SSA 2017 Annual Meeting Announcement

Seismological Society of America
Technical Sessions
18–20 April 2017
Denver, Colorado

IMPORTANT DATES	
Meeting Pre-Registration Deadline	10 March 2017
Hotel Reservation Cutoff	24 March 2017
Online Registration Cutoff	7 April 2017
Pre-Meeting Workshops	17 April 2017
Opening Reception	17 April 2017
Technical Sessions	18–20 April 2017
Additional Workshops	18–20 April 2017
Field Trips	21 April 2017

PROGRAM COMMITTEE

The 2017 Technical Program Committee consists of co-chairs Rich Briggs and Gavin Hayes (U.S. Geological Survey), Rick Aster (Colorado State University), Shideh Dashti (Colorado University), Whitney Trainor-Guitton (Colorado School of Mines), Christine Puskas (UNAVCO), and Mark Zellman (Fugro Consultants).

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TECHNICAL PROGRAM

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

LECTURES

President's Address
James J. Mori will present the President's Address at the Annual Luncheon on Tuesday, 18 April 2017.

Joyner Lecture
William R. Lettis, Lettis Consultants International, Inc., will present the Joyner Lecture at 5:45 PM on Wednesday, 19 April 2017. The 2017 Joyner Lecture is titled "Seismic Hazard Analysis and Capturing Uncertainty—Just How Uncertain Should We Be?"

The earthquake engineering community and regulatory agencies are moving, at varying rates, toward risk-informed engineering decisions and design. Risk-informed decision making, in turn, requires that probabilistic seismic hazard analyses explicitly and transparently incorporate uncertainty in hazard-significant seismic source and ground motion parameters. The

Earth science community, following the scientific method, often leads to publication of a "proponent" interpretation or model with little or no expression of uncertainty beyond the limits of the immediate data that were considered in the research. This practice leaves it incumbent on the Probabilistic Seismic Hazards Assessment (PSHA) analyst (often a consultant) to capture the proper range of uncertainty for a parameter based on the body of published literature or, at times, based on the analyst's own interpretations of available data. This is an important, often critical, interface issue between the Earth science community and the engineering community. Over time, some published interpretations or models become incorporated into "common belief" and become accepted paradigms whose uncertainties are rarely challenged even when more recent data or studies no longer support (if not outright reject) the original interpretation or model. Emerging best practice, originating in the nuclear industry, is to use a formal, structured process to capture the center, body, and range of uncertainty for inputs to a hazard model. This process engages the Earth science community as resource (*e.g.*, data) and proponent (*e.g.*, interpretation or model) experts, and requires the PSHA analysts to consider whether full parameter uncertainties are captured within the available data or whether uncertainties ought to extend beyond the available data, expert interpretations, and current paradigms. An overall goal of current PSHA practice ought to be the focus on capturing the full range of uncertainty, so that the next generation of PSHA, which will be constructed with more and better information, will have results that fall within today's uncertainty limits. This presentation will address some of the issues and questions that have evolved in the assessment of uncertainty and include suggestions for a path forward in improved communication of uncertainty between the Earth scientist and the PSHA practitioner.

TOWN HALL MEETING

On Monday, 17 April, 6:30–8 PM, we will hold a Town Hall Meeting titled "Human-Induced Earthquakes: Come Meet the Experts." This is open to the public and will feature an overview presentation on the subject, accompanied by a panel discussion headed by four experts:

1. Justin Rubinstein, U.S. Geological Survey
2. Kathleen Staks, Colorado Department of Natural Resources
3. Stuart Ellsworth, Colorado Oil and Gas Conservation Commission
4. Julie Shemeta, MEQ Geo

IGNITE TALKS

The Ignite Talks, a new feature of the SSA Annual Meeting, comprise an hour of 12 five-minute talks. The talks will take place at 6:30 PM on Tuesday, 18 April 2017.

The Boom-Glider: A Dispersed Acoustic Wave from the 2014 Antares Rocket Explosion

Bowman, Daniel (dbowma@sandia.gov)

Frequency dispersion, while common in seismology, is rarely observed in geocoustics. However, the 2014 Antares rocket explosion generated a dispersive infrasound wave that traveled almost 1,000 kilometers along the Eastern seaboard. This was likely the most extensive recording of dispersive infrasound in history due to the dense Transportable Array microbarometer network in place at the time. Using inversion techniques derived from seismology and the high resolution Hilbert-Huang Transform, we investigate the atmospheric structure that gave rise to this unique wave form.

How Stochastic Modeling is Driving the Next Generation of Resilience

Stillwell, Kate (kstillwell@jumpstartrecovery.com)

Microinsurance for natural disasters can build lasting social impact and financial resilience, but it's only feasible with comprehensive understanding of the probabilities and uncertainties of the payout triggers. This presentation shows an example of how stochastic modeling underpins the development of a parametric earthquake policy for California, which has the potential to speed up recovery for both individuals and the affected region as a whole. We will describe the process and lessons learned in applying model outputs for practical development of an insurance product.

"Earthquake Desks" for Bhutan's Schools: An Affordable, Technologically Feasible, Interim and Yet Controversial Method of Improving School Earthquake Safety

Tucker, Brian (tucker@geohaz.org)

The right way to provide school earthquake safety is with seismically resistant school buildings, but this takes human and financial resources and time that many countries at risk from earthquakes don't have. We offered Bhutan an affordable, technologically feasible, interim solution. An Israeli-designed "Earthquake Desk" can withstand vertical loads up to one ton dropped from a height of 3.5 meters, which is significantly stronger than common desks. By training Bhutan furniture manufacturers, we created a low-cost, local supply of these desks, and by involving the nation's Ministry of Education, we created a sustainable demand for them.

Communicating the Quakes in the New Zealand

McBride, Sara (s.mcbride@gns.cri.nz)

How do we talk about earthquakes in New Zealand? With numerous large earthquakes in the country since 2009, public interest in geological hazards has grown at an astounding rate. So how do we, as a science agency (GeoNet and GNS Science) in New Zealand, effectively communicate about earthquakes? Hint: It involves a lot of social science research combined with savvy communication practice.

Earthquakes in the Anthropocene

Quigley, Mark (mark.quigley@unimelb.edu.au)

Human activities including the injection and withdrawal of subsurface fluids, mining, and the impoundment of surface waters can influence the rates and locations of earthquakes. Through infrastructure development and land-use changes, humans can also change the way that earthquake-induced phenomena such as surface ruptures, rockfalls, landslides, liquefaction features, flooding, and subsidence are expressed relative to their pre-Anthropocene counterparts. In using geologic analogues to forecast the effects of future earthquakes, one must be mindful of intervening anthropogenic modifications to the region of interest.

Access and Integration of Geodetic Data to Enhance Hazard Preparedness, Response, and Mitigation

Rowan, Linda (rowan@unavco.org)

UNAVCO, the community, and the facility provide critical services for natural hazards preparation, response and mitigation efforts. Geodetic data such as GPS/GNSS, SAR satellite imagery and ground-based and airborne Lidar imagery are becoming a more integral part of hazard resiliency, hazard forecasts and/or hazard early warning. Geodetic data is valuable for helping with many hazards, such as earthquakes, volcanic unrest, tsunamis, floods, fires, droughts, severe weather, hurricanes, sea level rise, glacial changes, avalanches, and even space weather. Now it is important to provide more access to geodetic data and to fully integrate geodetic data into resiliency, forecasts, and warning systems.

2,000 Years of Earthquake Sounds in 5 Minutes

Michael, Andrew (michael@usgs.gov)

"...previous to an earthquake, a roaring is usually heard," wrote Lucius Annaeus Seneca, circa 65 CE, in "Naturales Quaestiones." From there, I will tour through historical catalogs of earthquake sounds, personal experience, how sounds are produced, and the use of sonified seismograms in education and art. This history includes seismological greats such as Mallet, Ewing, and Benioff, along with our contemporaries. Along the way, we will listen to recordings of sounds from the free field, people reacting to earthquakes, sonified seismograms, and snippets of music and art pieces, only some of which were created by seismologists.

Citizen Seismology in Taiwan: Why We Failed and What Is the Future?

Chen, Kate Huihsuan (katepili@gmail.com)

The citizen seismic network in Taiwan is dying. Despite lots of workshops and activities, even with a near-real time earthquake game competition and board game (quake-nop-oly) developed along the way, we came to realize the huge gap between what people need and what we do. And to bridge the gap, a new generation of the citizen seismic network is needed. Imagine at work you receive the alarm from sensors at home that tells you the location, size, and type of anomalous shaking events in the neighborhood. Can this future warning system happen, allowing citizens to perform emergency response? This is a story about facing the challenge, transforming the doubt of "why do I care?" to action in a future Internet-based world.

Emerging Opportunities in Planetary Seismology

Kedar, Sharon (Sharon.Kedar@jpl.nasa.gov)

In the coming years NASA will launch missions to explore Mars, our Moon, and the Ocean Worlds of the Solar System. The seismological community is faced with multiple challenges in introducing seismological exploration to such missions: Most landed missions are focused on the near surface; Seismometers, are perceived as complex and adding risk to inherently complicated lander missions; Finally, due to the long breadth required in the planning and execution of planetary seismology missions, it is challenging for many to invest in an endeavor that may not materialize for decades. We will discuss these challenges and approaches to overcoming them.

Temblors and Tweets

Guy, Michelle (mguy@usgs.gov)

Vast numbers of people immediately turn to social media and apps in the seconds following earthquakes. Information on social media travels faster than seismic waves can reach globally distributed seismic instruments. Here are some ways our community capitalizes on the free, ubiquitous, and independent data from crowd sources.

Managing the Explosion of High-Resolution Topography for Active Fault Research

Arrowsmith, Ramon (ramon.arrowsmith@asu.edu)

Centimeter to decimeter-scale 3D sampling of the Earth surface topography coupled with photorealistic coloring of point clouds and texture mapping of meshes enables a wide range of science applications. The configuration and state of the surface is valuable, and repeat surveys enable quantification of topographic change. I will present recent updates to the OpenTopography system and discuss opportunities for the community.

Dark Energy and Earthquakes: Elastic Strain Invisible to Geodesy

Bilham, Roger (bilham@colorado.edu)

Geodesy has great utility where strain changes are rapid, but less so where they are slow. It is useless where strain is stagnant, yet most of the world's earthquakes draw wholly or in part on this invisible reservoir of dark strain energy. Is there a fix?

WORKSHOPS

Probabilistic Seismic Hazards Assessment: From Basics to Induced Seismicity

Monday, 17 April 2017, 2–5 PM
Registration Required.
Fee: $10 for SSA Student Members and Transitional Members; $50 for SSA Regular Members; $75 for Non-Members

Workshop leaders: Gail Atkinson, a Professor of Earth Sciences and the NSERC/TransAlta/Nanometrics Industrial Research Chair in Hazards from Induced Seismicity at Western University in Canada; Mark Petersen, U.S. Geological Survey; Chuck Mueller, U.S. Geological Survey; and Morgan Moschetti, U.S. Geological Survey.

This workshop will introduce the key ingredients of Probabilistic Seismic Hazards Assessment (PSHA): seismogenic zonation and ground motion prediction equations. A set of seismogenic source models, sometimes termed as "earthquake rupture forecasts", describes what kinds of earthquakes are possible in the future and how frequently they might occur. The model must specify the size distribution of these future earthquakes (the Gutenberg-Richter law), including an assessment of the maximum possible event size, their depth distribution, and faulting styles. The historical and instrumental catalogs are often the primary information for defining source models and their quality, homogeneity, and completeness needs to be assessed in detail. The determination of ground motion prediction equations involves developing a model that expresses the amplitudes of ground motion—peak ground acceleration, peak ground velocity, and spectral acceleration—as a function of earthquake magnitude, distance, site effects, and other factors; the model also needs to characterize the uncertainty and variability in the model. Such models are typically a blend of empirical regression constrained by seismological considerations regarding functional form. The two ingredients are then combined, most commonly using the PSHA method developed by Cornell (*e.g.*, BSSA, 1968) and McGuire (*e.g.*, 2004 EERI monograph). A common assumption has been that earthquakes are randomly distributed at a constant rate in time (*i.e.*, stationary in time), but this is changing rapidly due to the influence of induced seismicity on earthquake occurrence. This workshop is presented jointly by SSA and the Community Online Resource for Statistical Seismicity Analysis (www.corssa.org).

Be a Better Reviewer, Advance Your Career

Monday, 17 April 2017, 2:30–4:30 PM
Registration Requested.
No Fee.

Workshop leaders: Roland Bürgmann of University of California, Berkeley, a BSSA associate editor emeritus; John Ebel of Boston College and founding editor-in-chief of SRL; and Brent Grocholski of Science and editor of all seismology papers for the journal.

This workshop will help you learn how to be a more reliable and productive reviewer for technical papers, and how to use the reviews you receive to improve your research and to build better relationships with your editors and peers. Participants will get an in-depth look at the steps needed to review colleagues' papers in constructive and reliable ways. They will also learn how becoming a good reviewer can help them develop their careers and contribute to the broader seismological community. The roles of the editors, the reviewers, the authors, and the journal production staff in the publication process will be discussed. Open to all questions about reviewing and publishing, the instructors are hoping for a lively Q&A session as in years past. The free workshop is geared toward students and early-career seismologists, but is open to all Annual Meeting attendees.

That Poster Is Just Fine And So Are You: Maintaining Self-Confidence and Balance in the Uncertain World of Early-Career Science

Wednesday, 19 April 2017, 8–9:30 PM
Registration requested.
No Fee.

Panelists: Margaret Benoit, Program Officer, National Science Foundation; Tobias Bischoff, Data Scientist; Ph.D. Environmental Science and Engineering, California Institute of Technology, 2016; Harmony Colella, Earthquake Hazard Mitigation Analyst at University of California, Berkeley/California Office of Emergency Services; Ian Miller, Chair, Department of Earth Sciences, Denver Museum of Nature And Science; Chris Rollins, Ph.D. Student, Seismological Laboratory, California Institute of Technology

Do you worry that the one figure where the fit isn't great will be the only thing anyone remembers about your poster? Do you feel like the two possible outcomes of that talk you're giving next week are "Audience Member Points Out Problem in Slide 6, Resulting in Complete Disaster That Everyone in Attendance Will Forever Associate with You" and "Somehow No One Points Out Problem in Slide 6, But It's Still All Wrong and They Probably Saw It"? Are you still kicking yourself over that conversation you had with your academic hero six years ago when you referenced the wrong paper? Does the idea of living a balanced life and doing things you like while at the same time somehow "winning" the academic "rat race" seem impossible? We're here with two things to say: 1) You're going to be okay; 2) Let's hear about it. This is a panel discussion geared toward early-career scientists and the issues that they often face—impostor syndrome, anxiety about the next step and the future, work/life balance, you name it—motivated by the observation that these issues seem to affect many of us and have made the road very rough for some. Bring your beef and let's discuss it, hear from people who have dealt with it, and work toward both awareness of these issues and ways that we can give each other a hand. We'll see you there.

Government Relations Informational Session: What's New in DC and How it Impacts You

Wednesday, 19 April 2017, 5–5:45 PM
No registration required.
No fee.

Workshop leader: Elizabeth Duffy, President of the Federal Affairs Office, Washington, D.C. and Government Affairs Coordinator for SSA.

Please join SSA's representative in Washington DC, Elizabeth Duffy, to discuss the new Congress and new Presidential Administration, the expected legislative priorities for federal science programs, and the future of earthquake funding. Intended to be an interactive discussion on the current legislative climate in Washington, Duffy will provide advice on strategies to promote effectively your science in Congress and take questions from participants to address general and specific concerns.

She brings more than 20 years of business, politics, and advocacy experience representing associations and organizations before Congress, including developing and implementing advocacy strategies and working to educate and inform members of Congress, federal agencies, and the Administration.

FIELD TRIPS

Geodynamics, Geophysics, and Geology of the Colorado Front Range

Friday, 21 April 2017, 9 AM–6 PM
Registration required.
Fee: $75 (lunch included).

Trip leaders: Will Levandowski (U.S. Geological Survey), Dean Ostenaa (Ostenaa Geologic), Zane Jobe (Colorado School of Mines), Rich Briggs (U.S. Geological Survey), and Mark Zellman (Fugro Consultants Inc.)

This field trip will visit sites that illustrate key geophysical and geological questions along the Colorado Front Range of the Rocky Mountains: What are the geodynamic drivers of broad deformation and focused seismicity along the Rocky Mountains/High Plains transition? What evidence for Cenozoic deformation is recorded in the Denver Basin and Quaternary surfaces along the Front Range? How did these beautiful mountains form and what processes are active today?

Stops extend into the Front Range west of Denver and tentatively include Lookout Mountain, where East meets West; a view of the Continental Divide from Genesee; the Rocky Mountain erosion surface at Evergreen; deformed strata of the Ancestral Rockies at Red Rocks Amphitheatre in Morrison; and evidence for Cenozoic deformation and erosion at North Table Mountain in Golden. Lunch will be provided at a local brewery. The trip begins and ends at the Sheraton Denver Downtown Hotel. Hiking will be minimal but dress for spring weather and for outdoor trip stops.

Facilities Tour of NEIC, NOAA, and UNAVCO

Friday, 21 April 2017, 8 AM–5 PM
Registration Required.
Fee: $75 (lunch included).

Trip leader: Gavin Hayes (U.S. Geological Survey)

This trip will visit three major Earth science facilities along the Colorado Front Range. Stops include a specialist's perspective on global earthquake response at the USGS National Earthquake Information Center (NEIC). In Boulder, participants will tour the National Oceanic and Atmospheric Administration (NOAA) David Skaggs Research Center with stops at the Space Weather Prediction Center, ESRL Global Monitoring Division for information on the carbon dioxide record, the National Weather Service Forecast Office, and Science On a Sphere. Finally, participants will tour the UNAVCO, Inc. global geodetic facility in Boulder. The trip begins and ends at the Sheraton Denver Downtown Hotel and hiking will be minimal. Lunch will be served at a local brewery.

The Epicenter of Induced Seismicity: Rocky Mountain Arsenal

Friday, 21 April 2017, 8:30 AM–4 PM
Registration Required.
Fee: $75 (box lunch included).

Trip leaders: Meghan Brown and Anne Sheehan (University of Colorado Boulder)

Deep injection during the 1960s at Rocky Mountain Arsenal (RMA), only 10 miles/15 kilometers from the 2017 Annual Meeting location, caused damaging earthquakes in the Denver region and awoke the scientific community to the problem of induced seismicity. This trip focuses on our current understanding of induced seismicity in the context of the history of RMA and lessons learned from recent regulatory frameworks. Stops include sites at RMA and a nearby injection well. The trip begins and ends at the Sheraton Denver Downtown Hotel. Hiking will be minimal but dress for spring weather and for outdoor trip stops. A box lunch will be provided.

PRELIMINARY SCHEDULE

Events will be held at the Denver Downtown Sheraton in Denver, Colorado. This schedule is subject to change.

Monday, 17 April

Board of Directors Meeting (9:30 AM–5:00 PM)
Workshop: Probabilistic Seismic Hazards Assessment: From Basics to Induced Seismicity (2:00–5:00 PM)
Workshop: Be a Better Reviewer, Advance Your Career (2:30–4:30 PM)
Registration (3:00–7:00 PM)
Opening Reception (5:00–7:00 PM)
Town Hall Meeting (6:30–8:00 PM)

Tuesday, 18 April

Technical Sessions (8:30 AM–5:45 PM)
Annual Luncheon (noon–2:00 PM)
Pint and a Poster (5:45–6:30 PM)
Ignite Talks (6:30–7:30 PM)
Student Reception (7:30–9:00 PM)
Early Career Reception (7:30–9:00 PM)

Wednesday, 19 April

Mentoring Breakfast (7:00–8:15 AM)
Technical Sessions (8:30 AM–5:00 PM)

Public Policy Luncheon (noon–1:15 PM)
Pint and a Poster (5:00–5:45 PM)
Workshop: Government Relations: What's New in DC and How it Impacts You (5:00–5:45 PM)
Joyner Lecture (5:45–6:45 PM)
Reception (6:45–8:00 PM)
Workshop: That Poster Is Just Fine and So Are You: Maintaining Self-Confidence and Balance in the Uncertain World of Early-Career Science (8:00–9:30 PM)

Thursday, 20 April
Technical Sessions (8:30 AM–5:30 PM)
Group Luncheon (noon–1:15 PM)
Pint and a Poster (2:45–3:45 PM)

Friday, 21 April
Field Trip: Facilities of NEIC, NOAA, and UNAVCO (8:00 AM–5:00 PM)
Field Trip: The Epicenter of Induced Seismicity: Rocky Mountain Arsenal (8:30 AM–4:00 PM)
Field Trip: Geodynamics, Geophysics, and Geology of the Colorado Front Range (9:00 AM–6:00 PM)

HOTEL AND TRAVEL INFORMATION

The conference will be held at the Denver Downtown Sheraton Hotel at 1550 Court Place, Denver, Colorado. SSA has a room block at the Sheraton with a room rate of $178 (plus applicable taxes). The room rate of $178 (plus applicable taxes) is the government per diem rate, so there is no need to register differently if you work for the US Government. Please note that the cutoff date for reservations at this rate is 24 March 2017.

INFORMATION FOR EXHIBITORS, SPONSORS, AND ADVERTISERS

Information for organizations wishing to register as exhibitors, sponsor events at the meeting, or advertise in the meeting program can be found on the SSA website. More information will be posted, as it is available, at: http://meetings.seismosoc.org/advertising-opportunities/

Technical Sessions

Advances in Earthquake Early Warning

Earthquake Early Warning (EEW) systems provide advance warning of potentially damaging ground shaking and enable the activation of protective actions to prevent or reduce injuries or economic losses. A variety of EEW alert capabilities are in operation or under development in multiple regions of high seismic risk around the world. These vary in complexity from systems that take relatively simple actions based on ground motions exceeding a threshold at a single site to network-based systems that track an evolving rupture across multiple sensors. All EEW systems must consider: 1) types and quality of available ground motion data (seismic, GNSS, etc.); 2) sensor layout including station distribution, telemetry, and latencies; 3) methodologies for estimating source properties and/or predicting ground motion; 4) communication and use of alerts; and 5) evaluation of system performance. We invite contributions that address all aspects of EEW systems from the theoretical underpinnings to education and outreach efforts.

Session Chairs: Elizabeth Cochran (ecochran@usgs.gov), Angela Chung (aichung@berkeley.edu), Douglas Given (doug@usgs.gov).

Advances in Seismic Full Waveform Modeling, Inversion, and Their Applications

3D full waveform modeling and inversion holds promise for more accurate accounts of wave propagation, higher-resolution Earth models, and better earthquake location and characterization. This session includes, but is not limited to, development and verification of full waveform forward modeling methods, and novel inverse algorithms, together with their applications in accurate source location (earthquakes or nuclear tests), imaging of velocity and attenuation structure at local to global scales, as well as full waveform migration. Topics related to quantitative interpretation of tomographic models (using seismological, geological or geochemical data) are also welcome.

Session Chairs: Nian Wang (nian_wang@uri.edu). Xueyang Bao (xybao@uri.edu), Dmitry Borisov (dborisov@princeton.edu), Youyi Ruan (youyir@exchange.Princeton.edu).

