Pn velocity of the uppermost mantle underneath the most active zone of Baikal rift is presented. In the Southern and Northern Baikal rift, clear low Pn velocity is observed, whereas Pn velocity is high in the Central Baikal rift, indicating a strong variation in the amount of lithospheric thinning that has taken place across the Baikal Rift. The obvious depth dependence of Pn anisotropy models within the upper mantle beneath the Hentey Mountains suggests different origins for different fabrics; the deeper anisotropy likely results from asthenospheric flow while the shallower fabric may result from preserved lattice preferred orientation (LPO) anisotropy in the uppermost mantle. Depth-dependent anisotropic structures and significantly low velocity are found beneath the Tien Shan orogenic belt, indicating that the lithospheric mantle is thinning due to delamination or a local asthenospheric upwelling.

Localizing Interseismic Deformation With Far-Field Loading Around Locked Strike-Slip Faults

ZHU, Y., University of Victoria, Victoria, Canada, yjzhu1995@gmail.com; WANG, K., Pacific Geoscience Center, Geological Survey of Canada, Sidney, Canada, kelin.wang@canada.ca; HE, J., Pacific Geoscience Center, Geological Survey of Canada, Sidney, Canada, jiangheng.he@canada.ca; NISSEN, E., University of Victoria, Victoria, Canada, enissen@uvic.ca; CAO, J., Institute

of Earthquake Forecasting, China Earthquake Administration, Beijing, China, caojianl@gmail.com

Localization of interseismic deformation around locked strike-slip faults is widely observed. The fault-parallel velocity is usually modelled by imposing full-rate creep directly below the locking depth. Here we study how localization may occur under far-field tectonic loading without this imposed creep. The Earth can be represented by an elastic lithosphere overlying a viscoelastic asthenosphere. We demonstrate that under end-member conditions the viscoelastic model can be further simplified into equivalent elastic models. For example, the elastic half-space model simulates an unrelaxed asthenosphere (at the beginning of the far-field loading), while the elastic plate model represents a fully relaxed asthenosphere (after many Maxwell times). Therefore, we can use elastic models to study to what degree far-field loading can cause the localization under these conditions. We find that the strike-length and continuity of locking is a key factor. With infinite locking length, little localization occurs in a plate model under any condition. The presence of a weak zone below the locking depth only slightly enhances localization, even in a half space. We show that in a more realistic situation, creeping segments may cause significant localization to adjacent locked segments. The results indicate, for example, localized deformation around the Carrizo segment of the San Andreas Fault is likely associated with its neighboring creeping segment. In addition, we examine the influence of previous earthquakes using viscoelastic models. If earthquake rupture is kinematically imposed to keep pace with long-term fault slip rate, as in the vast majority of earthquake cycle models, numerous earthquakes serve to develop a zone of viscous shear below the locking depth. Our results suggest that this is almost equivalent to imposing full-rate creep below the locking depth. Localization of deformation in a viscoelastic Earth with neither deep creep nor seismic rupture imposed is still an unresolved problem.

A Seismic Event From a Limestone Mine Collapse in Southern Korean Peninsula

KIM, G., Korea Institute of Geoscience and Mineral Resources, Daejeon, Korea, Republic of, gandalf@kigam.re.kr; CHO, C., Korea Institute of Geoscience and Mineral Resources, Daejeon, Korea, Republic of, nemex@kigam.re.kr; CHE, I., Korea Institute of Geoscience and Mineral Resources, Daejeon, Korea, Republic of, che10@kigam.re.kr

We have studied a seismic event which had happened on 23rd February, 2016 in Korea. The event's location has been estimated to be Uljin city in southern Korean Peninsula. Seismic waveforms of the event have shown well developed intermediate period surface waves and weaker body waves with relatively long period signals. This feature of waveforms has not been usual in earthquakes in Korean Peninsula. We have analyzed source characteristics of the event by estimating moment tensor. We have found that the source has non double-couple characteristics. One of our best fit model has been composed 41% CLVD and 58% ISO with Mw 4.4. The moment tensor analysis has shown that the event could be happened from non-tectonic sources like mining activity. Waveform analysis of a station near to the epicenter has shown that several events with smaller size have precede main event. We have surveyed the location and have found that a limestone mine collapse had been resulted in the event.

The 2015 Plainfield, CT Earthquake Swarm: Induced Earthquakes Due to an Abandoned Quarry?

EBEL, J. E., Weston Observatory, Boston College, Massachusetts, USA, ebel@bc.edu; STARR, J., Weston Observatory, Boston College, Massachusetts, USA, jcstarr45@gmail.com; AUBIN, P. W., GEI Consultants, Inc., Illinois, USA, paubin@geiconsultants.com; THOMAS, M. A., Department of Energy and Environmental Protection, Connecticut, USA, margaret.thomas@ct.gov

From January until July 2015 an active earthquake swarm took place in the town of Plainfield, CT. The swarm was preceded by three small earthquakes in October and November of 2014 (M_{Lg} 0.9, 0.6 and 0.9), and it started in earnest on 8 January 2015 with an earthquake of M_{Lg} 2.0. The largest event of M_{Lg} 3.1 took place on 12 January 2015, and it was felt throughout eastern Connecticut and all of Rhode Island. Many of the earthquakes of the swarm were felt or heard by local residents. On 13 January 2015 Weston Observatory, in conjunction with the Connecticut Geological Survey, installed four portable seismographs in the epicentral area to record the swarm events, and those instruments recorded earthquakes to July 2015. Using data from the regional and local seismic stations, at least 180 earthquakes have been confirmed, and the portable instruments contain signals from another 200 detections that may also be very small events. Absolute event locations computed using data from the portable seismic stations trend along the eastern and southwestern sides of a dry abandoned rock quarry at focal depths ranging from about 1.6 km depth to just below the earth's surface. The seismicity along the eastern side of the quarry parallels the 45° west-dipping nodal plane of the pure thrust focal mechanism of the M_{Lg} 3.1 event. The events east of the quarry follow the mylonitic Lake Char Fault zone, a structure that runs from southern Connecticut into Massachusetts. The events southwest of the quarry trend toward the northwest and are on-strike with a northwest-striking fault that is mapped about 3 km northwest of the quarry. The locations of the events in the Plainfield swarm along with the focal mechanism of the largest event suggest that the removal of the rock load from the 20-m deep quarry may have induced this earthquake swarm. Why no earthquakes were detected from this locality until several years after the quarry was abandoned is not known.

22 May 1971 and 1 May 2003 Bingöl Earthquakes in Eastern Turkey

KALAFAT, D., Bogazici University, Istanbul, Turkey, kalafato@boun.edu.tr; CAKIR, R., Independent Researcher, cakir.recep@gmail.com

The Eastern Turkey region is the most tectonically deformed area of the Anatolian plate and is under compression due to the relative movement of the Arabian and Eurasian plates in general. The Anatolian plate bounded by the North Anatolian (NAFZ) and Eastern Anatolian Fault Zones (EAFZ) moves relatively westward. We evaluated Bingol Earthquakes (M> 6.0) occurred in 1971 and 2003 located within the EAFZ and this fault zone occurs due to the movement of the parts.

The most important earthquakes occured in Bingöl area during the instrumental period are the 1971 and 2003 earthquakes. Bingöl Fault starts from the south of Bingöl and extends along the Göynük stream valley. This fault length is about 75 km, which is northern portion of the EAFZ and joins the NAFZ after passing through the villages of Serpmekaya and Sakaören. The 22 May 1971 Bingöl Earthquake surface rupture is followed to Göynük stream and extends southward from Sarıçiçek towards Çeltiksuyu villages. The observed faults showed a strike-slip with a left lateral movement and the fault plane solutions supported the field surface rupture observations.

The other important earthquake occurred on May 1st, 2003, which killed 176 and injured 521 people in nearby living environment. The epicentral area is between the Balıkçay village plateau, Hanoçayırı-Kurtuluş and Sudüğünü Plateau. The macroseismic epicenter of the earthquake is approximately at 12 km distance between the district of Elçağını-Elmaçayırı and Sudüğünü plateaus. It was observed that the epicenter of Bingöl earthquake was highly compatible with the NW-SE trending faults. In this study, we give fault plane solutions of 12 earthquakes (Mw> 5.0) between 1971-2015 time period in Bingöl. Our stress analysis shows that the main stress axes in the region are dominated by NW-SE directional compression and strike-slip faulting characterized by NE-SW extension axes.

Optimized Moment Tensor Inversion in Effective Three-Dimensional Seismic Earth's Model

BURGOS, G., CEA, Arpajon, France, gael.burgos@cea.fr; GUILLOT, L., CEA Centre - DAM France, Arpajon, France, laurent.guillot.blr@gmail.com; LANDES, M., CEA Cemtre - DAM France, Arpajon, France, matthieu.landes@cea.fr; CAPDEVILLE, Y., LPG, Universite de Nantes, Nantes, France, yann.capdeville@univ-nantes.fr; SHAPIRO, N., Institut de Physique du Globe de Paris, Paris, France, nshapiro@ipgp.fr

The robustness of moment tensor inversion for source characterization relies on the accuracy of the Earth's seismic model, and the method used to compute Green's tensor in it.

Many moment tensor inversions are based on Green's functions calculated with approximate methods, which reproduced a limited part of the seismic wavefield, and are built on 1-D models or ad hoc 2-D or 3-D averages.

3-D seismic models and full numerical Green's functions can now be derived thanks to the recent advances in high-performance computing and seismic techniques, but some issues remain: taking the crust into account, or imaging it, still is a difficult task; and if done, the necessary fine spatial discretization for numerical seismic wave propagation within this highly heterogeneous medium, leads to time-consuming simulations, even for long-period signals.

Eventual remedies mainly involves the use of an artificial crustal layer or so-called 'junk crust' (Fichtner & Igel 2008).

We have developed a non-linear, stochastic inversion procedure to generate 3-D models adapted to numerical simulation of the full seismic wavefield.

This probabilistic approach is based on the parametrization of models using an optimized basis of smooth functions constructed by principal component analysis of an effective reference model (using some filtering inherited from the homogenization theory).

It provides a reduced and optimized parameter space for the Bayesian inversion of an ensemble of 1-D seismic models. An appraisal step of the ensemble of models is added to regularize the 3-D model laterally.

Using CUB (Shapiro & Ritzwoller 2002) as a starting block, our procedure allows for the determination of a three-dimensional, effective, seismic Earth model, and of full 3-D Green's functions - procured at a relatively low numerical cost with spectral element's simulations.

As an illustration, we generate optimized 3-D models and associated full 3-D Green's functions to invert for moment tensors associated to several events, and compare the results to those obtained using a more classical procedure.

Seismicity in the Region of the Gulf of California, Mexico From 1900 to 2018

CASTRO, R. R., Centro de Investigación Científica y de Educación Superior de Ensenada, Ensenada, Mexico, raul@cicese.mx; MENDOZA, A., Centro de Investigación Científica y de Educación Superior de Ensenada, Ensenada, Mexico, antonio@cicese.mx; PÉREZ-VERTTI, A., Centro de Investigación Científica y de Educación Superior de Ensenada, Ensenada, Mexico, aperez@cicese.mx

We prepare a catalog of earthquakes that occurred in the region of the Gulf of California, Mexico between 1900 and 2018. The coordinates of the hypocenters were retrieved from catalogs of the National Seismological Service of UNAM (National Autonomous University of Mexico), the Seismological Network of CICESE (Centro de Investigación Científica y de Estudios Superiores de Ensenada, Baja California, México) and the International Seismological Centre (ISC). We also included events recorded by regional stations of the Broadband Seismological Network of the Gulf of California (RESBAN) operated by CICESE and by a temporal array of ocean-bottom seismographs, of the SCOOBA experiment that operated in the southern gulf (Sumy *et al.*, 2013).

The catalog consists of more than 3600 shallow earthquakes with magnitudes M < 7. We also compile focal mechanisms from the GCMT catalog to analyze the tectonic features of the gulf region. The seismicity tends to concentrate along the North America-Pacific plate boundary and the main earthquakes occur on or near the active transform faults, particularly in the southern Gulf of California. However, the spatial distribution of seismicity in the northern gulf is more complex.

Focal Mechanisms of Microseismicity in the San Jacinto Fault Zone Region of Southern California

WHITE, M. C. A., University of Southern California, California, USA, malcolm.white@usc.edu; BEN-ZION, Y., University of Southern California, California, USA, benzion@usc.edu; VERNON, F. L., University of California, San Diego, California, USA, flvernon@ucsd.edu

Earthquake focal mechanisms contain important information on the geometry of fault zones and rupture kinematics, but remain challenging to derive for small earthquakes. Despite recent progress toward applying full-waveform inversion techniques to small earthquakes, such methods remain intractable for most detectable events. Using automated processing procedures, we develop a catalog of >100,000 earthquakes in the magnitude range -1.8 to 5.4 for the San Jacinto fault zone region in Southern California, and then derive focal mechanisms by analyzing P-wave first-motion polarities (FMPs). To overcome the challenge of reliably determining FMP of low-SNR waveforms from small earthquakes, we gather and stack similar waveforms (minimum cross-correlation coefficient of 0.8) to increase SNR. A bootstrap sampling procedure yields a set of stacked waveforms for each similarity-gather (with at least 10 traces), and each stack is independently analyzed for FMP using *PhasePApy* (Chen and Holland, 2016). All arrivals in a single similarity-gather are assigned the same FMP, and the bootstrap procedure yields a measure of stability for the observation. Picks deemed unstable are omitted from further processing, and stable picks are inverted for focal mechanisms using *HASH* (Hardebeck and Shearer, 2002). We will present details of the method, comparisons with conventional single-trace analysis, and features of the focal mechanisms derived for the study region.

Joint Analysis of Seismic, Geologic, Resistivity and Topographic Data Collected Within the San Jacinto Fault Zone Trifurcation Area Near Anza, California

SHARE, P., Scripps Institution of Oceanography, University of California, San Diego, California, USA, pshare@ucsd.edu; ŠTĚPANČÍKOVÁ, P., Institute of Rock Structure and Mechanics, Czech Academy of Sciences, Prague, Czech Republic, petra.stepancikova@gmail.com; TABOŘÍK, P., Institute of Rock Structure and Mechanics, Czech Academy of Sciences, Prague, Czech Republic, petr.taborik@post.cz; STEMBERK, J., Institute of Rock Structure and Mechanics, Czech Academy of Sciences, Prague, Czech Republic, kuba.stemberk@gmail.com; ROCKWELL, T. K., San Diego State University, California, USA, trockwell@sdsu.edu; WADE, A., Arizona State University, Arizona, USA, amwade2@asu.edu; ARROWSMITH, R., Arizona State University, Arizona, USA, ramon.arrowsmith@asu.edu; DONNELLAN, A., Jet Propulsion Laboratory, California Institute of Technology, California, USA, andrea@jpl.caltech.edu; VERNON, F. L., Scripps Institution of Oceanography, University of California, San Diego, California, USA, flvernon@ucsd.edu; BEN-ZION, Y., University of Southern California, California, USA, benzion@usc.edu

We present results from complementary seismic, geologic, DC resistivity and topographic surveys at the Sage Brush Flat site along the Clark fault (CF) in the San Jacinto fault zone trifurcation area southeast of Anza, CA. Joint interpretation of these datasets, each with unique spatiotemporal characteristics, allow us to better understand the properties of the shallow fault zone at this structurally complex site. Mapping at the surface shows the CF consisting of three main subparallel strands within a <100 m zone with varying degrees of damage along them. These strands intersect units of banded gneiss and tonalite, and various sedimentary units. Seismic properties are derived from data of a spatially dense rectangular array with 1108 sensors spaced 10-30 m apart over a 0.36 km^2 area. Shallow P-wave velocities (V_P) are obtained by inversion of travel times associated with 24 Betsy Gun shot sources. S-wave velocities (V_S) are extracted from a recent ambient noise-based tomography model. Subsurface electrical resistivities are obtained through inversion of apparent resistivity data from a 3D survey consisting of 7 ~250-m-long parallel profiles (4 m electrode spacing) that were ~20 m apart spanning all three CF strands and orientated roughly SW to NE. Topography with resolution of several cm is obtained from images collected with a small UAV.

At <100 m depths, V_S properties correspond mostly to rock type (gneiss=generally low; tonalite=generally high). The V_P model in addition contains its lowest velocities within the shallow sedimentary basins. In contrast, the three CF strands have anomalously low electrical resistivities (40-100 ohm.m), with the two SW-most strands having the lowest values. A shallow trench reveals a well-defined fault core a few m wide along these strands. The employed seismic imaging tools probably have too low resolution to adequately resolve this fault feature. The low resistivity and localized damage structure point to increased strain conditions within the fault core, which correlates with a local topographic high.

Remote Triggering of Microseismicity at Mt. Erubus, Antarctica

PENG, Z., Georgia Institute of Technology, Georgia, USA, zpeng@gatech.edu; LI, C., Georgia Institute of Technology, Georgia, USA, lchenyu@gatech.edu; WALTER, J., University of Oklahoma, Oklahoma, USA, jwalter@ou.edu; JI, M., Georgia Institute of Technology, Georgia, USA, jizong0520@gatech.edu; LIU, G., Changbaishan Volcano Observatory, Antu, China, cbslgm@126.com; ASTER, R., Colorado State University, Colorado, USA, rick.aster@colostate.edu

Recent studies have found clear evidence of remotely triggered microseismicity at many active volcanoes during surface wave of large distant earthquakes. However, in many cases, triggered seismicity was only recorded by a single or a few seismic stations, making it difficult to locate the source and understand the triggering mechanism. Here we conduct a systematic search for remotely triggered seismicity at Mt. Erebus, Antarctica, using seismic data recorded by the permanent Mt. Erebus Volcano Observatory Seismic Network. Mt. Erebus is a heavily glaciated large stratovolcano on Ross Island, Antarctica. It is the southernmost active volcano on Earth and is adjacent to the US Antarctic McMurdo Station. With ongoing small-scale eruptions, a persistent lava lake, and long-term monitoring infrastructures, it is a natural laboratory to study volcanic processes and interactions between volcanoes, earthquakes and ice dynamics. So far we have found clear evidence of triggered seismicity at Mt. Erubus during the 2010 Mw 8.8 Maule, Chile earthquake. High-frequency seismic signals are recorded by multiple stations during the short-period Rayleigh waves of the Maule mainshock, suggesting that they are likely driven by dilatational stress perturbations. This behavior is similar to our recent observations triggered ice quakes at other stations in Antarctica during the Chile mainshock, and Erebus is known to host swarms of shallow near-summit ice quakes. However, it is not completely clear whether those triggered events at Mt. Erubus are associated with magma, tectonic, or ice movements. Our next step is to accurately locate those remotely triggered events, and compare them with background cryo- and volcanic seismicity to better understand their source locations and triggering mechanism. In addition, we plan to conduct a systematic search for other remotely triggered seismicity in the Mount Erebus region to constrain the triggering threshold and necessary conditions.

Interseismic Velocity Data Along the Conjugate Strike-Slip Faults From Sentinel-1 Satellite

LI, Y., Institute of Crustal Dynamics, China Earthquake Administration, Beijing, China, whlys@163.com

The geologic observations presented above suggest that conjugate strike-slip faults are significant structures along the Bangong-Nujiang suture zone in central Tibet. However, some small fault zones located inside the Qinghai Xizang Plateau, especially in the secondary blocks, have not attracted enough attention. For example, a series of V-shaped conjugate strike slip fault systems between Lhasa block and Qiangtang block. The V-shaped conjugate strike slip fault zone is composed of a series of small fault zones with oblique lines. It is an important product of the neotectonic movement in the Qinghai Tibet Plateau. It plays an important role in the deformation of the East-West extensional tectonic deformation in the Qinghai Tibet Plateau. This study will use InSAR technology to obtain the surface deformation information of conjugate strike-slip faults (Bengco Fault and Dongqiao Fault). The two faults are nearly 300 km in length. Therefore, the wide range SAR data should be selected (for example, Sentinel-1 IW mode SAR width is 250km) and used to obtain the active fault deformation signal in the whole conjugate strike slip fault at one time, which will help the overall analysis of the fault distribution. We will analysis the whole motion characteristics of conjugate strike-slip faults, investigate the strain accumulation of tectonic deformation in time and space. It is helpful to understand the characteristics of a series of conjugate strike slip faults developed in the middle part of the Qinghai Tibet Plateau.

The M7 Anchorage Earthquake: Testing the Resiliency of South-Central Alaska

Poster Session · Friday · 26 April · Grand Ballroom

A Cursory Study of Behavior of Three Instrumented Buildings During the Recent M7.0 Anchorage, AK, Earthquake of November 30, 2018

CELEBI, M., U.S. Geological Survey, California, USA, celebi@usgs.gov

This is a study of the recorded responses of three buildings instrumented by the U.S. Geological Survey (USGS) in Anchorage, AK during the M7.0 Anchorage, AK earthquake of November 30, 2018 (8:29:28 AKST, epicentral coordinates: 61.340N 149.937W, depth 40.9 km) [www.strongmotioncenter.org, last accessed December 18, 2018]. The earthquake caused strong shaking in Anchorage since the well-known 1964 M9.2 earthquake. The three buildings are identified by the number of stories they have (see Table 1). Essential dynamic characteristics of each building and significant behavioral aspects, such as beating and torsional motions are identified. In Table 1, recorded peak accelerations, displacements, and average drift ratios computed using the peak displacements at the roof levels are provided. These average drift ratios imply that the motions are at levels expected not to cause damage to the buildings. Visualization videos of both the 14-story and 20-story buildings are depict overall shaking of the buildings during the earthquake.

Table 1: Number of stories, heights, peak accelerations and displacements, average drift ratios [H = Height, GRPA = Ground peak, RP = Roof peak, a = acceleration (g), d = displacement (cm), ADR = Average Drift Ratio, f = fundamental freq. (Hz)].

Building	H (m)	GRP	RP		ADR	f	
		a	a	d	(%)	(Hz)	
14-story (Frontier)	51.5	0.19	0.22	23.8	0.3	0.45(NS)	0.35(EW)
20-story (Atwood)	80.5	0.21	0.44	30.0	0.4	0.44(NS)	0.37(EW)
22-story (Hilton)	74.0	0.21	0.65	21.8	0.35	0.41(NS	0.41(EW)

Intraslab Deformation in the 30 November 2018 Anchorage, Alaska Mw 7.0 Earthquake

LIU, C., China University of Geoscience, Wuhan, China, liuchengli@cug.edu.cn; LAY, T., University of California, Santa Cruz, California, USA, tlay@ucsc.edu

On 30 November 2018, Anchorage, Alaska was strongly shaken by an M_W 7.0 earthquake that ruptured within the underthrust Pacific plate at a depth of from 45 to 65 km. Ground failures occurred in saturated lowlands filled with sediments, producing notable road damage, but there was limited structural damage in Anchorage, only ~12 km south of the epicenter. The earthquake had a normal faulting geometry with a shallowly dipping east-west tension axis indicating intraslab deformation, likely between the underthrust Yakutat terrane and adjacent Pacific seafloor. Separate and joint inversions of teleseismic *P* and *SH* waves, regional strong ground motions, and GPS static displacements provide a weak preference for a westward steeply-dipping rupture plane with up to 2 m of slip distributed over a single slip patch with dimensions of 20 km x 20 km. The rupture duration was ~12 s. Aftershocks occur at shallower depths than the mainshock slip zone.

Effect of Surficial Geology on Earthquake Ground Motions From the 2018 Mw 7.0 Anchorage Earthquake in Anchorage, Alaska

CANNON, E. C., Golder Associates, Alaska, USA, ecannon@golder.com; DUTTA, U., University of Alaska Anchorage, Alaska, USA, udutta2@alaska.edu; THORNLEY, J., Golder Associates, Alaska, USA, john_thornley@golder.com

The November 30, 2018 M_w=7.0 Anchorage earthquake was widely felt across southcentral Alaska. The City of Anchorage experienced perceived shaking ranging between strong and very strong levels, based on the United States Geological Survey ShakeMap for the earthquake. The maximum peak ground acceleration (PGA) recorded by strong ground motion stations in Anchorage was over 0.5 g in southeast Anchorage. Short period (0.2 second) spectral accelerations exceeded 1.2 g at stations in southwest and west Anchorage. One-second spectral accelerations exceeded 0.4 g in the Anchorage downtown area. This distribution and variation of intensity of shaking across the Anchorage area is a function of glacial and post-glacial deposits, and associated geologic processes related to deposition and erosion. The primary surficial geologic units in the Anchorage area include the Elmendorf glacial outwash deposits, cohesive and non-cohesive facies of the Bootlegger Cove Formation, Late Pleistocene glacial deposits, Holocene alluvial deposits, and bedrock of the Chugach Mountains. In addition, after the Late Pleistocene glaciers retreated, peat and organic deposits formed in many areas. The pattern of PGA values from the Anchorage earthquake generally indicates that the mid- to lower values of PGA occurred at stations located on glacial, glaciodeltaic, and alluvial deposits. The mid- to high values of PGA occurred at stations located in proximity to the Bootlegger Cove Formation deposits. One of the largest measured PGA values occurred in southeast Anchorage at a station located in the foothills of the Chugach Mountains. This area is mantled by glacial deposits but also contains fine-grained sand and silt deposits, and peat/organic deposits. The range and distribution of strong ground motion shaking across Anchorage highlights the importance of geologic factors contributing to ground motion responses.

Co-Seismic Vertical Deformations of the 30 November 2018 M7.0 Anchorage Earthquake, Alaska

KÖKSAL, D., Dokuz Eylül University, Izmir, Turkey, duygu.koksal@ogr.deu.edu.tr; CAKIR, R., Independent Researcher, cakir.recep@gmail.com; ERONAT, H. A., Dokuz Eylül University, Izmir, Turkey, husnu.eronat@deu.edu.tr

A M7.0 earthquake occurred on November 30th, 2018, at about 50 km depth and located 14 km NNW of Anchorage, Alaska. This intraplate earthquake caused some major structural damages in and near the city of Anchorage, and aftershock distribution shows significant deformation in the NNE direction of the city. We analyzed co-seismic displacements using Single Look Complex (SLC) Sentinel-1 SAR images in order to understand rupture behavior of this event. We used two Sentinel-1A SAR images (track=131, descending, dates= 2018-11-22 and 2018-12-04), distributed by European Space Agency (ESA), for Interferometric Synthetic Aperture Radar (InSAR) solutions. We constructed unwrapped/wrapped InSAR phase and deformations images by using SNAP software distributed by ESA. We followed the data processing steps of co-registration with enhanced spectral diversity, interferogram generation, deburst, topographic phase removal, Goldstein phase filtering, multilooking and phase unwrapping. We used the GETASSE30 DEM to remove topographic effect on the phase image. Goldstein Filter was run to reduce the noise. To increase the signal-to-noise ratio (S/N), multi-looking was also applied on filtered images by assigning the range and azimuth numbers to 10 and 3, respectively. We then generated a line-of-sight (LOS) vertical displacement image by using SNAPHU (Statistical-Cost, Network-Flow Algorithm for Phase Unwrapping) software distributed by Stanford University , which is a two-dimensional phase unwrapping algorithm essential for surface deformation studies. Our LOS vertical deformation analysis shows a 50 to 60mm vertical downward displacements in the main aftershock distribution area. These results are also consistent with the real-time GPS (vertical component) measurement about 60mm downward displacements measured in the aftershock area.

Impacts on School Resilience Caused by the M7 November 30, 2018 Anchorage Earthquake

HASSAN, W., University of Alaska Anchorage, Alaska, USA, wmhassan@alaska.edu; MOTTER, C., Washington State University, Washington, USA, c.motter@wsu.edu; THORNLEY, J., Golder Associates, Alaska, USA, john_thornley@golder.com; RODGERS, J., GeoHazards International, California, USA, rodgers@geohaz.org

The M7 2018 Anchorage earthquake caused damage to Anchorage and Matanuska-Susitna (Mat-Su) Valley schools, resulting in many remaining closed for a week or more for cleanup and repairs. Most damage was to suspended ceilings and the lights, heating and piping in and above ceilings. Schools were typically built to comply with seismic design codes instituted after the M9.2 1964 earthquake, and limited structural damage was observed. We compare observed damage to the spectral accelerations and peak ground velocity estimated and measured near several schools. Two schools in Eagle River, and one in Big Lake, suffered structural damage significant enough to close them for the rest of the school year. Structural damage to the gymnasium at an additional Mat-Su school caused closure. Observed structural damage was to reinforced masonry and concrete. Many older schools are wood-frame, and suffered no apparent structural damage. Non-structural damage to ceilings caused school closures for up to one week in Anchorage and up to two weeks in the Mat-Su Valley.

Many schools were in session at the time of the earthquake, and despite ceiling damage and falling of ceiling tiles, books and supplies (heavy furniture was anchored), both school districts reported very few injuries. Statements by the school districts, media reports, and field interviews with administrators indicate that along with structural performance, preparedness measures, including regular "Drop, Cover and Hold On" drills, were responsible for the low number of injuries. The combination of life-safety structural performance, anchoring of heavy furnishings, and student preparedness and drills to practice protective action appears to have protected students. If districts want to reduce lost instructional time, however, more attention must be paid to ensuring nonstructural components such as ceilings have adequate seismic design, and that older schools are seismically evaluated and strengthened or replaced if needed.

Analysis of Spatial Variation of Seismic Ground Motions in the Anchorage Bowl From 30th November, 2018 Anchorage Earthquake (Mw 7.0)

DUTTA, U., University of Alaska Anchorage, Alaska, USA, udutta2@alaska.edu; THORNLEY, J., Golder Associates, Alaska, USA, john_thornley@golder.com; UDDIN, M. S., University of Alaska Anchorage, Alaska, USA, muddin3@alaska.edu; YANG, Z., University of Alaska Anchorage, Alaska, USA, zyang2@alaska.edu

An M 7.0 earthquake vigorously shook Anchorage, the largest city in the state of Alaska on 30th November, 2018. The quake was located about 14 km northwest of Anchorage and at a depth of 41.8 km on the subducting Pacific plate, underneath the North American plate. The ground motions were recorded by approximate twenty-five 3-component accelerometer sensors deployed at various parts of the Anchorage bowl covering major geological units. The maximum value of peak ground acceleration (PGA), with maximum 0.5 g is observed towards the southeastern part of the area, which clearly shows the influence of subsurface soil on the recorded ground motions. The spectral accelerations (SA), spectral velocity (SV) and the spectral displacement (SD) of the recorded ground motions are computed at each site in the interval between 0.04 sec to 15.0 sec. The maximum SA at periods of 0.2 sec and 1.0 sec are observed over the area dominated by the sensitive Bootlegger Cove Formations. The spectral displacement values are found to be well correlated with the observed damages at different parts of the area. The site response (SR) at each station site has also been computed from Fourier amplitude spectra of recoded S-wave motions of 10 s duration starting from the S-wave arrival, using the standard spectral ratio (SSR) and horizontal to vertical ratio (HVR) methods in the frequency range from 0.5 Hz to 10.0 Hz. The observed SSR values are averaged over two frequency bands namely Low-Frequency Band (LFB) and High-Frequency Band (HFB) with central frequency at 1.0 Hz and 5.0 Hz, respectively. A strong correlation between the spatial distribution of the average SSR at LFB and HFB and the local geology is noticed in the area.

Stochastic Modeling of the November 30th M7.0 Anchorage Earthquake

DOW, S. K., University of Alaska Anchorage, Alaska, USA, skd@shanwil.com; DUTTA, U., University of Alaska Anchorage, Alaska, USA, udutta2@alaska.edu

The November 30th M7.0 earthquake near Anchorage, Alaska provided the strongest ground motions yet recorded on the Anchorage area strong motion network. These recordings allow for a comparison to be made between actual and synthetic time histories in a part of Alaska with frequent seismicity. Acceleration time histories were generated through stochastic finite source modeling for several strong motion stations in the Anchorage Bowl and the Fourier Amplitude Spectra was used to determine how well the models matched the recorded data. The earthquake rock motion was modeled using the finite source based stochastic modeling technique that is used in the EXSIM program developed by Boore and others. The finite fault method allows the fault to be divided into subfaults which are each modeled like a point source and are then summed in a time delayed fashion to account for rupture propagation. Parameters such as shear wave velocity were fixed based on literature and arrival time matching for the event and the fault parameters such as strike, dip, slip distribution, and hypocenter depth and location were fixed based on the CMT and USGS fault plane solutions. The soil column effects were taken into account through the use of site response relationships from previously recorded data in the Anchorage Bowl. Creating a stochastic model of this earthquake allows refinement of the parameters used for stochastic modeling in the Anchorage area, leading to the possibility of more accurate models of other, potentially more catastrophic, scenario earthquakes being generated.

Delaney Park Downhole Array in Anchorage, Alaska—Site Properties Inferred From M7 Anchorage, Alaska Earthquake

KALKAN, E., U.S. Geological Survey, California, USA, ekalkan@usgs.gov; WEN, W., Key Lab of Structures Dynamic Behavior and Control of the Ministry of Education, Harbin Institute of Technology, Harbin, China, wenweiping.hit@gmail.com

We used waveforms from the moment magnitude (M) 7.0 Anchorage earthquake and six select aftershocks, ranging from M4.2 to 5.7, to quantify site properties including shear-wave velocity profile, predominant frequencies, site amplification, soil damping and shear modulus at Delaney Park in downtown Anchorage, Alaska. The waveforms were recorded by surface and six borehole (up to 61 m depth) three-component accelerometers. The deconvolution of the waveforms at various borehole depths on horizontal sensors with respect to the corresponding waveform at the surface provides incident and reflected traveling waves within the soil. The shear-wave velocities determined from these events are consistent, and agree well with the in-situ measurements. The site amplification based on surface-to-downhole traditional spectral ratio (SSR), response spectral ratio (RSR), cross-spectral ratio (c-SSR), and horizontal-to-vertical spectral ratio (HVSR) of the surface recordings was also evaluated. Based on c-SSR, we computed the site amplification as 4.8 at 1.35 Hz (0.74 s), close to the predominant frequency of the soil column. This amplification matches with the average amplification reported in and around Anchorage by previous studies.

USGS— FEMA Collaboration on Post-Earthquake Loss Estimates and Assessments: A Case Study of the November 30, 2018 M7.0 Anchorage, Alaska Earthquake

BAUSCH, D., NiyamIT, Hawaii, USA, dbausch@niyamit.com; BURNS, J., NiyamIT, Colorado, USA, jburns@niyamit.com; WALD, D. J., U.S. Geological Survey, Colorado, USA, wald@usgs.gov; JAISWAL, K., U.S. Geological Survey, Colorado, USA, kjaiswal@usgs.gov; MARANO, K., U.S. Geological Survey, Colorado, USA, kmarano@usgs.gov; ROZELLE, J., FEMA, Colorado, USA, jesse.rozelle@fema.gov; CHATMAN, A., Pacific Disaster Center, Hawaii, USA, achatman@pdc.org

Hazus is a GIS-based loss estimation tool developed by the Federal Emergency Management Agency (FEMA) in collaboration with National Institute of Building Sciences (NIBS) to quantify impacts due to earthquakes, hurricanes, floods and tsunamis. The Hazus Earthquake model methodology was developed in coordination with experts in engineering and seismology envisioning the future needs for development of mitigation plans and policies, emergency preparedness and response, and recovery planning. Credible and concise impact estimates can be cumbersome and time consuming to generate from the Hazus model, so it has been used primarily for long-term earthquake risk assessment projects. However, Hazus was successfully deployed in the aftermath of the M7.0 Anchorage, Alaska earthquake in November 2018 to generate damage estimates and circulate them among response authorities less than 12 hours after the event. These rapid Hazus loss assessments contributed to an expedited Presidential Disaster Declaration for this earthquake and helped support the Preliminary Damage Assessment (PDA). The calculation and communication of such rapid loss results were made possible by recent improvements in coordination between the Hazus Program, the U.S. Geological Survey's National Earthquake Information Center (USGS NEIC), and the Pacific Disaster Center (PDC). USGS ShakeMap data are rapidly integrated into Hazus model runs, and data for a one-page summary of Hazus Earthquake model results can be generated within minutes now instead of hours. The soon-to-be released 2PAGER summary product was developed in collaboration with USGS NEIC program staff to complement their automated PAGER report. These upgrades have drastically reduced the time required to generate and distribute succinct financial and human earthquake impact estimates.

Comparisons of Site-Specific Ground Motion Estimates and Observations in the 2018 Anchorage M 7.0 Earthquake

WONG, I. G., Lettis Consultants International, Inc., California, USA, wong@lettisci.com; THOMAS, P., Lettis Consultants International, Inc., California, USA, thomas@lettisci.com

The lack of significant structural damage in the Anchorage area in the 30 November 2018 Mw 7.0 earthquake was credited to the robust seismic design

regulations and construction that occurred after the 1964 Great Alaska Mw 9.2 earthquake notwithstanding the event was at a depth of 47 km. Reported PGA values in the 2018 earthquake ranged from 0.12 to 0.47 g within hypocentral distances of 56 km. Wong et al. (2010; 2014) performed site-specific probabilistic seismic hazard analyses for the Anchorage area and more recently, for four representative sites that ranged from firm soil to soft rock (Vs30 236 to 570 m/sec). The site-specific PGA estimates for a return period of 2475 years were higher than 0.9 g. In contrast, the 2007 National Seismic Hazard Maps for Alaska (firm rock Vs30 of 760 m/sec) indicate PGA values at the same return period of about 0.7 g. The differences between our site-specific estimates and the National Seismic Hazard Maps stem not only from site conditions but also from differences in the ground motion models (GMMs) and modeling of the Wadati-Benioff (WB) zone. The 2007 USGS maps used pre-2003 GMMs and modeled the WB zone using their gridded seismicity approach. In the latter, they modeled uniform average rates on planes at constant depths between 50-80 km and 80-120 km beneath Anchorage. In our site-specific analyses, the WB zone, which controlled the PGA hazard at most return periods, was modeled based on the geometry of the dipping subducting slab. Acceleration response spectra from our site-specific studies, the National Seismic Hazard Maps, IBC, and the 2018 strong motion recordings are compared in order to assess the adequacy of the IBC design ground motions in Anchorage as compared to site-specific analyses.

Large Intraslab Earthquakes

Poster Session · Friday · 26 April · Grand Ballroom

Remote Dynamic Triggering of Intermediate-Depth Earthquakes in the Mariana Subduction Zone Following the 2012 Indian Ocean Earthquake

PRICE, A., Washington University in St. Louis, Missouri, USA, acprice@wustl.edu; WIENS, D. A., Washington University in St. Louis, Missouri, USA, doug@wustl.edu

Although remote dynamic triggering of shallow earthquakes has been well documented, there are no previous reported cases of remote dynamic triggering of intermediate-depth earthquakes. The mechanism producing intermediate depth earthquakes is still uncertain, so observations of dynamic triggering could provide important insights. The 2012 April 11 Indian Ocean M8.6 earthquake and the M8.2 aftershock were unusually prolific in triggering remote shallow earthquakes worldwide. Analysis of data from a temporary, amphibious array in the Mariana subduction zone reveals a dynamically triggered earthquake sequence of intermediate-depth earthquakes following the M 8.2 aftershock. The first event occurs 6 minutes after the long-period Rayleigh wave arrival. The intermediate-depth seismicity rate increases to 12 times the background seismicity rate in the hour immediately following and continues at twice the background seismicity rate for the subsequent 24 hours. A majority of the events identified in the first 24 hours have locations of 160-240 km depth and are clustered in the subducting slab beneath the Northern Mariana Islands.

Although previous studies of remote shallow earthquake triggering by the 2012 Indian Ocean earthquakes suggested triggering by Love waves, calculated radiation patterns at intermediate depths show the Mariana Islands lie along the Rayleigh wave amplitude maxima, with maximum amplitudes at long periods (T > 100 s). Conversely, this azimuth corresponds to a Love wave node and amplitudes are small at all periods. The slight density change associated with the passage of the Rayleigh wave may have triggered dehydration reactions, which is associated with a proposed mechanism that produces intermediate-depth earthquakes, on optimally-oriented, critically stressed faults.

One Doublet in Two Slabs: The 2018 Mw 8.2 and 7.9 Fiji Deep Earthquakes

JIA, Z., California Institute of Technology, California, USA, zjia@caltech.edu; SHEN, Z., California Institute of Technology, California, USA, zshen@caltech.edu; ZHAN, Z., California Institute of Technology, California, USA, zwzhan@caltech.edu; LI, C., Georgia Institute of Technology, Georgia, USA, lchenyu1992@gmail.com; PENG, Z., Georgia Institute of Technology, Georgia, USA, zpeng.seismo@gmail.com; GURNIS, M., California Institute of Technology, California, USA, gurnis@gps.caltech.edu

The cold Fiji-Tonga subduction zone accounts for >75% of cataloged deep earthquakes but none of the largest ten in the last century. On 19 August 2018 and 06 September 2018, a deep earthquake doublet with moment magnitude (M_w) 8.2 and 7.9 struck the Fiji area, providing a rare opportunity to interrogate the behaviors of great deep earthquakes in their still enigmatic mechanism. We image the rupture process of the doublet by subevent inversion, where we invert waveforms of teleseismic P, SH, and depth phases pP for multiple subevents' centroid times, locations, durations, and moment tensors. The subevent model for the M_w 8.2 earthquake shows two stages of rupture on multiple faults that features different focal mechanisms, rupture area and aftershock productivities. The M_w 7.9 event has ~30% non-double-couple component, which is also reflected by the diverse subevent focal mechanisms. By cursory examination, the doublet rupture dimensions and aftershock productivities are similar to the 1994 Bolivia M_w 8.2 earthquake in a warm slab, instead of the 2013 Okhotsk M_w 8.3 event in a cold slab. This appears to contradict the traditional view that slab temperature controls deep earthquakes. However, we find that neither event was confined within the cold Tonga slab core: the M_w 8.2 ruptured mostly in the warmer rim of the Tonga slab and the M_w 7.9 occurred in a warm relic slab leaning on top of the Tonga slab. The Fiji doublet demonstrates local slab temperature as the critical factor for deep earthquakes, and reveals complex interaction of subducted slabs in Tonga.

Aftershock Sequences of Intermediate-Depth Earthquakes Beneath Japan

BAEZ, C. M., Saint Louis University, Missouri, USA, cara.baez@slu.edu; WARREN, L. M., Saint Louis University, Missouri, USA, linda.warren@slu.edu

Deep earthquakes have been observed to have fewer aftershocks than shallow earthquakes. To determine whether the observed differences are real or due to observational constraints, we study intermediate-depth aftershock sequences beneath Japan using the Japan Meteorological Agency (JMA) earthquake catalog from May 2002 through February 2016. We identify 17 intermediate-depth earthquakes (70-305 km depth) with local magnitude MJ ≥ 5.7 for further analysis. The mainshocks typically occur at the edges of patches with high background seismicity rates and the aftershocks tend to occur within the same patches. For the high-seismicity and aftershock volume around each earthquake, we calculate the cumulative number of earthquakes with time and the seismicity rate for earthquakes above the magnitude of completeness. For 7 of the earthquakes, we observe aftershock sequences similar to those for shallow earthquakes: the number of earthquakes increases immediately following the earthquake and exponentially decays with time with a p value of ~1. In contrast to shallow aftershock sequences, the magnitude differential between the mainshock and largest aftershock is typically 2-3.5 units. This large magnitude differential would prevent us from observing most aftershocks for the remaining 10 earthquakes. Using an earthquake catalog with a magnitude of completeness 4-5 units below the mainshock magnitude, we are able to observe productive aftershock sequences for intermediate-depth earthquakes beneath Japan.

The September 19, 2017 (Mw 7.1), Intermediate-Depth Mexican Earthquake: A Slow and Energetically Inefficient Deadly Shock

MIRWALD, A., Universidad Nacional Autónoma de México, Mexico City, Mexico, aron.mirwald@gmail.com; CRUZ-ATIENZA, V. M., Universidad Nacional Autónoma de México, Mexico City, Mexico, cruz@geofisica.unam.mx; DÍAZ-MOJICA, J., Universidad Nacional Autónoma de México, Mexico City, Mexico, eljonjairo@gmail.com; IGLESIAS, A., Universidad Nacional Autónoma de México, Mexico City, Mexico, arturo@igeofisica.unam.mx; SINGH, S. K., Universidad Nacional Autónoma de México, Mexico City, Mexico, krishnamex@yahoo.com; VILLAFUERTE, C., Universidad Nacional Autónoma de México, Mexico City, Mexico, villafuerte.cd@gmail.com; TAGO, J., Universidad Nacional Autónoma de México, Mexico City, Mexico, josue.tago@gmail.com

We investigate dynamic source parameters of the M_W7.1 Puebla-Morelos intermediate depth earthquake (IDE) (h = 57 km) of September 19, 2017, that caused a devastation in Mexico City. Our simple, elliptical source model, coupled with a new Particle Swarm Optimization algorithm, revealed rupture propagation within the subducted Cocos plate, featuring a high stress drop ($\Delta\tau = 14.2 \pm 5.8$ MPa) and a remarkably low radiation efficiency ($\eta r = 0.16 \pm 0.09$). Fracture energy was large ($G = (1.0 \pm 0.3) \times 10^{16}$ J), producing a slow dissipative rupture ($Vr/Vs = 0.34 \pm 0.04$) with scaling-consistent radiated energy ($Er = (1.8 \pm 0.9) \times 10^{15}$ J) and energy-moment ratio ($Er/M0 = 3.2 \times 10^{-5}$). About 84% of the available potential energy for the dynamic rupture was dissipated in the focal region, likely producing friction-induced melts in the fault-core with 0.2-1.2 cm width due to heat production (700–1200°C temperature rise). Such source features seem to be a universal signature of IDEs.

Reference: Mirwald, A., V. M. Cruz-Atienza, J. Díaz-Mojica, A. Iglesias, S. K. Singh, C. Villafuerte and J. Tago. The September 19, 2017 (Mw7.1), intermediate-depth Mexican earthquake: a slow and energetically inefficient deadly shock. Accepted in the Geophysical Research Letters, January 2019.

Intraslab Versus Megathrust Earthquakes: Spectral Characteristics Result in Distinct Lacustrine Deposits

VAN DAELE, M., Ghent University, Gent, Belgium, maarten.vandaele@ugent.be; VANNESTE, K., Royal Observatory of Belgium, Brussels, Belgium, kris.vanneste@oma.be; MOERNAUT, J., University of Innsbruck, Innsbruck, Austria, jasper.moernaut@uibk.ac.at; ARAYA-CORNEJO, C., Universidad

Bernardo O'Higgins, Santiago, Chile, c.arayacornejo@gmail.com; PILLE, T., Ghent University, Gent, Belgium, thomaspille@hotmail.com; SCHMIDT, S., Université de Bordeaux, Bordeaux, France, sabine.schmidt@u-bordeaux.fr; KEMPF, P., Geological Survey of Belgium, Brussels, Belgium, pkempf.work@gmail.com; MEYER, I., Ghent University, Gent, Belgium, inka.meyer@ugent.be; CISTERNAS, M., Pontifícia Universidad Católica de Valparaíso, Valparaíso, Chile, marco.cisternas@pucv.cl

Subduction zone seismicity arises from megathrust, crustal and intraslab earthquakes, and understanding the recurrence patterns of each type is crucial for hazard assessments. Specifically intraslab earthquakes have recently proven to pose a significant hazard along subduction zones, as evidenced by the destructive September 2017 Chiapas M_w 8.2 (Mexico) earthquake and the recent November 30 2018 M_w 7.0 Anchorage (Alaska) earthquake. Interestingly, intraslab earthquakes have a higher-frequency source spectrum then megathrust earthquakes as a result of the higher stress drop for a given magnitude. Here we compare acceleration response spectra of recent and historical intraslab and megathrust earthquakes along a longitudinal profile in central Chile and show that this difference in source frequency spectrum increases when moving land inward (*e.g.*, towards the Andes in South America). We further illustrate how these different response spectra provide an opportunity for lacustrine paleoseismology, as higher-frequency accelerations from intraslab earthquakes are hardly attenuated in rocks of a lake's watershed, whereas lower-frequency accelerations from megathrust earthquakes are amplified in soft lake sediments. We indeed observe this in Lo Encañado Lake, located in the central Chilean Andes, where megathrust earthquakes merely trigger subaquatic (soft sediment) slope failures, while intraslab earthquakes also trigger subaerial rock slides/avalanches, resulting in an additional postseismic turbidite in the lake. We conclude that lakes may be the only geological archives that hold intraslab paleoseismic records, and that lakes in other subduction zones (*e.g.*, Cascadia) may hold similar records. Combining this kind of lacustrine records with coastal and deep-marine paleoseismology will permit the construction of recurrence models for the different seismogenic sources, and to evaluate the temporal correlations among them, thereby improving hazard assessments.