Assessment and Management of Hazards from Seismicity Induced by Hydraulic Fracturing

There has been growing recognition of the potential for hydraulic fracturing to induce significant (M>3) earthquakes in a small percentage of horizontal well completions. Assessment and mitigation of potential hazards from this seismicity pose unique challenges due to the highly clustered nature of the activity in time and space, and the difficulty of predicting in advance whether such activity will occur. It is also not clear what mitigation measures might be effective once a sequence has been initiated. We invite papers dealing with all aspects of this particular problem, including earthquake nucleation processes, assessment and characterization of sequences and their likelihood, regional variability of susceptibility, ground motions generated by sequences, traffic light protocols, and hazard assessment and mitigation.

Session Chairs: Gail Atkinson (gmatkinson@aol.com), David Eaton (eatond@ucalgary.ca), Ryan Schultz (Ryan.Schultz@aer.ca), Honn Kao (honn.kao@canada.ca).

Characterization of the Stress Field and Focal Mechanisms for Earthquake Source Physics and Fault Mechanics

Accurate estimation of the state of stress and pore fluid pressure is important for understanding processes leading to fault reactivation and earthquake nucleation. The main purpose of this session is to foster communication between researchers from different fields focussing on characterization of the stress field at global, regional (*e.g.,* near large tectonic structures or subduction zones), and local scale (*e.g.,* in relation to man-made perturbations). Of particular interest is the link between stress field and pore pressure estimations from seismology and state-of-the-art modeling approaches. Contributions may regard (but are not limited to) studies of:

- New techniques to improve characterization of stress field orientation, stress magnitudes and pore pressure, or comparisons of existing techniques.
- Structural, tectonic or dynamic factors perturbing the stress field (*e.g.,* large magnitude earthquakes, anthropogenic activities, temperature changes, aftershock/foreshock sequences, fault bends), implications of these perturbations and their spatio-temporal extent.
- Analysis of earthquake moment tensors: relation with the stress field and implications for earthquake source physics.
- Orientation, consistency, and associated seismic hazard of fault structures with respect to the local/regional stress field. Implications for the frictional properties of faults and/or formation and growth of faults.
- Stress heterogeneity at different scales and potential relation with varying earthquake source physics (*e.g.,* stress drop, b-value).
- The role of the background stress field and pore pressure for earthquake triggering via stress redistribution.

Session Chairs: Patricia Martínez-Garzón (patricia@gfz-potsdam.de), Jeanne L. Hardebeck (jhardebeck@usgs.gov), Martha Savage (Martha.Savage@vuw.ac.nz), Marco Bohnhoff (bohnhoff@gfz-potsdam.de).

Closing the Gap between Laboratory-based Damping Models and Observed Attenuation of Seismic Waves in the Field

Seismic wave attenuation is an important topic for both seismology and engineering. It plays a key role in the prediction of ground motions, the estimation of site effects, and the evaluation of seismic hazards. The seismic quality factor, Q, is a dimensionless quantity that is inversely proportional to the attenuation of elastic wave energy, and it is widely used in engineering seismology. Damping ratio, ξ, is used to quantify energy dissipation in geotechnical engineering, and it is obtained through laboratory experiments that primarily measure hysteresis. Dynamic testing of small-scale soil samples can only characterize material damping and fails to capture other mechanisms of attenuation as they occur in the field (*e.g.,* scattering). However, laboratory-based damping ratio curves are typically used with no modification for differences between the laboratory and field conditions. The high-frequency spectral decay parameter, κ, is based on characteristics of low-intensity ground motions recorded directly in the field, which makes it an observable parameter that quantifies total path attenuation. The main purpose of this session is to bring together researchers focused on the characterization of damping from different perspectives in an attempt to improve our ability to constrain this elusive parameter. Contributions may regard (but are not limited to) studies of: 1) quantification of the attenuation of seismic waves from field, laboratory, and numerical studies; 2) comparisons of material damping values determined through different approaches; 3) innovative methodologies for quantifying anelastic attenuation; 4) methodologies for harnessing data from field and laboratory studies; and 5) implications of attenuation and its associated uncertainty in site response analysis and site-specific seismic hazard assessment.

Session Chairs: Albert Kottke (albert.kottke@gmail.com), Ashly Cabas (amcabasm@ncsu.edu).

Computational Infrastructure and Data for Enhancing Earthquake Science

Advances in earthquake science are becoming increasingly tied to advances in computational infrastructure. Because earthquake processes span multiple spatial and temporal scales, ranging from microscopic, millisecond source physics to long-term, global tectonic scales, earthquake scientists must rely on computational laboratories to integrate disparate data sets and perform simulation experiments. This session focuses on 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.

Session Chairs: Lisa Grant Ludwig (lgrant@uci.edu), Andrea Donnellan (andrea.donnellan@jpl.nasa.gov).

Earthquake Complexities Revealed by Kinematic and Dynamic Modeling and Multiple Geophysical Data Sets

In recent years, spatiotemporal and geometrical earthquake rupture complexities have been imaged with increasing detail. In particular, large to great earthquakes ($M > 7$) often show segmented rupture, involve multiple faults, and trigger large nearby aftershocks almost instantaneously. The complexity of large earthquakes challenges traditional source imaging approaches and motivates developments of novel methods to map the space-time evolution of the rupture process. The use of multiple data sets, such as seismic, geodetic, and tsunami measurements, opens an avenue for future improvements in kinematic source modeling, but requires new statistical means to optimally weight individual data sets. Similarly, appropriately quantifying the uncertainties of the resulting source models is needed to assess which parts of the rupture process are well imaged. At the same time, incorporating local geology, regional tectonics, and principles of earthquake dynamics is very valuable to understand and interpret the observed rupture pattern.

This session discusses new approaches, new data sets, and latest findings in kinematic source imaging and dynamic rupture modeling. We invite contributions related to kinematic source imaging with new methods, improved uncertainty quantification, and using multiple data sets. In particular, we solicit studies that provide unified interpretations of observed kinematic rupture patterns with earthquakes dynamics, as well as post-seismic and interseismic processes and the local tectonic framework. We also solicit contributions on dynamic rupture simulations on geometrically complex faults, and studies that incorporate new rupture physics and laboratory rupture experiments that are reconciled with geophysical observations.

Session Chairs: Wenyuan Fan (w3fan@ucsd.edu), P. Martin Mai (martin.mai@kaust.edu.sa), David D. Oglesby (david.oglesby@ucr.edu).

Earthquake Geology and Paleoseismic Studies of the Intermountain West: New Methods and Findings on Seismic Hazard Characterization of Low Slip Rate Faults

The intermountain west is a broad region characterized by distributed faulting with relatively low slip rates and long recurrence intervals. These factors create a unique set of challenges for geologists and seismologists tasked with understanding the seismic hazard of the region. Despite these difficulties, scientists are developing innovative methods to characterize faults, assess seismic activity, and place constraints on contemporary deformation of the intermountain west. These studies are progressing the methodologies for evaluation of seismic hazard, and improving informed decision making by regulatory and planning agencies. We invite studies from researchers and practitioners presenting new results of this nature within the intermountain west region, including but not limited to: the Walker Lane, Basin and Range, and the Rio Grande Rift.

Particular topics of interest include: 1) paleoseismic estimates of earthquake recurrence, magnitude, slip rate, and rupture extent; 2) application of high-resolution topography; 3) objective techniques for evaluating paleoseismic data quality and synthesizing datasets; 4) integration of geologic and geodetic data; and 5) techniques for evaluating fault segmentation and multi-fault rupture.

Session Chairs: Seth Dee (sdee@unr.edu), Stephen Angster (angster41@gmail.com).

Earthquake Impacts on the Natural and Built Environment

In this session, we invite presentations on earthquake effects and their impacts. This includes models of landslides, liquefaction, lateral spreading, surface fault rupture, building damage, and infrastructure/lifeline performance, as well as broader multi-hazard impact analyses. We encourage submissions on empirical and analytical models, sensitivity analyses, data analyses, and scenario exercises. Given the challenges of linking secondary effects and their impacts to simplified shaking parameters, we also encourage submissions on innovative parameterizations of ground motion shaking intensity to account for cumulative energy, frequency content, and duration effects. Similarly, we hope to include recent developments on proxies for predicting the likelihood and the spatial distribution of earthquake ground failure impacts.

Session Chairs: Eric Thompson (emthompson@usgs.gov), Kate Allstadt (kallstadt@usgs.gov), Kishor Jaiswal (kjaiswal@usgs.gov), Nilesh Shome (nilesh.shome@rms.com).

Earthquake Interaction and Triggering: From Near Field to Far Field, From Natural to Induced

Unraveling patterns and mechanisms of earthquake triggering is important for understanding earthquake occurrence and seismic hazard forecast. For example, aftershocks are consequences of static and/or dynamic stress perturbations from mainshocks. Whereas static-stress triggering is most effective at near field, dynamic-stress triggering has been widely reported to cause earthquakes and nonvolcanic tremor remotely. Recent studies show dynamic triggering is common in the near-to-intermediate field, and capable to cause damaging earthquakes. Faults near oil-and-gas and geothermal fields are also highly susceptive to dynamic triggering. Such observations lead to questions regarding fault friction properties, tectonic stress conditions, and fault hydraulic responses. This session discusses new observations and models related to earthquake interaction and triggering. We invite contributions from studies of near-field to remote earthquake triggering and studies of natural and anthropogenically induced earthquake interactions. We also solicit research of hydro-mechanical modeling and dynamic simulations of fault interactions, which incorporate laboratory experiments and field observations.

Session Chairs: Wenyuan Fan (w3fan@ucsd.edu), Andy Barbour (abarbour@usgs.gov), Xiaowei Chen (xiaowei.chen@ou.edu).

Earthquake Rapid Response

Rapid deployments of seismic arrays and GPS receivers after recent large earthquakes demonstrate the power of well-recorded aftershock sequences and the postseismic deformation field to shed light on earthquake ruptures and transient processes associated with these events. In the wake of large earthquakes, coordinated, dense, well-positioned deployments of seismic arrays, GPS receivers, and EM/MT instruments, combined with field studies and satellite-based geodetic measurements and imagery, provide a high-resolution definition of the rupture zone, rupture-limiting structures, and insight into postseismic deformation, earthquake triggering, the role of fluids in faulting, changes in material properties, and fault zone healing. Data from earthquake rapid response efforts can advance earthquake forecasting research and yields a densely sampled high-resolution data set to characterize in detail earth structure and to image fault networks.

We invite abstracts that report results from post-earthquake response efforts and aftershock studies, address the benefits of multidisciplinary data collected after an event, present ideas about how to better coordinate efforts and improve efficiencies of rapid deployments, and technological developments that enhance our ability to effectively deploy instruments and/or collect field data after large events.

Session Chairs: Anne Meltzer (ameltzer@lehigh.edu), Jay Pulliam (Jay_Pulliam@baylor.edu), Dan McNamara (mcnamara@usgs.gov).

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 details. In addition, studying relations between static and dynamic source parameters and earthquake size is essential to understanding the self-similarity of rupture process and scaling laws and to improving our knowledge on ground motion prediction equations.

This session focuses on methodological as well as observational aspects of earthquake source parameters of natural or induced earthquakes in broad range of magnitudes from large to small earthquakes, including acoustic emissions in laboratory experiments. Presentations of new approaches of focal mechanisms determination, 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 and to self-similarity of earthquakes.

Session Chairs: Vaclav Vavrycuk (vv@ig.cas.cz), Grzegorz Kwiatek (kwiatek@gfz-potsdam.de), German Prieto (g.prietocruz@gmail.com).

Earthquakes and Tsunamis

This general session brings together a collection of presentations with the common theme of Earthquakes and Tsunamis.

Session Chairs: Rich Briggs and Gavin Hayes (2017program@seismosoc.org).

Emerging Opportunities in Planetary Seismology

In the coming years and decades NASA may launch missions to explore Mars, our Moon, and the Ocean Worlds of the Solar System (*e.g.,* Europa and Enceladus, and Titan). The InSight (Interior Exploration using Seismic Investigations, Geodesy, and Heat Transport) mission that will land on Mars in November 2018 will be the first Mars lander to place an ultra-sensitive broadband seismometer on the planet's surface. The Lunar Geophysical Network, identified as a high-priority New Frontiers class mission in the Planetary Science Decadal survey, seeks to understand the nature and evolution of the lunar interior from the crust to the core. In addition, concepts are being developed to explore the interior of Venus, asteroids and comets.

The objectives of these missions vary. While InSight and the Lunar Geophysical Network are primarily geophysical missions, missions to our Ocean Worlds focus on the detection of life and conditions for life. Despite these differing emphases, mapping the shallow and deep interior of planetary bodies is essential, as their interiors hold the clues for understanding their planetary evolution as well as for determining their thermal and chemical makeup and thus their habitability. The tool that can most efficiently reveal the detailed structures of planetary interiors is seismology.

This session invites presentations on seismological exploration of planetary interiors. Authors are invited to present re-analysis of data from past missions (Apollo and Viking) and from terrestrial analogs, as well as concepts, models, and simulations of seismological studies that could be included in future missions to the Solar System.

Session Chairs: Sharon Kedar (Sharon.Kedar@jpl.nasa.gov), Steve Vance (Steven.D.Vance@jpl.nasa.gov), Nicholas Schmerr (nschmerr@umd.edu).

Estimating Earthquake Hazard from Geodetic Data

Geodetic techniques such as GPS and InSAR provide a critical constraint for quantifying earthquake hazard by recording the active accumulation of tectonic strain across seismogenic faults. Geodetic observations are particularly important in regions with sparsely mapped faults and/or few geologic slip rate estimates, such as inland Alaska, and in regions with known seismic hazard but broadly distributed strain, like the Basin and Range. However, geodetic estimates of fault slip rates can vary significantly for a single fault or region and may differ from geologic rates on the same fault. These discrepancies may reflect model assumptions since geodetic observations of the interseismic phase of the earthquake cycle must be interpreted in the context of a prescribed deformation model. They may also reflect transient processes due to post-seismic relaxation, glacial isostatic adjustment, and aseismic slip events that bias inferred interseismic deformation rates and, in turn, long-term fault slip rate estimates. We invite contributions that describe the application of geodetic data to earthquake hazard estimation in a variety of settings worldwide. We also seek contributions that present new approaches to addressing the challenge of effectively incorporating geodetic information into seismic hazard assessment. Some questions of interest include:

- How can we best utilize geodetic observations in regions with few mapped structures or regions with low strain rates but known seismic hazard?
- What is the role of off-fault deformation in geodetically observed strain rates, and what fraction of deformation occurs between major faults?
- Can we identify the cause of discrepancies between geodetic and geologic slip rate estimates for the same fault?
- By what metrics should geodetic models be assessed?
- How do we assess uncertainty and the impact of modeling assumptions?
- How do we estimate long-term fault slip rates in the presence of transient deformation signals (*e.g.*, glacial isostatic adjustment, postseismic relaxation, slow slip events, etc.)?

Session Chairs: Jeff Freymueller (jfreymueller@alaska.edu), Elieen Evans (eevans@usgs.gov), Jessica Murray (jrmurray@usgs.gov).

Fault Mechanics and Rupture Characteristics from Surface Deformation

High-quality surface data (*e.g.,* point clouds, digital elevation models, and digital imagery) have become more readily available and easier to process and analyze with advances in acquisition technologies and computer processing capabilities. Accurate renditions of co- and post-seismic surface deformation permit characterization of fault and damage zone properties for scales and at resolutions that were not previously possible. This session addresses advances in earthquake and fault science using the newest generation of digital imagery and topography data. We encourage submissions that use continuous surface data (*e.g.,* lidar, structure-from-motion, InSAR, UAVSAR, pixel tracking) to study fault mechanics and properties, including damage zone width and asymmetry, near and far-field displacement fields, shallow slip deficit, and scarp morphology and degradation.

Session Chairs: Lia Lajoie (lajoie.lia.j@gmail.com), Kendra Johnson (kejohnso@mymail.mines.edu), Edwin Nissen (enissen@mines.edu).

Fine Scale Structure of the Crust and Upper Mantle

Recent advances in seismology have enabled increased resolution of structure in the crust and upper mantle, such as refined images of the Moho, sharp boundaries at the base of or within oceanic lithosphere, the lithosphere-asthenosphere boundary beneath continents, mid-lithospheric discontinuities, depth resolution of both azimuthal and radial anisotropy, etc. This session will highlight both new techniques for resolving structure and results that bear on geodynamic questions. Lev P. Vinnik, who will receive the Reid Medal in 2017, will give a keynote lecture in this session.

Session Chairs: Peter Molnar (molnar@colorado.edu), Barbara Romanowicz (barbara@seismo.berkeley.edu), Steven Roecker (roecks@rpi.edu).

Forecasting Aftershock Sequences in the Real World

Over the last two years, seismologists have produced forecasts for a number of aftershock sequences, including the ongoing Christchurch, New Zealand, earthquake sequence which began in 2010 with the M7.0 Darfield event, the 2015 M7.8 Gorkha, Nepal, earthquake; the 2016 M7.0 Kumamoto, Japan, earthquake; the 2016 M6.2 Amatrice, Italy, earthquake; the 2016 M5.8 Pawnee, Oklahoma, United States, earthquake; and earthquake swarms near San Ramon and Bombay Beach, California, United States. Each sequence has raised challenging situations for the calculation of earthquake probabilities and their communication to the public, emergency managers, and other users. As systems that make these forecasts on a routine basis become operational we need to capture these lessons in the numerical software and presentation methods. We invite presentations on the application of earthquake clustering problems to these real-world situations as well as discussions of challenges faced in modeling and communication of forecasts; this could include related advances in statistical seismology and the social science of communication.

Session Chairs: Andrew Michael (michael@usgs.gov), Matt Gerstenberger (m.gerstenberger@gns.cri.nz), Warner Marzocchi (warner.marzocchi@ingv.it).

From Field Site to Data Center: Network Innovations for Earthquake Early Warning

With the advent of Earthquake Early Warning (EEW), seismic networks must now process real-time data within several seconds. Robust station architecture, reliable low-latency telemetry links, and streamlined data acquisition workflows are necessary for successful EEW systems. Networks must include multiple layers of redundancy while remaining highly secure, because as earthquake alerts become public and widespread, EEW systems may become prime targets for hackers. We invite you to share your innovations and challenges in this new era of seismic data acquisition. From the field site to the data center, how have you improved your network's robustness, reliability, and security?

Session Chairs: Christopher Bruton (cpbruton@gps.caltech.edu), Rayo Bhadha (rayo@gps.caltech.edu).

The Future of Past Earthquakes

The broad field of earthquake geology, which includes paleoseismology, provides approaches for quantifying the longer term behavior of active structures and active regions in time and space. Since the mid-1960s, when trenching was first used for simple fault location primarily in California, investigations of the rupture behavior of seismogenic structures have spread worldwide to all tectonic settings, including subduction zones. Using improved and new techniques for dating geologic deposits and geomorphic surfaces, incorporating high-resolution ground-based and satellite imagery for measuring coseismic surface and longer-term displacements, and investigating sites with long records of earthquake occurrence and event slip, earthquake geologic studies have expanded our four-dimensional understanding of active earthquake systems and provided fundamental data for seismic hazard analysis.

This Special Session will include invited and contributed papers that present the current status and future directions of research in earthquake geology. We encourage papers examining all tectonic settings, fast and slow, and especially those incorporating new concepts, methods, and data that: a) define single-source and regional earthquake cycles; b) quantify earthquake rupture recurrence and slip models and their uncertainties; c) provide comparisons between short-term deformation rates from GPS, InSAR, and historical seismic moment release estimates with longer-term geologic slip rates and earthquake recurrence rates; d) develop insights into controls on dynamic rupture propagation and improve estimates of paleo and future fault rupture lengths; and e) use paleoseismic observations to suggest new constraints in modeling seismic hazard.

Session Chairs: David Schwartz (dschwartz@usgs.gov), Ramon Arrowsmith (ramon.arrowsmith@asu.edu), William Lettis (lettis@lettisci.com), Koji Okumura (kojiok@hiroshima-u.ac.jp), Daniela Pantosti (daniela.pantosti@ingv.it), Thomas Rockwell (trockwell@mail.sdsu.edu).

Geoacoustics: Infrasound and Beyond

Acoustic waves encode information about events occurring at or above the Earth's surface, and they often image wind and temperature fields in regions inaccessible to most other measurement techniques. Thus, atmospheric acoustics is both a vital complement to seismic monitoring as well as a means of investigating signals that interact poorly with the solid Earth. We encourage contributions from the many diverse subfields of geoacoustics, including signal analysis, propagation modeling, source physics, and sensor technology.

Session Chairs: Daniel Bowman (dbowma@sandia.gov), Stephen Arrowsmith (jarrow@sandia.gov), Omar Marcillo (omarcillo@lanl.gov).

Ground Motions and GMPEs

This general session brings together a collection of presentations with the common theme of Ground Motions and Ground Motion Prediction Equations (GMPEs).

Session Chairs: Rich Briggs and Gavin Hayes (2017program@seismosoc.org).

Importance of Long-Period Ground Motions in Seismic Design of Structures

Records from instrumented structures clearly show that long-period ground motions are an important factor affecting the response of flexible structures, such as tall buildings, long bridges, and base-isolated structures. Large earthquakes can generate such waves at distances far beyond those considered in seismic hazard assessment. There is a need for a more accurate description of long-period ground motions in seismic design codes.

This session invites papers related to the long-period ground motions and their effects on structures, including the characterisation of long-period motions for seismic design, recorded response of structures to long-period motions, and modifications of attenuation equations and response spectra to better incorporate long-period motions.

Session Chairs: Erdal Safak (erdal.safak@boun.edu.tr), Eser Cakti (eser.cakti@boun.edu.tr).

Induced Seismicity—The European Perspective

Different to North America, fracking in Europe is still in experimental stage, and wastewater injection is limited to smaller volumes. Thus the most problematic cases of induced seismicity in public concern stem from conventional gas production (depletion), underground gas storage, geothermal and mining operations, and some dam induced events. Also legal aspects differ fundamentally since land ownership in Europe is restricted to shallow surface while any royalties from subsurface exploitation go directly to state budgets. Lack of personal benefit and densely populated areas caused massive public concern even after moderate seismicity. It resulted in servere reduction of production (Groningen gas field/NL) to permanent stop (Mirandola oil field/IT), canceled project developments (Basel geothermal/CH and Castor gas storage/ES), and severe delays in fracking conventional, *e.g.*, tight gas reservoirs. All interventions were causing significant economic loss, and raised high regulatory demands for future planning. Our session focusses on case studies, modeling, and design of regulatory measures for the addressed situations, and comparison to U.S. and Canadian approaches.

Session Chairs: Manfred Joswig (joswig@geophys.uni-stuttgart.de), Joshua White (white230@llnl.gov), Mariano Garcia-Fernandez (mariano.garcia@csic.es).

Integrated and Geophysical Investigations for Site Characterization of Critical Facilities and Infrastructure

Development of a comprehensive geologic and geotechnical model is an essential element for siting and design studies of critical facilities and potentially aging infrastructure such as large LNG and nuclear facility foundation footprints, levees, dams, and linear alignments for pipelines. Multidisciplinary investigations, including a range of geophysical, aerial, surface, subsurface, field, and laboratory testing, are required to develop a defensible and dependable site model; *e.g.*, including multiple independent methods to derive critical design inputs, such as shear wave velocity for seismic site response. Significant advances in geophysical exploration and processing, geospatial data collection and analyses, surveying, remote sensing and drone technology, and field testing have made large integrated field investigations more economical and dependable. Tricky site and subsurface conditions previously notoriously difficult to characterize, such as underground voids from karst or mining, are now being evaluated by investigation programs that integrate the latest non-intrusive and intrusive methods.