Stress Drop Estimates of Deep Earthquakes Based on Empirical Green's Function Analysis

LIU, M., University of Michigan, Michigan, USA, meichenl@umich.edu HUANG, Y., University of Michigan, Michigan, USA, yiheh@umich.edu; RITSEMA, J., University of Michigan, Michigan, USA, jritsema@umich.edu

Stress drop is a critical source parameter indicating stress release during an earthquake. It is a fundamental question whether deep earthquakes exhibit similar source processes as shallow earthquakes though, we lack a comprehensive understanding of stress drop for deep earthquakes owing to insufficient dataset. Here we aim to better understand the source processes of deep earthquakes with accurate stress drop estimations and will investigate whether stress drops of deep (> 400 km) earthquakes are much larger than those of shallow earthquakes due to the increase of shear strength with depth.

To obtain the stress drop pattern of deep earthquakes, we estimate their corner frequencies using the spectral ratios based on empirical Green's functions(eGfs). Our analysis uses both P waves and S waves recorded by global and regional seismic stations and assumes Brune's spectral model. We have identified more than 100 pairs of master events and their eGfs occurred since 2000. Each pair meets the criteria of magnitude difference larger than 0.5 and hypocentral distance within 50 km. Our preliminary corner frequency estimates for Mw6.0 - Mw8.2 deep earthquakes lead to similar stress drop ranges to shallow earthquakes of 0.03 - 30MPa and 0.01 - 10Mpa from S and P wave analysis, respectively. We will further investigate the uncertainty in the corner frequency estimates and the spatial variation of stress drop of deep earthquakes.

Matched Filter Detection of the 2018 Fiji Deep Doublet Sequences

LI, C., Georgia Institute of Technology, Georgia, USA, lchenyu@gatech.edu; PENG, Z., Georgia Institute of Technology, Georgia, USA, zpeng@gatech.edu; ZHAN, Z., California Institute of Technology, California, USA, zwzhan@caltech.edu; JIA, Z., California Institute of Technology, California, USA, zjia@caltech.edu; SHEN, Z., California Institute of Technology, California, USA, zshen@caltech.edu

The Tonga-Fiji subduction zone is located in the border of Australian and Pacific plates and contains more than 2/3 of globally recorded deep focus earthquakes (depths larger than 300 km). On August 19th 2018, a magnitude 8.2 earthquake with depth of 556 km occurred in the Tonga-Fiji region. Two weeks later, another magnitude 7.9 earthquake with depth of 655 km struck nearby area about 250 km southwest to the Mw8.2 Fiji earthquake. The second deep earthquake is likely triggered by the Mw8.2 earthquake, because it occurred in an isolated slab with very low background seismicity and low aftershock productivity. The occurrence of these two earthquakes offers a great opportunity to study the interactions and physical mechanisms of deep earthquakes. However, there are still some missing aftershocks for both earthquakes, likely because their signals are contaminated by mainshock waveforms and coda waves. This could be improved by matched-filter detection. In this study, we perform a systematic detection and relocation to foreshocks and aftershocks associated with this doublet sequence. We used more than 500 aftershocks available in the ISC catalog as templates for detection of 30 days after the Mw8.2 earthquake, and detected more than 1000 and 50 aftershocks for both earthquakes respectively. We plan to extend the detection window longer times before and after the M8.2 and M7.9 earthquakes, and relocate these newly detected events to better illuminate spatio-temporal evolutions of seismicity in this region.

Precise Relocation of Deep Double Earthquake Subevents

LIU, J., Saint Louis University, Missouri, USA, junjie.liu.1@slu.edu; WARREN, L. M., Saint Louis University, Missouri, USA, linda.warren@slu.edu

Below a depth of 70 km, the high confining pressure and temperature should prevent brittle failure from occurring. To explain the occurrence of deep earthquakes down to nearly 700 km depth, three mechanisms have been proposed: dehydration embrittlement, transformational faulting, and thermal shear instability. Each mechanism has a different implication for the rupture process of the earthquake, including whether or not the same fault segment can slip more than once. Overlapping rupture zones may result in repeating earthquakes. For three earthquakes in the Tonga and Kuril subduction zones, ranging in depth from 102-539 km and magnitude from 6.2-6.7, we observe repeating earthquakes separated by ~3 s. These events, which we call double earthquakes, have two subevents of similar duration and amplitude separated by nearly the same amount of time at all stations. For each double earthquake, we download from IRIS all available vertical-component seismograms recorded at epicentral distances of 0°-95° and use cross-correlation to measure the relative arrivals times of the two events for the P and pP arrivals. We use the relative arrival times to locate the subevents relative to one another and compare the subevent offset with the rupture dimensions. If the same patch of fault slipped twice, it would be compatible with the thermal shear instability model.

Structural Seismology: From Crust to Core

Poster Session · Friday · 26 April · Grand Ballroom

Surface Wave Tomography via Higher-Order Interferometry

ZHANG, S., University of Colorado Boulder, Colorado, USA, shzh3924@colorado.edu; FENG, L., University of Colorado Boulder, Colorado, USA, lili.feng@colorado.edu; WANG, H., University of Colorado Boulder, Colorado, USA, hongda.wang@colorado.edu; RITZWOLLER, M., University of Colorado Boulder, Colorado, USA, mike.ritzwoller@colorado.edu

Although traditional ambient noise interferometry does not work for asynchronously deployed seismic stations, the method of higher-order interferometry provides one possible way to bridge stations that were not deployed simultaneously. For two asynchronous receivers, a backbone station that overlaps both in operation could serve as a virtual source (via noise interferometry). As a consequence, higher-order interferograms based on both direct and coda waves of the noise interferograms may reveal the seismic wavefields between two asynchronously deployed receivers. To analyze the characteristics of direct and coda wave interferometry empirically in both continental and oceanic settings, we use the EarthScope Tranportable Array (TA) and the Cascadia Initiative Array, respectively. Comparing coda wave with direct wave interferometry, our results indicate that the former can provide more new paths (nonexistent from standard ambient noise interferometry), while the latter requires fewer backbone stations to reach high quality records and may provide more reliable measurements at longer periods. The deployment of the TA in Alaska provides the unprecedented opportunity to image the lithospheric structure of Alaska. Higher-order interferometry can bridge numerous historical networks in Alaska and show promise to achieve enhanced resolution, broader bandwidth, and reduced uncertainties in tomographic maps and structural models. Furthermore, the enhancement in ray path coverage may prove to be an essential element for the study of azimuthal anisotropy. These conclusions may be significant for the design of future seismic array configurations in Alaska, in oceanic settings, and elsewhere.

Radial Anisotropy of Antarctica From Surface Wave Ambient Noise Tomography

ZHOU, Z., Washington University in St. Louis, Missouri, USA, zhou.z@wustl.edu; WIENS, D. A., Washington University in St. Louis, Missouri, USA, doug@wustl.edu; SHEN, W., Stony Brook University, New York, USA, weisen.shen@stonybrook.edu; HANSEN, S., University of Alabama, Alabama, USA, shansen@geo.ua.edu; ASTER, R., Colorado State University, Colorado, USA, rick.aster@colostate.edu; NYBLADE, A., Pennsylvania State University, Pennsylvania, USA, aan2@psu.edu

Antarctica is the most southern continent on Earth, where permanent ice covers more than 95% of the surface. The harsh climate and remoteness hinder data collection and require that we obtain optimal results from sparse seismic networks. Whereas most seismic studies invert only Rayleigh wave data, Love wave phase and group velocities provide better resolution of shallow crustal structure as well as allow for evaluation of radial anisotropy. In this study, we derive crustal and uppermost mantle shear wave velocity model for the West Antarctica and part of East Antarctica using both interstation Love and Rayleigh wave Greens functions estimated from cross-correlation of ambient noise records. We use all available broadband data collected in Antarctica over the past 18 years, including that from recent temporary arrays such as TAMSEIS, AGAP, TAMNNET, RIS and POLENET/ANET. We use a time-frequency phase-weighted stacking method, that expands the reliable period range of Love wave group and phase velocity measurements from 6 – 30 s to 6 – 40 s and, compared with linear stacking, permits many more station pairs to be analyzed. Group and phase velocity maps of both Rayleigh and Love waves are obtained and are then inverted for a shear wave velocity structure using a Monte Carlo inversion method. Most of the major features of the V_{SH} structure are consistent with the V_{SV} structure derived by Heeszel *et al.*(2016) and Shen *et al.*(2018) that inverted Rayleigh waves alone inversion. Major geological features in Antarctica,such as the thick sediments in the Ross Embayment and the crustal root beneath the Gamburtsev Subglacial Mountains are evident in the V_{SH} structure. However, some shallow structural details are visible in the V_{SH} structure that were not seen in V_{SV} structure,such as the Polar Subglacial Basin and the Byrd Subglacial Basin. Joint inversion of Love and Rayleigh wave data allows us to determine the radial anisotropic structure of the crust and uppermost mantle,and the uppermost mantle of West Antarctica shows strong positive ($V_{SH} > V_{SV}$) radial anisotropy.

Different Patterns of Northward Advancing Indian Plate Beneath Western Tibet Revealed by Anisotropy Tomography

ZHANG, H., Institute of Tibetan Plateau Research, Chinese Academy of Sciences, Beijing, China, zhangheng415@itpcas.ac.cn; LI, Y., National University of Singapore, Singapore, Singapore, ceeliyy@nus.edu.sg

We analyze the teleseismic travel time data recorded by 70 temporary stations from the Y2 and ANTILOPE-1 arrays using the radial anisotropy tomography to investigate the upper mantle structure beneath western Tibet. Two distinct regions are separated by a layered belt along 80°E, which is interpreted as the subducted Indian plate. In the eastern part, a high-velocity zone with positive radial anisotropy has been detected, which is consistent with our previous results. To the west, we observed a layered radial anisotropic structure although the velocity is relatively high from 70 km to 250 km depth. Combing our results with geological, geochemistry and GPS study, we propose that such local feature (the layered belt) may result in the tearing of northward advancing Indian plate. In addition, the different features between the western and eastern side of our study region indicate the existence of remnant Eurasian lithosphere.

Seismic Anisotropy of the Crust and Upper Mantle Beneath the Northeastern Margin of the Tibetan Plateau

JU, C., Institute of Tibetan Plateau Research, Chinese Academy of Sceinces, Beijing, China, juchanghui@itpcas.ac.cn; ZHANG, H., Institute of Tibetan Plateau Research, Chinese Academy of Sciences, Beijing, China, zhangheng415@itpcas.ac.cn; ZHAO, J., Institute of Tibetan Plateau Reserach, Chinese Academy of Sciences, Beijing, China, zhaojm@itpcas.ac.cn

We investigate the seismic anisotropy of the crust and upper mantle beneath the northeastern margin of the Tibetan Plateau (NETP) at 55 stations from a temporary experiment (ANTILOPE-IV) operated from 2010 to 2013 using teleseismic shear wave splitting (SWS) measurements. Assuming a single-layer anisotropic model, we obtain 631 pairs of SKS splitting parameters represented by fast polarization directions (FPDs) and delay times (DTs). The general orientations of the seismic anisotropy in the NETP indicate WNW-ESE direction, with average FPD of ~92.9° and average DT of ~1.20 s. Most of the FPDs follow the tectonic trends except those in the Qaidam basin and southwestern Qilian orogen. The stacking FPDs in the Altyn Tagh fault and northwestern Qilian orogen is NW-SE trending, parallel or sub-parallel to the azimuthal anisotropy of the Pn wave and the direction of the absolute plate motion, indicating the major source of the anisotropy is the asthenosphere flow. The FPDs beneath the East Kunlun-West Qinling Fault are E-W and/or ENE-WSW trending, parallel or subparallel to the azimuthal anisotropy of the Pn wave and the trend of the regional geological structures. The FPDs beneath the Qaidam basin are NE-SW trending, parallel to the direction of the GPS velocity, inferring that the source of the observed anisotropy is from the crust and the upper mantle lithosphere. The results of the SWS lead to a vertically coherent deformation pattern in NETP.

Seismological Explorations of Earth's Outer Core: Normal Mode and Body Wave Analyses

IRVING, J. C. E., Princeton University, New Jersey, USA, jirving@princeton.edu; COTTAAR, S., University of Cambridge, Cambridge, United Kingdom, sc845@cam.ac.uk; LEKIC, V., University of Maryland, Maryland, USA, ved@umd.edu; WU, W., Princeton Unversity, Princeton, United Kingdom, wenbow@princeton.edu

Earth's outer core is a source of both the geodynamo and heat for mantle convection. However, we still do not fully understand its chemical composition, and there debate about whether the uppermost outer core may contain a stratified layer which may be enriched in light elements. We present low frequency normal mode and high frequency body wave investigations of the outer core's properties.

Normal mode oscillations of the whole Earth, excited by large earthquakes, are sensitive to the large-scale variations in velocity and density. We use the centre frequencies of hundreds of oscillations to infer the bulk properties of the outer core. We carry out a Bayesian inversion using a mineralogical Equation-of-State framework to infer the outer core's velocity, density and mineralogical properties, under the assumption that the outer core is well mixed and adiabatic. The model we produce, EPOC, describes the Elastic Parameters of the Outer Core. EPOC predicts seismic velocities at the top of the outer core which are closer to existing body-wave models than to PREM, resolving a long-standing discrepancy. EPOC also fits normal-mode data better than the Preliminary Reference Earth Model. We also consider the effects of relaxing our assumptions that (i) there is no stratified layer at the top of the outer core, and (ii) that PREM is correct outside the outer core.

To better assess the uppermost outer core, which is may be termed the E' layer, we use a novel, iterative measurement technique to measure SmKS differential travel times. SmKS waves are particularly sensitive to the E' layer, and reflect (m-1) times from the underside of the core-mantle boundary. We find that the SmKS differential travel times are better described by models with seismic velocities in the E' layer slower than PREM, such as EPOC or body-wave derived KHOMC (Kaneshima and Helffrich, 2013).

Crustal Seismic Discontinuities Under Mexico City Observed With Receiver Functions

PITA-SLLIM, O. D., Universidad Nacional Autónoma de México, Mexico City, Mexico, oliv.dayanara@gmail.com; PEREZ-CAMPOS, X., Universidad Nacional Autónoma de México, Mexico City, Mexico, xyoli@igeofisica.unam.mx; AGUILAR-VELÁZQUEZ, M. J., Universidad Nacional Autónoma de México, Mexico City, Mexico, manuel.aguilar.411@gmail.com; RODRÍGUEZ, M., Universidad Nacional Autónoma de México, Mexico City, Mexico, miguel561a@gmail.com; GONZÁLEZ, A., Universidad Nacional Autónoma de México, Mexico City, Mexico, adrianag@sismologico.unam.mx; ESPINOSA, V. H., Universidad Nacional Autónoma de México, Mexico City, Mexico, victore@sismologico.unam.mx; BELLO, D., Universidad Nacional Autónoma de México, Mexico City, Mexico, delia@sismologico.unam.mx; QUINTANAR, L., Universidad Nacional Autónoma de México, Mexico City, Mexico, luisq@igeofisica.unam.mx; RAMÍREZ-GUZMÁN, L., Universidad Nacional Autónoma de México, Mexico City, Mexico, lramirezg@iingen.unam.mx; CÁRDENAS, A., Universidad Nacional Autónoma de México, Mexico City, Mexico, arturo@sismologico.unam.mx; PÉREZ, J., Universidad Nacional Autónoma de México, Mexico City, Mexico, jesus@sismologico.unam.mx; RODRÍGUEZ-RASILLA, I., Universidad Nacional Autónoma de México, Mexico City, Mexico, ivan@sismologico.unam.mx

Mexico City is the seat of the Mexican government and the most populated city of the country. It was settled on top of a sedimentary basin which cause amplification to seismic waves of large subduction earthquakes occurring at the Pacific Coast, more than 350 km away, as well as for near intraplate earthquakes, such as the 19 September 2017, Mw7.1, Puebla-Morelos earthquake.

With the purpose of improving our knowledge of the seismic structure of the city and reducing the uncertainty when modeling strong motion in the basin, an ambitious experiment started in May 2017. This experiment consists in installing from 18-22 broadband stations for 3 to 5 days in a site to continuously record; the stations are then relocated to a new site for a similar period, integrating a dense grid of measuring points with ~500 m spacing. Additionally, 18 stations which have been recording continuously since 2010, from the 'Red Sísmica del Valle de México'(RSVM) are available. We also use data from nine stations of the MesoAmerican Subduction Experiment, a previous array that crossed Mexico City from south to north between 2014 and 2015; and a permanent broadband station of Servicio Sismológico Nacional (SSN, National Seismological Service, Mexico)

In this work, we obtain receiver functions, from both the temporal and permanent RSVM and SSN stations. Despite the small number of teleseisms registered in the temporary array, but given the small distance between stations, it is possible to identify the Ps converted waves from the Mohörovic discontinuity, as well as from other shallower crustal discontinuities. Furthermore, it is possible to differentiate the receiver functions that have gone through shallow low-velocity layers from the ones that have not, being able to identify the presence of the lake sediments. This project has been funded by Secretaría de Ciencia y Tecnología e Innovación (SECITI), project SECITI/073/2016.

Seismic Crustal Velocity and Structure of the Texas-Gulf of Mexico Passive Margin From Waveform Inversion Using Global Optimization

THANGRAJ, J., Baylor University, Texas, USA, joseph_thangraj@baylor.edu; PULLIAM, J., Baylor University, Texas, USA, jay_pulliam@baylor.edu

The Gulf of Mexico (GoM) basin was formed as the Yucatan block rifted away from North America at ~165 Ma. After rifting, seafloor spreading started at ~150 Ma which continued till ~138 Ma. However, due to the thick layers of sediments that now blanket the region, important details, including the style of rifting and degree of extension of the surrounding GoM passive margin, remain unclear. Deep sediments attenuate seismic waves, making it difficult to identify and analyze teleseismic arrivals and rates of local seismicity are quite low.

We use data from the X4 2010-13 seismic array, a transect across the Gulf Coastal Plain. X4 extends across the GoM passive margin from Matagorda Island to the Llano Uplift and consists of 22 broadband, three-component seismometers with Reftek 130 digitizers.

We observe direct S and SsPmp arrivals from a teleseismic earthquake at an epicentral distance of $\sim 60^0$, as is common. The amplitude of postcritical SsPmp tends to be large and easily observed without stacking multiple events. However, we also observe another wave that arrives between direct S and SsPmp, which we interpret to be a P reflection from the basement after an S-to-P conversion and reflection at the surface (SsPbp). SsPbp is expected to have a fairly large amplitude due to a large impedance contrast between. The deep layer of sediments produces good time separation so the three arrivals are distinct. Waveform modeling provides strong constraints on the impedance contrasts of the sediment/basement and the Moho interfaces by matching the waves' arrival times and amplitudes

Our waveform modeling uses the reflectivity method for forward calculations of waveforms and simulated annealing, a global optimization algorithm, to guide a broad search of locally 1D models. Initial models for the inversion are produced via travel time tomography using local and teleseismic earthquakes and direct waves identified via seismic interferometry performed with a 160-km, 412-geophone short-period array that partly overlaps the X4 array.

Mantle Discontinuities From Reflected Phases in the Tonga Subduction Zone

HRUBCOVA, P., Institute of Geophysics, Prague, Czech Republic, pavla@ig.cas.cz; VAVRYCUK, V., Institute of Geophysics, Prague, Czech Republic, vv@ig.cas.cz

The Tonga subduction zone is a result of the Pacific Plate subducting under the Australian Plate. This zone, submerging steeply with a dip of about 60 degrees, is the most linear, fastest converging, and seismically active of any of the world's subduction zones. Its rapid convergence rate accounts for the highest level of deep moderate-size seismicity in the circum-Pacific zone. In our study, we focus on earthquakes located in the Tonga subduction zone and process them for indications of major discontinuities in the mantle. We select the earthquakes included in the Harvard Centroid Moment Tensor (CMT) Catalog with the magnitude of Mw>5.5 in a depth range of 100-600 km in the period of 1999-2016 and process their waveform recordings from stations of the Global Seismograph Network (GSN). For the analysis, we select the stations azimuthally distributed around Tonga in the epicentral distance of 0-60 degrees searching for phases reflected from the mantle discontinuities. Detection of phases is based on the calculation of the arrival times with the TauP ray-tracing code for the ak135 velocity model. During data processing we test different depths of clustered seismicity and calculate traveltime curves to sort out stations where the reflected phases are well identified and do not overlap other high-energy phases. The phase detection is enhanced by optimum filtering, by alignment and cross-correlation of traces, by hypocentral-depth sorting, and by equidistant plotting of traces in seismic sections. The waveform processing is performed for each station individually, which enables to detect the target phases generated by mantle discontinuities and invert their traveltime arrivals for depths and their respective lateral variations.

Inversions of Teleseismic P-Wave Coda Autocorrelations for Estimating Crustal Structure Below a Floating Ice Platform

BAKER, M. G., Colorado State University, Colorado, USA, mgbaker@colostate.edu; ASTER, R., Colorado State University, Colorado, USA, rick.aster@colostate.edu; WIENS, D. A., Washington University in St. Louis, Missouri, USA, doug@wustl.edu; NYBLADE, A., Pennsylvania State University, Pennsylvania, USA, aan2@psu.edu; BROMIRSKI, P. D., Scripps Institution of Oceanography, California, USA, pbromirski@ucsd.edu; GERSTOFT, P., Scripps Institution of Oceanography, California, USA, pgerstoft@ucsd.edu; STEPHEN, R. A., Woods Hole Oceanographic Institution, Massachusetts, USA, rstephen@whoi.edu

Autocorrelation of teleseismic P-wave coda is an emerging technique for imaging crustal-scale features. The autocorrelation method emphasizes reflections of the incident signal between the free surface and sub-surface seismic discontinuities, in contrast to the P-to-S conversions utilized by the more traditional receiver function method. This distinction is especially relevant for stations sited on floating ice, where high velocity contrasts yield large amplitude reverberations and the intervening water layer decouples teleseismic S-wave energy. We present a workflow for preprocessing and single-station inversion of teleseismic P-wave autocorrelation data recorded on the Ross Ice Shelf during a two-year deployment of 34 broadband seismometers. We show that the three-channel signal-to-noise ratio power spectral densities (*i.e.*, the Fourier transforms of the autocorrelations) can yield accurate estimates of ice and water layer thicknesses. We also present Moho depth estimates from single-station Markov Chain Monte Carlo inversions and compare these values to estimates from continental-scale array methods.

Pattern of Seismic Anisotropy in the Crust and Upper Mantle Around the Margin Zone of Eastern Tibetan Plateau

GAO, Y., Institute of Earthquake Forecasting, China Earthquake Administration, Beijing, China, qzgyseis@163.com; SHI, Y., Institute of Earthquake Forecasting, China Earthquake Administration, Beijing, China, shiyutao3995@126.com; WANG, Q., Institute of Earthquake Forecasting, China Earthquake Administration, Beijing, China, sunny-wangqiong@163.com

By reason of the collision between the Indian plate and the Eurasian plate and the obstruction from South China block, Tibetan Plateau intensely lifts with strong deformation from northeast margin to southeast margin. Seismic anisotropy is useful in study of lithosphere deformation and asthenosphere flow. In southeast margin of Tibetan Plateau, it is claimed as important matter flow channel. However, in the eastern margin, the matter flow is blocked by the Sichuan basin within South China block. The northeast margin is still argued if matter flow channel or not. We collect seismic records by permanent seismic stations and temporary seismic arrays to get anisotropic distribution in the lithosphere around the margin zone of eastern Tibetan Plateau.

In southeast margin zone of Tibetan Plateau, seismic data by small local earthquakes are adopted to measure shear-wave splitting in the crust, as well as teleseismic data of global striking earthquakes to measure splitting of XKS (SKS, PKS and SKKS phases) in the lithosphere. Results show different pattern between seismic anisotropy in the crust and in the upper mantle, indicating different deformation style.

In east margin zone of Tibetan Plateau, anisotropic pattern shows different spatial distribution, indicating different subzone of seismic anisotropy in the crust. The crustal anisotropy changes along Longmenshan faults. Complicated anisotropy suggests influences from tectonics, faults and stress.

In northeast margin zone of Tibetan Plateau, we obtain crustal anisotropy by shear-wave splitting of local records and lithospheric anisotropy by XKS splitting of teleseismic records. Crustal anisotropy shows subzone pattern, different from XKS splitting. Also, we compare azimuthal anisotropy in whole crust by receiver functions technique. Seismic anisotropy suggests coherent deformation between the crust and the upper mantle, indicating mainly vertical deformation. [This study is supported by NSFC Project 41730212]

SSsPmp: Can We Expand the Applicable Epicentral Distance (Δ) for Virtual Deep Seismic Sounding?

WANG, S., Stanford University, California, USA, axelwang@stanford.edu; KLEMPERER, S., Stanford University, California, USA, sklemp@stanford.edu

Virtual Deep Seismic Sounding (VDSS) infers crustal depth from the travel-time difference (T_{VDSS}) between teleseismic direct *S* and *SsPmp* (Tseng *et al.*, 2009). *SsPmp* is produced by *s*-to-*P* conversion at the free surface forming a virtual source, followed by wide-angle *P*-to-*p* reflection at the Moho. Because the *Pmp* leg undergoes total internal reflection at the Moho, *SsPmp* has large amplitude and is often directly readable from individual band-pass filtered seismograms. However, to achieve the wide-angle reflection requires a ray parameter similar to the near-Moho $1/V_P$, and suitable sources for VDSS are typically deep enough (> c. 60 km) and within a narrow range of Δ (~ 30° to 50°). VDSS has been successfully applied in both western China and across the USA, but many potential target areas on Earth lack suitable subduction seismicity at the appropriate Δ. Yu *et al.* (2013) used particle-motion analysis to allow VDSS analysis of shallow sources, but their method requires complicated data processing, forsaking the simplicity of VDSS.

Here we attempt to expand the applicable Δ for VDSS sources to c. 65° to 105°, while retaining the inherent simplicity of VDSS, by using *SS* instead of *S* phases. We seek to identify *SSsPmp* following *SS*, even though *SS* has a period typically longer (> 20 s) than the usual T_{VDSS} (< 10 s). Data from GSN station FFC located at Flin Flon, Canada, display *SS* arrivals that appear to include a delayed compressional component: initial pure shear motions followed closely by a distinct vertical component that oscillates in the same polarity as the radial component. Our recognition of this vertical component as *SSsPmp* is supported by synthetics for a simple crustal model that produce similar seismograms. The now-popular particle motion analysis of *SsPmp* is not easily applicable to *SSsPmp* due to the considerable overlap of shear and compressional motions. Instead, we obtain T_{VDSS} using synthetics to fit the vertical component of *SSsPmp*.

Shear Wave Velocity Model of the Southeastern United States From Ambient Noise Tomography With Double Beamforming

BARMAN, D., Baylor University, Texas, USA, debajeet_barman1@baylor.edu; PULLIAM, J., Baylor University, Texas, USA, jay_pulliam@baylor.edu; QUIROS, D., Baylor University, Texas, USA, diego_quiros@baylor.edu

Determining the structural relationship between the Gondwanan Suwannee terrane (SWT) and adjacent terranes in the southeastern United States can help constrain the late Paleozoic accretionary formation history of Laurentia, the tectonics of the Alleghanian orogeny, and the nature of the breakup of Pangaea. Our modeling approach consists of two parts: 1) Compute Rayleigh wave group velocity maps using double beamforming to obtain the most accurate dispersion relations and 2) estimate a shear wave velocity model using "ant colony" inversion. We also compare the ant colony result to estimates produced with Markov Chain Monte Carlo inversion.

Vertical component seismograms are used from more than 400 stations of USArray, ANSS, and regional networks for the years 2010-present. Rayleigh wave group velocity dispersion curves are calculated between station pairs using double beamforming to admit only components of surface waves that propagate along great circle paths. Cross-correlations between vertical component of ambient noise data from subarrays are stacked between array centers as a function of velocity, azimuth, and time (*i.e.*, a vespagram is produced) and frequency-time analysis is applied with phase-matched filters to create group velocity dispersion curves. Dispersion curves are used to obtain Rayleigh wave group velocity maps for the entire region and the maps are used to constrain locally 1D shear wave velocity models found via ant colony nonlinear optimization. Ant colony optimization is a computationally efficient and stable swarm intelligence method. The method has been shown to converge quickly to the global solution and to produce an accurate model.

Preliminary results with six months of data for a portion of the study region show significant differences between group velocity values and structural boundaries obtained with double beamforming and a conventional approach. Interpretations of the region's tectonic history are therefore also affected.

Ambient Noise Tomography of the Saudi Arabian Shield

CIVILINI, F., U.S. Geological Survey, California, USA, fcivilini@gmail.com; MOONEY, W. D., U.S. Geological Survey, California, USA, mooney@usgs.gov; ZAHRAN, H. M., Saudi Geological Survey, Jeddah, Saudi Arabia, zahran.hm@sgs.org.sa

Saudi Arabia is located in a tectonically active region: spreading occurs to the west and south in the Red Sea rift and the Gulf of Aden and is accommodated by a fold and thrust belt in the Zagros mountains to the north-east. The geology in western Saudi Arabia is primarily dominated by the Arabian Shield, a ~725,000 km^2 surface expression of Precambrian rock, which is locally covered by Cenozoic basaltic lava called "harrats". In 2009, an earthquake swarm caused by a dike intrusion at Harrat Lunayirr prompted the need of new hazard models for this region.

Reliable high-resolution shear-wave crustal velocity models provide critical information about the composition and other physical properties of the crust and are required to accurately assess seismic hazards. We used surface waves generated by ambient seismic noise to develop surface-wave dispersion maps and a pseudo-3D shear-wave velocity model for the Arabian Shield. Teleseismic P-waves are detected in the ambient noise records, and their detection is attributed to the lack of attenuation in the Arabian Shield. Rayleigh and Love dispersion maps show low crustal surface-wave velocities (on the order of -5%) in the northern harrats (> 24° N).

Each node in the dispersion maps (size 0.2° x 0.2°) was inverted to shear-velocity using the Neighborhood Algorithm and an input model based on the results of a country-wide refraction survey. We found low shear-velocities in both the upper and lower crust co-located with the northern harrats but only in the lower crust for the southern harrats.

On the Application of Phase-Weighted Stacking to Suppression of Sediment Reverberations in Receiver Functions

BALL, J. S., University of Colorado Boulder, Colorado, USA, justin.ball@colorado.edu; SCHULTE-PELKUM, V., University of Colorado Boulder, Colorado, USA, vera.schulte-pelkum@colorado.edu

Teleseismic receiver function (RF) analysis is now a preeminent methodology for imaging the Moho using passive seismic data. Since the method's inception, reverberations within shallow sediment layers have presented a formidable obstacle to RF practitioners due to their tendency to overprint deeper converted arrivals usually targeted for study. Significant progress toward mitigation of shallow reverberations in receiver functions is advancing on several fronts: data-driven approaches like sequential H-K stacking, and model-based approaches ranging from reverberation removal filters to full-waveform inversion. Here, we hope to demonstrate a simple tool to augment all approaches by constraining the arrival times of Moho Ps, using RF phase information obtained via the Hilbert Transform to clearly identify conversions whose amplitudes may otherwise be obscured by shallow reverberations.

We show that, prior to the arrival of the Moho Ps phase, the Phase-Weighted Stack (PWS) of slowness-binned RFs closely matches the impulse response of the sediment layers, given the sediment reverberations do not exhibit significant moveout. When the Moho Ps arrives, the Phase Stack diverges from unity due to the moveout of the crustal arrival. Thus, so long as the sediment reverberations do not move out, the residual between PWS and binned RFs can be used to identify the arrival times of the Moho Ps phase, even if its amplitude is overprinted by shallow reverberations.

In the course of developing this method, we investigated the practical limitations of applying PWS to RF data using numerical experiments, from which we derived basic constraints useful to assess the validity of applying PWS to real data. We show that, for RFs constructed from Gaussian pulses, PWS artifacts correlate with deviations from Gaussian support in RF instantaneous frequencies and vanishing RF amplitudes. Using these observations to implement minimal PWS quality-control, we show significant improvement in reverberation removal results for synthetic data and TA stations in the Williston Basin.

Emerging Science from the EarthScope Transportable Array in Alaska and Western Canada

Poster Session · Friday · 26 April · Grand Ballroom

A High-Resolution 3D Vs Model of Alaska Revealed by Surface Waves

FENG, L., University of Colorado Boulder, Colorado, USA, lili.feng@colorado.edu; RITZWOLLER, M., University of Colorado Boulder, Colorado, USA, michael.ritzwoller@colorado.edu; LIU, C., University of Colorado Boulder, Colorado, USA, chuanming.liu@colorado.edu; SHEN, W., Stony Brook University, New York, USA, weisen.shen@stonybrook.edu

Alaska is tectonically complex, including subduction zones, the highest mountains in North America, and the cordilleran-cratonic boundary. Although the expression of these geological structures in the deeper crust and upper mantle remains relatively unclear, the deployment of the EarthScope Transportable Array (TA) provides a new data of exceptional quality that can be exploited to improve knowledge of earth structure beneath Alaska. Based on the seismic data collected by the TA and several other local and regional networks, we present a 3D Vs model of the crust and upper mantle using surface wave datasets constructed by joint inversion of Rayleigh wave phase and group dispersion measurements extracted from both ambient seismic noise and earthquake records. We apply a Bayesian Monte Carlo approach in the inversion procedure to these data to constrain the isotropic Vs structure of the crust and uppermost mantle. The posterior distribution that results yields probabilistic information about Vs structure, including the mean model and model uncertainty. The 3D model captures many structural features, including the major sedimentary basins, the subducting Pacific plate to a depth of about 150 km, the craton underlying the North Slope, and a large region of deformation surrounding the Alaska range in central Alaska. We test the model using receiver functions, which are highly complicated across much of Alaska, in order to provide insight into future model improvements in the near future.

The Investigation of the Alaskan Interior Using Ambient Seismic Noise

BOSCHELLI, J., Saint Louis University, Missouri, USA, joshua.boschelli@slu.edu; HERRMANN, R. B., Saint Louis University, Missouri, USA, robert.herrmann@slu.edu

In 2018, a surge in large magnitude earthquakes within the Alaskan interior has prompted an in-depth investigation of the region's crustal structure, revealing a scale of complexity and heterogeneity not previously recognized. The techniques of ambient seismic noise were used on a combination of seis- mic stations from the EarthScope FlexArray experiment and various arrays within British Colombia to extract group and phase velocities for both the vertical and transverse components of the resultant cross-correlated wave forms. The inversion of the dispersion curves provide clear distinctions be- tween the basin and mountain ranges, highlighting the complex geological history of the region. In addition, the regional seismic velocities vary longi- tudinally from the northern extent of the Rocky Mountains to the coast of the Arctic Sea, which is exhibited by the greater North American continent albeit on a much larger scale. The radical differences of the seismic profile along with the recent increase in earthquake activity and high resolution of this study provides a valuable insight into a region with a relatively high seismic hazard, that until now has not been fully investigated .

Identification and Relocation of Earthquakes in the Sparsely Instrumented Mackenzie Mountain Region, Yukon and Northwest Territories, Canada

HEATH, D. C., Colorado State University, Colorado, USA, david.heath@colostate.edu; ASTER, R., Colorado State University, Colorado, USA, rick.aster@colostate.edu; SCHUTT, D., Colorado State University, Colorado, USA, derek.schutt@colostate.edu; FREYMUELLER, J. T., Michigan State University, Michigan, USA, freymuel@msu.edu; CUBLEY, J., Yukon College, Whitehorse, Canada, jcubley@yukoncollege.yk.ca

The Mackenzie Mountains are an actively uplifting and seismogenic arcuate thrust belt lying within the Yukon and Northwest Territories. Seismic activity in the region is poorly constrained due to a historically very sparse seismograph distribution. In this study, new data are analyzed from the ~875 km-long Mackenzie Mountains temporary (FDSN 7C) network located in the Cordillera-Craton region adjacent to and within the Mackenzie Mountains, in conjunction with Transportable Array and other sparsely distributed stations in the region. Using detection algorithms developed by Kushnir *et al.* [1998] and Roecker *et al.* [2006], signals are identified and subsequently associated across the network to identify events, establish phase onsets and estimate hypocenter locations. In this preliminary study, data from the first full year of the Mackenzie Mountains network deployment (September 2016 - September 2017) are processed and compared to earthquake catalog records maintained by the USGS. This study will further improve the regional earthquake catalog by detecting smaller-magnitude earthquakes with reasonable confidence. Future work on this project will require expanding the earthquake catalog to include all available data from the region during the two-year large-scale temporary seismograph deployment, and to interpret seismicity and areas of uplift in the context of regional-scale faults, geomorphology, and other geologic structures. Results from this study should provide new insight into the regions of active faulting within the Mackenzie Mountain uplift and to activity along large strike slip features, such as the Tintina Fault. Additionally, the Mackenzie Mountain region is identified as having high seismic hazard, and results will inform understanding of the regional geology and seismicity from a hazards and risk perspective for northwestern Canada [Natural Resources Canada, 2015].

Multi-Scale Lithospheric Architecture of Alaska Inferred From Receiver Functions

MILLER, M. S., Australian National University, Canberra, Australia, meghan.miller@anu.edu.au; O'DRISCOLL, L. J., University of Oregon, Oregon, USA, lodrisco@uoregon.edu; PORRITT, R. W., University of Texas, Texas, USA, rwporritt@ig.utexas.edu; ROESKE, S. M., University of California, Davis, California, USA, smroeske@ucdavis.edu

We present receiver function images of crustal and lithospheric architecture based on broadband seismic data across the region that are now constrained by new data from the EarthScope Transportable Array (TA). The resulting receiver functions (Ps and Sp) reproduce many of the Moho depth variations previously modeled by both more concentrated arrays, primarily in south-central Alaska, using receiver functions and tomographic imaging. However, these new results provide significantly more detailed images of the entire state that illustrate the accretionary tectonic history of the continental lithosphere in the region. The geologic mosaic of terranes, adjacent multi-phase plate boundary in the south, rapid lateral topographic variations, and heterogeneous distribution of strain throughout Alaska are reflected in complex tectonic history and geology of the region. The variable thickness of the crust and lithosphere reflects inherited structure from Mesozoic to early Cenozoic convergent and extension events that in some regions is being extensively modified by ongoing convergence and collision, particularly along the active southern margin. Combining three different receiver function methodologies for both Ps and Sp – Common Conversion Point (CCP) stacking, receiver function stacks, and receiver gathers - for viewing and imaging P receiver functions allows for an interpretation of Alaskan crustal structure that spans multiple scales.

Mapping the Alaskan Moho: An Exercise in Reproducible Science

MORESI, L., University of Melbourne, Melbourne, Australia, louis.moresi@unimelb.edu.au; MILLER, M. S., Australian National University, Acton, Australia, meghan.miller@anu.edu.au

In Miller & Moresi (2018), we presented a series of Moho depth maps for the Alaskan region based on *P* receiver function estimates using data from all available broadband instrumentation from 1999 to April 2018 including the USArray Transportable Array. The average Moho depths beneath individual broadband stations were presented first as spot measurements and then used to produce a series of interpolated smooth surfaces by an adaptive triangulation process followed by the fitting of a bicubic spline. The interpolated surfaces included a measure of confidence in the interpolation to help etermine a preferred model. The resulting Moho depth map (single continuous surface) provided a reasonable estimate of the Earth's outermost layer thickness beneath Alaska as constrained by receiver functions for use in applications such as tomography, regional-scale interpretations, or simulations of seismic waves.

REPRODUCIBILITY & REUSE

Making research reproducible means providing the entire workflow from data, through software and post-processing freely available. Not only can somebody repeat experiments and verify them, they can build upon them. In lab-based disciplines, there are many further challenges, but in research that is predominantly based on data processing, this is an achievable goal today.

We have released all of the background for our paper on the Alaska Moho to make it transparent and reproducible. Open source software is one thing (the software and raw moho picks are available through pip install miller_alaska-moho_srl2018), but to manage versions and operating system changes, we have packaged everything in a docker container that can be launched here: https://mybinder.org/v2/gh/lmoresi/miller-moho-binder/publication

NOTES & REFERENCE

Meghan S. Miller, Louis Moresi; Mapping the Alaskan Moho. Seismological Research Letters ; 89 (6): 2430–2436. doi: https://doi.org/*10.1785/0220180222*

The software and data for this model is available via github accessed via the following doi:10.5281/zenodo.1459110

New Constraints on Crust and Mantle Structure Surrounding the Beaufort Sea, Western Canadian Arctic

SCHAEFFER, A. J., Natural Resources Canada, Sidney, Canada, andrew.schaeffer@canada.ca; AUDET, P., University of Ottawa, Ottawa, Canada, paudet@uottawa.ca; CAIRNS, S., Northwest Territories Geological Survey, Yellowknife, Canada, scott_cairns@gov.nt.ca; ELLIOTT, B., Northwest Territories Geological Survey, Yellowknife, Canada, barrett_elliott@gov.nt.ca; FALCK, H., Northwest Territories Geological Survey, Yellowknife, Canada, hendrik_falck@gov.nt.ca; BOSTOCK, M. G., University of British Columbia, Vancouver, Canada, bostock@eos.ubc.ca; DARBYSHIRE, F., University of Quebec at Montreal, Montreal, Canada, darbyshire.fiona_ann@uqam.ca; ESTEVE, C., University of Ottawa, Ottawa, Canada, ceste044@uottawa.ca; SNYDER, D., Natural Resources Canada, Ottawa, Canada, david.snyder@canada.ca

The formation and evolution of the western Canadian Arctic Archipelago represents a long-standing tectonic puzzle. The eastern Beaufort Sea juxtaposes young Arctic Ocean with Paleo-Proterozoic Canadian Shield. Controlled source off-shore seismic data suggest that Banks Island represents the western edge of the rifted margin established during the opening of the Arctic Ocean. In this scenario rifting caused Banks Island to subside and accumulate sediments rich in petroleum source material. Conversely, surface-wave based velocity models of North America indicate velocities at 100-150 km depths similar to those beneath Canada's diamond mines in the central Slave craton. These results suggest Banks Island basement is part of the Canadian Shield and any kimberlites are promising diamond candidates. Furthermore, the southern Beaufort Sea Mackenzie Delta margin represents a well-developed fold and thrust belt ≤65 Myrs old but has only been recently recognized as likely active. This belt accommodates either slow thrusting of continental crust over the oceanic crust, or underthrusting of the oceanic crust beneath the margin.

We exploit data from new land seismic networks to investigate crustal structure and seismicity of the Beaufort Sea and surroundings. A key question is how mantle structure typical of the Canadian Shield is reconciled with crust of a rifted passive margin. Specifically, inference of thick cratonic-like lithosphere underlying Banks Island is incompatible with a tectonically disrupted and thinned margin of the Canada Basin. Preliminary results of crust and mantle structure from dispersion analysis, 1D inversion, and receiver function analyses, indicate a ~30 km deep Moho beneath the Beaufort Sea and Banks Island, with slight thinning northwards towards Prince Patrick and Melville Islands. Mantle velocities remain elevated, indicative of cooler lithosphere. Anisotropy orientations from SKS splitting indicate margin parallel fabrics, perpendicular to those expected for a tectonically extended margin; however, their source depths remain elusive.

New Frontiers in Global Seismic Monitoring and Earthquake Research

Poster Session · Friday · 26 April · Grand Ballroom

Global and Local Scale High-Resolution Seismic Event Catalogs for Algorithm Development and Testing

YOUNG, C. J., Sandia National Laboratories, New Mexico, USA, cjyoung@sandia.gov; LINVILLE, L., Sandia National Laboratories, New Mexico, USA, llinvil@sandia.gov; AUR, K. A., Sandia National Laboratories, New Mexico, USA, kaaur@sandia.gov; BROGAN, R., ENSCO, Inc., Florida, USA, brogan.ronald@ensco.com

During the development of new seismic data processing methods, the verification of potential events and associated signals can present a non-trivial obstacle to the assessment of algorithm performance, especially as detection thresholds are lowered to include anthropogenic signals from surface and shallow underground sources. In particular, we note that without a complete and accurate catalog, it is not possible to accurately calculate either precision or recall. Here we present two 14-day seismic event catalogs, one developed in Utah for local-scale event processing using data from the University of Utah Seismic Station network, and the other developed for global-scale processing using data from the International Monitoring System (IMS). Each catalog was built manually by an expert analyst to comprehensively identify events from all sources that were locatable using phase arrival timing and (when available) directional information, resulting in number of event increases compared to existing catalogs of 4300% in Utah and 650% globally. The catalogs additionally contain challenging event sequences (prolific aftershocks and small events at the detection/location threshold) and novel event types and sources (infrasound only events, long-wall mining events) that make them useful for algorithm testing and development, as well as being valuable for the unique tectonic and anthropogenic event sequences they contain.

Recent Upgrade of the ISC Bulletin and Associated Datasets

STORCHAK, D. A., International Seismological Centre, Thatcham, United Kingdom, dmitry@isc.ac.uk; DI GIACOMO, D., International Seismological Centre, Thatcham, United Kingdom, domenico@isc.ac.uk; LENTAS, K., International Seismological Centre, Thatcham, United Kingdom, kostas@isc.ac.uk; BROWN, L., International Seismological Centre, Thatcham, United Kingdom, lonn@isc.ac.uk; HARRIS, J., International Seismological Centre, Thatcham, United Kingdom, james@isc.ac.uk

The International Seismological Centre (ISC) continues with its mission of producing the most long-term, comprehensive and homogeneous summary of instrumentally recorded seismicity on a global scale, primarily based on seismic bulletin reports from ~150 seismic networks worldwide. Several associated datasets such as the ISC-GEM, ISC-EHB, GT and the Event Bibliography further expand the ISC data for use in different research fields.

Although the ISC data are not produced close to real time, they remain an important data source for calibration of real-time earthquake monitoring techniques and a good reference point for assessment of their results.

Recent upgrades included the releases of

- rebuilt ISC Bulletin for the 1964-1984 period, where all hypocentres and teleseismic magnitudes have been recomputed using the current standard event location procedure (Bondar and Storchak, 2011), ak135 velocity model and all reported seismic phases; previously missing data from permanent and temporary deployments have been added and general cleaning of the Bulletin has been done;

- 6th version of the ISC-GEM catalogue most notably advanced with the earthquake mechanisms from scientific literature and continental earthquakes of smaller magnitudes;

- re-worked and reviewed ISC-EHB dataset for 2000-2015;

- first ISC-authored set of fault plane solutions for moderate earthquakes that occurred during 1938-1979 and 2011-2016; this also marked the beginning of routine use of freely available waveforms at the ISC to automatically determine and make available the polarities of first motions of P-waves and corresponding fault plane solutions, some of which are not given by other global or regional agencies.