This session is intended to encompass the broad range of approaches used to achieve site characterization objectives. Topics of interest include airborne and land-based survey and measurement, geophysical surveys (*e.g.*, HVSR, SPAC, SASW, MAM, MASW, IMASW, ReMi, down hole and cross hole seismic), destructive subsurface exploration and testing, and development of integrated geoscience databases and models. Examples are sought where multiple measurement methods of critical design parameters were applied for input to foundation evaluation, seismic response, soil-structure interaction, fault characterization, subsurface void detection, marine paleoseismology, IBC Site Class, liquefaction susceptibility, and mining applications. Advances in passive and active seismic sourcing and acquisition approaches are of interest. Also invited are updates on the Consortium of Organizations of Strong Motion Observation Systems (COSMOS) and the Development of the International Guidelines for the Application of Non-Invasive Geophysical Techniques to Characterize Seismic Site Conditions. Discussion of the challenges of meeting end-user expectations and objectives is encouraged. Defining the three-dimensional distribution of geologic features and geotechnical conditions can now be performed to a degree that was unprecedented even 5 to 10 years ago, and this session invites discussion of advancements to integrated approaches.

Session Chairs: Jamey Turner (j.turner@fugro.com), Jeffrey Bachhuber (jeff.bachhuber@pge.com), Osman El Menchawi (OElMenchawi@fugro.com), Daniel O’Connell (d.oconnell@fugro.com).

Intraplate Earthquakes: Central and Eastern North America and Worldwide

Low strain rates and long recurrence intervals pose particular challenges to our understanding of the characteristics of and mechanisms responsible for seismicity in plate interiors. Nevertheless, although large historic intraplate earthquakes are less frequent than their plate-boundary counterparts, when intracontinental seismicity intersects with society it can have damaging effects.

This special session seeks to span the spectrum of studies on intraplate seismicity: its spatial and/or temporal distribution, scaling relationships, the role of crustal and/or upper mantle structures and dynamics, and seismic hazard implications. We invite contributions from new results derived from the use of EarthScope Transportable Array data and from studies worldwide.

Session Chairs: Lillian Soto-Cordero (lis213@lehigh.edu), Christine Powell (capowell@memphis.edu), Will Levandowski (wlevandowski@usgs.gov).

Machine Learning and its Application to Earthquake and Explosion Signal Analysis

This session focuses on the application of machine learning techniques to the analysis of seismic, infrasound, hydroacoustic, remote sensing, electromagnetic, and other signals. The goals of machine learning applied to these signals include improved signal and event detection, phase identification, event discrimination, signal association, explosive yield estimation, and general signal and source characterization.

Session Chairs: Timothy Draelos (tjdrael@sandia.gov), Hunter Knox (haknox@sandia.gov).

Novel Approaches to Understanding Active Volcanoes

Recent advances over a range of geophysical techniques offer unique opportunities for improving our understanding of active volcanic systems. New developments in volcano seismology have allowed for the identification of several categories of volcanic seismic events, and more definitive interpretations of these events in terms of different physical processes. Novel approaches in tomographic and other seismic methods and the increasing capability for deploying large N-arrays at volcanoes allow for a more precise picture of magma storage and migration to emerge. Widespread availability of continuous seismic data, often analyzed in conjunction with other data streams, has facilitated many studies aimed at better constraining the dynamic nature of volcanic unrest. These studies may help to more accurately track and forecast volcanic activity through time. In this session, we welcome studies that employ novel geophysical methods and/or new datasets to better understand the distribution and migration of magma and volatiles at active volcanoes. We are especially interested in studies that combine seismology with other monitoring or modeling techniques, such as ground deformation, gas monitoring, infrasound, petrology, and fluid dynamics of magmatic systems. One of the seismological aspects we wish to emphasize in this session is the interaction of magma with hydrothermal systems and the resulting seismic signatures.

Session Chairs: Ninfa Bennington (ninfa@geology.wisc.edu), Stephen McNutt (smcnutt@usf.edu), Jeremy Pesicek (jpesicek@usgs.gov), Richard Aster (rick.aster@colostate.edu), Matthew Haney (mhaney@usgs.gov).

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

Continuous development of numerical modeling methodology in seismology is not only driven by emerging requirements in observational seismology (*e.g.*, the advent of very dense seismic arrays; demand for near-real-time simulations; the multi-scale, multi-physics modeling of seismic phenomena; etc.), but also by developments in the mathematical sciences, and through the adaptation of methods originating in other scientific fields. Moreover, future methods for very large scale simulations will be increasingly influenced by (and may in turn influence) the evolution of computer architectures and programming models.

This session is a forum for presenting advances in numerical methodology, whether the principal context is observational, mathematical/numerical, or computational.

We invite contributions focused on development, verification and validation of numerical-modeling methods, and methodologically important applications especially to earthquake ground motion, rupture dynamics and seismic noise. 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. We especially encourage contributions related to the fast-emerging field that integrates dynamic event modeling with simulation of the full seismic cycle.

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

Observations and Mechanisms of Anthropogenically Induced Seismicity

Human-induced earthquakes continue to be on the forefront of seismological research, not least due to the series of recent earthquakes above M4 close to disposal and hydraulic fracturing wells in Oklahoma and British Columbia, including the Mw5.8 Pawnee earthquake, the potentially largest induced earthquake to date.

The present view of induced seismicity has been refined substantially over the past years and decades, emphasizing that induced pressure changes and elastic stress relaxation processes are the dominant mechanisms for inducing earthquakes. In addition, several studies highlighted that induced earthquake sequences can be identified by statistically significant deviations from stationary behavior. Such deviations include, for example, increasing background rates, which facilitate induced earthquake detection even in regions with much previous seismic activity. Physical differences between induced and tectonic earthquake ruptures are still debated, and identification of potential differences is hindered by limited monitoring resolution. Such differences are detectable in small-scale laboratory and meso-scale controlled injection experiments, which produce much plastic deformation and aseismic slip. In addition, it has been recognized that the specific geological setting is pivotal for the potential to induce earthquakes. Several observations suggest that vertically confined but laterally extensive, high-permeability reservoirs overlying crystalline basement formations are associated with relatively far reaching pore pressure diffusion and transmission to seismogenic depth resulting in higher induced seismicity potential.

While the present advances are encouraging, there are many outstanding scientific questions that prevent effective mitigation strategies. These outstanding issues include but are not limited to constraints on maximum magnitudes and focal depth, the importance of the preexisting stress field and secondary earthquake triggering, the role of fault damage zones and high permeability channels, and potentially characteristic differences of induced earthquake source spectra and moment tensors.

We solicit laboratory, theoretical and observational studies that examine induced seismicity sequences and the contributions of fluid pressures and elastic stresses. We specifically invite contributions that focus on mechanisms of and mitigation strategies for induced earthquakes.

Session Chairs: Thomas Goebel (tgoebel@ucsc.edu), Thomas Braun (thomas.braun@ingv.it), Ivan Wong (wong@lettisci.com), Justin Rubinstein (jrubinstein@usgs.gov).

Overcoming Challenges in Seismic Risk Communication

More than half of the U.S. population lives in areas of moderate to high seismic risk. However, this risk can be difficult to convey and is often not well understood by lay populations. This session explores the challenges of communicating seismic risk and presents proven or proposed solutions. Topics considered include but are not limited to: seismic hazard maps; induced seismicity; low-probability, high-consequence events in the Heartland; life-safety vs. performance-based earthquake engineering; preparing for megaquakes; and aftershock risk communication. This session draws from multiple disciplines, including: geophysics, seismology, structural engineering, emergency management, social sciences, and risk communication.

Session Chairs: Sean McGowan (sean.mcgowan@fema.dhs.gov), Taojun Liu (taojun.liu@colorado.edu).

Paleoseismology of Subduction Earthquake Cycles

Coastal, lacustrine, and offshore paleoseismology assess the geological record of earthquakes over multiple cycles of strain accumulation and release. These studies provide critical information that advance understanding and modeling of seismic hazards, including associated tsunami, at all major subduction zones. Contributions to practical earthquake hazard assessment include the identification of great (magnitude 8 or 9) earthquakes during the Holocene, where instrumental seismicity detects moderate to large (magnitude 6 or 7) earthquakes or none at all; estimating recurrence intervals of great earthquakes; and defining along-strike and down-dip patterns of rupture on the megathrust. Since publication of the seminal paper (Atwater, 1987) and widespread adoption of well-tested field and analytical methods debate moved on to questions critical for hazard assessment, emergency planning and international building code design (Mueller *et al.*, 2015). Key issues include the extent of past great earthquake ruptures, the identification of boundaries between rupture patches, the persistence or transient state of these boundaries over multiple earthquake cycles, recurrence intervals of great earthquakes along strike, the role of aseismic slip, and whether parts of plate boundaries that are currently creeping have generated great earthquakes in the past and may do so again in the future.

We invite contributions that address these issues through field-based observations, historical reconstructions of earthquakes that occurred prior to global seismic networks, and modeling. Studies that combine multiple approaches are encouraged.

Session Chairs: Rob Witter (rwitter@usgs.gov), Ian Shennan (ian.shennan@durham.ac.uk).

PSHA Source Modeling: Approaches, Uncertainty, and Performance

Source modeling in Probabilistic Seismic Hazard Analysis (PSHA) is evolving rapidly in response to increasingly complex source models, increasingly parameterized ground motion models (GMMs), and a desire in most applications to better understand the epistemic uncertainties associated with each. The recently completed Pacific Earthquake Engineering Research (PEER) Center's PSHA code verification project provided an opportunity to compare results from a variety of public and private codes. While there was good agreement between the codes for relatively simple source models, the project spawned rich discussion and exposed a broad variety of modeling approaches with regard to more complex models where, for example, hanging-wall terms were considered, the depth distribution of ruptures were a focus, and approximations of the finiteness of point sources were applied, among others. A common theme that emerged was that convergence between codes could often be attained by increasing the discretization of different model components, for example, the distribution density of point sources or the number of magnitude bins in magnitude-frequency distributions, with commensurate increases in processing time.

Whereas general engineering applications of PSHA have long focused on mean hazard, increasing attention is being paid to understanding the associated uncertainties that are usually considered in site-specific analyses. Such uncertainties are often quite large, and this raises the questions: How does one balance modeling choices in light of uncertainty and performance considerations? At what point do increases in model complexity cease to add value to a PSHA? We invite submissions that focus on all aspects of PSHA source models and the uncertainties associated with the parameterization thereof. We are particularly interested in generating discussion on and sharing results that exhibit the sensitivity of hazard values to alternate modeling choices. Presentations should frame those choices in the context of both source and GMM uncertainty with a focus on what is most important for the particular PSHA application at hand.

Session Chairs: Peter Powers (pmpowers@usgs.gov), Christie Hale (christie.d.hale@berkeley.edu).

Recent Advances in Earthquake Triggering and Aftershock Forecasting

When a major earthquake strikes, the resulting devastation can be compounded or even exceeded by the subsequent cascade of triggered seismicity. Recent examples are the M6's Kumamoto 2016 events in Japan followed by a M=7.0 almost within a day and the raising concerns after the M=6.2 Amatrice earthquake in Central Apennines, relatively close to the 2009 L'Aquila earthquake. This session focuses on recent progress of physics-based and statistical aftershock forecasts but also on advances in understanding other types of earthquake triggering including remote dynamic triggering and tremor.

We invite contributions focusing on the challenges behind understanding earthquake triggering, improving operational forecasts, and how our observational monitoring capabilities enable us to develop skillful models. Related topics include: operational earthquake forecasting models, aftershock occurrence statistics, real-time earthquake catalogs and the uncertainties behind seismic parameters, forecast validation, triggered tremor, and remote dynamic triggering following regional and global events.

Session Chairs: Margarita Segou (msegou@bgs.ac.uk), Andrea Llenos (allenos@usgs.gov).

Recent Advances in Very Broadband Seismology

Observational seismology is fundamentally limited by our ability to record seismic signals across a very large bandwidth. The sensitivity of modern seismic instrumentation to non-seismic noise sources as well as other undesirable signals can limit our ability to record seismic events with high fidelity. The purpose of this session is to communicate recent advances in seismic instrumentation and deployment methods, as well as observations that highlight the heavy demands on instrumentation of very broadband seismology. Abstracts that highlight recent advances, techniques, or methods for seismic instrumentation, seismic network advances, or advances in Earthquake Early Warning instrumentation are encouraged. We also encourage abstracts that focus on long-period or high-frequency seismology that could show limitations in our ability to record such signals.

Session Chairs: Adam Ringler (aringler@usgs.gov), David Wilson (dwilson@usgs.gov), Robert Anthony (ranthony3036@gmail.com).

Recent Innovations in Geophone Array Seismology

The availability of geophone systems that allow continuous recording of seismic signals has opened up many new directions and applications in seismology research. Compared to broadband sensors, these geophone systems are generally cheaper and easier to deploy. These systems can be rapidly deployed (*e.g.*, important for aftershock studies) and have a minimal environmental impact (*e.g.*, important in sensitive areas). The low cost and ease of deployment also allows these instruments to be deployed in very large numbers, as "large N" arrays, which can reduce or eliminate spatial aliasing by recording a well-sampled wavefield. These geophones typically have a corner frequency of 5-Hz or 10-Hz and can record single or three-component data. As a result, they are ideal for crustal-scale, high-resolution imaging studies using both active and passive sources.

In this session, we invite abstracts that are related to geophone array, full wavefield, or "large N" seismology, broadly defined. Studies can include, but are not limited to: instrument/sensor development, ambient noise tomography, active-source and earthquake seismology, and microseismicity, aftershock, and other environmental seismic signal monitoring. We particularly encourage abstracts that are related to the IRIS Oklahoma community full-wavefield experiment.

Session Chairs: Fan-Chi Lin (FanChi.Lin@utah.edu), Marianne Karplus (mkarplus@utep.edu).

Recent Moderate Oklahoma Earthquakes: Widely Felt and Often Damaging

While historically moderate earthquake (M5–6) are rare in Oklahoma, recently the State has experienced an unprecedented number of moderate events. First, on 13 February 2016, a Mw 5.1 earthquake occurred near Fairview, Oklahoma. On 3 September 2016, near the city of Pawnee, Oklahoma experienced its largest historic earthquake (Mw 5.8). Most recently, on 6 November 2016, a Mw 5.0 earthquake occurred near Cushing, Oklahoma, resulting in significant damage to homes and businesses. All of these moderate earthquakes have occurred in a region of Oklahoma that has seen an unprecedented increase in earthquake rate, largely considered to be caused by an increase in wastewater injection. As earthquakes of this size are uncommon in the Central and Eastern U.S., these events present a unique opportunity to improve our understanding of intraplate events. As well, the wide variability in their seismic characteristics and their proximity to wastewater disposal presents a unique dataset to explore the complex link between injection and seismicity. We invite papers on a wide variety of subjects related to these earthquakes, including but not limited to: (1) constraining and comparing the source characteristics of these events; (2) describing observed ground-motions and intensities; (3) investigating the potential relationship between these events and wastewater disposal; (4) exploring the societal impacts of the earthquakes in terms of preparedness, business impacts, and oil and gas regulatory and emergency management response. Our aim is to have a wide variety of presentations that explore a broad range of observations from these events.

Session Chairs: William Yeck (wyeck@usgs.gov), Robert Williams (rawilliams@usgs.gov), Justin Rubinstein (jrubinstein@usgs.gov).

Regional Variations in Seismological Characteristics: Implications for Seismic Hazard Analysis

The prediction of potential earthquake shaking that could occur at a site from nearby earthquakes is a key part of a seismic hazard assessment study. This is achieved by employing empirically derived ground motion models (GMM), also called ground motion prediction equations (GMPEs). An important issue in seismic hazard analysis is the regional variation in ground motions and the resulting variability in the prediction for the median motions and the aleatory variability. The increase in available global databases of earthquake records has made the regional variations in the ground motions become rather evident. Recent NGAWest2 (*e.g.*, Boore *et al.*, 2014) and European models (Kuehn and Scherbaum, 2016; Kotha *et al.*, 2016) have included the regional variations in their median predictions. These variations were essentially identified/accounted in terms of the variation in inelastic attenuation in their models. Additionally, the near source hazard can be more influenced by regional variations in source properties, *e.g.,* fault rupture kinematics and stress drop (stress parameter). In the context of seismic hazard analysis, it is also important to study the regional variation in associated uncertainty along with the median ground motions.

Thus, in order to have a robust basis for model selection and thereby constraining the epistemic uncertainty, additional research on the regional variation of ground motion and on the regional variations in physical/seismological characteristics (and corresponding epistemic uncertainties in the parameterization) are needed. In this session we welcome studies focused on investigating regional variation in seismological characteristics such as in source (stress drop and fault kinematics), attenuation, and site characteristics. In addition to research in the engineering seismology and seismic hazard domain, we also encourage submissions related to core seismological/geophysical studies that can provide useful guidance to ground motion model development. The subsequent step (after selection of ground motion models) is to adjust the ground motions to account for regional variations. Thus studies involving strategies/methods for physically consistent adjustment of median ground motion and aleatory uncertainties are also encouraged for the submission.

References:

Boore, D. M., Stewart, J. P., Seyhan, E., and Atkinson, G. M. (2014). NGA-West2 Equations for Predicting PGA, PGV, and 5% Damped PSA for Shallow Crustal Earthquakes. Earthquake Spectra , 30 (3), 1057-1085.

Kotha, S. R., Bindi, D., and Cotton, F. (2016). Partially non-ergodic region specific GMPE for Europe and Middle-East. Bulletin of Earthquake Engineering , 14, 1245-1262.

Kuehn, N., and Scherbaum, F. (2016). A partially non-ergodic ground-motion prediction equation for Europe and the Middle East. Bulletin of Earthquake Engineering , 14(10), 2629-2641.

Session Chairs: Sanjay Bora (bora@gfz-potsdam.de), Adrian Rodriguez-Marek (adrianrm@vt.edu), Marco Pagani (marco.pagani@globalquakemodel.org).

Scaling and Empirical Relationships of Moderate to Large Earthquakes: Re-scaling or Re-thinking?

Magnitude versus rupture size is a key point in many seismological fields, and in seismic hazard assessment in particular.

Despite the efforts spent by the international community on this topic, the basic dataset for deriving empirical relationships or confronting theoretical models gathers few hundreds of events, and the homogeneity in the measure (of energy release and fault/rupture size) is not always guaranteed.

In particular, moderate earthquakes are poorly represented in those relationships. The session aims at debating: 1) the structure and upgrading mechanisms of a repository for the collection of certified data; 2) the contribution of new technologies (*e.g.,* INSAR data) to acquire data; 3) the lessons learned in case studies, about generalisation or regionalisation of magnitude versus size relationships.

Session Chairs: Laura Peruzza (lperuzza@inogs.it), P. Martin Mai (martin.mai@kaust.edu.sa), Lucilla Benedetti (benedetti@cerege.fr).

Seismology Software Tools That Improve What We Do and How We Do It

In today's world the number of scientific software tools that exist freely and in the open is staggering. We invite implementers and users alike to present the software tools they use, build, operate, contribute to, and practice with, to share strengths and improvements that we all can gain from in seismology. It may be data acquisition tools converging on standards supporting more data across more instrument types (*e.g.,* search indexes, time series databases, NoSQL), or data analysis tools with inline visualizations (*e.g.,* IPython notebook, Kibana), data parsing and processing tools (*e.g.,* ObsPy, R), web services following common standards for broader and easier data sharing (*e.g.,* GeoJSON, QuakeML), or open source encouraging broader collaboration (*e.g.,* GitHub, Docker Hub). There is great potential in what software tools can help us accomplish. Share your tools, standards, and best practices that can improve how we do seismology.

Session Chairs: Michelle Guy (mguy@usgs.gov), Eric Martinez (emartinez@usgs.gov).

Seismotectonics

This general session brings together a collection of presentations with the common theme of Seismotectonics.

Session Chairs: Rich Briggs and Gavin Hayes (2017program@seismosoc.org).

Source Discovery Using Differential Methods: Applications to Explosion Monitoring

Geophysical techniques for explosion monitoring have advanced spectacularly in the nearly 60 years since the first fully contained underground nuclear test Rainier was conducted in September 1957 in Southern Nevada, and significantly in the nearly 20 years since the CTBT (Comprehensive nuclear-Test-Ban Treaty) was signed in September 1996. Many current seismic techniques use differential methods (*e.g.,* ratios, differences, cross-correlation, etc.) to significantly lower detection thresholds, obtain unprecedented relative location precision and determine more accurate source parameter differences (*e.g.,* magnitude, mechanism, depth, etc.). For spatially clustered sources (*e.g.,* nuclear test sites, earthquake sequences, injection wells, etc.) where differential techniques effectively cancel path effects, they are yielding exciting new insights into seismic source processes.

One area of high interest is North Korea (DPRK—Democratic People's Republic of Korea). North Korea is the only country to have conducted declared nuclear tests in this century, five in total, two of them in 2016 (as of this writing on 1 October). In this session we seek studies applying differential methods to the DPRK and other nuclear explosives testing sites to explore the advances and challenges of applying these techniques to improve monitoring capabilities. We seek related studies that apply differential techniques to other source types and regions to improve processing and geophysical understanding. We also welcome related studies that explore new datasets, techniques and analyses to advance explosion monitoring.

Session Chairs: William Walter (walter5@llnl.gov), Joshua Carmichael (joshuac@lanl.gov), Steven Gibbons (steven@norsar.no).

SSA-ESC Joint Session on Advances in Geotechnical Borehole Arrays, Data and Analyses

The design objective of geotechnical borehole arrays is to capture instrumental observations of the earthquake effects associated with the penultimate event in the region in which the array is deployed. The broader objective is to capture a suite of earthquakes covering a range of ground motions and strain levels that include the effects of the near-surface geology from linear through nonlinear behavior. These observations are the empirical case histories that are used to validate the constitutive models in site-specific ground response analysis, providing direct in situ evidence of soil nonlinearity and liquefaction. Geotechnical borehole array data when coupled with nearby structural arrays provide insights into soil-foundation-structure interaction.

This session aims to bring together the Engineering, Seismological, and Geophysical communities and create a platform for discussion and exchange concerning borehole arrays, data, and applications. We welcome contributions from all aspects of borehole data analysis, including, but not limited to: interferometry, material properties in the linear and non-linear range, liquefaction, site response, amplification, and attenuation. We encourage novel and hybrid applications of vertical arrays, including coupled subsurface-and-superstructure arrays. We also seek to hear from those installing new arrays, compiling new databases of downhole data, and to discuss new possibilities for applications.

Session Chairs: Jamison Steidl (steidl@eri.ucsb.edu), Ramin Motamed (motamed@unr.edu), Umit Dikmen (umit.dikmen@boun.edu.tr), Stefano Parolai (parolai@gfz-potsdam.de).

The Subduction Zone Observatory

The Subduction Zone Observatory (SZO) concept is a multidisciplinary facility stretching along a significant portion of one or more of the circum-Pacific subduction zones, providing a comprehensive suite of onshore and offshore observations to understand the entire subduction zone system.

The success, knowledge, and experience of EarthScope provides a launching point for the creation of such a facility. The observatory's goal is to provide an integrated, interdisciplinary approach, with broad international participation, to understand subduction zones as complex systems. SZO research will illuminate the underlying processes that govern subduction zones at multiple temporal and length scales, from earthquake rupture to long-term tectonics, and have significant societal relevance, given the population centers adjacent to subduction zones are subject to earthquake-, tsunami-, and volcano-related hazards.

Seismological, geodetic, and tsunami-related investigations are fundamental to the SZO's goals. We invite contributions that address the basic question of what the science targets of the SZO should be. Furthermore, we encourage contributions from recent results in subduction zone science and hazards that exemplify the potential advantages of a multidisciplinary and international facility.