First Results of CISA, The New Central Italy Seismic Array

BRAUN, T., Istituto Nazionale di Geofisica e Vulcanologia, Arezzo, Italy, thomas.braun@ingv.it; CACIAGLI, M., Istituto Nazionale di Geofisica e Vulcanologia, Bologna, Italy, marco.caciagli@ingv.it; FAMIANI, D., Istituto Nazionale di Geofisica e Vulcanologia, Roma, Italy, daniela.famiani@ingv.it; GOVONI, A., Istituto Nazionale di Geofisica e Vulcanologia, Rome, Italy, aladino.govoni@ingv.it; HANDEREK, K., Ludwig Maximilian University of Munich, Munich, Germany, karolinahanderek@ymail.com; MARIOTTI, M., SARA Electronic Instruments, Perugia, Italy, mauro.mariotti@sara.pg.it; MARTINI, M., Osservatorio Meteo-Sismico, Perugia, Italy, dir.martini@gmail.com; THOROSSIAN, W., Istituto Nazionale di Geofisica e Vulcanologia, Rome, Italy, william.thorossian@ingv.it; WASSERMANN, J. M., Geophysical Observatory, LMU, Munich, Germany, jowa@geophysik.uni-muenchen.de

During the last decades, seismic monitoring experienced important advances by introducing small aperture arrays and dense seismic networks equipped with high-dynamic-range instrumentation. This new recording reality allowed to lower significantly the monitoring threshold, to identify in quasi real time active seismo-tectonic structures and to reveal information about the seismic source and its rupture dynamics. The application of array techniques, as beamforming and f-k analysis use the coherence properties of the recorded wavefield for increasing the S/N-ratio, to determine back-azimuth and apparent velocity of the incoming wavefield and to automatically locate the seismic events of small magnitudes.

We realized the first permanent small aperture array installation in Italy, called CISA (Central Italy Seismic Array) composed of 9 three-component seismic sensors installed at interstation distances from 100 - 500 m and a maximal extension of 1000 m. CISA's circular configuration and its geographical position is aimed to monitor the microseismicity of Central Italy at a local and regional range, including the epicentral area of the 2016/17 seismic sequence, as well as the geothermal areas in the western sector.

CISA's challenges are to decrease the detection threshold of the microseismicity, to identify active faults in Umbria by analysis of the microseismicity and to study in detail the rupture dynamics of moderate earthquakes, by using source scan algorithm. Seismic data are transmitted in real-time to the data center of SARA-electronic (Perugia) by ordinary 4G-LTE router and then forwarded to the observatories of Arezzo and Munich by using seedlink protocol. An ObsPy module manages the fk-detection, calculating in real-time backazimuth, slowness, gain and semblance. On a local scale CISA is expected to operate in a magnitude range from $0<M<3$, which could be easily extended to $3<M<6$ by installing additional accelerometers.

IRIS DMC's Latest Data Products

BAHAVAR, M., Incorporated Research Institutions for Seismology, Washington, USA, manoch@iris.washington.edu; TRABANT, C., Incorporated Research Institutions for Seismology, Washington, USA, chad@iris.washington.edu; VAN FOSSEN, M., Incorporated Research Institutions for Seismology, Washington, USA, mick@iris.washington.edu; AHERN, T., Incorporated Research Institutions for Seismology, Washington, USA, tim@iris.washington.edu; CARTER, J., Incorporated Research Institutions for Seismology, Washington, USA, jerry@iris.washington.edu

The IRIS Data Management Center (DMC) has been serving the seismological research community with data-derived products since 2009. We are currently serving 29 distinct data products that can be use by researchers working in related disciplines and beyond. In this presentation we will highlight 4 new developments as follows:

The Surface-Wave Radiation Patterns (SWRP*) is our latest data product. Following major earthquakes, radiation patterns at a set of frequencies are generated and made available from our product repository. The SWRP product also provides an interactive web-based application to generate radiation patterns for arbitrary source parameters, allowing users to explore the effect of parameters on the directional dependency of surface waves.

Our recent Exotic Seismic Events Catalog (ESEC**) product provides information on non-earthquake seismic events such as landslides, debris flows, dam collapses, etc. that generate seismic signals but are rarely included in earthquake catalogs.

The DMC's Earth Model Collaboration (EMC) currently hosts more than 64 contributed Earth models. In addition to our browser-based visualization tools, we now offer a set of plugins for 3D desktop visualization using ParaView. The plugins are customizable to allow users to visualize their own Earth models or auxiliary data in 3D.

We have also released a Python package to compute horizontal-to-vertical spectral ratios (HVSR) using available power spectral density (PSD) estimates of ambient noise available from the DMC's quality assurance system. These measurements can be readily used to compute site response for seismic stations.

* SWRP: developed by Boris Rösler and Suzan van der Lee (Northwestern University)

** ESEC: developed and maintained in collaboration with Kate Allstadt (USGS) and Steve Malone (PNSN)

Performance and Future Development of the Chilean Seismic Network

BARRIENTOS, S. E., Universidad de Chile, Santiago, Chile, sbarrien@csn.uchile.cl

The National Seismological Center (CSN) of the University of Chile initiated in 2013 the implementation of a network of 65 permanent real-time six-component broadband and strong motion stations together with the installation of 130 Global Navigation Satellite Systems (GNSS) receivers; an off-line independent network of 297 strong ground motion instruments complement the system. The main portion of the deployment was completed within three years with later additions in specific zones of interest.

The network was designed to provide fast and accurate estimates of earthquake source parameters of potentially devastating earthquakes for emergency response applications, and was also capable of comprehensive characterization of Chilean seismicity, necessary for long-term hazard assessment and mitigation activities. In near-real-time applications, as well as in the near field, the GNSS stations become critical for determination of fault finiteness of M ~ 7 or larger earthquakes that affect the coastal part of the country. We will present recent developments in rapid earthquake characterization using as examples the observations made for large earthquakes in the country: from the M8.2, April 1, 2014 event to the M6.9, April 24, 2017 earthquake.

Additionally, the network presently covers regions not monitored previously in a continuous manner at this scale, particularly in austral Chile, and clear patterns of seismicity are emerging after two years of operations in these areas.

As for future developments, a prototype of an integrated accelerometer device has been developed and tested for deployment in Central Chile as part of an Earthquake Early Warning System.

Oklahoma Geological Survey Regional Network

WALTER, J., University of Oklahoma, Oklahoma, USA, jakeiwalter@gmail.com; OGWARI, P. O., University of Oklahoma, Oklahoma, USA, pogwari@ou.edu

The Oklahoma Geological Survey (OGS) monitors seismicity throughout the state of Oklahoma utilizing permanent and temporary seismometers installed by OGS and other agencies, while maintaining an earthquake catalog. The OGS seismic network was recently added to ANSS as a self-supporting network and cooperates with USGS in contributing to the ANSS Comprehensive Earthquake Catalog. In Oklahoma, prior to 2009 background seismicity rates were about 2 M3.0+ earthquakes per year, which increased to 579 and 903 M3.0+ earthquakes in 2014 and 2015, respectively. The peak in the seismicity rate has since fallen to 624, 304, and 194 M3.0+ earthquakes in 2016, 2017, and 2018, respectively. The catalog is complete down to M2.3 from mid-2014 to present, despite the significant workload for a primarily state-funded regional network. Analysts continue to work backwards to complete the catalog in earlier years, as time allows. Unique challenges associated with being the de-facto earthquake information source include providing regulators, *i.e.* the Oklahoma Corporation Commission, with earthquake locations and magnitude within minutes of an event so that their "traffic-light" protocol may be effectively applied. Thus, we have an improved local magnitude scale with a Richter attenuation curve tuned to Oklahoma. We have also begun exploring daily matched-filter detection and machine learning methods to improve network operations. In addition, we have begun a citizen-scientist driven, educational seismometer program by installing Raspberry Shake geophones throughout the state at local schools. Educational aspects of that program include teacher-driven curriculum development facilitated during professional development workshops for teachers. Raspberry Shakes to our earthquake information center, and we utilize the data for earthquake locations and research in areas of the state with sparse broadband or short-period seismographs. The future seismic hazard of the state portends a continued need for expansion and densification of seismic monitoring throughout Oklahoma.

The Advanced National Seismic System Comprehensive Earthquake Catalog

EARLE, P., U.S. Geological Survey, Colorado, USA, pearle@usgs.gov; AMBRUZ, N. B., U.S. Geological Survey, Colorado, USA, nambruz@usgs.gov; FEE, J. M., U.S. Geological Survey, Colorado, USA, jmfee@usgs.gov; MARTINEZ, E. M., U.S. Geological Survey, Colorado, USA, emartinez@usgs.gov

The U.S. Geological Survey (USGS) maintains a repository of earthquake bulletins and higher-level products such as earthquake slip models, "Did You Feel It?" reports, ShakeMaps, PAGER impact estimates, earthquake summary posters, and tectonic summaries. Together, this archive is known as the USGS Advanced National Seismic System (ANSS) Comprehensive Catalog or "ComCat". Over the past several years, an effort has been made to expand ComCat by integrating global and regional historic catalogs. The archive's collection of hypocenter and magnitude information often with supporting phase arrival-time and amplitude measurements is extensive. Presently, ComCat contains information on about three million earthquakes. Data for global earthquakes are primarily from the ISC-GEM catalog and the USGS National Earthquake Information Center's PDE bulletin that, in turn, contains contributions from many non-U.S. networks. The majority of the U.S. earthquakes are contributed by the USGS-supported ANSS regional seismic networks. In this presentation, we provide potential users with an overview of ComCat contents. We show how ComCat completeness evolves over time for different regions and summarize the contributions of the major contributing catalogs. We also present a description of the tools and semi-automated quality-control procedures developed to uncover errors including systematic magnitude biases, missing time periods, duplicate event postings, and incorrectly associated events. Finally, we discuss future development and design ideas that will continue to improve the quality and content of ComCat.

Exploring the Use of Deep-Learning to Aid Global Earthquake Monitoring at the NEIC

YECK, W. L., U.S. Geological Survey, Colorado, USA, wyeck@usgs.gov; PATTON, J. M., U.S. Geological Survey, Colorado, USA, jpatton@usgs.gov; ROSS, Z. E., California Institute of Technology, California, USA, zross@gps.caltech.edu; EARLE, P., U.S. Geological Survey, Colorado, USA, pearle@usgs.gov; BENZ, H. M., U.S. Geological Survey, Colorado, USA, benz@usgs.gov

Recent research exploring the application of deep learning to seismic problems has demonstrated its vast potential. Here we explore the use of neural networks to predict seismic source characteristics from waveform data to aid in local-to-global real-time earthquake monitoring at the NEIC. In a simple framework, seismic arrival detections made from standard picking methods (*e.g.*, STA/LTA) can be fed to trained neural network models to predict seismic phase type, event distance, and potentially a variety of other source-specific characteristics. We leverage the Advanced National Seismic System comprehensive catalog (ComCAT) to compile a dataset of millions of phase arrivals from the National Earthquake Information Center's (NEIC) Preliminary Determination of Epicenters Bulletin, with associated phase labels (Pg, Pn, P, Sg, Sn, S, and Noise), event distances, magnitudes, and azimuths. We then extract waveforms from the Incorporated Research Institutions for Seismology Data Management Center, and use this data set to train models to classify various source characteristics. This catalog encompasses a wide range of station-event distances, event magnitudes, event types, and station types. Given a single three-component waveform, our models are successful at classifying P, S, and noise and are able to discern local from teleseismic arrivals, but are inaccurate at estimating intermediate source distances (~5-30 degrees). We discuss the implementation of these classifiers into the NEIC's real-time systems, including the implementation of these source estimates into our operational associator GLASS3. We find that implementations as simple as removing STA/LTA picks classified with a high probability of being noise can reduce spurious detections from our associator by ~25%.

Next Generation Seismic Detection

Poster Session · Friday · 26 April · Grand Ballroom

Applying Waveform Correlation to Aftershock Sequences Using a Global Sparse Network

SUNDERMIER, A., Sandia National Laboratories, New Mexico, USA, asunder@sandia.gov; TIBI, R., Sandia National Laboratories, New Mexico, USA, rtibi@sandia.gov; YOUNG, C. J., Sandia National Laboratories, New Mexico, USA, cjyoung@sandia.gov

Studies have shown that waveform correlation is effective in detecting similar seismic waveforms from repeating earthquakes, including aftershock sequences. Monitoring agencies have shown interest in adopting techniques to quickly characterize aftershock sequences to reduce the amount of effort required by analysts to add aftershocks to event bulletins. Our experiment uses waveform templates recorded by multiple stations of the IMS network during the first 12 hours after the mainshock to detect and identify aftershocks that occur during the subsequent week. We present methods for station and template selection, threshold setting, and event detection that are specialized for aftershock processing in a sparse, global network. We apply the methods to several aftershock sequences to evaluate the potential for establishing a set of standard aftershock waveform correlation processing methods that can be effective for operational monitoring systems with a sparse network. We compare candidate events detected with our processing methods to the LEB bulletin to develop an intuition about potential reduction in analyst effort.

Real-Time In-Situ Seismic Imaging

SONG, W., University of Georgia, Georgia, USA, wsong@uga.edu; KEDAR, S., Jet Propulsion Laboratory, California Institute of Technology, California, USA, sharon.kedar@jpl.nasa.gov

We present a Real-time In-situ Seismic Imaging (RISI) System, which is a wireless seismic network that senses and processes seismic signals and computes a 3D subsurface image in-situ in real-time. The basic mechanism is: seismic waves propagating/reflected/refracted through subsurface enter a wireless network of sensors, where a 2D or 3D image is computed and recorded; a control software may be connected to this network to allow view of the 2D/3D image and adjustment of settings such as resolution, filter, regularization, and other algorithm parameters. System prototypes based on seismic imaging have been designed. RISI technology is envisioned as a game changer to transform many subsurface survey and monitoring applications, including oil/gas exploration and production, subsurface infrastructures and border security, wastewater and CO2 sequestration, earthquake and volcano hazard monitoring.

A Progress Report on a Large MERMAID Deployment Into the Pacific Ocean

SIMON, J. D., Princeton University, New Jersey, USA, jdsimon@princeton.edu; SIMONS, F. J., Princeton University, New Jersey, USA, fjsimons@princeton.edu; NOLET, G., Université Nice Sophia Antipolis, Valbonne, France, nolet@geoazur.unice.fr

Between late June and early September of 2018, eighteen of the newest-generation, commercially-available MERMAID floats were deployed into the Southern Pacific Ocean. We present the most comprehensive report to date on the quality and quantity of data returned thus far, and offer a broad overview of MERMAID data in general: how it looks and its utility. As of November, 2018, MERMAIDs had sent to shore nearly 500 seismograms from the Southern Pacific Ocean, about 90% of which have been matched to the global catalog. The remaining unmatched data represent small earthquakes deep in the ocean that otherwise go undetected by the global seismic network. MERMAID is an acronym for Mobile Earthquake Recorder in Marine Areas by Independent Divers. It is an autonomous, freely-drifting oceanic float that records the acoustic wavefield at mid-column depths. The float itself is an adjustable buoyancy glass sphere that includes a GPS receiver, two-way Iridium communication for data transfer in near real time to and from the float, and a hydrophone. A standard dive cycle goes something like this: upon surfacing MERMAID sends its current location and any data it recorded during its last dive, downloads instructions for the next dive, descends to a specified depth (generally between 1500 and 2000 m), and activates its hydrophone to passively record the acoustic wavefield. The data is passed in real-time through an onboard detection algorithm that triggers an immediate surfacing if a signal is deemed to have a high likelihood of being generated by an earthquake. Signals with lower likelihoods of being generated by an earthquake are written to an onboard buffer and sent during the next surfacing, either when a higher-likelihood signal is recorded, or a predetermined maximum dive duration has been reached, whichever comes first. In this way MERMAID delivers seismograms in near real time from the oceans, often within hours after large events.

Is the Sangre de Cristo Fault in the Rio Grande Rift Reawakening?

BELL, J. P., University of Colorado Boulder, Colorado, USA, jackson.bell@colorado.edu; SHEEHAN, A. F., University of Colorado Boulder, Colorado, USA, anne.sheehan@colorado.edu; KIRKHAM, R. M., GeoLogical Solutions, Colorado, USA, rmk@gojade.org; HARRIS, D., Deschutes Signal Processing LLC, Oregon, USA, oregondsp@gmail.com; YECK, W. L., U.S. Geological Survey, National Earthquake Information Center, Colorado, USA, wyeck@usgs.gov

In November of 2018, residents living near Great Sand Dunes National Park reported hearing and feeling multiple earthquakes, and reports of additional earthquakes have continued. These earthquakes occurred on or near the Sangre de Cristo Fault, a major west dipping normal fault within the Rio Grande Rift in south-central Colorado and north-central New Mexico. The fault is capable of generating earthquakes M7 or greater (McCalpin, 1982), but it has not ruptured with a large, damaging earthquake in historic times. This 250-km-long fault runs along the east side of the San Luis Valley at the base of the Sangre de Cristo Mountains. Based on geomorphic expression, the fault is subdivided into three sections (Ruleman and Machette, 2007): a northern section extends from near Poncha Pass to the base of Blanca Peak in Colorado; a central section continues southward to the Colorado-New Mexico state line; and a third section goes southward beyond Taos, New Mexico. McCalpin (1982, 2006) conducted paleoseismic investigations of the northern section, and Crone *et al*. (2006) studied the central section. These studies indicate that the rupture history of the fault is complex; that multiple late Quaternary ruptures characterize the fault, with slip rates ranging from ~0.06 to 0.2 mm/yr. Between 1970 and 2017, only three earthquakes were recorded by the USGS in the vicinity of the northern section of the fault. Using the earthquakes reported by local residents as templates, we form a subspace detector using data from a seismometer located at Great Sand Dunes National Park (US.SDCO, 12km away). We detect many small previously unreported earthquakes (~M 0.0+, up to 200 per day). Using all high signal-to-noise detected events, we form a detector and process the long-term continuous data at stations US.SDCO, TA.S22A, TA.T25A, and TA.Q24A. These newly detected events give new insight into the low-rate seismicity on the Sangre de Cristo fault.

Incorporating AI in Routine Seismic Network Operations in Southern California

HAUKSSON, E., California Institute of Technology, California, USA, hauksson@caltech.edu; ROSS, Z. E., California Institute of Technology, California, USA, zross@gps.caltech.edu; BHADHA, R., California Institute of Technology, California, USA, rayo@gps.caltech.edu; YU, E., California Institute of Technology, California, USA, eyu@gps.caltech.edu; ANDREWS, J. R., California Institute of Technology, California, USA, jrand@gps.caltech.edu

Caltech and USGS operate the Southern California Seismic Network (SCSN) to provide timely disaster mitigation in the form of earthquake early warning (EEW), event notification, ShakeMap, and other data products to more than 20 million people living astride the Pacific and North America plate boundary. The EEW project (ShakeAlert) analyzes SCSN data to issue alerts to pilot users such as major utilities, hospitals, schools, and government agencies, some of them also host sensors and provide user feedback. A seismic moment tensor to identify the causative fault and evaluate tsunami hazards is also determined. In case of unusual activity, seismologists provide near real-time situational awareness to warn of increased hazards levels.

For over two years, the SCSN has been importing its entire seismic data streams of ~14Mbits/sec into the Amazon Web Services (AWS) cloud. Currently, we have the AQMS software deployed on several EC2 instances, and we routinely report origins, magnitudes, moment tensor and ShakeMaps from the cloud directly into PDL, which in turn are posted on the USGS/NEIC web pages within two minutes. The SCSN products are also made available on the SCEDC and SCSN web sites hosted by AWS, which ensures information availability during peak demand times. We are also archiving the current waveform data (since 2017) in the AWS S3 Glacier part of the cloud.

To facilitate our next step in using cloud computing, we have developed machine learning (ML) algorithms to pick phases such as P and S phases, and to determine the polarity of P-waves. We have also developed an ML phase associator (PhaseLink) to reliably detect earthquakes occurring concurrently, like during an aftershock sequence. To deploy these ML algorithms for dependable and scalable routine processing, we plan to use cloud native principles such as microservices and serverless architecture; and AWS products like Kinesis, Lambda, Batch and Analytics for seismic data processing.

Methods for Site Response Estimation

Poster Session · Friday · 26 April · Grand Ballroom

Strong Ground Motion Site Effects in the Central United States: Issues and Alternatives

WANG, Z., University of Kentucky, Kentucky, USA, zmwang@uky.edu; CARPENTER, S., University of Kentucky, Kentucky, USA, seth.carpenter@

uky.edu; WOOLERY, E. W., University of Kentucky, Kentucky, USA, woolery@uky.edu

Ground-motion site effects are of concern in the central United States, particularly for communities sitting on thick sediments in the Mississippi and Ohio River Valleys. Site effects were found to be the cause of damage in Maysville, Ky., from the 1980 Sharpsburg earthquake, for example. Since the early 1990s, we have collected data necessary for quantifying site effects, including shear-wave velocities, borehole logs, and recordings of ambient noise and local earthquakes; these data have enabled us to conduct thorough studies on site effects for various locations in the region. Our results indicate that the key parameters influencing site effects are shear-wave velocity structure, unlithified soil-column thickness, damping, nonlinear response of sediments, and bedrock shear-wave velocity. We also found no clear relationship between V_s30 (average shear-wave velocity for the top 30 m) and the site characteristics (*i.e.*, transfer function), which are determined by those key parameters and the impedance contrast between bedrock and the sediment overburden. Thus, V_s30 is not an appropriate parameter for quantifying site effects in in the central United States.

We have found that horizontal-to-vertical spectral ratios (HVSR) of weak-motion S-waves from earthquakes approximates site transfer functions at frequencies up to the fifth resonant mode, and can be used as an alternative for predicting site response in the central United States. This low-cost and accurate technique is a means to quantify the response of the entire unlithified soil column, even at deep-soil (> 100 m) sites. We also found that the S-wave HVSR demonstrates characteristics of nonlinear response: Resonant frequencies decrease with increasing ground motions at strong-motion stations in China and Japan. Thus, the S-wave HVSR can be used as an empirical transfer function.

A Graphical Dispersion Curve Editing Tool for Seismic Site Characterization Using Surface Waves

YONG, A., U.S. Geological Survey, California, USA, yong@usgs.gov; MCPHILLIPS, D., U.S. Geological Survey, California, USA, dmcphillips@usgs.gov; MARTIN, A. J., GEOVision, Inc., California, USA, amartin@geovision.com

Analysis of surface waves within a few tens of meters of Earth's surface may resolve the seismic velocity structure, which is essential data for predicting earthquake ground shaking. Many surface wave techniques, including both active and passive methods, calculate dispersion curves from raw seismic data. These curves are scatter plots that show the relationship between phase velocity and wavelength (or frequency) and may be inverted to yield shear-wave velocity as a function of depth. However, the inversion resolution is limited by non-uniqueness, the computational cost of forward models, and the complexity of empirical dispersion curves, which frequently include multiple modes and considerable noise. The analyst can often overcome these limitations most efficiently by visually inspecting the dispersion curve, removing higher modes and spurious data, and finally substituting a polynomial fit for the trimmed data. Here, we present a computer program for graphically editing and fitting dispersion curves: trimDispCurve v. 1.2. The program is currently coded in Matlab, and a Python implementation is in progress. The program takes as input an array of phase velocity and wavelength (or frequency) data that defines a dispersion curve. The program then plots the dispersion data and allows the user to iteratively select points in the plot for deletion. The user can either select points individually or define polygons to delete larger groups of points. The user may then experiment with polynomial fits of any order. The program outputs both the trimmed dispersion curve and the polynomial approximation as delimited text files that are suitable for input into inversion programs. We expect that this program will be particularly useful for analysts who wish to combine multiple surface-wave methods in order to achieve optimum resolution over a wide range of depths.