Session Chairs: Diego Melgar (dmelgar@berkeley.edu), Lee Liberty (lliberty@boisestate.edu), Jeff Maguire (jmcguire@whoi.edu).

Theoretical and Methodological Innovations for 3D/4D Seismic Imaging of Near-surface, Crustal, and Global Scales

This session will focus on recent theoretical and methodological developments of seismic imaging and monitoring (*i.e.*, time-resolved imaging) techniques to better understand the

Earth′s structure on various scales. In previous years, imaging techniques have developed rapidly thanks to the advent of high-density networks, new modeling techniques, and unprecedented computation capacities. This includes, for example, seismic noise surface wave tomography, accurate estimation of source locations of microseismic events, and full-wave inversion with active/passive sources. However, significant problems, both well-known and lesser-known, remain. These include model resolution, uncertainty, reproducibility, nonlinearity, and non-uniqueness.

We invite novel approaches for solving common practical problems for 3D/4D imaging. To this regard, we welcome innovations and advances in physics-based imaging, 3D/4D tomography, waveform tomography, new migration techniques, advanced signal processing, multi-component seismic noise correlations, monitoring and locating of velocity changes, and joint inversion of multiple geophysical observations. Presentations of ideas to overcome effects of structure outside the modeled region, uneven ray coverage, and limitation of resolution will be also included in this session. Studies that compare real-Earth results obtained using different methods, and assess repeatability, are particularly encouraged as well as methods to establish best practice for the proper implementation of synthetic reconstruction tests.

Session Chairs: Marco Pilz (marco.pilz@sed.ethz.ch), Nori Nakata (nnakata@ou.edu).

Theoretical and Practical Advances in Ambient Noise and Coda Studies

The past decade has featured numerous advances in passive imaging using ambient noise and multiply scattered seismic coda from earthquakes or other sources. The inherent simplicity of many applications has generated a swath of mainstream tools and applications now being used over all frequency-wavenumber scales. With the advent of large-N networks and emerging opportunities for scattered and 4D seismological imaging, we seek contributions on refining our use of large datasets and diverse uses and applications related to further extracting accurate Green's functions and physical parameters using seismic interferometry.

Session Chairs: Julien Chaput (jchaput82@gmail.com), Hsin-Hua Huang (abuzah3@gmail.com).

To Tweet or Not To Tweet: Effective Use of Social Media for Citizen Science and Science Communication

The advent of social media has changed the way that people around the world communicate with one another. Young people in particular rely increasingly on social media, including Facebook and Twitter, rather than conventional news outlets, to stay abreast of current affairs. This development poses challenges as well as opportunities for Earth scientists interested in science communication to a broad audience. The challenges associated with the use of Twitter, for example, for serious science communication are manifest: "Tweets" are limited to 140 characters, and the free-for-all nature of the Twitter information network creates an echo chamber in which the signal-to-noise ratio can be low. The potential opportunities provided by social media sites such as Twitter, Facebook, and Instagram can be less apparent. Yet social media sites like Facebook and Twitter provide an important opportunity for crowd-sourced reporting and communication when a natural disaster occurs, as well as opportunities for broad dissemination of scientific results of interest to a broad audience, and a unique ability to reach teenagers and young adults. Twitter feeds can even be exploited for gathering of invaluable crowd-sourced data following earthquakes and other natural disasters. For this session, which will include introductory tutorials for social media newbies, we invite abstracts focused on the use of social media for both scientific research and science communication.

Session Chairs: Susan Hough (hough@usgs.gov), Julian Lozos (julian.lozos@csun.edu), Christine Goulet (cgoulet@usc.edu), Paul Earle (pearle@usgs.gov).

Toppled and Rotated Objects in Recent, Historic, and Prehistoric Earthquakes

The main purpose of the session is to bring together researchers with diverse backgrounds (*e.g.*, seismology, engineering, history, heritage conservation) who are interested in the behavior of objects, monuments, or simple structures during earthquakes and the stories which deformed, rotated or toppled objects can tell. The session will cover all aspects of toppled or rotated objects or simple structures which have suffered heavy deformation or damage during earthquakes. Topics will include: (1) observations, (2) documentation, (3) model building, (4) restoration, (5) mapping, and (6) correlation with geology.

Recent earthquake research has postulated correlation between the reaction of objects (monuments, columns, tombstones, etc.) and the seismic source in addition to local effects due to geological site conditions. As the laws of physics are time invariant, knowledge gained in reconnaissance surveys from well-studied instrumental earthquakes can reveal information about ground motions during historical and prehistorical earthquakes. Particular interest will be directed to man-made structures; however, due to similarities of the techniques used to study precariously balanced rocks and speleothems, contributions from these fields are also welcome.

Session Chairs: Klaus-G. Hinzen (hinzen@uni-koeln.de), Rasool Anooshehpoor (Rasool.Anooshehpoor@nrc.gov).

Understanding and Modeling Ground Motions and Seismic Hazard from Induced Earthquakes

Performing a Probabilistic Seismic Hazard Analysis (PSHA) for induced seismicity is very difficult because we have neither a complete understanding of the genesis and recurrence of induced earthquakes nor a comprehensive model for the ground motion excited by them. Whether there is a fundamental physical difference between natural and induced events is still an open question, and how any potential difference manifest themselves in the ground motion is of great interest. Furthermore, the level of seismic activity may be dependent on human activity, complicating any hazard analysis. We seek contributions that will help establish the modeling input parameters that are critical for the analysis, including controls on both seismic activity and ground motion, the building blocks of a PSHA. For earthquake activity, this may include including declustering earthquake catalogs or determining rates, hypocenters, or maximum magnitudes. By combining information on the state of stress, hydrologic properties of injection formations and the basement, and the locations and orientations of faults with injection data, we have the possibility of building predictive models that anticipate the seismic potential of an area based on its past history. On the ground motion side, we encourage contributions related to understanding if ground motion from induced events is similar or different to existing models, or how ground motion scales at very close distances to these shallow events. This could include testing of existing GMPEs, development of new empirical or simulation-based GMPEs, or understanding of the source, path, or site controls on observed ground motion. We encourage submissions regarding the phsyical parameters controling ground motion genesis (such as stress drop or depth) or propagation (attenuation or other path effects). In particular, resolving if these stress drop of these events is similar or very different from that of other tectonic environments is of great interest. Addressing the trade offs in stress drop and hypocentral depth is also of great interest. We especially encourage novel, creative, and grounbreaking presentations on concepts that contribute to advancing next-generation induced earthquake PSHA models.

Session Chairs: Annemarie Baltay (abaltay@usgs.gov), Daniel McNamara (mcnamara@usgs.gov), Eric Thompson (emthompson@usgs.gov), Mark Petersen (mpetersen@usgs.gov).

Varied Modes of Fault Slip and their Interactions—Slow Earthquakes, Creep to Mega Quakes

Faults show a diverse mode of slips—from slow earthquakes, shallow creep to supershear rupture and damaging fast megathrust earthquakes. Slow earthquakes appear to play an important role in the seismic cycles of major faults. They typically occur at the edges of the seismogenic zone, and radiate seismic energy in the form of tremor, low and very low frequency earthquakes. Slow slips are often inferred to be the driving mechanism of migrating swarms of regular fast micro-earthquakes. Regular earthquakes including large damaging megathrust quakes, on the other hand, seem to show different source characteristics. How these different modes of fault slip operate and interact remains an enigma. In addition, frictional properties that control these modes are poorly understood. We invite abstracts on the diverse behavior of fault slip including but not limited to slow slip, tremor, low and very low frequency earthquakes, aseismic slip, fault creep, and fast megathrust earthquakes. Multidisciplinary studies incorporating observations and modeling focusing on the mechanism and interactions of different modes of fault slip are encouraged.

Session Chair: Abhijit Ghosh (aghosh.earth@gmail.com).

Verification and Validation of Earthquake Occurrence and Hazard Forecasts

Earthquake occurrence, hazard forecasts (hazard maps), and nowcasts have long lagged behind similar applications, such as weather, economic, or population forecasts and nowcasts, in addressing issues of verification and validation. Validation asks how well the algorithm used to produce the forecast implements the conceptual model ("have we built the model right?"). Verification asks how well the model forecasts the observations that actually occur ("have we built the right model?"). In recent years, this situation has been changing, in part via adopting ideas from other forecasting applications. We invite papers dealing with issues such as defining forecast goals, improving forecasts with new data or methodology, testing forecasts against observations, assessing forecast uncertainties, and better using forecasts for hazard mitigation.

Session Chairs: Seth Stein (seth@earth.northwestern.edu), John Rundle (john.b.rundle@gmail.com), Mark Petersen (mpetersen@usgs.gov).

The Mw7.8 Kaikoura Earthquake

The Mw7.8 Kaikoura Earthquake of 13 November 2016 was the largest on-land earthquake to affect New Zealand in recorded history. It is the fourth earthquake larger than M7 to occur in New Zealand over the last seven years, equating to much higher rates than the background and suggesting the possibility of strong temporal clustering. The earthquake occurred in a region of complex tectonics in which the dominant accommodation of plate convergence transitions between subduction to the north and continental strike-slip to the south. The event was geometrically complex, with numerous mapped surface ruptures and surface displacements of over 10 meters. The earthquake produced a tsunami with recorded tide-gauge measurements over two meters. Notably, the event also triggered numerous slow-slip events on the subduction system to the north of the earthquake. In this session, we invite contributions covering all aspects of this earthquake including but not limited to studies of clustering and triggering, source processes, slow slip processes, and statistical characterization of the sequence.

Session Chairs: Bill Fry (b.fry@gns.cri.nz), Matt Gerstenberger (m.gerstenberger@gns.cri.nz).

Overview of Technical Program

ORAL SESSIONS

Tuesday, 18 April

Time	*Plaza D*	*Plaza E*	*Plaza F*
8:30–9:45 AM	Paleoseismology of Subduction Earthquake Cycles	Forecasting Aftershock Sequences in the Real World	Earthquake Source Parameters: Theory, Observations and Interpretations
10:45 AM–noon			
2:15–3:30 PM	The Subduction Zone Observatory	Advances in Earthquake Early Warning	
4:30–5:45 PM			To Tweet or Not To Tweet: Effective Use of Social Media for Citizen Science and Science Communication
5:45–6:30 PM	Pint and a Poster		
6:30–7:30 PM	Ignite Talks Plenary		
7:30–9:00 PM	Student Reception and Early Career Reception		

Wednesday, 19 April

Time	*Plaza D*	*Plaza E*	*Plaza F*
8:30–9:45 AM	Fine Scale Structure of the Crust and Upper Mantle	Observations and Mechanisms of Anthropogenically Induced Seismicity	Source Discovery Using Differential Methods: Applications to Explosion Monitoring
10:45 AM–noon			
1:30–2:45 PM		Assessment and Management of Hazards from Seismicity Induced by Hydraulic Fracturing	The Mw7.8 Kaikoura Earthquake
3:45–5:00 PM	Recent Advances in Earthquake Triggering and Aftershock Forecasting		
5:00–5:45 PM	Pint and a Poster		
5:45–6:45 PM	Joyner Lecture		
6:45–8:00 PM	Reception		

Governor's Square 14	Governor's Square 15	Governor's Square 16	Governor's Square 12
Numerical Modeling of Earthquake Ground Motion, Rupture Dynamics and Seismic Wave Propagation	Varied Modes of Fault Slip and their Interactions—Slow Earthquakes, Creep to Mega Quakes	Computational Infrastructure and Data for Enhancing Earthquake Science	Novel Approaches to Understanding Active Volcanoes
Integrated and Geophysical Investigations for Site Characterization of Critical Facilities and Infrastructure	Earthquake Interaction and Triggering: From Near Field to Far Field, From Natural to Induced	Seismology Software Tools That Improve What We Do and How We Do It	Closing the Gap between Laboratory-based Damping Models and Observed Attenuation of Seismic Waves in the Field
		Geoacoustics: Infrasound and Beyond	Theoretical and Practical Advances in Ambient Noise and Coda Studies
Pint and a Poster			
Ignite Talks Plenary			
Student Reception and Early Career Reception			

Governor's Square 14	Governor's Square 15	Governor's Square 16	Governor's Square 12
Regional Variations in Seismological Characteristics: Implications for Seismic Hazard Analysis	From Field Site to Data Center: Network Innovations for Earthquake Early Warning	Earthquake Rapid Response	Overcoming Challenges in Seismic Risk Communication
	Machine Learning and its Application to Earthquake and Explosion Signal Analysis		
Earthquake Impacts on the Natural and Built Environment	Recent Innovations in Geophone Array Seismology	SSA-ESC Joint Session on Advances in Geotechnical Borehole Arrays, Data and Analyses	Estimating Earthquake Hazard from Geodetic Data
		Scaling and Empirical Relationships of Moderate to Large Earthquakes: Re-scaling or Re-thinking?	
Pint and a Poster			
Joyner Lecture			
Reception			

Thursday, 20 April

Time	*Plaza D*	*Plaza E*	*Plaza F*
8:30–9:45 AM	Earthquake Complexities Revealed by Kinematic and Dynamic Modeling and Multiple Geophysical Data Sets	Understanding and Modeling Ground Motions and Seismic Hazard from Induced Earthquakes	The Future of Past Earthquakes
10:45 AM–noon			
1:30–2:45 PM	Characterization of the Stress Field and Focal Mechanisms for Earthquake Source Physics and Fault Mechanics	Recent Moderate Oklahoma Earthquakes: Widely Felt and Often Damaging	Earthquake Geology and Paleoseismic Studies of the Intermountain West: New Methods and Findings on Seismic Hazard Characterization of Low Slip Rate Faults
4:00–5:15 PM		Induced Seismicity—The European Perspective	Seismotectonics

POSTER SESSIONS

Tuesday 18 April

- Earthquake Source Parameters: Theory, Observations and Interpretations
- Integrated and Geophysical Investigations for Site Characterization of Critical Facilities and Infrastructure
- The Subduction Zone Observatory
- Numerical Modeling of Earthquake Ground Motion, Rupture Dynamics and Seismic Wave Propagation
- Forecasting Aftershock Sequences in the Real World
- Paleoseismology of Subduction Earthquake Cycles
- Computational Infrastructure and Data for Enhancing Earthquake Science
- Novel Approaches to Understanding Active Volcanoes
- Geoacoustics: Infrasound and Beyond
- Earthquake Interaction and Triggering: From Near Field to Far Field, From Natural to Induced
- Advances in Earthquake Early Warning
- Varied Modes of Fault Slip and their Interactions—Slow Earthquakes, Creep to Mega Quakes
- Seismology Software Tools That Improve What We Do and How We Do It
- To Tweet or Not To Tweet: Effective Use of Social Media for Citizen Science and Science Communication
- Closing the Gap between Laboratory-based Damping Models and Observed Attenuation of Seismic Waves in the Field
- Theoretical and Practical Advances in Ambient Noise and Coda Studies

Wednesday 19 April

- Fine Scale Structure of the Crust and Upper Mantle
- Source Discovery Using Differential Methods: Applications to Explosion Monitoring
- Observations and Mechanisms of Anthropogenically Induced Seismicity
- Assessment and Management of Hazards from Seismicity Induced by Hydraulic Fracturing
- Recent Innovations in Geophone Array Seismology
- Regional Variations in Seismological Characteristics: Implications for Seismic Hazard Analysis
- Estimating Earthquake Hazard from Geodetic Data
- The Mw7.8 Kaikoura Earthquake
- Recent Advances in Earthquake Triggering and Aftershock Forecasting
- Earthquake Impacts on the Natural and Built Environment
- Earthquake Rapid Response

	Governor's Square 14	*Governor's Square 15*	*Governor's Square 16*	*Governor's Square 12*
	Verification and Validation of Earthquake Occurrence and Hazard Forecasts	Advances in Seismic Full Waveform Modeling, Inversion and Their Applications	Recent Advances in Very Broadband Seismology	Theoretical and Methodological Innovations for 3D/4D Seismic Imaging of Near-surface, Crustal, and Global Scales
				Earthquakes and Tsunamis
	PSHA Source Modeling: Approaches, Uncertainty and Performance	Intraplate Earthquakes: Central and Eastern North America and Worldwide	Toppled and Rotated Objects in Recent, Historic, and Prehistoric Earthquakes	Emerging Opportunities in Planetary Seismology
			Fault Mechanics and Rupture Characteristics from Surface Deformation	Importance of Long-Period Ground Motions in Seismic Design of Structures

Poster Sessions (continued)

Wednesday 19 April (continued)

- SSA-ESC Joint Session on Advances in Geotechnical Borehole Arrays, Data and Analyses
- Overcoming Challenges in Seismic Risk Communication
- From Field Site to Data Center: Network Innovations for Earthquake Early Warning
- Scaling and Empirical Relationships of Moderate to Large Earthquakes: Re-scaling or Re-thinking?
- Machine Learning and its Application to Earthquake and Explosion Signal Analysis
- Ground Motions and GMPEs

Thursday 20 April

- Recent Moderate Oklahoma Earthquakes: Widely Felt and Often Damaging
- Induced Seismicity—The European Perspective
- Understanding and Modeling Ground Motions and Seismic Hazard from Induced Earthquakes
- The Future of Past Earthquakes
- Earthquake Complexities Revealed by Kinematic and Dynamic Modeling and Multiple Geophysical Data Sets
- Earthquakes and Tsunamis
- Seismotectonics
- PSHA Source Modeling: Approaches, Uncertainty and Performance
- Recent Advances in Very Broadband Seismology
- Advances in Seismic Full Waveform Modeling, Inversion and Their Applications
- Characterization of the Stress Field and Focal Mechanisms for Earthquake Source Physics and Fault Mechanics
- Intraplate Earthquakes: Central and Eastern North America and Worldwide
- Theoretical and Methodological Innovations for 3D/4D Seismic Imaging of Near-surface, Crustal, and Global Scales
- Toppled and Rotated Objects in Recent, Historic, and Prehistoric Earthquakes
- Fault Mechanics and Rupture Characteristics from Surface Deformation
- Importance of Long-Period Ground Motions in Seismic Design of Structures.
- Earthquake Geology and Paleoseismic Studies of the Intermountain West: New Methods and Findings on Seismic Hazard Characterization of Low Slip Rate Faults
- Verification and Validation of Earthquake Occurrence and Hazard Forecasts
- Emerging Opportunities in Planetary Seismology

Program for 2017 SSA Annual Meeting

Presenting author is indicated in bold.

Tuesday, 18 April—Oral Sessions

Time	*Plaza D*	*Plaza E*	*Plaza F*	*Governor's Square 14*
	Paleoseismology of Subduction Earthquake Cycles Session Chairs: Rob Witter, Ian Shennan (see page 556).	**Forecasting Aftershock Sequences in the Real World** Session Chairs: Andrew Michael, Matt Gerstenberger, Warner Marzocchi (see page 545).	**Earthquake Source Parameters: Theory, Observations and Interpretations** Session Chairs: Vaclav Vavrycuk, Grzegorz Kwiatek, German Prieto (see page 542).	**Numerical Modeling of Earthquake Ground Motion, Rupture Dynamics and Seismic Wave Propagation** Session Chairs: Peter Moczo, Steven Day, Jozef Kristek (see page 553).
8:30 AM	INVITED: Implications of the Kaikoura Earthquake on Hikurangi Subduction Seismogenesis, New Zealand: Insights from Paleoseismology. **Berryman, K.**, Clark, K., Cochran, U., Van Dissen, R., Langridge, R., Little, T., Litchfield, N., Villamor, P., Hamling, I., Wallace, L., Bannister, S.	Forecasting Aftershocks and the Complexity of Implementing Simple Models. **Michael, A. J.**, Field, E. H., Hardebeck, J. L., Llenos, A. L., Page, M. T., van der Elst, N., Jeria, C., Singhal, S., Chen, D.	INVITED: A New Strategy for Earthquake Focal Mechanisms Using Waveform-Correlation-Derived Relative Polarities and Cluster Analysis: Application to a Fluid-Driven Earthquake Swarm. **Shelly, D. R.**, Hardebeck, J. L., Ellsworth, W. L., Hill, D. P.	Broadband Synthetic Seismograms for Magnitude 9 Earthquakes on the Cascadia Megathrust Derived From 3D Finite-Difference Simulations and Stochastic Synthetics. **Frankel, A.**, Wirth, E., Vidale, J., Stephenson, W., Marafi, N.
8:45 AM	INVITED: The Application of Diatoms to Reconstruct the History of Subduction Zone Earthquakes and Tsunamis. **Dura, T.**, Hemphill-Haley, E., Sawai, Y., Horton, B. P.	A Prototype Operational Earthquake Loss Model for California Based on UCERF3-ETAS – A First Look at Valuation. **Field, E. H.**, Porter, K., Milner, K. R.	INVITED: Ambient Noise Moment Tensor (ANMT) Estimation. **Dreger, D. S.**, Lindsey, N.	Various Modes of Rupture Directivity as Inferred from Joint Source Inversions and Ground Motion Simulations. **Koketsu, K.**, Kobayashi, H., Miyake, H.
9:00 AM	INVITED: Limits of Coastal Evidence for Large Subduction Earthquakes: How Big is Still Too Small to Detect?. **Briggs, R. W.**, Barnhart, W. D.	Characterizing the Triggering Susceptibility of Characteristic Faults. **Page, M. T.**, van der Elst, N. J., Shaw, B. E.	Estimating Moment Tensors Using Virtual Seismometers. Morency, C., **Matzel, E. M.**	A Blind Test of the Local-Scale Adjoint Tomography. Kubina, F., Michlik, F., **Moczo, P.**, Kristek, J., Stripajova, S.
9:15 AM	INVITED: STUDENT: Sedimentary Records from Lakes: How They Can Help Improve Our Understanding of Subduction Earthquake Cycles in Alaska. **Praet, N.**, Moernaut, J., Van Daele, M., Haeussler, P. J., De Batist, M.	Operational Earthquake Forecasting of Aftershocks for New England. **Ebel, J. E.**, Fadugba, O., Moulis, A., Dahal, N. R., Kafka, A. L.	Analysis of the 2016 Seismic Sequence in Central Italy. **Braun, T.**, Cesca, S., Grigoli, F., Kriegerowski, M., Lopez Comino, J. A., Dahm, T.	Validation of a 3D Geological Model for the Numerical Simulation of Earthquake Ground Motion in Emilia (Italy). Klin, P., Laurenzano, G., Romano, M. A., **Priolo, E.**, Martelli, L.

Time	Governor's Square 15	Governor's Square 16	Governor's Square 12
	Varied Modes of Fault Slip and their Interactions—Slow Earthquakes, Creep to Mega Quakes Session Chair: Abhijit Ghosh (see page 563).	**Computational Infrastructure and Data for Enhancing Earthquake Science** Session Chairs: Lisa Grant Ludwig, Andrea Donnellan (see page 538).	**Novel Approaches to Understanding Active Volcanoes** Session Chairs: Ninfa Bennington, Stephen McNutt, Jeremy Pesicek, Richard Aster, Matthew Haney (see page 551).
8:30 AM	INVITED: Interaction between Slow and Fast Slips in the Japan Trench: Prospect from Near Field Ocean Bottom Seismic and Geodetic Observations. **Ito, Y.**, Katakami, S., Ohta, K., Uemura, M., Muramoto, T., Garcia, E. S. M.	INVITED: Science Gateways for Enhancing Earthquake Science. **Pierce, M. E.**, Wang, J., Dhumal, H., Marru, S., Donnellan, A.	INVITED: Volcanic Tremor and Plume Height Hysteresis from the March 2016 Eruption of Pavlof Volcano, Alaska. **Fee, D.**, Haney, M. M., Matoza, R. S., Van Eaton, A. R., Cervelli, P., Schneider, D. J., Iezzi, A. M.
8:45 AM	Aleutian Array of Arrays (A-Cubed): Simultaneous Imaging of Continuous Activity of Slow Earthquakes and Volcanic System in the Aleutian Islands. **Ghosh, A.**, Li, B.	INVITED: The SCEC Software Ecosystem for Enhancing Earthquake System Science Research. **Maechling, P. J.**, Bielak, J., Callaghan, S., Cui, Y., Field, E., Gill, D., Goulet, C. A., Graves, R., Jordan, T. H., Milner, K., Olsen, K., Taborda, R., Shaw, J., Silva, F.	Ground-Coupled Air Waves at Pavlof Volcano, Alaska During the 2007 Eruption and Their Potential for Eruption Monitoring. Smith, C. M., **McNutt, S. R.**, Thompson, G.
9:00 AM	Seismic Coupling of Fast and Slow Ruptures on a 760 mm Laboratory Fault. **McLaskey, G. C.**, Yamashita, F.	INVITED: CIG Community Standards and Best Practices for Scientific Software. **Hwang, L. J.**, Kellogg, L. H.	Detecting Magmatic Activity over Multiple Volcanic Eruption Cycles via Ambient Noise Interferometry: A Study of Veniaminof Volcano, Alaska. **Bennington, N. L.**, Haney, M. M.
9:15 AM	STUDENT: Very Low Frequency Earthquakes (VLFEs) in Cascadia during Episodic Tremor and Slip (ETS) Events and Inter-ETS Period. **Hutchison, A. A.**, Ghosh, A.	INVITED: UNAVCO Computational Infrastructure Enhancing Earthquake Science. Miller, M. M., Meertens, C. M., Mattioli, G. S., **Mencin, D. J.**	INVITED: Seismic Evidence for a Cold and Hydrated Mantle Wedge beneath Mount St Helens. **Hansen, S. M.**, Schmandt, B., Levander, A., Kiser, E., Creager, K. C., Abers, G. A., Mann, M. E., Vidale, J. E.

Time	*Plaza D*	*Plaza E*	*Plaza F*	*Governor's Square 14*
	Paleoseismology of Subduction Earthquake Cycles	**Forecasting Aftershock Sequences in the Real World**	**Earthquake Source Parameters…**	**Numerical Modeling of Earthquake Ground Motion…**
9:30 AM	INVITED: 3D Simulations of Megathrust Earthquakes in Cascadia – Implications of Paleoseismic Evidence for the Down-Dip Rupture Extent and Along-Strike Rupture Variability. **Wirth, E.** A., Frankel, A.	The Time-History of a Forecast: The Case Study of Central Apennines. **Segou, M.**, Mancini, S.	P-Waveform Inversion for Moment Tensors Using the Principal Component Analysis. **Vavrycuk, V.**, Adamova, P.	Using CyberShake 3D Ground Motion Simulation Workflows to Advance Central California PSHA. **Callaghan, S. A.**, Maechling, P. J., Goulet, C. A., Milner, K. R., Graves, R. W., Olsen, K. B., Jordan, T. H.
9:45 – 10:45 AM	Posters and Break			
	Paleoseismology of Subduction Earthquake Cycles (continued)	**Forecasting Aftershock Sequences in the Real World** (continued)	**Earthquake Source Parameters: Theory, Observations and Interpretations** (continued)	**Numerical Modeling of Earthquake Ground Motion, Rupture Dynamics and Seismic Wave Propagation** (continued)
10:45 AM	Recording and Preservation Sensitivities for Paleoseismic Data on the Cascadia Margin. **Goldfinger, C.**	Forecasting the 2016 Bombay Beach, CA Swarm. **Llenos, A. L.**, Page, M. T., van der Elst, N. J.	INVITED: Radiated Energy Enhancement and Rupture Complexity of Large Subduction-Zone Earthquakes. Ye, L., **Lay, T.**, Kanamori, H.	On the Fast and Efficient Broadband Simulation of Earthquake Strong-Motion with Basin Generated Surface Waves. **Halldorsson, B.**, Meza-Fajardo, K., Papageorgiou, A. S.
11:00 AM	Temporal Variability of Interseismic Strain Accumulation along Subduction Megathrusts, on Timescales of Decades to Centuries. **Meltzner, A. J.**, Philibosian, B., Sieh, K.	Earthquake Forecasting for the November 2016 Kaikoura, New Zealand Mw 7.8 Earthquake. **Gerstenberger, M. C.**, Rhoades, D., Christophersen, A., Horspool, N., Harte, D., Bannister, S., Fry, B., Wallace, L.	STUDENT: Another Look at the Foreshocks of the 1999 Mw 7.1 Hector Mine, California, Earthquake. **Yoon, C. E.**, Ellsworth, W. L., Beroza, G. C.	STUDENT: Salvus: A Flexible Open-Source Package for Waveform Modeling and Inversion from Laboratory to Global Scales. **Afanasiev, M.**, Boehm, C., van Driel, M., Krischer, L., May, D., Rietmann, M., Fichtner, A.
11:15 AM	The December 25, 2016, M7.6, Southern Chile Earthquake and its Relation to the 1960 Rupture. **Barrientos, S. E.**, CSN Team	INVITED: Challenges and Successes of Communicating the M7.8 Kaikoura Earthquake Operational Earthquake Forecast. **McBride, S. K.**, Gerstenberger, M., Potter, S., Christophersen, A. M., Rhoades, D., Balfour, N.	Complex Spatiotemporal Evolution of Seismicity and Source Parameters of the 2008 Mw 4.9 Mogul Earthquake Swarm in Reno, Nevada. **Ruhl, C. J.**, Abercrombie, R. E., Smith, K. D., Zaliapin, I.	Off-Fault Deformation and Shallow Slip Deficit from Dynamic Rupture Simulations with Fault Zone Plasticity. **Roten, D.**, Olsen, K. B., Day, S. M.

Time	*Governor's Square 15*	*Governor's Square 16*	*Governor's Square 12*
	Varied Modes of Fault Slip and their Interactions…	**Computational Infrastructure and Data…**	**Novel Approaches to Understanding Active Volcanoes**
9:30 AM	INVITED: Repeating and Triggered Slow Slip Events in the Near-Trench Region of the Nankai Trough Detected by Borehole Observatories. **Saffer, D. M.**, Araki, E., Kopf, A. J., Wallace, L. M.	Simulation Based Earthquake Forecasting with RSQSim. **Gilchrist, J. J.**, Jordan, T. H., Dieterich, J. H., Richards-Dinger, K. B., Shaw, B. E.	INVITED: The iMUSH (imaging Magma Under mount St. Helens) Project. **Creager, K. C.**, Ulberg, C. W., Vidale, J. E., Meng, X., Han, J., Abers, G. A., Crosbie, K., Schultz, A., Bowles-Martinez, E., Kiser, E., Levander, A., Moran, S., Denlinger, R., Thelen, W., Sisson, T., Blatter, D., Clynne, M., Peacock, J., Bedrosian, P., Bachmann O., Wanke, M., Hansen, S., Schmandt, B., Hill, G. J.
9:45 – 10:45 AM		Posters and Break	
	Varied Modes of Fault Slip and their Interactions—Slow Earthquakes, Creep to Mega Quakes (continued)	**Computational Infrastructure and Data for Enhancing Earthquake Science** (continued)	**Novel Approaches to Understanding Active Volcanoes** (continued)
10:45 AM	Large Earthquakes and Creeping Faults. **Harris, R. A.**	STUDENT: Collaboratory for Interseismic Simulation and Modeling (CISM). **Milner, K. R.**, Jordan, T. H., Gilchrist, J. J., Goulet, C. A., Maechling, P. J., Richards-Dinger, K. B., Dieterich, J. H., Field, E. H.	Revisiting Seismicity Prior and during Cotopaxi´s 2015 Eruptive Activity, Ecuador. **Ruiz, M. C.**, Hernández, S., Viracucha, E. G., Pacheco, D., Mothes, P. A.
11:00 AM	INVITED: Late-Interseismic State of the Alpine Fault and the Australia–Pacific Plate Boundary in the Central South Island, New Zealand — Constraints from Scientific Drilling, Low-Frequency Earthquakes, and Microseismicity. **Townend, J.**, Deep Fault Drilling Project (DFDP) Science Team	Software vs. Data: The FORCE11 Citation Principles. **Hwang, L. J.**, Katz, D. S., Kellogg, L. H., Niemeyer, K. E., FORCE11 Software Citation Working Group	The Use of Low-Amplitude Non Harmonic Tremor to Estimate Long-Term Gas Emission at Pacaya Volcano. **Waite, G. P.**, Lanza, F.
11:15 AM	Systematic Search for Repeating Earthquakes in New Zealand. **Peng, Z.**, Fry, B., Wallace, L., Yao, D.	Using GPU Clusters to Detect Millions of Small Earthquakes in Southern California with Template Matching. **Ross, Z. E.**, Hauksson, E., Maechling, P., Beroza, G. C.	Magma Migration at Active Volcanoes in the North Kivu Region Tracked Using Seismic Techniques and Space-Based Sulfur Dioxide Emission Estimates. **Barrière, J.**, Oth, A., Theys, N., d'Oreye, N., Kervyn, F.

Time	*Plaza D*	*Plaza E*	*Plaza F*	*Governor's Square 14*
	Paleoseismology of Subduction Earthquake Cycles	**Forecasting Aftershock Sequences in the Real World**	**Earthquake Source Parameters...**	**Numerical Modeling of Earthquake Ground Motion...**
11:30 AM	Paleoseismology of Large Earthquakes Resulting from Continental Subduction along the Himalayan Frontal Thrust of Nepal. **Wesnousky, S. G.**, Kumahara, Y., Chamlagain, D., Pierce, I. K., Angster, S., Reedy, T.	Operational Earthquake Forecasting Six Years into the Canterbury Sequence: Lessons for Initial and Ongoing Communications. **Wein, A. M.**, Becker, J., McBride, S., Potter, S.	Seismic Source Parameters of the Induced Seismicity at the Geysers Geothermal Area, California, by a Generalized Inversion Approach. **Picozzi, M.**, Oth, A., Parolai, S., Bindi, D., De Landro, G., Amoroso, O., Emolo, A.	EDGE: Extreme-Scale Discontinuous Galerkin Environment. **Breuer, A.**, Heinecke, A., Cui, Y.
11:45 AM	Possible Sedimentary Evidence for Paleoearthquakes and the 2016 November M 7.8 Kaikoura Earthquake along the Hikurangi Subduction Zone. Barnes, P. M. B., Orpin, A. R. O., Howarth, J. H., **Patton, J. R. P.**, Lamarche, G. L., R/V Tangaroa Shipboard Science Team	INVITED: Japanese New Guidelines for the Seismic Forecast Information after Big Earthquakes. **Kamaya, N.**, Hashimoto, T.	Source Parameters for Events in the Central and Eastern United States. **Pasyanos, M. E.**, Gok, R., Barno, J. G.	Toward Exascale Seismic Simulations with SW4. **Petersson, N. A.**, Sjogreen, B., Rodgers, A. J.
Noon–2:15 PM	Lunch			
	The Subduction Zone Observatory Session Chairs: Diego Melgar, Lee Liberty, Jeff Maguire. (see page 559).	**Advances in Earthquake Early Warning** Session Chairs: Elizabeth Cochran, Angela Chung, Douglas Given (see page 535).	**Earthquake Source Parameters: Theory, Observations and Interpretations** (continued)	**Integrated and Geophysical Investigations for Site Characterization of Critical Facilities and Infrastructure** Session Chairs: Jamey Turner, Jeffrey Bachhuber, Osman El Menchawi, Daniel O'Connell (see page 549).
2:15 PM	Updates on The Subduction Zone Observatory Workshop. **McGuire, J. J.**, Melgar, D., Liberty, L. M.	INVITED: How "Good" are Real-Time Ground Motion Predictions from Earthquake Early Warning Systems? **Meier, M. A. M.**	INVITED: Earthquake Stress Drop: Source Scaling, Uncertainties, and Complexity of Small Earthquakes. **Abercrombie, R. E.**	INVITED: Measurement- and Proxy-Based VS30 Estimates. **Yong, A.**
2:30 PM	INVITED: STUDENT: Crustal Deformation Following Great Subduction Earthquakes Controlled by Mantle Rheology and Earthquake Magnitude. **Sun, T. S.**, Wang, K. W., He, J. H.	The Effect of Ground-Motion Variability on the Accuracy of Earthquake Early Warning. **Minson, S. E.**, Baltay, A. S., Meier, M. A., Hanks, T. C., Cochran, E. S.	Improving Earthquake Source Parameters Estimation with Adaptive Window Spectral Analysis. **Prieto, G. A.**	INVITED: Direct Evaluation of S-Wave Amplification Factors from Microtremor Horizontal-to-Vertical Ratios: Empirical Corrections to "Nakamura" Method. **Kawase, H.**, Nagashima, F., Nakano, K., Mori, Y.

Time	*Governor's Square 15*	*Governor's Square 16*	*Governor's Square 12*
	Varied Modes of Fault Slip and their Interactions…	**Computational Infrastructure and Data…**	**Novel Approaches to Understanding Active Volcanoes**
11:30 AM	INVITED: Enhanced Detection of Earthquake Swarms in Southern Mexico and Relationships to Slow Slip. **Brudzinski, M. R.**, Fasola, S. L., Holtkamp, S. G., Skoumal, R. J., Cabral-Cano, E., Arciniega-Ceballos, A.	Using GeoGateway to Explore Off-Fault Deformation along the San Andreas Fault in the Carrizo Plain, CA. Grant **Ludwig, L.**, Donnellan, A., Parker, J. W.	STUDENT: Magma Imaging with Seismic Dense Array: A Case Study from Krafla, Iceland. **Kim, D.**, Brown, L. D., Árnason, K., Águstsson, K., Blanck, H.
11:45 AM	Shallow and Deep Creep Events Observed and Quantified Arrays of Creepmeters and Strainmeters. **Bilham, R.**, Mencin, D. J., Hodgkinson, K.	STUDENT: Tsunami Early Warning through Earthquake, Tsunami, and Ionosphere Simulation. **Wilson, J. M.**, Rundle, J. B., Donnellan, A., Song, Y. T., Komjathy, A., Savastano, G.	INVITED: Using Dense Geophone Arrays to Image Subsurface Hydrothermal Structure in the Upper Geyser Basin, Yellowstone National Park. **Farrell, J.**, Lin, F. C., Wu, S. M., Smith, R. B., Karplus, M.
Noon–2:15 PM	Lunch		
	Earthquake Interaction and Triggering: From Near Field to Far Field, From Natural to Induced Session Chairs: Wenyuan Fan, Andy Barbour, Xiaowei Chen (see page 540).	**Seismology Software Tools That Improve What We Do and How We Do It** Session Chairs: Michelle Guy, Eric Martinez (see page 558).	**Closing the Gap between Laboratory-based Damping Models and Observed Attenuation of Seismic Waves in the Field** Session Chairs: Albert Kottke, Ashly Cabas (see page 537).
2:15 PM	What Really Triggers Earthquakes? **Segou, M.**, Parsons, T.	INVITED: The ANSS Station Information System: A Centralized Station Metadata Repository for Populating, Managing and Distributing Seismic Station Metadata. **Yu, E.**, Acharya, P., Jaramillo, J., Kientz, S., Hauksson, E.	STUDENT: Insights into Small-Strain Damping from Borehole Array Recordings. **Tao, Y.**, Rathje, E.
2:30 PM	Preparation Phase of a M4.2 Earthquake below the Eastern Sea of Marmara Offshore Istanbul Observed from GONAF Downhole Recordings. **Bohnhoff, M.**, Malin, P. E., Bluemle, F., Dresen, G., Ceken, U., Kadirioglu, F. T., Kartal, R. F., Yanik, K.	INVITED: The Global Earthquake Model (GEM) Suite of Tools for Seismic Hazard Modeling. **Pagani, M.**, Weatherill, G. A., Garcia, J., Poggi, V., Styron, R.	Adjustments to Small-Strain Damping and Soil Profile Assumptions to Improve Site Response Predictions. **Kaklamanos, J.**, Bradley, B. A., Moolacattu, A. N., Picard, B. M.

Time	Plaza D	Plaza E	Plaza F	Governor's Square 14
	The Subduction Zone Observatory	**Advances in Earthquake Early Warning**	**Earthquake Source Parameters...**	**Integrated and Geophysical Investigations...**
2:45 PM	INVITED: STUDENT: Ocean Bottom Pressure Measurements for Detecting Vertical Seafloor Deformation. **Cook, M. J.**, Sasagawa, G. S., Zumberge, M. A., Wilcock, W. S. D., Schmidt, D. A., Roland, E.	Comparing Operational Performance of the Virtual Seismologist and FinDer for Earthquake Early Warning. **Massin, F.**, Boese, M., Cauzzi, C. V., Clinton, J. F.	Self-Similarity of M1 to 8 Earthquakes through Ground-Motion Modeling, and Special Attributes of Small Magnitude Earthquakes. **Baltay, A.**, Hanks, T. C., Vernon, F. L.	INVITED: State-of-Practice of Site Characterization: The Role of Seismic Investigation and Land Management Policies . **D'Amico, S.**, Albarello, D.
3:00 PM	INVITED: Geometrical Effects of Megathrust Faults on Slow Slip Events and Seismic Ruptures. **Liu, Y. J.**, Li, D., Yu, H. Y.	G-FAST Earthquake Early Warning Performance for Simulated Cascadia Megathrust Events. **Crowell, B. W.**, Melgar, D., Schmidt, D. A., Bodin, P., Vidale, J. E.	STUDENT: Stress Drop and Source Scaling of Recent Earthquake Sequences in the Central and Eastern United States. **Wu, Q.**, Chapman, M. C.	INVITED: Site Characterization for Safety-Related Nuclear Facilities: ASCE 1 Update. **Zafir, Z.**, Bachhuber, J. L.
3:15 PM	Rupture Segmentation and Variable Coupling along the Sunda Megathrust: The Case from Geodesy for an Ocean-Bottom Seismometer Array Offshore Sumatra. **Hill, E. M.**, Meltzner, A. J., Lindsey, E. O., Hananto, N., Muzli, M., Feng, L., Wei, S., Salman, R., Bradley, Sieh, K., McGuire, J.	INVITED: Fakequakes: Broadband Simulation for Hazards. **Melgar, D.**, Ruhl, C. J., Allen, R. M.	On the Variation of Strong-Motion Parameters in the Context of the Specific Barrier Model. **Halldorsson, B.**, Papageorgiou, A. S., Sonnemann, T., Hrafnkelsson, B.	INVITED: Update of Regulatory Guide 1.132. Wang, W., **Heeszel, D.**
3:30–4:30 PM	Posters and Break			
	The Subduction Zone Observatory (continued)	**Advances in Earthquake Early Warning** (continued)	**To Tweet or Not To Tweet: Effective Use of Social Media for Citizen Science and Science Communication** Session Chairs: Susan Hough, Julian Lozos, Christine Goulet, Paul Earle (see page 563).	**Integrated and Geophysical Investigations for Site Characterization of Critical Facilities and Infrastructure** (continued)
4:30 PM	The Alaska-Aleutian Megathrust Fault System: Upper Plate Response to Plate Boundary Conditions. **Liberty, L. M.**, Haeussler, P. H., Ramos, M.	INVITED: Earthquake Early Warning for the West Coast of the U.S.. **Hartog, J. R.**	INVITED: Social Media in the Wake of a Quake: A Science Journalist's Perspective. **Witze, A.**	Inversion of Irregular Vibroseis Data For 3D Shallow Velocity Structure. **O'Connell, D. R. H.**, Chen, W. Y., Fernandez, A., Travasarou, T.

Time	*Governor's Square 15*	*Governor's Square 16*	*Governor's Square 12*
	Earthquake Interaction and Triggering…	**Seismology Software Tools That Improve What We Do…**	**Closing the Gap between Laboratory-based Damping Models…**
2:45 PM	Modeling Repeating Earthquake Interactions: Triggering Effect from Nearby Microseismicity. **Chen, K. H.**, Johnson, K., Burgmann, R., Nadeau, R. M.	INVITED: Product Distribution Layer. **Fee, J. M.**	INVITED: Laboratory-Based Measurements of Material Damping of Soil and Rock. **Stokoe, K. H.**
3:00 PM	Regional and Stress Drop Effects on Aftershock Productivity of Large Megathrust Earthquakes. **Wetzler, N. W.**, Brodsky, E. E. B., Lay, T. L.	INVITED: Libcomcat: Tools for Automated Earthquake Information Extraction. **Hearne, M. G.**	INVITED: Seismic Wave Attenuation in the Shallow Geological Layer: Results from Different Approaches and Open Issues. **Parolai, S.**
3:15 PM	INVITED: Remote Triggering of Microearthquakes and Deep Tectonic Tremor in New Zealand Following the 2016 M7.8 Kaikoura Earthquake. **Peng, Z.**, Fry, B., Chao, K., Meng, X.	STUDENT: Using a Fast Similarity Search Algorithm to Identify Repeating Earthquake Sequences. **Shakibay Senobari, N.**, Funning, G. J.	INVITED: Capturing the Source and Site High Frequency Attenuation Properties (κ0). **Bora, S. S.**, Cotton, F., Mayor, J.
3:30–4:30 PM	Posters and Break		
	Earthquake Interaction and Triggering: From Near Field to Far Field, From Natural to Induced (continued)	**Geoacoustics: Infrasound and Beyond** Session Chairs: Daniel Bowman, Stephen Arrowsmith, Omar Marcillo (see page 547).	**Theoretical and Practical Advances in Ambient Noise and Coda Studies** Session Chairs: Julien Chaput, Hsin-Hua Huang (see page 561).
4:30 PM	Testing for the 'Predictability' of Dynamically Triggered Earthquakes in Geysers Geothermal Field. **Aiken, C.**, Meng, X., Hardebeck, J.	STUDENT: Quantifying River Turbulence: New Insights into the Fluvial Seismo-Acoustic Field. **Ronan, T. J. R.**, Lees, J. M. L., Mikesell, T. D. M., Anderson, J. A.	STUDENT: Estimating the Effect of Non-Diffuse Noise on Ambient Seismic Noise Cross-Correlations in Southern California. **Liu, X.**, Beroza, G. C., Nakata, N.