Site Response of Levees From a 4 Element Accelerometer Array at Sherman Island, CA

FLETCHER, J., U.S. Geological Survey, California, USA, jfletcher@usgs.gov; ERDEM, J., U.S. Geological Survey, California, USA, jerdem@usgs.gov

We installed 4 accelerometer stations on the southwest side of Sherman Island in the Sacramento/San Joaquin Delta to investigate linear and non-linear site response of the levees. Each station has a 3-component accelerometer with a 4g clipping level and a sample rate of 200sps. One station is on the crest and one is near the base of the levee. The interstation spacing ranges from 40 to 150m. We have since recorded 3 events on all 4 instruments with magnitudes of 3.1, 2.8 and 3.5. The closest was the first event centered at Oakley, CA, which was only about 6 km away (depth = 10.4 km). Accelerograms for this event were characterized by very impulsive arrivals that were highly polarized with large S waves on the horizontal components , but not on the vertical components. Peak acceleration and velocity show larger values on the levee compared to the base station with peak velocities 66% larger on the crest compared to the base. Spectral ratios of the crest divided by the base show amplification of about 4 between 2 and 3 Hz with sharp peaks at frequencies greater than 10 Hz. The Crocket event (M3.5, Nov. 10, 2018) is further away and has more emergent arrivals. It is located at the southern end of the West Napa fault. Spectral ratios of the crest divided by the base station show a broad amplification between 2 and 15 Hz. In conclusion levee crests do amplify ground motion values as shown by comparing peak acceleration or velocity and as shown in spectral ratios.

An Examination of Low-Frequency Amplification and High-Frequency Attenuation Effects in the Gulf and Atlantic Coastal Plain Using Spectral Ratios

GUO, Z., Virginia Tech, Virginia, USA, gzhen@vt.edu; CHAPMAN, M. C., Virginia Tech, Virginia, USA, mcc@vt.edu

The Atlantic and Gulf coastal plains contain Cretaceous and Cenozoic sedimentary sequences of variable thickness. We investigate the differences in response of sites in the coastal plain relative to sites outside that region using Fourier spectral ratios from 17 regional earthquakes occurring in 2010-2018 recorded by the EARTHSCOPE transportable array and other stations. We find that coastal plain sites experience amplification of low-frequency ground motions and attenuation of high-frequencies relative to average site conditions outside the coastal plain.

We use stacked coda and Lg spectra for sites outside the coastal plain as a reference. The spectral ratios at high-frequencies give estimates of the difference between kappa at coastal plain sites and the reference condition. Kappa values determined from the coda are strongly correlated with the thickness of the sediment section and agree well with previous estimates determined from Lg. Average estimates of kappa reach ~ 120 ms at Gulf coastal stations overlying ~12 km of sediments. Relations between Lg spectral ratio amplitudes versus sediment thickness in successive frequency bins exhibit consistent patterns, which were modeled using piecewise linear functions at frequencies ranging from 0.1 to 2.86 Hz. For sediment thickness greater than approximately 0.5 km, the spectral amplitude ratio at frequencies greater than approximately 3 Hz is controlled by the value of kappa. Fourier amplitude spectral ratios at frequencies between ~ 1.0 and 0.1 Hz are strongly dependent on sediment thickness. For example, at 0.1 Hz, the mean Fourier amplitude ratio (coastal plain/reference) is approximately 2.7 for sediment thickness 12 km.

Analysis of residuals between observed and predicted ground motions suggests that incorporating the amplification and attenuation as functions of sediment thickness may improve ground motion prediction models for the Coastal Plain region.

Basement Topography of Kathmandu Valley by Array Microtremor Observations

POOVARODOM, N., Thammasat University, Pathumthani, Thailand, pnakhorn@engr.tu.ac.th; JIRASAKJAMROONSRI, A., Thammasat University, Pathumthani, Thailand, amorntep_aj@hotmail.com; CHAMLAGAIN, D., Tribhuvan University, Kathmandu, Nepal, deepakchamlagain73@gmail.com; WARNITCHAI, P., Asian Institute of Technology, Pathumthani, Thailand, pennung.ait@gmail.com

Earthquake vulnerability of Kathmandu valley is considerably high, due to the active tectonics and local fragile geological conditions. The valley is approximately 30 km in the east – west and 25 km in the north – south directions. It is an intermontane basin with young soft fluvio-lacustrine sediments with thickness variation from place to place and surrounded by mountains on all sides. The 2015 Gorkha earthquake (Mw 7.8) revealed effects of soil sediments on ground motion characteristics as the horizontal components during the main shock exhibit long dominant period component in the range of about 4 to 5 second. This unusual long period wave could possibly be resulted from the soft soil layer. The effects of thick soil sediments on ground motion characteristics have long been recognized from major earthquakes, however, past studies on this issue are still quite primitive. As the site conditions especially at deeper level are very important, this research aims to explore such information for Kathmandu valley by microtremor observation. Array microtremor tests were conducted for 30 sites by the Centerless Circular Array technique (CCA) which has been developed to provide accurate phase velocity up to very long wavelength comparing with conventional microtremor methods. Different sized array arrangements were set with radius ranging from 1 to 120 m. The derived phase velocity dispersion curves from the observations provide long detectable wavelength and sufficient accuracy for inversion of shear wave velocity profile of sedimentary sites down to 500-1,000 m. The depths of basement were clearly identified from the level with shear wave velocity greater than 2,000 m/s. The inferred depth of basement ranges from 10 m at rock outcrop or basin edge to about 600 m in the central of the studied area.

The basement topography derived by this study is in good agreement with the gravity survey from the past research.

Exploring Alternative Pathways for Modelling Site Response for Seismic Risk at a Regional Scale using Insights from Strong Motion Databases

WEATHERILL, G., GFZ German Research Centre for Geosciences, Potsdam, Germany, gweather@gfz-potsdam.de; KOTHA, S., GFZ German Research Centre for Geosciences, Potsdam, Germany, sreeram.reddy.kotha@gfz-potsdam.de; COTTON, F., GFZ German Research Centre for Geosciences, Potsdam, Germany, fabrice.cotton@gfz-potsdam.de

Characterisation of site amplification is a critical element of any assessment of seismic risk. At a regional scale the limited and variable spatial coverage of quantitative site properties mean that approaches to model site amplification may differ from those encountered at a site-specific level, and careful treatment of uncertainty is needed in this case. Recent regional seismic risk models have modelled sites in terms of a "proxy" 30m-average shearwave velocity (V_{S30}) inferred from topographic slope, or similar geomorphological information. Whilst this allows for V_{S30} to be input into ground motion models at regional or even global scales, rarely is the inherent uncertainty of this parameter incorporated faithfully into seismic risk calculations. Seeking an approach for site response modelling that is applicable at a continental scale, we explore the correlations between observed strong motion recordings and various proxies that can be mapped at a large scale. Using strong motion data from Japan and Europe, taking observed site amplification as a period-dependent station-to-station random effect from a mixed-effects regression of a ground motion model, it is shown that amplification can be characterized as a direct function of topography (without the need to derive or infer V_{S30}) and is conditioned upon the geological setting. This approach can ensure that the higher uncertainty is propagated into the risk calculation, whilst still achieving the desired spatial coverage. Its feasibility for use in a pan-European seismic risk analysis is explored and comparisons made with more conventional site-specific approaches for predicting amplification at selected test sites.

Seismic and Liquefaction Hazard Maps for Dyer County, Northwestern Tennessee

CRAMER, C. H., Center for Earthquake Research and Information, University of Memphis, Tennessee, USA, ccramer@memphis.edu; VAN ARSDALE, R. B., University of Memphis, Tennessee, USA, rvanrsdl@memphis.edu; ARELLANO, D., University of Memphis, Tennessee, USA, darellan@memphis.edu; PEZESHK, S., Univeristy of Memphis, Tennessee, USA, spezeshk@memphis.edu; HORTON, S. P., Center for Earthquake Research and Information, University of Memphis, Tennessee, USA, shorton@memphis.edu; WEATHERS, T., University of Memphis, Tennessee, USA, twathers@memphis.edu; NAZEMI, N., University of Memphis, Tennessee, USA, nnazemi@memphis.edu; TOHIDI, H., University of Memphis, Tennessee, USA, htohidi@memphis.edu; BHATTARAI, R., Center for Earthquake Research and Information, University of Memphis, Tennessee, USA, rrbhtti@memphis.edu; REICHENBACKER, R., University of Memphis, Tennessee, USA, rmrchnbc@memphis.edu

A five-year seismic and liquefaction hazard mapping project for five western Tennessee counties began in 2017 under a Disaster Resilience Competition grant from the U.S. Department of Housing and Urban Development to the State of Tennessee. The project supports natural hazard mitigation efforts in the counties of Lake, Dyer, Lauderdale, Tipton, and Madison. The county seismic hazard maps for Lake County in northwestern most Tennessee were completed in early 2018 and similar maps for Dyer County will be completed in early 2019. Additional geological, geotechnical, and geophysical information has been gathered in Lake and Dyer Counties to improve the base northern Mississippi Embayment hazard maps of Dhar and Cramer (2017). Information gathered includes additional geological and geotechnical subsurface exploration logs, water table level data collection and measurements, new measurements of shallow and deep shear-wave velocity (Vs) profiles, and the compilation of existing Vs profiles in and around the counties. Improvements are being made in the 3D geological model, water table model, the geotechnical liquefaction probability curves, and the Vs correlation with lithology model for Lake and Dyer Counties. Resulting improved soil response amplification distributions on a 0.5 km grid will be combined with the 2014 U.S. Geological Survey seismic hazard model (Petersen *et al.*, 2014) earthquake sources and attenuation models to add the effect of local geology for Lake and Dyer Counties. Resulting products will be similar to the Memphis and Shelby County urban seismic hazard maps recently updated by Cramer *et al.* (2018).

Seismic Response Estimation of the Site of the Italian Accelerometric Station IT.CSA

FAMIANI, D., Istituto Nazionale di Geofisica e Vulcanologia, Roma, Italy, daniela.famiani@ingv.it; CARA, F., Istituto Nazionale di Geofisica e Vulcanologia, Roma, Italy, farizio.cara@ingv.it; BORDONI, P., Istituto Nazionale di Geofisica e Vulcanologia, Roma, Italy, paola.bordoni@ingv.it; BRUNORI, C., Istituto Nazionale di Geofisica e Vulcanologia, Roma, Italy, carloalberto.brunori@ingv.it; DI GIULIO, G., Istituto Nazionale di Geofisica e Vulcanologia, Roma, Italy, giuseppe.digiulio@ingv.it; FELICETTA, C., Istituto Nazionale di Geofisica e Vulcanologia, Milano, Italy, chiara.felicetta@ingv.it; MERCURI, A., Istituto Nazionale di Geofisica e Vulcanologia, Roma, Italy, alessia.mercuri@ingv.it; PIZZIMENTI, L., Istituto Nazionale di Geofisica e Vulcanologia, Roma, Italy, luca.pizzimenti@ingv.it; TODRANI, A., Università di RomaTre, Roma, Italy, alessandro.todrani@uniroma3.it; CULTRERA, G., Istituto Nazionale di Geofisica e Vulcanologia, Roma, Italy, giovanna.cultrera@ingv.it

The seismic characterization of a site where an accelerometric station is installed is an important task for contributing in the ground motion assessment. This work concerns the site of the accelerometric station IT.CSA, belonging to the Italian Strong Motion Network (Civil Protection Department). This station is located in the municipality of Cannara, Umbria Region (Central Italy) and from its installation in 1986, recorded approximately sixty earthquakes ($M \geq 4$) including events from 1997 Umbria-Marche and 2016 Central Italy seismic sequences. The geological setting of the area consists of a sedimentary deep basin (approximately 1km deep) typical of central Appennines, where Quaternary alluvial deposits overlap a stiff Miocenic geologic bedrock.

The seismic characterization of the IT.CSA site was faced trying to retrieve a characteristic velocity profile by means of 2D passive array data. We installed two different seismic arrays, one equipped with 3-component Lennarts-5s velocimeters and Reftek 130 digitizers, the second by using 72 4.5 Hz vertical geophones connected through cables to three Geode digitizers. The two arrays have been designed with a similar geometry (spiral shape) but with different interstation distance and maximum aperture. This strategy was supposed to be able to reconstruct, with a good resolution, both the shallower and the deeper part of the velocity profile. The collected data have been first processed with the FK analysis to retrieve the dispersion curve and then inverted jointly with the experimental ellipticity (H/V) curve obtained at a station installed close to station IT.CSA. We believe that with this procedure we reconstructed a reliable velocity profile up to the seismic and geologic bedrock.

Shear-Wave Velocity and Seismic Response Estimates From the Southern Isoseismal Region of the 1886 Charleston Earthquake: Results From a Seismic Land Streamer System

CLIZZIE, N. L., Boise State University, Idaho, USA, nicoleclizzie@u.boisestate.edu; LIBERTY, L. M., Boise State University, Idaho, USA, lliberty@boisestate.edu

The 1886 M~7 earthquake damaged Charleston's infrastructure and killed more than 100 people. Today, ground amplification from a similar earthquake would devastate the region. For this fault mapping and site response study, we acquired 14 km of seismic data over five field days using a 72-channel, 90 m land streamer/accelerated weight drop system along city streets. The data collection was located within the southern isoseismal zone of the 1886 earthquake. We acquired shots every 2.5 m to obtain more than 5,000 dispersion curves and 360,000 first arrival picks. We estimate shear wave velocity (Vs) from phase velocity-frequency picks for the fundamental mode using a range of inversion approaches. We estimate p-wave velocity (Vp) by inverting first arrival picks. For our site response analysis, we assume a two-layer velocity model that represents Holocene sediments over older strata. Because Vp results are sensitive to water saturation that crosses lithologic boundaries, we rely on Vs to map Holocene layer thickness, to estimate resonant frequencies, and to estimate ground surface amplification. We compare our Vs results to mapped geology, layer thickness derived from auger holes, and to coincident seismic reflection results that we generated from the same dataset. We estimate Vs for Holocene sediments, late Pleistocene Wando Formation, middle Pleistocene Ten Mile Formation, and Tertiary Ashley Formation. We find the thickness of Holocene strata lies mostly at depths less than 30 m below the land surface. We suggest that this shallow boundary controls site amplification and that the seismic land streamer approach provides a rapid and effective high frequency site response tool for urban areas.

Site Response Taxonomy for Assessing Complexity Using H/V Ratios for Mexico City

PONTRELLI, M., Tufts University, Massachusetts, USA, marshall.pontrelli@tufts.edu; BAISE, L. G., Tufts University, Massachusetts, USA, laurie.baise@tufts.edu

Sedimentary basins with high impedance contrasts pose a significant risk to infrastructure and local populations when strong shaking from local site response during an earthquake occurs. In standard site response analyses, we generate a theoretical transfer function between the base of the soil layer and the surface by assuming vertically propagating shear waves through horizontal, laterally homogenous soil systems, a set of assumptions collectively referred to as "SH1D". In real soil systems, however, these assumptions tend to collapse due to wave scattering through heterogenous materials, significant attenuation, non-vertical incidence, and other complexities in the subsurface. In many cases, therefore, it is essential to perform more robust site response analyses. In work by Thompson *et al.* (2012), the authors developed a taxonomy using surface-downhole spectral ratios from weak ground motions for classifying a site's resonant behavior referenced to the SH1D condition. In this work, we apply the taxonomy to single station recordings by using Nakamura's H/V ratio (Nakamura, 1989) as a first estimate of the site empirical transfer function (Lermo and Chávez-Garcia, 1994) using ground motion data from 224 earthquakes at 68 stations from the Mexico RACM network. The H/V ratio method is non-intrusive, requires one three component seismometer station and can use microtremor data or earthquake records, thus allowing for rapid, cheap field collection (Yilar *et al.* 2017). Mexico City is an ideal test case for this method, as the region consists of high impedance contrast between the lakebed sediments and underlying materials. Nakamura's technique is known to perform well at identifying the site response resonant behavior in this type of environment (Bonnefoy-Claudet *et al.* 2006; Parolai, 2002). We show that the H/V ratio shape, when averaged over many earthquakes is similar to the traditional spectral ratio which means that the H/V ratio is an appropriate estimate for the empirical transfer function within the Thompson *et al.* taxonomy in Mexico City.

Identifying Diffuse Random Seismic Noise and Monitoring Temporal Changes of Velocities With H/V Spectral Ratios of Such Data

MENG, H., University of Southern California, California, USA, haoranme@usc.edu; BEN-ZION, Y., University of Southern California, California, USA, benzion@usc.edu

We develop a method to identify portions of continuous waveforms that are random and diffuse, using statistical characteristics in time and frequency domains along with signal correlations among neighboring frequencies. The ratios of Fourier amplitude spectra of the horizontal (H) to vertical (V) components of the diffuse waveform portions are used to monitor temporal changes of seismic velocities. The H/V spectral ratio and uncertainties are stably estimated with daily averaged spectra of qualified diffuse noise windows recorded at various sensors in southern California. An initial application to broadband station at the Piñon Flat Observatory shows a clear change at the time of the 2010 Mw 7.2 El Mayor – Cucapah Earthquake followed by a recovery. Updated results will be presented at the meeting.

Investigating the Effects of Uncertainties in Equivalent Linear Site Response Models

YARAHMADI, A., University of Memphis, Tennessee, USA, yrahmadi@memphis.edu; PEZESHK, S., The University of Memphis, Tennessee, USA, spezeshk@memphis.edu

There are several examples throughout the history of earthquakes that show how soil and geological features can amplify destructive effects of an earthquake. Performing site response analysis (SRA) is a good way to capture the behavior of local conditions of the soil in case of large earthquakes. There are two sources of uncertainty in performing SRA. First, it is the variability that exists in different seismic input records and second, is the uncertainties that exist in characterizing the represented soil profile at the study site. Parameters such as shear wave velocities, layer thickness, bedrock depth, shear modulus reduction G/G_{max} and damping curves have significant role in a site response analysis. In this study we are focusing to evaluate the uncertainties in these parameters of the soil. We evaluate the effects of uncertainties for each parameter separately and also evaluate them together to figure out how they affect the results of SRA.

To quantify uncertainties, for this study we consider actual recorded ground motions in a series of downhole arrays at the rock and the ground surface. By comparing the observed surface ground motion with predicted results from SRA, we can compute the uncertainties. Computer program SHAKE91 is used to perform 1-D equivalent SRA and we take advantage of KIK-Net vertical seismometer arrays, which provide variety of stations with numerous ground motions of different earthquakes.

Knowing the effects of uncertainties of the soil on SRA increase the precision of equivalent linear SRA and in many cases lowers the need of time consuming procedures like nonlinear site response analysis.

Modeling of Empirical Transfer Functions Including 3D Velocity Structure

HU, Z., University of California, San Diego, California, USA, zhh076@ucsd.edu; ROTEN, D., San Diego State University, California, USA, droten@sdsu.edu; OLSEN, K. B., San Diego State University, California, USA, kbolsen@sdsu.edu; DAY, S. M., San Diego State University, California, USA, sday@sdsu.edu

Site response can be an important factor in estimating seismic hazard. However, conventional simplified modeling of site amplification with assumptions of plane SH waves propagating vertically through layered homogeneous media often poorly predicts the empirical transfer function (ETF), particularly where large lateral variations of velocity are present. Here, we use physics-based simulations that naturally incorporate the complex subsurface material properties and provide synthetic ground motions to compute theoretical transfer functions (TTF). We calibrate the 3D subsurface geometry by means of the topography near the sites and incorporate information from a suite of Vs profiles obtained from borehole logs. By comparing TTFs to the estimated ETFs at selected sites (*e.g.* the KiK-net sites and the Garner Valley Downhole Array site), we show how simulations in the calibrated 3D medium, including statistical distributions of small-scale heterogeneities, are able to adequately model the site amplification. We show that the velocity variations play a considerable role in determining both the frequency and amplitude of the site response. Properly calibrated spatial variation of the sediments below the site, including the slope of the edges and the depth to the bedrock, significantly improves the fit to the ETFs. In some cases, the Vs profiles derived from the borehole measurements are unable to produce TTFs consistent with the observed ETFs. The results emphasize the importance of reliable calibration of subsurface structure and material properties in site response studies.

On the Importance of the in Situ Characterization of Rock Stations: Differences Between Inferred and Measured Information From the French Accelerometric Network (RAP)

HOLLENDER, F., CEA - DEN - Cadarache, Saint Paul lez Durance, France, fabrice.hollender@cea.fr; CUSHING, E. M., Institut de Radioprotection et de Sûreté Nucléaire, Fontenay-aux-Roses, France, edward.cushing@irsn.fr; CORNOU, C., ISTerre, University Grenoble-Alpes / USMB / CNRS / IFSTTAR / IRD, Grenoble, France, cecile.cornou@univ-grenoble-alpes.fr; MAUFROY, E., ISTerre, University Grenoble-Alpes / USMB / CNRS / IFSTTAR / IRD, Grenoble, France, emeline.maufroy@univ-grenoble-alpes.fr; TRAVERSA, P., EDF, CEIDRE/TEGG/SGG, Aix-en-Provence, France, paola.traversa@edf.fr

Most of the previous estimations of site conditions (soil class, V_{S30}) of the French accelerometric network (RAP) stations have been inferred on the basis of indirect information, as geological map interpretation.

Over the last years, geophysical surveys allowed performing *in situ* measurements of ~50 stations in very various geological contexts. These surveys consisted in surface wave-based methods involving both active (Multichannel Analysis of Surface Waves: MASW) and passive methods (Ambient Vibration Array: AVA) using array from 10 m up to 1 km of aperture. This acquisition layout allowed extracting shear wave velocity profiles from surface up to few hundreds of meters, providing at the same time a rather good vertical resolution within the shallow layers.

Unsurprisingly, the new measured V_{S30} values are significantly lower in comparison with the previous inferred values. We discuss the difference between inferred and measured values and we try to understand the origin of this difference, introducing the nature of lithology (limestone, granite,...) but also using weathering and fracturing estimation from a priori information. We propose a 'rescaling' of methods used to infer value from indirect information. This allows proposing new inferred V_{S30} value for stations that did not benefit so far from in situ characterization.

We also discuss about the high frequency amplification induced at most rock site due to the weathering of shallow layers and its impact on seismologic data analysis.

Mainshock Event-Term Calibration Using Temporal Portable Seismic Network Recorded Aftershocks

KWAK, D., Hanyang University, Ansan, Korea, Republic of, dkwak@hanyang.ac.kr; AHN, J., Korea Meteorological Administration, Seoul, Korea, Republic of, propjk@korea.kr

We investigate the possibility of the mainshock event-term calibration using aftershock events observed in more densely located velocimeters. An intensity map for a specific event provides a vital role to analyze the damage status, but it requires seismic records as well as understanding of ground motion distribution and site amplification effects. The map is generated using a local GMPE, regional site characterization, and ground motion observations. Herein, the median of local GMPE is modified by the mean trend of ground motion records to incorporate event-specific ground motion distribution trend, called event-term correction. The modification is effective if abundant seismic records are available especially in close distance to the source within which usually the severe damage is observed, but unfortunately the seismic stations are sparse due to high maintenance and installation cost.

The 2017 M5.4 Pohang earthquake struck south-east part of South Korea which damaged regional society. The mainshock ground motion was recorded by semi-permanent seismic stations maintained by Korea Meteorological Administration (KMA) and Korea Institute of Geoscience and Mineral Resources, and aftershock ground motions in adjacent to damaged regions were recorded by temporal portable velocimeters installed after the mainshock in addition to the permanent stations by KMA. Since the portable stations are relatively densely located near the source, they give an opportunity to calibrate the event-term more precisely in near-source distance. In this study, we seek to find the possibility of the adjustment of the mainshock event-term calibration using the aftershock event-terms. This example will provide a framework estimating more precise seismic intensity map of the mainshock from aftershock events observed in more densely located seismic stations.