Time	*Plaza D*	*Plaza E*	*Plaza F*	*Governor's Square 14*
	The Subduction Zone Observatory	**Advances in Earthquake Early Warning**	**To Tweet or Not To Tweet…**	**Integrated and Geophysical Investigations…**
4:45 PM	INVITED: Plate Boundary Transitions in SZO - Learning from Processes at the Mendocino Triple Junction. **Furlong, K. P.**	Towards an Earthquake and Tsunami Early Warning in the Caribbean: The Puerto Rico Case. **Huerfano, V. A.**, Vanacore, L., Lopez, A.	INVITED: USGS Social Media Strategy. **Horvath, S. R.**, Other panel participants: Paul Earle (USGS) and Susan Hough (USGS)	Advancements in Identifying Subsurface Abandoned Mine Voids: Integration of Historic Data, LiDAR, Multi-Method Surface Seismic, Borehole Imaging, and Remediation, Wyoming USA. **Turner, J. P.**, O'Connell, D. R. H., Nuttall, J., Pfeiffer, J., Steele, L.
5:00 PM	STUDENT: Defining the Temporal Relationship between Afterslip and Aftershocks Using Dense Seismic and Geodetic Networks in Nicoya, Costa Rica. **Hobbs, T. E.**, Newman, A. V., Peng, Z.	Rapid Determination of P-Wave-Based Energy Magnitude: Insights on Source Parameter Scaling of the 2016 Central Italy Earthquake Sequence. **Picozzi, M.**, Bindi, D., Brondi, P., Di Giacomo, D., Parolai, S., Zollo, A.	INVITED: Social Media for Scientists: Why, Where and How. **Bohon, W.**	Slip Rate of the Hosgri Fault Based on the Sedimentary Record of Plio-Quaternary Sediments within a Right-Stepping Extensional Pull-Apart. McGinnis, R. N., **Stamatakos, J. A.**, Morris, A. P., Ferrill, D. A., Smart, K. J., Juckett, M. R.
5:15 PM	INVITED: Three-Dimensional Velocity Models from the iMUSH Active-Source Seismic Experiment. **Kiser, E.**, Levander, A., Zelt, C., Palomeras, I., Schmandt, B., Hansen, S., Creager, K., Ulberg, C., Abers, G., Crosbie, K., Harder, S.	Triggered Earthquake During the 2016 Kumamoto Earthquake (Mw7.0): Importance of Real-Time Shake Monitoring for Earthquake Early Warning. **Hoshiba, M.**, Ogiso, M.	INVITED: To Tweet or Not To Tweet: Is it Even a Question? **Bossu, R.**, Roussel, F., Fallou, L., Steed, R., Farras, C., Mazet Roux, G.	Empirical Characterization of Extreme Ground Motion at Soft-Sediment Sites. **Pilz, M.**, Fäh, D.
5:30 PM	Strategies for Developing Capacity Building, Education, and Outreach in Conjunction with a Subduction Zone Observatory. **Pulliam, J.**, Charlevoix, D. J., Bartel, B. A.	INVITED: Towards Internet of Things Earthquake Early Warning: A Pilot Network in Chile. **Brooks, B. A.**, Minson, S. E., Böse, M., Ericksen, S., Barrientos, S., Baez, J. C., Cochran, E., Smith, D. E., Duncan, C., Guillemot, C., Murray, J. R., Langbein, J. O., Glennie, C. L.	Shaping the Earth, One Tweet at a Time. **Rowan, L. R.**, Bartel, B. A.	Constraining Shallow Shear Wave Velocities Using the Initial Portion of Local P Waves Recorded at ANSS and EarthScope Transportable Array in the CEUS.. **Hosseini, M.**, Somerville, P. G., Skarlatoudis, A., Bayless, J., Thio, H. K.
5:45–6:30 PM	Pint and a Poster			
6:30–7:30 PM	Ignite Talks Plenary			
7:30-9:00 PM	Student Reception and Early Career Reception			

Time	*Governor's Square 15*	*Governor's Square 16*	*Governor's Square 12*
	Earthquake Interaction and Triggering…	**Geoacoustics: Infrasound and Beyond**	**Theoretical and Practical Advances in Ambient Noise and Coda Studies**
4:45 PM	INVITED: Investigating Earthquake Stress Release from Triggered Seismicity in Geothermal and Induced Seismicity Regions. **Velasco, A. A.**, Alfaro-Diaz, R.	INVITED: Prospects for Enhanced Infrasound Sensitivity from a Balloon-Borne Platform. **Young, E. F.**, Bowman, D., Arrowsmith, S. J., Boslough, M., Lees, J., Klein, V., Abernathy, R., Hargather, M.	Seismic Interferometry at a Large, Dense Array: Imaging the Source Physics Experiment. **Matzel, E. M.**, Mellors, R. J., Magana-Zook, S.
5:00 PM	On the Importance of Surface Deformation for Understanding Time-Dependent Seismic Hazard Due to Fluid-Injection. **Shirzaei, M.**	Socorro and Wanaka: Balloon Borne Infrasound Expeditions. **Lees, J. M.**, Bowman, D. C.	On the Application of Super-Resolution Array Processing Methods for Characterizing Earth's Short-Period Seismic Noise Field. **Marcillo, O. E.**, Euler, G., Koper, K.
5:15 PM	A Physical Mechanism for Earthquake Dynamic Triggering in Fluid Regions. **Zheng, Y.**	Three-Dimensional Local Infrasound Simulation Capability with In Situ Atmospheric Measurements. **Kim, K.**, Rodgers, A., Seastrand, D.	Short Period Surface-Wave Tomography in Central and Eastern US. **Herrmann, R. B.**, Ammon, C. J., Benz, H. M., Xia, Y.
5:30 PM	What Water Pressure is Needed to Trigger Earthquakes? **Mori, J.**	Applying a Revised Attenuation Versus Distance Stratospheric Wind Correction to Infrasound Data. **Hertzog, J. T.**, Brogan, R., Clauter, D. A.	Using Discrete Wavelet Transforms to Discriminate Between Noise and Phases in Seismic Waveforms. **Ray, J.**, Hansen, C., Forrest, R., Young, C. J.
	Pint and a Poster		
	Ignite Talks Plenary		
	Student Reception and Early Career Reception		

Earthquake Source Parameters: Theory, Observations and Interpretations (see page 571).

1. Student: Estimating the Magnitude of Laboratory-Generated Seismic Events Using a Ball Drop Empirical Green's Function (EGF) Method. McLaskey, G. C., **Wu, B. S.**
2. Student: Multichannel Deconvolution for Earthquake Apparent Source-Time Functions. **Plourde, A. P.**, Bostock, M. G.
3. Estimating Lg Wave Source Time Functions with Multiple Green's Function Events. **Gallegos, A. C.**, Xie, J.
4. Student: Diverse Seismic Signals Associated with the Sinkhole at Napoleonville Salt Dome, Louisiana. **Nayak, A.**, Dreger, D. S.
5. Student: Towards Automated Estimates of Directivity and Related Source Properties of Small to Moderate Earthquakes with Second Seismic Moments. **Meng, H.**, Ben-Zion, Y., McGuire, J.
6. Uncertainties in Spectral Models from Empirical Green's Function Analyses. **Van Houtte, C.**, Denolle, M.
7. An Alternate Noise Parameterization for Moment Tensor Estimation. **Baker, B.**, Stachnik, J.
8. Automated Estimation of Rupture Directivity in Small to Moderate Earthquakes. **Ross, Z. E.**, Ben-Zion, Y.
9. Seismic Moment Tensor Catalogue for the Central Mediterranean Area. **D'Amico, S.**
10. Student: Constraining Earthquakes Source Properties Using Depth Phases. **Florez, M. A.**, Prieto, G. A.
11. Source Inversion Using Regional and Teleseismic Data: Using a Multi-Objective Optimization to Constrain the Source of the M5.4 2016 September 12 South Korea Earthquake.. **Letort, J.**, Guilhem Trilla, A., Ford, S., Myers, S. C.
12. The 2016 Grand Wash, Arizona Earthquake Swarm. **Brumbaugh, D. S.**
13. Source Mechanisms of Induced Earthquakes In The Geysers Geothermal Reservoir. **Yu, C.**, Vavryčuk, V., Admová, P., Kwiatek, G., Bohnhoff, M.
14. Investigation of Source Parameters of the Gyeongju Earthquake Sequence of 2016. **Sheen, D. H.**, Rhee, H. M.
15. Source Parameter Validations Using Multiple-Scale Approaches for Earthquake Sequences in Oklahoma: Implications for Earthquake Triggering Processes. **Chen, X.**, Abercrombie, R. E.
16. Insights into Volcanic Processes in the East Africa Rift Using Small, Temporary Seismic Networks. **Patlan, E.**, Velasco, A. A., Wamalwa, A., Kaip, G.
17. Student: Analysis of the 30 July 1972 MW 7.6 Sitka Earthquake Aftershock Sequence. **Ochoa-Chavez, J. A.**, Doser, D.
18. Student: Moderate Sized Events (3 Mw 5.4–5.6) and Aftershock Relocations of the 2016-2017 Nine Mile Ranch Earthquake Sequence near Hawthorne, Nevada. **Hatch, R. L.**, Smith, K. D., Abercrombie, R. E., Ruhl, C.
19. Student: Variations in Earthquake Source Properties along a Developing Transform Plate Boundary. **Neely, J. S.**, Huang, Y., Furlong, K. P.
20. A Comparison of Different Methods of Calculating Source Spectra and Stress Drop in Southern California. **Abercrombie, R. E.**, Shearer, P. M., Trugman, D. T.
21. Source Spectra and Magnitude Scaling of Induced Earthquakes in Oklahoma and Kansas. **White, I.**, Withers, K., Moschetti, M., Choy, G.
22. A Local Magnitude Formula for Western Canada Sedimentary Basin. **Yenier, E.**
23. ML-Mw Magnitude Relationship: Western Alberta Case Study. **Yenier, E.**, Baturan, D.

Integrated and Geophysical Investigations for Site Characterization of Critical Facilities and Infrastructure (see page 576).

24. Fault-Zone Exploration in Highly Urbanized Settings Using Guided Waves: An Example from the Raymond Fault, Los Angeles, California. **Catchings, R. D.**, Hernandez, J. L., Sickler, R. R., Goldman, M. R., Chan, J. H., Criley, C. J.
25. Student: Characterization of Earthquake Site Amplification in Alberta, Canada, for Induced-Seismicity ShakeMap Applications. **Farrugia, J. J.**, Molnar, S. E., Atkinson, G. M.
26. Estimation of Kappa for Gyeongju Area in South Korea and Kappa Scaling Factors for NGA-West2 Ground Motion Prediction Equations. **Park, S. J.**, Lee, J. M., Baag, C. E., Choi, H., Noh, M.
27. Comparing Earthquake-Based P-Wave and Traditional Array-Based Methods for Obtaining VS30. **Herrick, J.**, Hosseini, M., Yong, A.
28. Student: Shear-Wave Velocity Analysis by Surface Wave Methods in the Boston Area. **Liu, S.**, Ebel, J. E., Urzua, A., Murphy, V.
29. Student: Comparison of Site Dominant Frequency from Earthquake and Microseismic Data in California. **Hassani, B.**, Yong, A., Atkinson, G. M., Feng, T., Meng, L.
30. A Dual-Approach Analysis of Lg Wave Site Amplification Using Site Response Ratios. **Xie, J.**, Chen, Y., Gellagos, A., Hardy, S.
31. Site Response Assessment in Two Geological Contexts, France. **Cauchie, L.**, Cushing, E. M., Gelis, C., Froment, B., Provost, L., Jomard, H.
32. Detection of Underwater Seismic Sources with T-wave Signals and Array Analysis. **Chang, E. T.**

33. Soil Effects in the City of Lorca (SE Spain) and Damage Distribution of the M 5.2 11 May 2011 Earthquake. **Jimenez, M. J.**, Albarello, D., Garcia-Fernandez, M., Massini, F., Lunedei, E.
34. Student: On the Bayesian Inference of Shear Wave Velocity Structure from Horizontal-To-Vertical Spectral Ratio. **Rahpeyma, S.**, Halldorsson, B., Hrafnkelsson, B., Polat, O.
35. Using Routine Multi-Method Shear-Wave Velocity Data (Vs30) as a First Approximation of Seismic Hazard Site Characterization. **Odum, J. K.**, Stephenson, W. J., Williams, R. A., Volti, T.
36. Student: The Role of Non-Invasive Ambient Noise Analysis in Improving Seismic Microzonation Mapping in Vancouver, British Columbia, Canada. **Jackson, F. A.**, Molnar, S. E.
37. Student: A Study of Vertical to Horizontal Ratio of Earthquake Components in the Gulf Coast Region. **Haji-Soltani, A.**, Pezeshk, S., Zandieh, A., Malekmohammadi, M.
38. Student: Estimation of the Site Amplification in the New Madrid Seismic Zone Using Regional and Local Earthquake Data. **Yarahmadi, A.**, Pezeshk, S.
39. Results of Six-Degree-of-Freedom Recording at The Geysers, California: True Backazimuth, Phase Velocity, and Site Characterization. **Malek, J.**, Brokesova, J.
40. Reducing Uncertainties in the Estimation of Deep VS Profiles at the Location of CERI Stations, Using Joint Inversion of Earthquake Receiver Functions and Site-Specific Geophysical Phase Velocity Dispersion Curves. **Hosseini, M.**, Somerville, P. G., Skarlatoudis, A., Bayless, J., Thio, H. K.
41. Seismic and Liquefaction Hazard Mapping and Early Earthquake Warning in West Tennessee. **Cramer, C.**, Van Arsdale, R., Arellano, D., Pezeshk, S., Horton, S., Bolarinwa, O.
42. Comparison of Earthquake Damage Patterns and Shallow-Depth vs Structure across the Napa Valley, Inferred from Multichannel Analysis of Surface Waves (MASW) and Multichannel Analysis of Love Waves (MALW) Modeling of Basin-Wide Seismic Profiles. **Chan, J. H.**, Catchings, R. D., Strayer, L. M., Goldman, M. R., Criley, C. J., Sickler, R. R., Boatwright, J.
43. Student: Geophysical Investigations for Site Characterization at Unstable Sea Cliffs: Case Study of Selmun (Malta). **D'Amico, S.**, Iannucci, R., Martino, S., Paciello, A., Farrugia, D., Galea, P., Panzera, F.
44. Student: High-Resolution Tomography of Vp, Vs, Vp/Vs, and Poisson's Ratios of Quaternary-Active Chabot Fault of the Hayward Fault Zone. **McEvilly, A. T.**, Strayer, L. M., Chan, J. H., Abimbola, A.
45. Student: Shallow vs Structure of Subsidiary Faults in the Hayward Fault Zone Inferred from Multichannel Analysis of Surface Waves (MASW). **Richardson, I. S.**, Strayer, L. M., Chan, J. H., McEvilly, A. T.
46. Rayleigh-Wave Phase Velocity (VR40) based VS30 Estimates. **Yong, A.**, Martin, A., Albarello, D.

The Subduction Zone Observatory (see page 591).

47. Live Tsunami Warning System. **Hayashi, M.**, Schirling, P., Honda, A.
48. Reevaluating the Tsunamigenic Potential of Shallow Subduction Zones from Probabilistic Megathrust Earthquake Source Models. **Jiang, J.**, Simons, M., Duputel, Z.
49. Slab2—Updated Subduction Zone Geometries and Modeling Tools. **Moore, G. L.**, Hayes, G. P., Portner, D. E., Furtney, M., Flamme, H. E., Hearne, M.
50. Student: Catalog of Near-Shore Seismicity in the Pacific Northwest from Cascadia Initiative OBS Data. **Stone, I.**, Vidale, J.
51. Student: Using Earthquake Body Wave Travel Times to Explore Upper Plate Structure along the Washington Forearc. **Myers, E. K.**, Roland, E. C.
52. Student: Cascadia Seismogenic Zone Seismicity as Detected by the Cascadia Initiative Amphibious Data. **Morton, E. A.**, Bilek, S. L., Rowe, C. A.
53. High-Resolution 3D Seismic Imaging of Reflectors above the Subducting Slabs and Slab-Mantle Interaction. **Zheng, Y.**, Li, L., Li, X., Hu, H.
54. Refine Fault Geometry with Broadband Waveform Modeling for Earthquake Source Parameters: Case Studies in Nepal and Sumatran Subduction Zones. **Wei, S. W.**, Wang, X., Wu, W. B.
55. Student: Mantle Serpentinization near the Mariana Trench Constrained by Ocean Bottom Surface Wave Observations. **Cai, C.**, Wiens, D. A., Lizarralde, D., Eimer, M.
56. A Review of the Complex Geometry of Cocos Slab under North America. **Pérez-Campos, X.**, Clayton, R. W., Rodríguez-Domínguez, M. A., Valenzuela, R., Husker, R., Iglesias, A., Singh, S. K.
57. Prediction of Ground Motion from Megathrust Earthquake Using the Ambient Seismic Field. **Viens, L.**, Denolle, M., Miyake, H.

Numerical Modeling of Earthquake Ground Motion, Rupture Dynamics and Seismic Wave Propagation (see page 584).

58. Three-Dimensional High-Performance Computing Simulations of Near-Fault Earthquake Ground Motions for Engineering Applications: Large Generic Events and Scenarios in the San Francisco Bay Area. **Rodgers, A. J.**, Pitarka, A., Petersson, N. A.
59. Performance of the Source Physics Experiment (SPE) Geological Framework Velocity Model with Stochastic Heterogeneity in Modeling SPE-6 Far-Field Waveforms. **Pitarka, A.**, Chiang, A., Wagoner, J., Ezzedine, S., Vorobiev, O., Walter, W.

60. STUDENT: Modeling Earthquakes and Source Physics Experiment Broadband Recordings at Regional Distances: Effects of Multiple Basins. **Dunn, M.**, Louie, J., Smith, K. D., Pitarka, A.
61. Modeling Topographic Effects and Site Response for Strong Ground Motions at Los Alamos National Laboratory, New Mexico.. **Larmat, C. S.**, Lee, R. C.
62. STUDENT: A Vs30-Dependent Sediment Velocity Model for High-Frequency Simulated Ground Motions in the Los Angeles Basin. **Shi, J.**, Asimaki, D.
63. Simulation on Strong Ground Motion of Xiaojiang Fault Zone. **Chen, X. L.**, Guo, J. P., Gao, M. T., Li, Z. C., Li, T. F.
64. STUDENT: Sedimentary Basin Amplification in the Puget Sound and Willamette Valley Regions: Observations from Local Earthquakes and 3D Simulations. **Thompson, M.**, Frankel, A. D., Vidale, J. E., Wirth, E. A.
65. STUDENT: Exploring the Implementation of an Equivalent Linear Method in 3D to Approximate Nonlinear Response in Regional Ground Motion Simulation. **Khoshnevis, N.**, Taborda, R.
66. 3D Dynamic Rupture Simulations along the Wasatch Fault, Utah, Incorporating Rough-Fault Topography. **Withers, K. B.**, Moschetti, M.
67. Ground Motion Variability and the Modeling of the Source of the 2011 Mw 5.2 Lorca Earthquake, SE Spain. Moratto, L., Saraò, A., Vuan, A., Mucciarelli, M., Jimenez, M. J., **Garcia-Fernandez, M.**
68. How to Anticipate Future Earthquake Characteristics on a Multi-Segmented Fault? A Practical Example of Dynamic Rupture Modeling to Evaluate the Maximum Magnitude. Durand, V., **Hok, S.**, Boiselet, A., Bernard, P., Scotti, O.
69. The SCEC Broadband Platform: Open-Source Software for Strong Ground Motion Simulation and Validation. **Silva, F.**, Goulet, C. A., Maechling, P. J., Callaghan, S., Jordan, T. H.
70. A Ground-Motion Prediction Equation for California Constructed Using an Artificial Neural Network. **Aagaard, B. T.**
71. Accurate and Efficient Viscoelastic Finite-Difference Simulations in Realistic Media with Material Discontinuities: The Method and Application to the Mygdonian Basin. **Kristek, J.**, Moczo, P., Kristekova, M., Chaljub, E.
72. STUDENT: Kinematic Rupture Generator Based on 3D Rough Fault Dynamic Rupture Simulations. **Savran, W. H.**, Olsen, K. B., Day, S. M.
73. STUDENT: Multicycle Dynamics of a 3D Strike-Slip Fault System with Bends. **Liu, D.**, Duan, B.
74. STUDENT: Earthquake Cycle Simulations with Rate-and-State Friction and Nonlinear Viscoelasticity. **Allison, K. L.**, Dunham, E. M.

Forecasting Aftershock Sequences in the Real World (see page 575).

75. Real-Time Completeness of the USGS ComCat Earthquake Catalog and Implications for Operational Aftershock Forecasting. **Hardebeck, J. L.**, Llenos, A. L., Michael, A. J., Page, M. T., van der Elst, N.

Paleoseismology of Subduction Earthquake Cycles (see page 587).

76. Late Holocene Paleoseismology of Shuyak Island, Surface Deformation and Plate Segmentation within the 1964 Alaska M 9.2 Earthquake Rupture Zone. **Shennan, I.**, Brader, M. D., Barlow, N. L. M., Davies, F. P., Longley, C., Tunstall, N.
77. Observations on the Distributions of Modern Benthic Diatoms to Improve Estimates of Past Coseismic Land-Level Changes, Humboldt Bay, California. **Hemphill-Haley, E.**
78. Evidence for Great Earthquakes of Variable Rupture Mode beneath Marshes of the Nehalem Estuary, Central Cascadia Subduction Zone. **Nelson, A. R.**, Sawai, Y., Hawkes, A., Engelhart, S. E., Witter, R. C., Bradley, L. A., Dura, T., Horton, B. P., Duross, C. B.
79. Possible Structural Evidence for Heterogeneous Plate Coupling and Linkages to Geodesy and Paleoseismology, Cascadia Margin, USA. **Goldfinger, C.**, Kane, T.
80. Possible Sedimentary Evidence for Paleoearthquakes along the Northern Lesser Antilles: Preliminary Results from CASEIS16. Feuillet, N., Beck, C., Cattaneo, A., Goldfinger, C., Guyard, H., Morena, P., Moreno, E., **Patton, J. R.**, Ratzov, G., Seibert, C., St-Onge, G., Woerther, P., Beauvais, Q., Bênatre, G., Bieber, A., Bouchet, O., Caron, B., Caron, M., Casse, M., Cavailhes, Del Manzo, G., Deschamps, C. E., Desiage, P. A., Duboc, Q., Fauquembergue, K., Ferrand, A., Hausmann, R., Jacques, E., Johannes, L., Laurencin, M., Leclerc, F., Leclerc, P., Monteil, C., Saurel, J. M.

Computational Infrastructure and Data for Enhancing Earthquake Science (see page 568).

81. UCVM: From Supercomputers to Laptops, Querying and Visualizing 3D Seismic Velocity Models. **Gill, D. J.**, Maechling, P. J., Jordan, T. H., Shaw, J. H., Plesch, A., Lee, E., Chen, P., Goulet, C. A., Taborda, R., Olsen, K. B., Callaghan, S.
82. STUDENT: Testing the Density of Seismic Networks with ShakeMap. **Hu, Z.**, Olsen, K. B.
83. Web-Based Database of Active and Passive Surface Wave Investigation Results for Site Classification. **Hayashi, K.**
84. STUDENT: A Detailed Automatic Seismicity Catalog (1998-2015) for the San Jacinto Fault Zone Region. **White, M.**, Ross, Z. E., Vernon, F. L., Ben-Zion, Y.

Novel Approaches to Understanding Active Volcanoes (see page 582).

85. Investigating the Relationship Between Deep Long-Period and Deep High Frequency Seismicity at Mammoth Mountain, California, 2012 – 2014. **Hotovec-Ellis, A. J.**, Shelly, D. R., Hill, D. P., Pitt, A. M., Dawson, P. B., Chouet, B. A.
86. Monitoring of Oregon and Washington Cascade Volcanoes: In a Time of Quiescence. **Darold, A.**, Pauk, B., Thelen, W., Kramer, R.
87. Searching for Correlations between Seismicity and Volcanic Eruptions for Improved Eruption Forecasting. **Pesicek, J. D.**, Ogburn, S., Wellik, J.
88. Hydroacoustic Observations of Recent Submarine Eruptions at Ahyi and Bogoslof Volcanoes. **Haney, M. M.**, Tepp, G., Lyons, J., Bohnenstiehl, D., Chadwick, B., Dziak, B., Fee, D., Searcy, C.
89. Student: Seismic Observations of a Lava Delta Collapse at Kīlauea Volcano, Hawai'i. **Shiro, B. R.**, Burgess, M. K., Thelen, W. A.
90. Student: Analysis of the Seismicity Occurred in the Volcano of San Miguel in the Years 2013 and 2014. **García Castro, R. A.**, Marroquín, M. G., Gómez, N. E.
91. KivuSNet: A Broadband Seismic Network for the Lake Kivu & Virunga Volcanic Region, Democratic Republic of the Congo. **Oth, A.**, Barrière, J., d'Oreye, N., Mavonga, G., Subira, J., Mashagiro, N., Kafudu, B., Fiama, S., Celli, G., Bigirande, J.d.D, Ntenge, A.J., Habonimana, L., Bakundukize, C., Kervyn, F.
92. Diverse Long Period Tremors and Their Implication on Degassing and Heating inside Aso Volcano. **Niu, J.**, Song, T. R.
93. Student: Analysis of Deep Long-Period Seismicity from a Subglacial Volcano in Marie Byrd Land, Antarctica. **McMahon, N. D.**, Aster, R. C., Myers, E. K., Lough, A. C.