Active and Passive Seismic Surveys Along the Eastern Shoreline of San Francisco Bay for Earthquake Hazard Assessment

CRAIG, M., California State University, East Bay, California, USA, mitchell.craig@csueastbay.edu; HAYASHI, K., Geometrics, California, USA, khayashi@geometrics.com; PANDIT, P., California State University, East Bay, California, USA, ppandit4@horizon.csueastbay.edu

Active and passive seismic surveys were conducted along the eastern shoreline of San Francisco Bay for earthquake hazard assessment. The surveys were motivated by the need for better site characterizaton of the rapidly developing East Bay. Shallow surveys were conducted at several locations along the Hayward and San Leandro shorelines. Sites include undisturbed marsh, former oxidation ponds, and areas filled with dredge spoils. Shear wave velocity was estimated using surface wave methods. The spatial autocorrelation (SPAC) method was used to obtain a dispersion curve that was inverted to obtain a shear-wave velocity model. Passive data were acquired using both cabled and nodal systems. The cabled system used a 48-channel spread with maximum sensor separation of 96 m at most sites, which typically provided depth penetration of at least 40 m. Shear-wave velocity in the upper 5 m was commonly 70-100 m/s, while velocity at 30-40 m depth was usually 200-300 m/s.

Passive nodal surveys were conducted using about 20 sensors with a maximum offset ranging from about 800 m to 2000 m, depending on the survey. Shear wave velocities were obtained to depths of 800 m at two sites and 1500 m at a third site. At a depth of 500 m, velocities at all three sites were similar, at 900 to 1000 m/s. At one of the sites, velocity at a depth of 1500 m was estimated to be 1750 m/s.

Ground-Motion Site Effects in Beijing Metropolitan Area

PENG, Y., Institute of Crustal Dynamics, China Earthquake Administration, Beijing, China, pengyj408@126.com; WANG, Z., Kentucky Geological Survey, University of Kentucky, Kentucky, USA, zhenming.wang@uky.edu; LYU, Y., Institute of Crustal Dynamics China Earthquake Administration, Beijing, China, luyj1@263.net; CARPENTER, S., Kentucky Geological Survey, University of Kentucky, Kentucky, USA, seth.carpenter@uky.edu; FANG, Y., Institute of Crustal Dynamics China Earthquake Administration, Beijing, China, fyyyfyyy@vip.qq.com; HUANG, S., Institute of Crustal Dynamics China Earthquake Administration, Beijing, China, huangshuai3395@163.com

Beijing Metropolitan Area had experienced many moderate to strong earthquakes in the past 500 years, the largest being the 1679 Sanhe-Pinggu (M 8.0) and 1976 Tangshan (M 7.8) earthquakes. More than 2,000 high rise buildings have been erected in recent years in the Area, which is underlain by thick Quaternary and Tertiary sediments. During the 1985 Michoacán earthquake (M 8.0), Mexico City experienced significant damage, particularly to six- to 15-story buildings, from site effects (*i.e.*, site resonances) due to underlying lake sediments. Thus, the Beijing Metropolitan Area faces significant seismic risk, particularly for high rise buildings, caused by potential site effects.

In this study, we determined shear wave velocity profiles at sites across the Beijing Metropolitan Area utilizing borehole data, ambient noise measurements, and broadband seismic data. Shear-wave velocities for shallow sediments were determined directly from borehole data, and the average shear-wave velocities of the entire sediment column were determined from the predominant frequencies of ambient noise. For the deeper sediments, shear-wave velocities were calculated from the shallow and average velocities. We also determined the other sediment dynamic properties, such as damping ratios and unit weights. We then conducted 1-D site response analyses.

The results show that the predominant (*i.e.*, first mode) site response periods vary from 0.1s for the shallow sites in the west to 3.6s for deep sites in the east. This predominant period range coincides with the predominant resonance periods of buildings with one to 36 stories. In other words, this study showed that site effect could be a significant potential problem for the area. In current Chinese engineering practice, the average shear-wave velocity of top 20 meters,Vs20, has been used as a key parameter to account for site effect. However, as shown in this study, Vs20 has no direct relationship with site effect. Thus, the use of Vs20 in earthquake engineering in the Beijing Metropolitan Area may not be appropriate.

A Global Mosaic Vs30 Map With Regional Map Insets

HEATH, D. C., U.S. Geological Survey, Colorado, USA, david.heath@colostate.edu; WALD, D. J., U.S. Geological Survey, Colorado, USA, wald@usgs.gov; WORDEN, C. B., U.S. Geological Survey, Colorado, USA, cbworden@usgs.gov; THOMPSON, E. M., U.S. Geological Survey, Colorado, USA, emthompson@usgs.gov; SMOCZYK, G. M., U.S. Geological Survey, Colorado, USA, gsmoczyk@usgs.gov

The shear wave velocity in the upper 30 meters of the earth's surface (Vs30) is a key parameter for estimating ground motion amplification as both a predictive and diagnostic tool for earthquake hazards. However, site-specific Vs30 measurements are rather limited, so geospatial inferences are necessarily made to interpolate and map Vs30 estimates elsewhere. A first-order approximation of Vs30 is commonly obtained via a topographic slope-based or terrain proxy (wherein steeper slopes generally indicate greater Vs30 values and gentler slopes indicate smaller Vs30 values) due to the widely available nature of digital elevation models; the USGS has produced such a map for the globe (https://earthquake.usgs.gov/data/vs30/). However, better-constrained Vs30 maps have been developed in many regions that are preferable to proxy-based Vs30 maps. Regional and local Vs30 maps employ Vs30 measurements, higher-resolution slope, lithologic, geologic, geomorphic, and other proxies, and often utilize refined interpolation schemes to achieve more accurate maps. Here we describe the development of a new hybrid global Vs30 map that defaults to the global slope-based Vs30 map but smoothly insets openly-available, high-quality regional Vs30 maps. Regional inset maps presently include California, Japan, Taiwan, New Zealand, Australia, Italy, Greece, Iran and others. Comparisons of the default slope-based proxy with the mosaic version (with higher-quality inset maps) are presented in terms of Vs30 differences as well as resulting amplification ratios. We aim to update the map regularly with the hope that new Vs30 regional maps become publicly available. USGS serves the new global Vs30 maps online via an ArcGIS web service; the underlying source code is provided on GitHub (https://github.com/usgs/earthquake-global_vs30).

Ground-Motion Correction Factors for the Atlantic Coastal Plain Strata of the Southeastern U.S.: Preliminary Results

PRATT, T. L., U.S. Geological Survey, Virginia, USA, tpratt@usgs.gov

The Atlantic Coastal Plain (ACP) strata are a landward-thinning sequence of unconsolidated or semi-consolidated sedimentary strata that cover areas of the southeastern United States to as much as 300 km inland. These strata have a strong effect on ground motions, causing amplification in the Washington, D.C. area contributing to the damage during the 2011 M5.8, Mineral, Virginia earthquake. Correction factors derived for sedimentary basins (z1.0 and z2.5) may not apply to the ACP strata, which dip at about 1 degree or less and do not have sloping basin edges to efficiently generate local surface waves. Corrections based on the fundamental frequency in thin strata have not been explored for the thick ACP strata. This study examines ground motion amplifications by ACP strata, and assesses frequency-dependent correction factors for ground motion estimates. Data from teleseisms recorded on crustal-scale seismic experiments are used to compute horizontal spectral ratios relative to bedrock sites on Piedmont rocks west of the ACP strata. The ratios were computed using 100-sec time windows encompassing the strongest shaking, with the two horizontal-component spectra being combined using the vector sum at each frequency. Results show the primary resonance peak caused by reverberations of vertically-traveling shear waves reflecting between the free surface and the strong reflector at the base of the ACP strata. At frequencies below the primary resonance peak the ACP strata do not amplify shear waves significantly, while peak amplifications at higher frequencies can average factors of 2 to 4. These results suggest that for a given thickness of ACP strata a frequency and amplitude of the primary resonance peak can be predicted. From these, correction factors specifying amplification versus frequency can be developed for the ACP strata. Such correction factors have the potential to improve ground motion predictions in deterministic and probabilistic seismic hazard analyses.

Problem Unsolved: Knowledge Gaps at the Intersection of Earthquake Engineering Practice and Research

Poster Session · Friday · 26 April · Grand Ballroom

Structural Health Monitoring Using Multi-Parameter Information: Case of the Kurpsai Dam in the Kyrgyz Republic

PILZ, M., GFZ German Research Centre for Geosciences, Potsdam, Germany, pilz@gfz-potsdam.de; FLEMING, K., GFZ German Research Centre for Geosciences, Potsdam, Germany, kevin@gfz-potsdam.de; BOXBERGER, T., GFZ German Research Centre for Geosciences, Potsdam, Germany, tobibo@gfz-potsdam.de; ORUNBAEV, S., Central Asian Institute for Applied Geosciences, Bishkek, Kyrgyzstan, s.orunbav@caiag.kg

Given the plans to construct hydroelectric dams in the Kyrgyz Republic, and the need to ensure the integrity of existing structures, techniques for gaining rapid and robust information about the dam structures and the surrounding slopes are required. Such techniques would be used to establish monitoring systems that will support the decision-making process in the event of an emergency. The MI-DAM project (MultI-parameter monitoring and risk assessment of hydroelectric DAMs in the Kyrgyz Republic) is setting out to develop, install and test a robust, cost-effective and flexible monitoring system at the Kurpsai Hydropower Station in Western Kyrgyzstan. The monitoring concept distinguishes between two time scales: the long-term monitoring of static deformations over days, months and years and the short-term monitoring of structural response to earthquake shocks and extreme operational regimes. While the long-term monitoring includes a combination of measurements of absolute static displacements by GPS sensors and by fibre optical strain sensors as well as long-term deformations measured by Interferometric Synthetic Aperture Radar (InSAR), the short-term changes in the dam and the surrounding hillsides are monitored by means of multi-parameter sensors placed at selected sites on the structure and surroundings based on a fully decentralised approach. Such an approach allows the critical parameters for monitoring (and, correspondingly, the fragility curves) to be directly integrated into the on-site calculations, allowing some degree of decision-making without the necessity of a remote centre. Strong motion recordings show that the dam exhibits a transient non-stationary behaviour as its fundamental frequency changes during each strong motion, then returning to the starting value after each event. Lapse time coherency allows for the monitoring of spatial changes in the phase of ground motion, indicating the opening/closing at the joints and lateral excitation.

Evaluation of LPI and LSN for South Korea Based on the Liquefaction Observations

KIM, M., UNIST, Ulsan, Korea, Republic of, miraekim@unist.ac.kr; KIM, H., KIGAM, Daejeon, Korea, Republic of, adoogen@kigam.re.kr; KIM, B., UNIST, Ulsan, Korea, Republic of, byungmin.kim@unit.ac.kr

The M5.4 earthquake occurred on November 15, 2017 in Heunghae eup, Pohang city, South Korea. This earthquake was recorded as the second largest instrumented earthquake in South Korea and caused numerous damages on grounds and structures. Among the other ground deformations such as settlements, cracks, and landslides, the hundreds of liquefaction-induced sand volcanos observed near the epicenter were the major issue. Korea Institute of Geoscience and Mineral Resources (KIGAM) recorded locations of those sand volcanos. We collected the existing boring data with Standard Penetration Test (SPT) N value from the Geotechnical Information Portal System and the local government offices. We also utilized the results of the boring and SPT which were performed immediately after the Pohang earthquake. Using the SPT N values and water table information from these boring data and the peak ground acceleration values obtained from the U.S. Geological Survey (USGS) Shake map, we computed Liquefaction Potential Index (LPI) following the procedure proposed by Iwasaki *et al.* (1978) and Liquefaction Severity Number (LSN) based on the approach by Tokimatsu and Seed (1987). By comparing the LPI and LSN values with the locations of sand volcanos, we found that the accuracies of both the LPI and LSN are approximately 70 %. We also computed probabilities of liquefaction in functions of LPI and LSN. It turns out that the liquefaction probabilities are approximately 0.1 and 0.6 when the LPIs are 5 and 12, respectively. The liquefaction probabilities are approximately 0.1 and 0.4 when the LSNs are 30 and 70, respectively.

An Empirical Model for the Inter-Frequency Correlation of Epsilon for Fourier Amplitude Spectra

BAYLESS, J., AECOM, California, USA, jeff.bayless@aecom.com; ABRAHAMSON, N., University of California, Berkeley, California, USA, abrahamson@berkeley.edu

An empirical ground motion model (GMM) is presented for the inter-frequency correlation of normalized residuals, epsilon (ε), for smoothed Fourier amplitude spectra (FAS). The inter-frequency correlation of ε (ρ_ε) model is developed for the smoothed effective amplitude spectrum (EAS), as defined by PEER (Goulet *et al.*, 2018). The EAS is the orientation-independent horizontal component FAS of ground acceleration. Ground-motion data are from the Pacific Earthquake Engineering Research Center (PEER) Next Generation Attenuation-West 2 (NGA-West2) database (Ancheta *et al.*, 2014), which includes shallow crustal earthquakes in active tectonic regions. The normalized residualsare obtained from the Bayless and Abrahamson (2019) GMM, are partitioned into between-event, between-site, and within-site components, and a model is developed for the total correlation between frequencies. The total correlation model features a two-term exponential decay with the natural logarithm of frequency. At higher frequencies, the model differs substantially from previously published models, where the ground-motion smoothing technique employed has a large effect on the resulting correlations. The empirical ρ_ε are not found to have statistically significant magnitude, distance, site parameter, or regional dependence, although potential regional variations should be studied further. The model is applicable for crustal earthquakes in active tectonic regions worldwide, for rupture distances of 0 – 300 km, M 3.0 – 8.0, and over the frequency range 0.1 – 24 Hz.

A New Model Database for Next-Generation Fault Displacement Hazard Analysis

SARMIENTO, A., University of California, Los Angeles, California, USA, sarmiento.alexandrac@gmail.com; ABRAHAMSON, N., University of California, Berkeley, California, USA, abrahamson@berkeley.edu; BAIZE, S., Institut de Radioprotection et de Sûreté Nucléaire, Fontenay-aux-Roses, France, stephane.baize@irsn.fr; BOZORGNIA, Y., University of California, Los Angeles, California, USA, yousef.bozorgnia@ucla.edu; CHEN, R., California Geological Survey, California, USA, rui.chen@conservation.ca.gov; COPPERSMITH, K. J., Coppersmith Consulting, Inc., California, USA, kcoppersmith@earthlink.net; DAWSON, T. E., California Geological Survey, California, USA, timothy.dawson@conservation.ca.gov; DONAHUE, J. L., JL Donahue Engineering, Inc., California, USA, jennifer@jldengineering.com; JACOB, V., SC Solutions, California, USA, vince@scsolutions.com; KETABDAR, M., Southern California Gas Company, California, USA, mketabdar@semprautilities.com; KOTTKE, A. R., Pacific Gas and Electric Company, California, USA, arkk@pge.com; KUEHN, N. M., University of California, Los Angeles, California, USA, kuehn@g.ucla.edu; LAVRENTIADIS, G., University of California, Berkeley, California, USA, glavrent@berkeley.edu; MADUGO, C., Pacific Gas and Electric Company, California, USA, c7m0@pge.com; MAZZONI, S., University of California, Los Angeles, California, USA, silviamazzoni@yahoo.com; MILLINER, C. W. D., Jet Propulsion Laboratory, California Institute of Technology, California, USA, christopher.milliner@jpl.nasa.gov; SHAMSAABADI, A., California Department of Transportation, California, USA, anoosh.shamsabadi@dot.ca.gov; SHANTZ, T., California Department of Transportation, California, USA, tom_shantz@dot.ca.gov; SHEN, A., University of California, Los Angeles, California, USA, shenandi@ucla.edu; THOMPSON, S. C., Lettis Consultants International, California, USA, thompson@lettisci.com; YOUNGS, R. R., John Wood Group PLC, California, USA, bob.youngs@woodplc.com

Recent technological advances, such as lidar and optical imagery correlation, have facilitated dense, high-resolution datasets that measure both "on-fault" and "off-fault" displacements (*i.e.*, discrete brittle slip and distributed inelastic strain, respectively) in surface-rupturing earthquakes. These datasets are a substantial improvement over older datasets that typically contain irregularly-spaced measurement locations, relatively few data points, and lack measurements off the primary rupture. Currently available fault displacement databases (*e.g.*, Wells and Coppersmith, 1994; Wesnousky, 2008) are comprised of vintage datasets that serve as the basis for Probabilistic Fault Displacement Hazard Analysis (PFDHA) models (*e.g.*, Youngs *et al.*, 2003; Petersen *et al.*, 2011; Lavrentiadis and Abrahamson, in prep.). The development of next-generation fault displacement models requires a modern database that can accommodate both vintage data and newer datasets. Toward this end, we are developing a structured relational database for fault displacements, modeled after the Next Generation Liquefaction (Brandenberg *et al.*, 2018) and the Next Generation Attenuation Subduction databases (Mazzoni *et al.*, in prep.). A relational database is ideal for compiling fault displacements because of the broad range of measurement types (*e.g.*, horizontal throw vs. horizontal slip; on-fault vs. off-fault) in the published literature. These dataset-specific attributes are easily retained in a relational database. A relational database can also accommodate new data that may become available in future studies (*e.g.*, displacement profiles in addition to point observations) as well as site-specific metadata (geology, groundwater depth, topography, etc.). Our database currently includes earthquake metadata, point displacement measurements, mapped surface ruptures, and geologic metadata. The compilation is anticipated to include about 30-40 earthquakes and can be used in new models to better constrain the amplitude and spatial distribution of both on-fault and off-fault deformation.

Seismic Land Streamer as a Tool for Liquefaction Hazard Assessment at the City Scale

ST CLAIR, J., Boise State University, Idaho, USA, jamesstclair@boisestate.edu; LIBERTY, L. M., Boise State University, Idaho, USA, lliberty@boisestate.edu; GRIBLER, G., Boise State University, Idaho, USA, gabegribler@u.boisestate.edu

Liquefaction may occur in seismically active regions where unconsolidated sediments host a shallow water table. Liquefaction hazard assesment requires knowledge of soil stiffness, water table depths and a reasonable estimate of earthquake magnitude and epicentral distance. While methods for assessing liquefaction potential from cone-penetrometer (CPT), standard penetration test, and/or shear wave velocity data are well established, the effort required to obtain in-situ measurements of soil stiffness and water table elevations, especially in urban settings, limit the data that support liquefaction susceptibility maps. We present a new approach to liquefaction risk assessment at the city scale, utilizing seismic land streamer data. The land streamer allows rapid collection of seismic data suitable for mapping compressional (Vp) velocities to estimate depth to water, shear wave (Vs) velocities of the upper 10 to 30 meters to measure soil stiffness, and reflection imaging to identify and characterize active faults. As an example of our approach, we present liquefaction susceptibility maps for Salt Lake City, Utah for a range of earthquake magnitudes and maximum horizontal accelerations. Our scenario maps utilize ~35 km of land streamer data obtained over eight field days and includes > 9000 vertical Vs profiles. To assess the liquefaction hazard, we compare Cyclic Stress Ratios (CSR) for a range of earthquake scenarios to the Vs-derived Cyclic Resistance Ratio (CRR) of the soils. Vs measurements are corrected for overburden and effective stresses utilizing water table depths measured from Vp tomograms and densities compiled from local CPT surveys. We identify both shallow groundwater and confined groundwater systems beneath the low elevation portions of downtown. We also find a general pattern of increasing Vs with increasing elevation, placing the highest liquefaction hazard beneath the densely-populated Salt Lake City urban corridor.

On the Selection of Proper Ground Motion Models for PSHA in Mainland Southeast Asia

SEYHAN, E., Risk Management Solutions, California, USA, emel.seyhan@rms.com

Southeast Asia is one of the most seismically active regions in the world with a wide range of tectonic settings, yet it is also among the regions with very limited ground motion modeling related data and studies. The scarcity in strong ground motion observations and limited studies, failing in capturing broadband coverage of predictor variable ranges, for the region makes it a challenging case to build and validate proper ground motion models for probabilistic seismic hazard and risk assessments. This study presents the process of selection of proper ground motion prediction equations (GMPEs) among the most recent global and local models for all tectonic settings and all ranges of predictor variables through Trellis analysis, weighting scheme, and spatial distribution of select intensity measures as PGA and spectral acceleration at spectral periods of 0.3, 1.0 and 3.0 sec. The goal is to supplement the existing knowledge and guidance that is insufficient due to available ground motion observation data and limited applicable studies. For example, a widely used reference, 2007 U.S. Geological Survey seismic hazard maps/study in Southeast Asia, has not yet been updated reflecting the most recent advances in ground motion modeling. Although it is not covered in this study, the resulting ground motion models are used in probabilistic seismic hazard analysis (PSHA) in comparison with reference seismic hazard studies suitable for the region.

The Use of a Seismic Database to Analyze Slow Dynamics as a Proxy of Damage

ASTORGA, A. L., Université Grenoble Alpes, CNRS, IRD, IFSTTAR, ISTerre, Grenoble, France, ariana-lucia.astorga-nino@univ-grenoble-alpes.fr; GUÉGUEN, P., Université Grenoble Alpes, CNRS, IRD, IFSTTAR, ISTerre, Grenoble, France, philippe.gueguen@univ-grenoble-alpes.fr; RIVIÈRE, J., Pennsylvania State University, Pennsylvania, USA, jacques.riviere@univ-grenoble-alpes.fr; KASHIMA, T., IISEE, Building Research Institute, Tsukuba, Japan, kashima@kenken.go.jp; JOHNSON, P., Los Alamos National Laboratory, New Mexico, USA, paj@lanl.gov

The passage of seismic waves causes variations in the elastic properties of the medium in which they propagate. These variations can be monitored throughout observables such as the fundamental frequency. When the perturbation arrives, a sudden alteration of the observables is detected, followed by a slow recovery when the wave excitation ends. This recovery is due to a multi-scale relaxation process, known as slow dynamics. Materials that exhibit slow dynamics have in common a small volume of elastically soft constituents distributed within a rigid matrix. This is a system formed by heterogeneities such as cracks, voids, joints between particles, etc., which are responsible for the general elastic behavior of the material. Slow dynamics is a universal phenomenon, *i.e.* it occurs in many physical systems, and it is observed at laboratory scale, seismological studies and structural response of buildings. Several studies have proved the direct relationship between slow dynamics and the level of heterogeneities, which is closely linked to damage.

We compiled earthquake data recorded in buildings and created a data bank of structural responses. We analyze the fundamental frequency recovery at two scales: after the strongest motion within the recording of one event (short-term recovery), and during long sequences of earthquakes (long-term recovery). Multi-scale relaxation models are applied to our data to study the behavior of different relaxation parameters that are able to characterize both transient and permanent fluctuations of structural state. Our results are compared with those observed in granular materials at laboratory and at the Earth's crust and fault zones.

Despite the difference between scales, conditions and level of complexity, the analogy between results allows us to confirm the universality of the slow dynamics, and its clear connection with the degree of fracturing and mechanical damage in structures. This makes the recovery process following strong seismic deformation an innovative way to monitor structural degradation.

Characterization of Earthquake Ground Motions for a Site in Papua New Guinea

NOVAKOVIC, M., Nanometrics Inc., Kanata, Canada, marknovakovic@nanometrics.ca; YENIER, E., Nanometrics Inc., Kanata, Canada, emrahyenier@nanometrics.ca; ATKINSON, G. M., Western University, London, Canada, gmatkinson@aol.com; ABRAHAMSON, N., University of California, Berkeley, California, USA, abrahamson@berkeley.edu; HOVEY, A., Klohn Crippen Berger, Brisbane, Australia, ahovey@klohn.com; QUINN, J., Klohn Crippen Berger, York, United Kingdom, jquinn@klohn.com; PADDINGTON, S., Newcrest Mining Limited, Melbourne, Australia, scott.paddington@newcrest.com.au; RUSSELL, C., Newcrest Mining Limited, Melbourne, Australia, colin.russell@newcrest.com.au

A seismic hazard analysis is being conducted for a site in Papua New Guinea. A preliminary analysis suggests that hazard is mostly controlled by crustal and intermediate subduction events within 100 km of the site. Here, we define a suite of ground motion predictions equations (GMPEs) for each source type that represent the median level and epistemic uncertainty of potential ground motions. We use the scaled-backbone approach to achieve this.