Geoacoustics: Infrasound and Beyond (see page 576).

94. Dispersed Acoustic Waves: Implications for Atmospheric Inversion and Source Location. **Bowman, D. C.**, Arrowsmith, S. J.
95. The Acoustic Signature of Underground Chemical Explosions during the Source Physics Experiment. **Bowman, D. C.**, Preston, L., Waxler, R., Whitaker, R., Jones, K. R., Albert, S.
96. Acoustic Yield Estimation Using Full Waveforms. **Arrowsmith, S.**, Bowman, D., Gramann, M.
97. Combining Seismic and Acoustic Event Catalogs to Better Understand the Nature of Individual Events. **Albert, S.**, Arrowsmith, S. J.
98. Improved Nearfield Dispersion Measurements from Analytic Representation of Time-Warped Acoustic Modes. **Ball, J. S.**

Earthquake Interaction and Triggering: From Near Field to Far Field, From Natural to Induced (see page 569).

99. Student: Enhanced Dynamic Triggering in Waste-Water Injection Sites near Woodward, Oklahoma. **Qin, Y.**, Chen, X., Peng, Z., Aiken, C.
100. Student: Triggering Mechanisms in Large Iranian Earthquake Sequences from Calibrated Relocations. **Karasozen, E.**, Nissen, E., Bergman, E. A., Ghods, A.
101. Student: Long-Term Seismic Behavior around the Epicenter of the 2008 Mw7.9 Wenchuan Earthquake. **Yao, D.**, Peng, Z., Ruan, X., Long, F., Su, J., Liu, X., Zhang, C.
102. Student: Possible Activation of Splay Faults During the 2006 Java Tsunami Earthquake. **Fan, W.**, Bassett, D., Shearer, P. M., Ji, C., Denolle, M.
103. Induced Intraplate Earthquakes in Colorado from Extreme Seismic Waves from the End-Cretaceous Asteroid Impact. **Sleep, N. H.**, Olds, P.
104. Student: Numerical Investigation of Interactions between Dynamic Stress and Pore Fluids in Earthquake Triggering. **Walker, R. L. W.**, Jha, B. J., Aminzadeh, F. A.
105. Student: Seismicity in the Mineral Mountains, Utah and the Possible Association with the Roosevelt Hot Springs Geothermal System. **Potter, S.**, Pankow, K., Moore, J., Allis, R.
106. Student: InSAR MSBAS Time-Series Analysis of Induced Seismicity in Colorado and Oklahoma. **Barba, M.**, Tiampo, K. F., Samsonov, S., Feng, W.
107. Student: Temporal Changes in Seismicity and Seismic Velocities in Salton Sea Geothermal Field. **Li, C.**, Peng, Z., Zhang, C., Yao, D., Meng, X.

Advances in Earthquake Early Warning (see page 565).

108. Student: Earthquake Early Warning Feasibility Study for the New Madrid Seismic Zone. **Ogweno, L. P.**, Withers, M. M., Cramer, C. H.
109. Earthquake Early Warning System for Schools in the Campania Region, Southern Italy. **Emolo, A.**, Picozzi, M., Festa, G., Zollo, A., Martino, C., Elia, L.
110. Analysis of Ambient Pre-Seismic Noise for Short-Term Advance Warning of Large Earthquakes. **Gupta, I. N.**, Wagner, R. A.
111. Reducing Alert Times for ShakeAlert's ElarmS Earthquake Early Warning Algorithm. **Terra, F.**, Hellweg, M., Allen, R. M., Chung, A. I., Strauss, J. A., Hensen, I. H., Neuhauser , D. S.

112. Evaluating the Geodetic Alarm System (G-larmS) Performance Using Synthetic Earthquakes. **Ruhl, C. J.**, Melgar, D., Grapenthin, R., Aranha, M., Allen, R. M.

Varied Modes of Fault Slip and their Interactions - Slow Earthquakes, Creep to Mega Quakes (see page 594).

113. Breaking Down Large Slow Slip into a Cascade of Aseismic Transients. **Frank, W. B.**, Rousset, B., Lasserre, C., Campillo, M.
114. Student: Tremor Modulation by Dynamic Stresses from Teleseismic Earthquakes in the Alaska-Aleutian Subduction Zone. **Li, B.**, Ghosh, A.
115. Coming up from the Deep? Seismological Evidence of Changing Slip-Regimes with Depth on the Alpine Fault, New Zealand.. **Chamberlain, C. J.**, Boese, C. M., Baratin, L., Townend, J.
116. Mixed Seismic/Aseismic Slip Transient in a Seismic Gap Region Revealed by Dense Geodetic Measurements: the 2011-2014 Pollino (Southern Italy) Earthquake Swarm. Cheloni, D., **D'Agostino, N.**, Selvaggi, G., Avallone, A., Fornaro, G., Giuliani, R., Reale, D., Sansosti, E., Tizzani, P.
117. Observing Episodic Tremor and Slip and Slow Slip Events in the GAGE Geodetic Networks. **Puskas, C. M.**, Hodgkinson, K., Phillips, D. A., Meertens, C. M.
118. Tremor and Slow Slip in an Antarctic Ice Stream. **Lipovsky, B. P.**, Dunham, E. M.

Seismology Software Tools That Improve What We Do and How We Do It (see page 589).

119. Invited: Seismology and GIS: USGS Near Real-Time Significant Earthquake and Earthquake Scenario GIS Feeds. **Smoczyk, G. M.**, Wald, D. J., Worden, C. B., Thompson, E. M., Quitoriano, V., Hearne, M. G.
120. Integrated Research, Development, and Operations of USGS Real-Time Earthquake Shaking and Impact Information Systems: An Update. **Wald, D. J.**, Allstadt, K., Hayes, G., Hearne, M., Jaiswal, K., Marano, K., Quitoriano, V., Thompson, E. M., Worden, C. B.
121. ISC-EHB: Reconstruction of the EHB Earthquake Database. **Engdahl, E. R.**, Weston, J., Harris, J., Di Giacomo, D., Storchak, D.
122. Invited: ShakeMap 4.0. **Worden, C. B.**, Thompson, E. M., Hearne, M. G., Luco, N., Wald, D. J.
123. Products and Services Available from the Southern California Earthquake Data Center (SCEDC) and the Southern California Seismic Network (SCSN). **Yu, E.**, Acharya, P., Bhaskaran, A., Chen, S., Andrews, J., Hauksson, E., Clayton, R. W.
124. Invited: Earthquake-Detection-Formats and HazDev-Broker: Standards for Formatting and Distributing Seismic Detection Data Using Open Source Software. **Patton, J. M.**, Guy, M. R.
125. EQcorrscan: Open-Source Python Package for Detection and Analysis of Near-Repeating Seismicity. **Chamberlain, C. J.**, Hopp, C., Warren-Smith, E., Baratin, L., Townend, J.
126. Invited: Advanced Data Selection for Research Ready Data Sets. **Bahavar, M.**, Trabant, C., Van Fossen, M., Weertman, B., Ahern, T.

To Tweet or Not To Tweet: Effective Use of Social Media for Citizen Science and Science Communication (see page 594).

127. Tweet-Based Earthquake Detections and Impact Assessment Integrated with Traditional Seismic Processing. **Guy, M.**, Earle, P., Turner, J., Allen, J.
128. Using Social Networks for Enhancing Outreach at the National Seismological Network of Costa Rica. **Linkimer, L.**, Carvajal, S.
129. South Napa in 140 Characters or Less: Earthquake Response via Twitter. **Lozos, J. C.**

Closing the Gap between Laboratory-based Damping Models and Observed Attenuation of Seismic Waves in the Field (see page 567).

130. Estimation of Site-Specific Kappa (κ_0)-Consistent Damping Values at Selected Stations from the KiK-net Database. **Cabas, A.**, Rodriguez-Marek, A., Bonilla, L. F.
131. Student: Utilizing California Vertical Array Data to Study Methods for Estimation of Small-Strain Damping in 1D Ground Response Analysis. **Afshari, K. A.**, Stewart, J. P. S.
132. Investigating the Low-Strain Dynamic Properties of Late-Glacial Silts and Clays in the Lab and the Field. **Crow, H. L.**, Cascante, G., Irfan, M., Khan, Z., Leboeuf, D., Sivathayalan, S., Motazedian, D.
133. The Contribution of Scattering to Near-Surface Attenuation. **Pilz, M.**, Fäh, D.
134. Exploration of Kappa Using 2D Numerical Simulation of Wave Propagation. Bonilla, L. F., **Gelis, C.**
135. Physical Consistency of Seismic Q for near Surface. **Morozov, I. B.**
136. High Frequency Attenuation of Regional Phases and Applications to Event Discrimination. **Pyle, M. L.**, Walter, W. R., Pasyanos, M. E.
137. A Comparison of Frequency-Dependent Attenuation in the Piedmont and Coastal Plain of the Southeastern US. **Chapman, M. C.**, Wu, Q.

Theoretical and Practical Advances in Ambient Noise and Coda Studies (see page 593).

138. Special Noise Field Characteristics of a Small Aperture Seismic Array on the Southeast Coast of China. **Hao, C. Y.**

139. Student: Rayleigh Wave Ellipticity and Anisotropy from Ambient Noise Cross-Correlations in Southern California. **Berg, E. M.**, Lin, F. C., Allam, A. A.

140. Student: A New Method to Determine Coda-Q, Magnitude of Earthquakes and Site Amplification. **Wang, W.**, Shearer, P.

Presenting author is indicated in bold.

Wednesday, 19 April—Oral Sessions

Time	*Plaza D*	*Plaza E*	*Plaza F*	*Governor's Square 14*
	Fine Scale Structure of the Crust and Upper Mantle Session Chairs: Peter Molnar, Barbara Romanowicz, Steven Roecker (see page 605)	**Observations and Mechanisms of Anthropogenically Induced Seismicity** Session Chairs: Thomas Goebel, Thomas Braun, Ivan Wong, Justin Rubinstein (see page 610)	**Source Discovery Using Differential Methods: Applications to Explosion Monitoring** Session Chairs: William Walter, Joshua Carmichael, Steven Gibbons (see page 620)	**Regional Variations in Seismological Characteristics: Implications for Seismic Hazard Analysis** Session Chairs: Sanjay Bora, Adrian Rodriguez-Marek, Marco Pagani (see page 617)
8:30 AM	Imaging the Farallon Slab and Other Upper-Mantle Structure under USArray Using Long-period Reflection Seismology. Buehler, J. S., **Shearer, P. M.**	STUDENT: Imaging the Pore-Pressure Diffusion and Triggering Front of Induced Seismicity in Guy-Greenbrier, Arkansas, by Mapping the Seismic B-Value. **Mousavi, S. M.**, Ogwari, P. O., Horton, S. P.	Absolute Locations of the North Korean Nuclear Tests Based on Differential Seismic Travel Times and InSAR. **Myers, S. C.**, Ford, S. R., Mellors, R., Ichinose, G.	INVITED: Regional Path and Site Effects in Ground Motion Models. **Stewart, J.**, Boore, D. M., Kishida, T., Parker, G. A., Seyhan, E., Zimmaro, P.
8:45 AM	INVITED: GLImER—A New Database of Teleseismic Receiver Functions for Global Imaging of Crustal and Upper Mantle Structure. **Rondenay, S.**, Spieker, K., Sawade, L., Farestveit, M., Drottning, A., Halpaap, F.	Testing the Quantitative Aftershock Productivity Forecast in Mining-Induced Seismicity. **Kozlowska, M.**, Orlecka-Sikora, B.	INVITED: Seismo-Acoustic Analyses of the DPRK Underground Nuclear Tests for the Estimation of Source Depth. **Assink, J. D.**, Averbuch, G., Smets, P. S. M., Evers, L. G.	
9:00 AM	INVITED: Constraining Fine Scale Lithospheric Structures by Full Waveform Inversion of Teleseismic Waves. **Chevrot, S.**	The 2016 Mw5.1 Fairview, Oklahoma Earthquakes: Evidence for Long-Range Poroelastic Triggering at >40 km from Fluid Disposal Wells. **Goebel, T. H. W.**, Weingarten, M., Chen, X., Haffener, J., Brodsky, E. E.	INVITED: Discrimination, Relocation, Magnitude Calculation and Yield Estimation of the North Korean Nuclear Tests. **Zhao, L. F.**, XIE, X. B., Wang, W. M., Fan, N., Hao, J. L., Zhao, X., Yao, Z. X.	STUDENT: Recommended Central and Eastern North America Seismic Site Amplification Models for USGS Map Applications. Parker, G. A., **Stewart, J. P.**, Harmon, J. A., Hashash, Y. M. A., Atkinson, G. M., Boore, D. M., Bozorgnia, Y., Darragh, R., Silva, W. J.
9:15 AM	INVITED: Tectosphere from Receiver Functions. **Vinnik, L. P.**	The Role of Pre-Injection Pore Fluid Pressure in Susceptibility to Induced Seismicity. **Levandowski, W.**, Weingarten, M., Walsh, F. R.	INVITED: Mb-Ms for the DPRK Announced Nuclear Tests. **Selby, N. D.**	Investigating Physical Explanations for Path Effects to Reduce Uncertainty in Ground Motion Prediction Equations. **Sahakian, V. J.**, Baltay, A. S., Hanks, T. C., Buehler, J. S., Kilb, D., Vernon, F. L.

Time	Governor's Square 15	Governor's Square 16	Governor's Square 12
	From Field Site to Data Center: Network Innovations for Earthquake Early Warning Session Chairs: Christopher Bruton, Rayo Bhadha (see page 608)	**Earthquake Rapid Response** Session Chairs: Anne Meltzer, Jay Pulliam, Dan McNamara (see page 600)	**Overcoming Challenges in Seismic Risk Communication** Session Chairs: Sean McGowan, Taojun Liu (see page 612)
8:30 AM	Borehole Instrumentation for Strong Ground Motion Monitoring at Swiss Nuclear Power Plant Sites. **Dalguer, L. A.**, Renault, P., Skolnik, D.	INVITED: Some Reflections on Aftershock Deployments in Distant Lands. **Hough, S. E.**	The Public Can Understand Risk and Cares about Building-Code Requirements for New Buildings. **Porter, K. A.**, Jones, L. M.
8:45 AM	INVITED: The Southern California Seismic Network, a Multi-Purpose Seismic Observatory. **Alvarez, M.**, Thomas, V., De Cristofaro, J., Hauksson, E., Bhadha, R., Stubailo, I., Bruton, C., Watkins, M.	INVITED: Complex Extensional Faulting and Stress Interactions in the Central Apennine Cluster: The 2016 Amatrice, Visso and Norcia, Italy, Earthquakes. **Melgar, D.**, Xu, X., Ruhl, C. J., Malagnini, L., Menichetti, M., Burgmann, R.	Human and Economic Losses for Earthquake Scenarios along the Himalayan Arc. Francis, J., **Wald, D. J.**, Briggs, R., Hayes, G., Hearne, M., Thompson, E. M., Allstadt, K., Jaiswal, K.
9:00 AM	INVITED: UC Berkeley Network Operational Improvements and Challenges for Earthquake Early Warning. **Neuhauser, D. S.**, BSL Operations Staff, UC Berkeley, Berkeley, CA, USA	Efficient Characterization of Subduction Zone Segmentation, Rupture Regions, and Seismic Structure: Examples from Large Magnitude Chile Earthquakes since 2010. **Russo, R.** M., Roecker, S. W., Comte, D.	Seismology Meets Theology: Advancing Earthquake Hazard Mitigation by Engaging Pakistan's Religious Community. **Hamburger, M. W.**, Hussain, A., Kakar, D. M., Lodi, S. H., Rafi, M. M., Tucker, B. E.
9:15 AM	INVITED: Reducing Digitiser Latency for Earthquake Early Warning: New Strategies for Seismic Hardware. Hicks, S. P., **Allardice, S.**, Hill, P., McGowan, M.	Subduction Zone Earthquake Rupture and Aftershock Sequences: Insights from the April 2016 Pedernales Earthquake, Ecuador. **Meltzer, A.**, Beck, S., Alvarado, A., Chambers, M., Charvis, P., Font, Y., Hernandez, S., Lynner, C., Regnier, M., Rietbrock, A., Ruiz, M., Soto Cordero, L., Sirait, A., Stachnik, J., Yepes, H.	School Seismic Safety Projects in Washington State, USA: A Critical Effort for Earthquake Resilient Washington. **Cakir, R.**, Walsh, T. J., Norman, D. K.

Time	Plaza D	Plaza E	Plaza F	Governor's Square 14
	Fine Scale Structure of the Crust and Upper Mantle	**Observations and Mechanisms of Anthropogenically…**	**Source Discovery Using Differential Methods…**	**Regional Variations in Seismological Characteristics…**
9:30 AM	INVITED: Tectosphere from Receiver Functions. **Vinnik, L. P.** (continued).	INVITED: Observations of Fault Zone Hydrogeologic Architecture. **Xue, L.**, Brodsky, E. E., Fulton, P. M., Allègre, V., Parker, B. L., Cherry, J. A.	Estimating and Exploiting the Outgoing Seismic Wavefield at the North Korean Nuclear Test Site. **Gibbons, S. J.**	Regional Fourier Amplitude Spectra Ground Motion Models Quantifying Source, Path and Site Contributions to Ground Motion in Canterbury and Central New Zealand. **Kaiser, A. E.**, Oth, A., Benites, R. A., Van Houtte, C.
9:45–10:45 AM	Posters and Break			
	Fine Scale Structure of the Crust and Upper Mantle (continued)	**Observations and Mechanisms of Anthropogenically Induced Seismicity** (continued)	**Source Discovery Using Differential Methods: Applications to Explosion Monitoring** (continued)	**Regional Variations in Seismological Characteristics: Implications for Seismic Hazard Analysis** (continued)
10:45 AM	Lithospheric Structure in Central California across the Isabella Anomaly and Tectonic Implications. **Dougherty, S. L.**, Clayton, R. W., Hansen, S. M., Schmandt, B.	Insight into Subdecimeter Fracturing Processes During Hydraulic Fracture Experiment in Äspö Hard Rock Laboratory, Sweden. **Kwiatek, G.**, Martínez-Garzón, P., Plenkers, K., Leonhardt, M., Arno, Z., Dresen, G., Bohnhoff, M.	Surface Wave Relative Amplitude and Travel-Time Anomalies from the 2009, 2013 and 2016 DPRK Declared Nuclear Explosions. **Ichinose, G. A.**, Ford, S. R., Myers, S. C., Pasyanos, M. E., Walter, W. R.	STUDENT: Site-Effects Model for Central and Eastern North America Based on Peak Frequency and Average Shear Wave Velocity. **Hassani, B.**, Atkinson, G. M.
11:00 AM	INVITED: Imaging Lithospheric Drips and Delaminations with Large Seismic Arrays. **Levander, A.**	A Macroscopic Study of the Spatio-Temporal Evolution of Induced Seismicity on Single Faults in Oklahoma and Southern Kansas. **Schoenball, M.**, Ellsworth, W. L.	The Influence of Topography on Regional P-Wave Observations from the North Korean Underground Nuclear Tests. **Reiter, D. T.**, Yoo, S. H.	Notes on Strong Ground Motions in the 2011 Fukushima-Hamadori Normal-Faulting Earthquakes. **Anderson, J. G.**, Kawase, H.
11:15 AM	Preliminary SKS/SKKS Shear Wave Splitting Results for the GRASP Seismic Array in the Dominican Republic. **Vanacore, E. A.**, Serevino, V., Pulliam, J., Huerfano, V., Rivera, E. P.	INVITED: Evaluating Mitigation Strategies for Induced Earthquakes in Light of Recent Moderate Oklahoma Earthquakes. **Yeck, W. L. Y.**, McNamara, D. E. M., Hayes, G. P. H., Rubinstein, J. L. R., Barnhart, W. D. B., Earle, P. S. E., Benz, H. M. B.	Constraints on Crustal Heterogeneity and Q(f) from Regional (<4 Hz) Wave Propagation for the 2009 North Korea Nuclear Test. **Olsen, K. B.**, Jacobsen, B. H., Begnaud, M., Phillips, S. W.	NGA-West2 Empirical Fourier and Duration Models for Active Crustal Regions to Generate Regionally Adjustable Response Spectra. **Bora, S. S.**, Cotton, F., Scherbaum, F.