A ground-motion database consisting of events of $4.0<Mw<8.0$ is compiled from available local and regional monitoring stations in the region. A candidate GMPE is selected for each source type as the central model, considering the data constraints and the model's ability to reproduce observed motions. The central model is then scaled to define the lower and upper branches of the GMPE suite. The scaling factors are determined considering alternative GMPEs, available ground-motion data and epistemic uncertainty recommended for other data-rich regions. Aleatory variability of ground motions is characterized by considering both the scatter of empirical data with respect to the derived GMPE suite, and the scatter observed in other data-rich regions.

A Site-Specific Probabilistic Seismic Hazard Analysis on Oahu Island in Hawaii

DOBER, M., AECOM, California, USA, mark.dober@aecom.com

We have performed a site specific probabilistic seismic hazard analysis (PSHA) for a site on Oahu Island in Hawaii. The seismic source characterization used in this analysis is based on the 1998 USGS seismic hazard model for Hawaii, described in Klein *et al.* (2001). Oahu is in a region of low seismicity, with the largest historical earthquake on Oahu being the 1871 Lanai earthquake, which has an estimated magnitude of 5.9. The event did extensive, but minor damage in

Honolulu. Currently, the highest hazard regions in Hawaii are on the flanks of the active volcanoes on the island of Hawaii (Big Island). Most large historical earthquakes are associated with the rupture of the rift zones along the flanks of Mauna Loa and Kilauea. The Big Island is modeled with multiple zones, including the "flank zones," source zones enclosing the caldera and rifts of Kilauea and multiple zones encompassing the Big Island, with the seismicity divided into shallow (< 20 km) and deep zones. As seismicity in Hawaii decreases with distance to the northwest from the active volcanoes, the rest of the Hawaiian Island chain outside the Big Island is modeled as a single source zone. For the source zones, we've used an updated earthquake catalog, including data from the 2018 eruption of Kilauea. This is over 20 years of additional data from that used in the 1998 USGS seismic hazard maps for Hawaii. For ground motion models, we utilized the NGA-West2 models for active crustal zones. Additionally, we used the ground motion model of Wong *et al.* (2012), developed for deep earthquakes (> 20 km) based on stochastic ground motion numerical modeling calibrated with the Hawaiian strong motion database, and Atkinson (2010) developed for both shallow and deep Hawaiian earthquakes using the Reference Empirical approach. The local seismic source zone controls the hazard for short periods (peak ground acceleration), while the long period (> 1 sec spectral acceleration) is controlled by the source zones of the Big Island, even though it is located close to 400 km from the project site.

Seismology BC(d)E: Seismology Before the Current (digital) Era

Poster Session · Friday · 26 April · Grand Ballroom

Was the 23 November 1873 California-Oregon Border Earthquake an Inslab Earthquake?

BROCHER, T., U.S. Geological Survey, California, USA, brocher@usgs.gov

The 23 November 1873 earthquake along the coast near the California-Oregon border is the largest historic earthquake in that area. Oregon and California newspaper reports from 1873 suggest that this M~6.75 earthquake occurred within the subducting oceanic Juan de Fuca slab. Historically, few felt aftershocks have followed inslab earthquakes beneath the Puget Lowland, whereas crustal or megathrust earthquakes near the coast are expected to have many more. Thus, an inslab origin for the 1873 earthquake is more consistent with the only three felt aftershocks reported following it. Newspapers reported that the region experiencing the highest seismic intensities (MMI=VII and VIII) was bounded by Crescent City, California, to the south, Port Orford, Oregon, to the north, and Jacksonville, Oregon, to the east. Subject to the caveat that we lack felt reports from offshore, these highest intensities are centered at 42.3°N and 123.9°W, about 35 to 40 km northeast of proposed intensity centers of Toppozada *et al.* (1981) and Bakun (2000). Newspaper reports that did not indicate that the earthquake was felt locally imply that the earthquake was not generally felt south of the southern edge of the subducting slab in northern California. Felt reports at San Francisco and Sacramento are the exception, perhaps related to local site amplification at those cities, and appear to represent outliers in that each city was surrounded by communities whose newspapers did not report that the earthquake had been felt locally. In addition, the earthquake was not generally reported felt east of locations where the top of the subducting slab is more than 80 km deep. The abrupt truncation of felt reports along the southern edge of the subducting slab and to the east would appear to be most consistent with an inslab earthquake. Depth contours to the top of the subducted slab at the location of the highest intensities indicate an earthquake depth of at least 20 km.

Recovery and Calibration of Legacy Analog Data From the Leo Brady Seismic Network for the Source Physics Experiment

YOUNG, B. A., Sandia National Laboratories, New Mexico, USA, byoung@sandia.gov; ABBOTT, R. E., Sandia National Laboratories, New Mexico, USA, reabbot@sandia.gov

The Leo Brady Seismic Network (LBSN) was established in 1960 by Sandia National Laboratories for monitoring underground nuclear tests (UGTs) at the Nevada Test Site—renamed in 2010 to the Nevada National Security Site (NNSS). The LBSN has been in various configurations throughout its existence, but it has been generally comprised of four to six stations at regional distances from the NNSS with evenly spaced azimuthal coverage. In the pre-digital era, LBSN data were transmitted as frequency-modulated (FM) audio over telephone lines to the NTS and recorded in analog on hi-fi 8-track AMPEX tapes. These tapes have been stored in temperature-stable buildings or bunkers on the NNSS and Kirtland Air Force Base in Albuquerque, NM for decades and contain the irreplaceable seismic record of hundreds of UGTs from the analog era. We have been developing a process over the past few years to recover and convert the data to digital waveforms, and we derive the full instrument response from historic descriptions of the seismograph and measurements of calibration pulses recorded on the seismographs, themselves. We present an example of the instrument response and calibrated data of the BOXCAR event on April 26, 1968 from a station in Leeds, UT, and compare its peak ground velocity to contemporaneous measurements from other seismic networks. Sandia National Laboratories is a multimission laboratory managed and operated by National Technology & Engineering Solutions of Sandia, LLC, a wholly owned subsidiary of Honeywell International Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525.

The 1933 Long Beach, California, Earthquake: Ground Motions and Rupture Scenario

HOUGH, S. E., U.S. Geological Survey, California, USA, hough@usgs.gov; GRAVES, R. W., U.S. Geological Survey, California, USA, rwgraves@usgs.gov

We present a first-ever synoptic characterization of the distribution of ground motions from the 11 March 1933 Mw6.5 Long Beach, California, earthquake, using available macroseismic and limited instrumental data. The detailed shaking intensity pattern supports the conventional association of the earthquake with the Newport-Inglewood fault; it further reveals a concentration of especially severe damage centered in the town of Compton, where several credible accounts suggest vertical ground motions exceeding 1g, and intensities as high as Modified Mercalli Intensity 9. We use the broadband simulation approach of Graves and Pitarka (2010) to develop a rupture scenario for the earthquake, informed by the detailed damage distribution. Overall, the predicted shaking matches the observed intensities well using a 25-km long by 12-km wide rupture model with a hypocenter at 11 km depth near the southern end of the rupture, and a high-slip-patch near the northern end of the rupture. The modeling predicts high peak ground velocities in some near-field regions where liquefaction was documented but observed shaking intensities were relatively low, suggesting that high-frequency (≈2-8 Hz) energy was de-amplified by nonlinear site response. The concentration of damage near Compton can be explained by a combination of local site amplification, source-controlled directivity, and three-dimensional basin effects whereby energy was channeled towards the central Los Angeles Basin. In contrast with other inferred high-strain regions, it appears that high frequency energy was not de-amplified in this area. The overall success of the modeling in matching observed intensities provides a measure of confidence that the same modeling approach can be used to predict shaking from future earthquakes, with the caveat that, where the response is strongly nonlinear, ground motions may be lower than predicted using a simple Vs30-based model for non-linear site response, as used in our modeling.

A Million Seismograms Lost and Found: Current Status of the Canadian Analog Seismogram Collection

BENT, A. L., Natural Resources Canada, Ottawa, Canada, allison.bent@canada.ca; COYLE, K., Natural Resources Canada, Ottawa, Canada, kathryn.coyle@canada.ca; CASSIDY, J. F., Natural Resources Canada, Sidney, Canada, john.cassidy@canada.ca

The first seismograph in Canada began operation in 1897. The number of stations gradually grew until the 1960s when a national network was developed, increasing the number of stations from 9 in 1955 to 30 by 1970. Expansion of the network has continued. The transition from an analog to a digital network took place primarily during the 1980s. Despite the loss of many seismograms over the decades, the Canadian analog seismogram collection is estimated to consist of about one million records spanning nearly a century. The location and status of the collection have changed several times, occasionally resulting in confusion over ownership. Pressure to dispose of the collection due to storage space issues waxes and wanes as the perceived value of the collection does. In early 2017, it was discovered that the building housing the collection, which had been slated to close in 2018, had closed in 2014 and no one seemed able to verify whether the collection had been moved or destroyed. Through persistent and tenacious questioning, the seismograms were eventually found safe and sound. They are currently housed in a climate-controlled facility with safeguards against hazards such as fire and flood, all of which will slow but not completely prevent the deterioration of these fragile paper records. Pressure to dispose of the collection has currently ceased but access to the data is complicated. The seismograms, which contain a wealth of underutilized information about earthquakes, explosions and other phenomena, cannot be fully exploited in their analog state. Attempts to microfilm the collection in the 1970s were not greatly successful. Improvements made to scanning hardware and digitizing software in recent years are promising but scanning and digitizing one million seismograms remains a daunting task.

Nevertheless, it is a long-term goal and we are exploring avenues to facilitate it and considering our priorities if a concerted digitizing effort can be made.

DigitSeis 1.5: Advances in Conversion of Paper Seismograms to Digital Time Series

LEE, T. A., Harvard University, Massachusetts, USA, thomasandrewlee@college.harvard.edu; ISHII, M., Harvard University, Massachusetts, USA, ishii@eps.harvard.edu; ISHII, H., Harvard University, Massachusetts, USA, hiromiishii@fas.harvard.edu

Prior to the arrival of modern-day digital seismometers, analog instruments recorded ground movement on paper helicorders. The data recorded via these instruments span a century and include records from every continent. Many of these irreplaceable records are luckily still extant and stored by various operators around the world (*e.g.*, universities, research institutions, governments, and private sector). These collections of analog seismograms represent vast untapped data resources with great potential for new scientific discoveries and public outreach. However, before any scientific investigation can happen, the data must be digitized into a format digestible to modern techniques. Consequently, over the last few years we have developed a MATLAB-based software, DigitSeis, which converts high-resolution scans of analog seismograms into digital time series. DigitSeis is currently the only existing digitization software which fully takes into the account the timemarks present in analog seismograms, both re-incorporating them into the waveforms, and using them to define timing. However, earlier versions of DigitSeis have relied on human input to help verify identification of timemarks and separate out crossing traces (such as those produces by a large earthquake). Consequently, strides have been made to optimize DigitSeis and its algorithms with the goal of being able to process images in a nearly fully-automated sense. These include application of techniques to better binarize images and new techniques for detecting and reconciling crossing traces.

Thirty Years of Activity of INGV Devoted to the Preservation of the Tangible and Intangible Heritage of Instrumental Seismology: A Bridge Between Science and Culture

FERRARI, G., Istituto Nazionale di Geofisica e Vulcanologia, Bologna, Italy, graziano.ferrari@ingv.it

Italy can boast a long as well as prestigious tradition in instrumental earthquake observation, and an important amount of data and instruments are still in historical observatories. In the past 30 years INGV has promoted two important projects for the research, recovery, reproduction, conservation and valorisation of this outstanding historical and scientific heritage: the TROMOS Project (1988 –) and the SISMOS Project (2000 -).

Since 2008 SISMOS combine the "philosophies" of the two projects into a single multidisciplinary, multicultural and multi-user approach. Hence the attention is drawn to the historical assets of Italian seismology both as scientific data and as cultural heritage.

SISMOS operates on a potential of few millions of seismograms recorded in Italy (1895 - 1984): about 400,000 of recordings have been catalogued and about 240,000 of these have been scanned.

On 2002 the ESC and SISMOS lauched the EuroSeismos project (2002 -), making possible to scan about 30,000 seismograms of the most important 20th Century Euro-Mediterranean earthquakes collected from 37 countries.

The scientific use of seismograms requires also some complementary documentation (seismic bulletins, articles in scientific journals, station notebooks, etc.) to extract the instrumental constants that SISMOS search and scan.

For the vectorisation of the seismograms, the Teseo2 software has been developed. This allows for the manual and semi-automatic follow up of the seismogram, resampling and alignment, curvature correction and time realignment, along with the saving of the results in different formats.

A restoration laboratory for seismograms and another for historical instruments are also operating.

A dedicated website (sismos.rm.ingv.it/en/) freely distributes the high resolution images of seismograms, about 500,000 pages of complementary documentation and Teseo2.

SISMOS has increased the number of researchers involved in the use of historical seismograms, making possible the instrumental study of some of the most important historical Euro-Mediterranean earthquakes.

Groundtruthing the August 6th 1788 Alaskan Earthquake: Missing Evidence, Mislocation or #Fakequake?

ENGELHART, S. E., University of Rhode Island, Rhode Island, USA, engelhart@uri.edu; WITTER, R. C., U.S. Geological Survey, Alaska, USA, rwitter@usgs.gov; BRIGGS, R. W., U.S. Geological Survey, Colorado, USA, rbriggs@usgs.gov; DURA, T., Virginia Tech, Virginia, USA, tinadura@vt.edu; KOEHLER, R. D., University of Nevada, Nevada, USA, rkoehler@unr.edu; VANE, C. H., British Geological Survey, Keyworth, United Kingdom, chv@bgs.ac.uk; NELSON, A. R., U.S. Geological Survey, Colorado, USA, anelson@usgs.gov; GELFENBAUM, G., U.S. Geological Survey, California, USA, ggelfenbaum@usgs.gov; HAEUSSLER, P. J., U.S. Geological Survey, Alaska, USA, pheuslr@usgs.gov

A recent SAFRR report highlights the Semidi segment of the Alaska-Aleutian subduction zone as having potential for producing a tsunami that would damage the Port of Los Angeles, California. First-hand historical accounts exist for an earthquake on July 21st 1788 at Three Saints Bay, Kodiak Island, which caused coastal subsidence (~1m) and tsunami inundation (~6-8m). Greater uncertainty surrounds reports of a second earthquake on August 6th, presumably the source of a 1788 tsunami that Russian church records from Unimak Island (800 km SW of Kodiak) suggest inundated the Shumagin and Sanak islands (570 and 730 km SW of Kodiak) up to 10–50 m. Here, we synthesize field evidence of coseismic land-level changes and tsunami inundation in 1788 from our investigations in the eastern Aleutians (2010-2018) with historical, archeological, and other published findings from Kodiak Island.

Stratigraphic records of coastal subsidence and tsunami deposits on Kodiak Island corroborate Russian accounts of a great earthquake in 1788. New field evidence from Sitkalidak Island (80 km SW of Kodiak) and nearby Old Harbor are consistent with analyses of archaeological findings and historical records of subsidence and tsunami inundation at Three Saints Bay (15 km SW of Old Harbor) and, when combined with results of earlier studies at Sitkinak Island and Chirikof Island, suggest a rupture length of >300 km. In contrast, there is no evidence for land-level changes or tsunami inundation in 1788 at Sanak, Simeonof, or Unga islands, where brief, second-and-third-hand Russian accounts report the highest tsunami waves. Tsunami deposits as high as 6 m that extend >800m inland at Sanak either date to the M8.6 1946 earthquake or pre-date the 1788 earthquake by >2000 years. Here we present alternative hypotheses that may explain the absence of stratigraphic evidence in the Shumagin and Sanak islands for a western rupture in August of 1788. These include an absence of suitable sedimentary recorders, mislocation in the historical reports, and foul play.

Apples and Oranges: Developing a Consistent Catalog of Local Magnitudes for the National Seismic Hazard Assessment of Australia

ALLEN, T., Geoscience Australia, Canberra, Australia, trevor.allen@ga.gov.au; MOSELEY, A., Geoscience Australia, Canberra, Australia, adrianne.moseley@ga.gov.au

Modern probabilistic seismic hazard assessments rely on earthquake catalogs consistently expressed in terms of moment magnitude, M_W. However, M_W is still not commonly calculated for small local events by many national networks. The preferred magnitude type calculated for local earthquakes by Australia's National Earthquake Alerts Centre is local magnitude, M_L. For use in seismic hazard forecasts, magnitude conversion equations are often applied to convert M_L to M_W. Unless these conversions are time-dependent, they commonly assume that M_L estimation has been consistent for the observation period. While Australian-specific local magnitude algorithms were developed from the late 1980s and early 1990s, regional, state and university networks did not universally adopt these algorithms, with some authorities continuing to use Californian magnitude algorithms. Californian algorithms are now well-known to overestimate earthquake magnitudes for Australia. Consequently, the national catalogue contains a melange of contributing authorities with their own methods of magnitude estimation.

The challenge for the 2018 National Seismic Hazard Assessment of Australia was to develop a catalog of earthquakes with consistent local magnitudes, which could then be converted to M_W. A method was developed that corrects magnitudes using the difference between the original (inappropriate) magnitude formula and the Australian-specific corrections at a distance determined by the nearest recording station likely to have recorded the earthquake. These corrections have roughly halved the rates of M_L 4.5 earthquakes in the Australian catalogue.

To address ongoing challenges for catalog improvement, Geoscience Australia is digitising printed and hand-written observations preserved on earthquake data sheets. Once complete, this information will provide a valuable resource that will allow for further interrogation of pre-digital data and enable refinement of historical catalogs.

Combining Geological and Seismological Methods to Re-Estimate the Magnitude of the 1920 Haiyuan Earthquake

OU, Q., University of Oxford, Oxford, United Kingdom, ouqi1005@gmail.com; KULIKOVA, G., University of Potsdam, Potsdam, Germany, galina.kulikova@geo.uni-potsdam.de; YU, J., University of Oxford, Oxford, United Kingdom, jingxingyuu@gmail.com; ELLIOTT, A. J., University of Oxford, Oxford, United Kingdom, austin.elliott@earth.ox.ac.uk; WALKER, R. T., University of Oxford, Oxford, United Kingdom, richard.walker@earth.ox.ac.uk; PARSONS, B., University of Oxford, Oxford, United Kingdom, barry.parsons@earth.ox.ac.uk

The magnitudes of large earthquakes are important not only because they represent the most devastating events that have occurred but also because of their key role in converting strain rate into earthquake rate for probabilistic seismic hazard assessment. Modern geodetic tools such as InSAR and GPS are generating velocity fields with increasing spatial and temporal resolution, allowing ever more detailed strain rate mapping. The magnitudes of the large historical events, however, are more challenging to determine. Due to their long recurrence periods, many of these events happened before the instrumental period. Their magnitudes were often converted from the intensity of shaking based on historical writings. This method has large uncertainty. The 1920 Haiyuan Earthquake in Gansu, China, is the largest known earthquake in the tectonically active Northeast Tibetan Plateau. It happened 30 years into the instrumental period, but 15 years before the concept of magnitude was coined. Its oft-quoted magnitude, M ~ 8.5, was derived from the intensity of shaking, which we now think is likely overestimated based on geological offset measurements. Early seismological studies were only based on waveforms from one or two stations due to the difficulties of data sharing at that time. However, good preservation and the mass digitization of historical seismograms and the availability of high-resolution optical satellite imagery offered us a golden opportunity to revisit this earthquake and reestimate its magnitude using a combined geological and seismological approach. First, horizontal offsets were measured from orthorectified Pleiades satellite imagery to give a moment magnitude of Mw = 7.64 ± 0.12. Second, historical seismograms were digitised and modelled to give mB = 7.89 ± 0.29, Ms = 8.22 ± 0.21 and Mw = 7.94 ± 0.14. These results confirm that the previously reported magnitude was overestimated. The newly estimated magnitudes will provide an important constraint for future seismic risk assessment in this area.

Joint Study of the 1952 Kern County Earthquake

CONDON, S. J., University of California, Santa Barbara, California, USA, scondon@ucsb.edu; JI, C., University of California, Santa Barbara, California, USA, chenji@ucsb.edu

Our understanding of earthquakes that occurred earlier than the WWSSN era is generally limited by the lack of quality observations. The 1952 Kern County earthquake, the second largest earthquake to occur in California in the 1900s, is no exception. Despite decades of research, significant discrepancies exist among seismic and geodetic interpretations for this event. Here, combining reported geodetic observations with a collection of previously unused, local seismic records, we conduct a series of finite fault inversions to constrain a slip model that is consistent with both datasets. Our results reveal that the 1952 Kern County earthquake had a complex rupture evolution. The rupture initiated on a low-angle fault with dominate strike-slip motion (strike=54°/ dip=36°/ rake=15°) then triggered an abnormally energetic rupture on a high-angle fault plane (strike=51°/ dip=75°), 1.5 s later. In the next three seconds, over 10 m slip accumulated on a 6 km by 6 km fault patch, near the hypocenter, with a cumulative seismic moment of 2.65×10^{19} N m (Mw 6.9). The average static stress drop of this subevent is ~50 MPa. The P wave excited by this powerful subevent saturated seismic records as far as Berkeley (430 km away). The rupture continuously propagated along strike at a slow speed of ~1.5 km/s and initiated another subevent 8 to 28 km away from the hypocenter, where the majority of moment release occurred. The total rupture has a duration ~20 seconds. Our estimate for the cumulative seismic moment is 1.37×10^{20} N m (Mw 7.4), most of which occurred within a 33 km section in the southwest portion of White Wolf fault (assumed to be 60 km long). The weighted, average rake-angle over the entire fault is 53°, falling between previous results based on individual seismic or geodetic data. We note that all three large Southern California earthquakes with significant thrust components (1954 Kern County, 1971 San Fernando, 1994 Northridge) share the same initiation pattern— a small nucleation phase followed by the failure of a patch with an abnormally high stress drop.

The Albuquerque Seismological Lab WWSSN Film Chip Preservation Project

ALEJANDRO, A. C. B., U.S. Geological Survey, New Mexico, USA, aalejandro@usgs.gov; HUTT, C. R., U.S. Geological Survey, Albuquerque Seismological Laboratory, New Mexico, USA, bhutt@usgs.gov; RINGLER, A. T., U.S. Geological Survey, Albuquerque Seismological Laboratory, New Mexico, USA, aringler@usgs.gov; MOORE, S. V., U.S. Geological Survey, Albuquerque Seismological Laboratory, New Mexico, USA, svmoore@usgs.gov; ANTHONY, R. E., U.S. Geological Survey, Albuquerque Seismological Laboratory, Albuquerque, United Kingdom, reanthony@usgs.gov; WILSON, D. C., U.S. Geological Survey, Albuquerque Seismological Laboratory, New Mexico, USA, dwilson@usgs.gov

From 1961 to 1996, the Albuquerque Seismological Laboratory (ASL) installed and operated the World-Wide Standardized Seismograph Network (WWSSN). Each station within the network consisted of three Benioff short-period sensors and three Sprengnether Press-Ewing long-period sensors along with recording, timing, and calibration equipment. Approximately 3.7 million single-day record film chips were created from station records (paper seismograms) covering the period from 1962 to 1978. Two almost complete copies of these film chips are still known to exist at the ASL and at the Lamont–Doherty Earth Observatory (LDEO) as well as a couple of partial sets in other locations. To better preserve the data on these film chips, a project to scan the film chips and to make these scans available through the Incorporated Research Institutions for Seismology (IRIS) was started by W. H. K. Lee. The initial focus was on scanning film chips from a collection of specific earthquakes and nuclear events as well as complete scans of a number of reference stations. However, additional scans containing seismograms useful for climate studies were also completed. As part of this report, we cataloged all of the scanned WWSSN film chips with the hope that it serves as useful documentation as to what film chips have been scanned and of the location of the scans themselves at the IRIS-Data Management Center (DMC) archive page.

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