Time	Governor's Square 15	Governor's Square 16	Governor's Square 12
	From Field Site to Data Center: Network Innovations for Earthquake Early Warning	**Earthquake Rapid Response**	**Overcoming Challenges in Seismic Risk Communication**
9:30 AM	Data Latency, Compression and Encryption. Steim, J. M., **Franke, M.**, Spassov, E. N.	INVITED: Structure of the Main Himalayan Thrust in Nepal Derived from Aftershocks of the 2015 M7.8 Gorkha Earthquake Recorded by the NAMASTE Rapid Response Seismic Network. **Karplus, M. S.**, Nabelek, J., Pant, M., Kuna, V., Sapkota, S. N., Adhikari, L. B., Velasco, A. A., Ghosh, A., Klemperer, S. L., Mendoza, M.	INVITED: Making Sense of Uncertainty: Risk Communication in the Context of Induced Seismicity. **Campbell, N. M.**, Vickery, J. L., Ritchie, L. A.
9:45–10:45 AM	Posters and Break		
	Machine Learning and its Application to Earthquake and Explosion Signal Analysis Session Chairs: Timothy Draelos, Hunter Knox (see page 609)	**Earthquake Rapid Response** (continued)	**Overcoming Challenges in Seismic Risk Communication** (continued)
10:45 AM	STUDENT: On the Use of Machine Learning for Seismic Event Detection. **Bergen, K. J.**, Beroza, G. C.	INVITED: Stranded Slip in the Himalayan Collision Zone and Its Implications for the Seismic Cycle. **Bendick, R.**, Mencin, D., Bilham, R., Burgmann, R.	Getting Ready for Earthquakes and Tsunamis in Puerto Rico: ShakeOut vs Caribe Wave Exercises. **von Hillebrandt-Andrade, C.**, Hincapié-Cárdenas, C., Vanacore, E., Huérfano, V. A., Báez-Sánchez, G., Gómez, G., Benthien, M. L., Wood, M.
11:00 AM	Uncertainty Estimation of Onset Arrival Times Using Parametric Bootstrap of Auto-Regressive Time Series. **Vollmer, C.**, Peterson, M. G., Stracuzzi, D. J.	2015 Mw 7.8 Gorkha Earthquake in Nepal: Imaging of Rupture Complexity and Aftershock Activity Using Global and Local Seismic Network. **Ghosh, A.**, Li, B., Mendoza, M.	
11:15 AM	Applying Machine Learning to Predict Failure. Rouet-LeDuc, B., Hulbert, C., Lubbers, N. E., Barros, K. M., **Johnson, P. A.**	INVITED: Expanding Scales of Rapid Seismic Deployments: New Tools and Techniques to Collect and Explore High-Resolution Datasets. **Cochran, E. S.**	Bhutan Earthquake Desks: An Affordable, Interim Method of Improving School Earthquake Safety in Countries with High Seismic Risk and Few Resources. Tshering, K. D., Bowden, T., Bruno, I., Brutter, A., Diwarkar, L., Kianirad, E., O'Donnell, A., Rodgers, J., **Tucker, B.**

Time	Plaza D	Plaza E	Plaza F	Governor's Square 14
	Fine Scale Structure of the Crust and Upper Mantle…	**Observations and Mechanisms of Anthropogenically …**	**Source Discovery Using Differential Methods…**	**Regional Variations in Seismological Characteristics…**
11:30 AM	INVITED: Lithospheric Foundering and Underthrusting Imaged beneath Tibet. **Niu, F.**, Chen, M., Tromp, J., Lenardic, A., Lee, C. T., Cao, W., Ribeiro, J.	Probing Injection-Induced Seismicity in Northern Oklahoma with a Dense Array. **Dougherty, S. L.**, Cochran, E. S., Harrington, R. M.	Physical Relations that Quantify the Significance of the Waveform Correlation: Application to the North Korean Explosions. **Carmichael, J. D. C.**	INVITED: Implications from Comparison of the Ground Motion Prediction Equation and Global Ground Motion Dataset. **Si, H.**, Koketsu, K., Miyake, H., Ibrahim, R.
11:45 AM	INVITED: Plateau Subduction, Intraslab Seismicity and the Denali Volcanic Gap. **Bostock, M. G.**, Chuang, L., Wech, A. G., Plourde, A. P.	Geothermal Induced Seismicity: What Links Source Mechanics and Event Magnitudes to Faulting Regime and Injection Rates? **Martinez-Garzon, P.**, Kwiatek, G., Bohnhoff, M., Dresen, G.	Surface Disturbances at the Punggye-ri Nuclear Test Site: Another Indicator of Nuclear Testing? **Pabian, F.**, Coblentz, D.	Reveal the Difference between Ground Motion Models under Correlated Observations. **Mak, S**
Noon–1:30 PM	Lunch			
	Fine Scale Structure of the Crust and Upper Mantle (continued)	**Assessment and Management of Hazards from Seismicity Induced by Hydraulic Fracturing** Session Chairs: Gail Atkinson, David Eaton, Ryan Schultz, Honn Kao (see page 596)	**The Mw7.8 Kaikoura Earthquake** Session Chairs: Bill Fry and Matt Gerstenberger (see page 624)	**Earthquake Impacts on the Natural and Built Environment** Session Chairs: Eric Thompson, Kate Allstadt, Kishor Jaiswal, Nilesh Shome (see page 598)
1:30 PM	INVITED: Linearization Scheme for 1D Anisotropic Inversion of P Receiver Functions. **Park, J.**	INVITED: Poroelastic Stress Change and Fault Slip Induced by Fluid Injection. **Liu, Y. J.**, Deng, K., Harrington, R. M.	INVITED: An Overview of the Seismic Source and Ground Motions during the Mw 7.8 Kaikoura Earthquake, New Zealand. **Kaiser, A. E.**, Horspool, N., McVerry, G., Holden, C., Hamling, I., Kaneko, Y., Benites, R., Wotherspoon, L., Fry, B., Houtte, C., Avery, H.	INVITED: HayWired Scenario Mainshock—Liquefaction Probability Mapping and Hazus Loss estimation. **Wein, A.**, Knudsen, K., Seligson, H., Jones, J.

Time	*Governor's Square 15*	*Governor's Square 16*	*Governor's Square 12*
	Machine Learning and its Application to Earthquake and Explosion Signal Analysis	**Earthquake Rapid Response**	**Overcoming Challenges in Seismic Risk Communication**...
11:30 AM	Machine and Auditory Clustering of a Large Set of Seismic Events. **Pate, A.**, Holtzman, B. K., Paisley, J. W., Waldhauser, F., Repetto, D.	STUDENT: Aftershock Sequence of the 2011 Virginia Earthquake with High Spatial Resolution and Low Magnitude Threshold Using the Dense AIDA Array and Back-Projection. **Beskardes, G. D.**, Hole, J. A., Wu, Q., Chapman, M. C., Davenport, K. K., Wang, K., Michaelides, M., Brown, L. D., Quiros, D. A.	How Science Impacts Decision Making: UCERF 3 Case Study for Loss Estimation in California. **Bolton, M. K.**, Thenhaus, P. C., Larsen, T.
11:45 AM	Examples and Analysis of Adaptive Self-Tuning of a Seismic Signal Detector. **Draelos, T. J.**, Knox, H. A., Peterson, M. G., Ziegler, A. E.	Aftershock Imaging with Dense Arrays (AIDA): Insights from the 2011 Mineral Springs Virginia RAPID Experiment. **Brown, L. D.**, Hole, J. A., Quiros, D. A., Davenport, K. K., Kim, D., Beskardes, G. D., Chapman, M. C., Mooney, W. D.	People Listen to Seismologists and Still Don't Prepare for Earthquakes...Why? **Lamontagne, M.**, Flynn, B.
Noon–1:30 PM	Lunch		
	Recent Innovations in Geophone Array Seismology Session Chairs: Fan-Chi Lin, Marianne Karplus (see page 615)	**SSA-ESC Joint Session on Advances in Geotechnical Borehole Arrays, Data and Analyses** Session Chairs: Jamison Steidl, Ramin Motamed, Umit Dikmen, Stefano Parolai (see page 622)	**Estimating Earthquake Hazard from Geodetic Data** Session Chairs: Jeff Freymueller, Elieen Evans, Jessica Murray (see page 603)
1:30 PM	INVITED: Structural Properties and Detection of Small Events in the San Jacinto Fault Zone and Other Southern California Regions Based on Seismic Array Data. **Ben-Zion, Y.**	Body Wave Interference at Borehole Receivers Helps to Define the Local Velocity Model. **Priolo, E.**, Laurenzano, G., Mucciarelli, M., Martelli, L., Romanelli, M.	INVITED: STUDENT: Estimating Interseismic Surface Strain and Moment Deficit Rates in Southern California Using Geodetic Data. **Maurer, J. L.**, Segall, P., Johnson, K.

Time	Plaza D	Plaza E	Plaza F	Governor's Square 14
	Fine Scale Structure of the Crust and Upper Mantle	**Assessment and Management of Hazards…**	**The Mw7.8 Kaikoura Earthquake**	**Earthquake Impacts on the Natural and Built…**
1:45 PM	INVITED: Fine Scale Structure of Seismic Anisotropy beneath Western Tibet.. **Levin, V.**, Schulte-Pelkum, V.	INVITED: Statistical Modeling of Induced Seismicity. **Shcherbakov, R.**	Multiple Fault Ground Surface Ruptures in the 14 November 2016 Kaikoura Earthquake, New Zealand. **Litchfield, N. J**., Benson, A., Bischoff, A., Hatem, A., Barrier, A., Nicol, A., Wandres, A., Lukovic, B., Hall, B., Gasston, C., Asher, C., Grimshaw, C., Madugo, C., Fenton, C., Hale, D., Barrell, D. J. A., Heron, D. W., Strong, D. T., Townsend, D. B., Noble, D., Fenton, F., Howarth, J., Pettinga, J., Kearse, J., Williams, J., Manousakis, J., Borella, J., Mountjoy, J., Rowland, J., Clark, K. J., Pedley, K., Sauer, K., Berryman, K. R., Hemphill-Haley, M., Stirling, M. W., Villeneuve, M., Cockroft, M., Khajavi, N., Barnes, P., Villamor, P., Carne, R., Langridge, R. M., Zinke, R., Van Dissen, R. J., McColl, S., Cox, S. C., Lawson, S., Little, T., Stahl, T., Cochran, U. A., Toy, V., Ries, W. F., Juniper, Z.	STUDENT: Can We Predict the Impact of Seismically Induced Landslides? **Jessee (Nowicki), M. A.**, Hamburger, M. W., Ferrara, M. R., Robeson, S., FitzGerald, C.
2:00 PM	Lithospheric Fabric and Shear Zones in Southern California and the Basin and Range from Anisotropic Receiver Function Conversions and Other Stress and Strain Observables. **Schulte-Pelkum, V.**, Becker, T. W., Miller, M. S.	A Seismological Overview of the Induced Earthquakes in the Duvernay Play near Fox Creek, Alberta. **Schultz, R.**, Wang, R., Gu, Y. G., Haug, K., Atkinson, G.	The M7.8 2016 Kaikoura Earthquake in the Context of the National Seismic Hazard Model. **Stirling, M. W.**, Gerstenberger, M. C.	INVITED: STUDENT: The Impact of Rockfalls on Dwellings During the 2011 Christchurch, New Zealand Earthquakes. **Grant, A.**, Wartman, J., Massey, C., Olsen, M. J., O'Banion, M., Motley, M.
2:15 PM	Comparative Riftology: Insights from Crustal Structure Into the Evolution of Continental Rifts and Passive Continental Margins. **Stein, S.**, Stein, C., Kley, J., Keller, G. R., Wysession, M., Fredricksen, A., Elling, R.	STUDENT: Event Origin Depth Uncertainty - Estimation and Mitigation Using Waveform Similarity. **Biryukov, A.**, Chzen, E., Dettmer, J., Eaton, D.	Widespread Triggering of Slow-Slip Earthquakes during the Mw7.8 Kaikoura Earthquake: Implications for Earthquake Forecasting. **Gerstenberger, M. C.**, Wallace, L., Fry, B.	Rapidly Imaging Earthquake Damage Using Satellite SAR Data: 2016 Central Italy Earthquakes. **Yun, S.**, Liang, C., Webb, F., Simons, M., Manipon, G., Dang, L., Fielding, E., Gurrola, E., Agram, P., Hua, H., Owen, S., Diaz, E., Milillo, P., Rosen, P.

Time	Governor's Square 15	Governor's Square 16	Governor's Square 12
	Recent Innovations in Geophone Array Seismology	**SSA-ESC Joint Session on Advances in Geotechnical Borehole Arrays…**	**Estimating Earthquake Hazard from Geodetic Data**
1:45 PM	Characterizing Fault Damage Zone Structure Using Low-Cost Large-N Temporary Deployments of Fairfield Nodal Three-Component Instruments: Case Studies from the San Jacinto and Denali Faults. **Allam, A. A.**, Lin, F., Share, P., Wang, Y., Rabade, S., Berg, E., Ben-Zion, Y., Vernon, F., Tape, C., Schuster, G., Karplus, M.	Variation of High Frequency Spectral Attenuation Kappa in Vertical Arrays: A Case Study from Istanbul. Tanircan, G., **Dikmen, S. U.**	STUDENT: Strain Accumulation on Faults beneath Los Angeles: The Importance of the Sedimentary Basin, the Roles of Thrust and Strike-Slip Faulting, and the Return Period of M>7 Earthquakes. **Rollins, J. C. R.**, Avouac, J. P. A., Landry, W. L., Barbot, S. D. B., Argus, D. F. A.
2:00 PM	INVITED: Data Mining of IRIS Wavefield Experiment in Oklahoma. **Nakata, N.**	STUDENT: Investigation of Bi-Directional Shaking Effects in One-Dimensional Site Response Analysis Utilizing Geotechnical Downhole Array Data. Li, G., **Motamed, R.**, Dickenson, S.	Moment Accumulation Rates on Faults in Southern California from GPS Data. **Johnson, K. M.**, Maurer, J., Segall, P.
2:15 PM	Shallow Crustal Structure Revealed by the Yangtze River Large Volume Airgun Shot Experiment in Eastern China. **Yao, H. J.**, She, Y. Y., Zhai, Q. S.	STUDENT: Seismic Non-Linear Behavoir of Soil Inferred by the Analysis of the Kik-Net Borehole Data. **Castro Cruz, D.**, Bertrand, E., Régnier, J., Courboulex, F.	Model Uncertainties in Geodetic Slip Rates for Seismic Hazard in California. **Evans, E. L.**

Time	Plaza D	Plaza E	Plaza F	Governor's Square 14
	Fine Scale Structure of the Crust and Upper Mantle	**Assessment and Management of Hazards…**	**The Mw7.8 Kaikoura Earthquake**	**Earthquake Impacts on the Natural and Built…**
2:30 PM	A New Lithospheric Density Model of the Conterminous United States and Implications for Intraplate Seismicity. **Levandowski, W.**, Herrmann, B., Boyd, O. S., Shen, W., Briggs, R. W., Gold, R. D.	Potential Seismic Hazards from Induced Earthquakes in Eastern Kentucky. **Wang, Z.**, Carpenter, N. S., Zhang, L. F.	Communicating Science at Speed: Lessons from Responding to the M7.8 Kaikoura Earthquake. **McBride, S. K.**, Kaiser, A., Gledhill, K., Jolly, G., Fry, W., Little, C., Balfour, N., Page, S., Holden, C.; Ristau, J.; Gerstenberger, M.; Leonard, G.; Bannister, S.; Rhoades, D.; Christopherson, A. M.; Potter, S.; Becker, J.; Johnston, D. M.; Wallace, L.; Cochran, U.; Clark, K.; Power, W.; Kaneko, Y; Jack, H.; Dellow, S.; Brackley, H.; Woods, R.; Daly, M.; Hamling, I.; Hreinsdottir, S.; Berryman, K.; Pinal, C.; Bland, L.; Villamor, P.; Van Dissen, R.; Thomson, J.; Massey, C.; Guest, R.; Clitheroe, G.; Townend, J.	INVITED: Improving Regional Liquefaction Hazard Maps Using Hydrological Remote Sensing Data: A Proof of Concept Study at Imperial County. **Mital, U.**, Asimaki, D., Rajasekaran, E., Das, N. N., Stock, J.
2:45–3:45 PM	Posters and Break			
	Recent Advances in Earthquake Triggering and Aftershock Forecasting Session Chairs: Margarita Segou, Andrea Llenos (see page 614)	**Assessment and Management of Hazards from Seismicity Induced by Hydraulic Fracturing** (continued)	**The Mw7.8 Kaikoura Earthquake** (continued)	**Earthquake Impacts on the Natural and Built Environment** (continued)
3:45 PM	INVITED: Triggering of Major Earthquakes near the Southernmost Terminus of the San Andreas Fault: Implications of Recent Earthquake Clusters for Earthquake Risk in Southern California. **Hauksson, E.**, Meier, M. A., Ross, Z. E., Jones, L. M.	INVITED: Correlation Algorithms to Better Characterize Seismicity Induced by Hydraulic Fracturing. **Brudzinski, M. R.**, Skoumal, R. J., Rakowski, J., Smith, S., Kozlowska, M. A., Baxter, N. D., Friberg, P. A., Currie, B. S.	Back-Projection of Regional Data Yields a Detailed Picture of Complex Multi-Fault Rupture During the Mw7.8 Kaikoura Earthquake. **Fry, B.**, Kao, H.	INVITED: STUDENT: Ground Motion Prediction Equations for Arias Intensity, Cumulative Absolute Velocity, and Peak Incremental Ground Velocity for Rock Sites in Different Tectonic Environments. **Bullock, Z.**, Dashti, S., Liel, A. B., Karimi, Z., Bradley, B. A.
4:00 PM	Foreshocks to Aftershocks: Insights into the M7.1 Te Araroa Earthquake (NZ), from Matched-Filter Detection. **Warren-Smith, E.**, Fry, B.	Dynamics of Fault Activation by Hydraulic Fracturing in Overpressured Shale Formations. **Eaton, D. W.**, Bao, X., Cheadle, B. A.	Reconciling the Dilemma of a Megathrust Earthquake or a Crustal Strike-Slip Faulting Event: The 2016 Kaikoura, NZ Earthquake. **Furlong, K. P.**, Herman, M. W., Hayes, G. P.	INVITED: Case Study: How Stochastic Modeling is Driving the Next Generation of Resilience. **Stillwell, K.**, Lee, Y. J., Huyck, C. K.

Time	*Governor's Square 15*	*Governor's Square 16*	*Governor's Square 12*
	Recent Innovations in Geophone Array Seismology	**SSA-ESC Joint Session on Advances in Geotechnical Borehole Arrays…**	**Estimating Earthquake Hazard from Geodetic Data**
2:30 PM	Imaging Seismic Structure of Geothermal Reservoir with Large N Array at Brady Hot Springs, Nevada. **Thurber, C.**, Zeng, X., Parker, L., Lord, N., Fratta, D., Wang, H., Matzel, E., Robertson, M., Feigl, K. L., PoroTomo Team	Investigation of Soil-Structure Interaction Effects through Wave Propagation Analysis in Building-Soil-Layers. Petrovic, B., **Parolai, S.**, Pianese, G., Dikmen, U. S., Moldobekov, B., Orunbaev, S., Paolucci, R.	A New Geodetically-Derived Seismicity Model for Italy. **D'Agostino, N.**
2:45–3:45 PM	Posters and Break		
	Recent Innovations in Geophone Array Seismology (continued)	**Scaling and Empirical Relationships of Moderate to Large Earthquakes: Re-scaling or Re-thinking?** Session Chairs: Laura Peruzza, P. Martin Mai, Lucilla Benedetti (see page 619)	**Estimating Earthquake Hazard from Geodetic Data** (continued)
3:45 PM	INVITED: Seismicity Detection and Signal Analysis with the Mount St Helens Nodal Array. **Hansen, S. M.**, Schmandt, B., Glasgow, M.	INVITED: Fault Slip Rate and Constant Stress Drop as Improvements to Magnitude-Length Scaling. **Biasi, G. P.**, Anderson, J. G., Wesnousky, S. G.	STUDENT: Slow Slip Events and the Earthquake Cycle: Nicoya, Costa Rica. **Voss, N. K. V.**, Dixon, T. H. D., Malservisi, R. M., Protti, M. P.
4:00 PM	INVITED: Nodal Seismic Recording of Aftershocks of the Mw5.8 Pawnee Earthquake. **Keranen, K.**, Gallacher, R., Savage, H. M.	INVITED: Earthquake Scaling Relationships Estimated from 25 Years of Source Models Derived from InSAR Data. **Funning, G. J.**, Weston, J., Ferreira, A. M. G.	INVITED: STUDENT: Geodetically-Constrained Viscoelastic Block Models and Time-Dependent Stress Transfer along the North Anatolian Fault. **DeVries, P. R.**, Krastev, P., Meade, B. J.

Time	Plaza D	Plaza E	Plaza F	Governor's Square 14
	Recent Advances in Earthquake Triggering...	**Assessment and Management of Hazards...**	**The Mw7.8 Kaikoura Earthquake**	**Earthquake Impacts on the Natural and Built...**
4:15 PM	Assessing WCEDS as an Alternative Pipeline Processing System. **Arrowsmith, S.**, Young, C., Pankow, K.	Mitigation Strategies to Prevent Damage to Critical Infrastructure Due to Induced Seismicity. **Atkinson, G. M.**	Preliminary Broadband Ground Motion Simulations of the 14 November 2016 Mw7.8 Kaikoura, New Zealand Earthquake. **Bradley, B. A.**, Razafindrakoto, H. N. T.	STUDENT: Broadband Ground Motion Simulation within the City of Duzce (Turkey) and Building Response Simulation. **Ozlu, E.**, Karimzadeh, S., Askan, A.
4:30 PM	Aftershock Duration and the Prevalence of Orphaned Aftershocks in the Apparent Background Rate. **van der Elst, N. J.**	Geomechanical Modeling of Induced Seismicity from Multi-Stage Hydraulic Fracturing. **Maxwell, S. C.**, Grob, M.	Kinematic Source Modeling and 3D Wavefield Simulations of the 2016 M7.8 Kaikoura Earthquake. **Holden, C. E.**, Kaneko, Y.	Practical Uses of a Scenario Describing Earthquake and Earthquake-Induced Landslide Impacts on Aizawl, India. Rodgers, J. E., **Clahan, K. B.**, Tobin, L. T., Kumar, H. K., Holmes, W. T., Seeber, L., Gahalaut, V. K., Ramancharla, P. K., Tlau, R., Jaisi, N., Zohmingthanga, Mintier, L., Katuri, A., Lalhmangaiha, D.
4:45 PM	Constraining the Magnitude of Extreme Aftershocks. **Shcherbakov, R.**, Zhuang, J., Ogata, Y.	Anisotropic Inhomogeneous Modeling of Hydraulic Fracturing Surveys. **King, J.**, Taylor, S., Hanson, D.	Improving Coseismic Landslide Models: Lessons Learned from the 2016 Kaikoura, New Zealand Earthquake. **Allstadt, K. E.**, Godt, J. W., Jibson, R. W., Rengers, F. K., Thompson, E. M., Wald, D. J., Massey, C. I., Cox, S. C.	Update to FEMA 366: Estimated Annualized Earthquake Losses for the United States. **Jaiswal, K. S.**, Bausch, D., Rozelle, J., Holub, J., McGowan, S., McAfee, S., Tong, M.
5:00–5:45 PM	Pint and a Poster			
5:45–6:45 PM	Joyner Lecture			
6:45–8:00 PM	Reception			

Time	*Governor's Square 15*	*Governor's Square 16*	*Governor's Square 12*
	Recent Innovations in Geophone Array Seismology	**Scaling and Empirical Relationships of Moderate to Large Earthquakes…**	**Estimating Earthquake Hazard from Geodetic Data**
4:15 PM	Calibrating Dense Spatial Arrays for Amplitude Statics and Orientation Errors. **Langston, C. A.**	Examination of Source Scaling Relations for Crustal Earthquakes in Japan. Irikura, K. I., **Miyake, H. M.**, Miyakoshi, K. M., Kamae, K. K., Yoshida, K. Y., Somei, K. S., Kurahashi, S. K.	Strain Invariance over an Earthquake Cycle and Geodetic Assessment of Seismic Hazard. Hussain, E., Wright, T. J., Walters, R. J., Bekaert, D. P. S., Lloyd, R., **Weiss, J. R.**
4:30 PM	INVITED: Using Graph Clustering to Locate Sources within a Dense Sensor Array. **Gerstoft, P.**, Riahi, N.	STUDENT: Surface Rupture Effects on Earthquake Moment-Area Scaling Relations. **Luo, Y.**, Ampuero, J. P., Miyakoshi, K., Irikura, K.	Dark Energy and Earthquakes: Elastic Strain Invisible to Geodesy. **Bilham, R.**, Mencin, D., Bendick, R., Burgmann, R.
4:45 PM	STUDENT: Weighted Random Sampling in Seismic Event Detection/Location (WRASED): Applications to Local, Regional, and Global Seismic Networks. **Zhu, L.**, Li, Z., Peng, Z., Liu, E., McClellan, J. H.	Italian Surface Faulting Earthquakes vs Empirical Scaling Laws. Cinti, F. R., **Pantosti, D.**, Civico, R., Villani, F., Pucci, S., De Martini, P. M.	INVITED: A Robust Estimation of the North American Intra-Continental Strain Rate Field with Implications for Seismic Hazard. **Kreemer, C.**, Hammond, W. C., Blewitt, G.
	Pint and a Poster		
	Joyner Lecture		
	Reception		

Fine Scale Structure of the Crust and Upper Mantle (see page 635).

1. Student: Lithospheric Structure of Canadian Lithosphere from Joint Interpretation of Receiver Functions and Regional Travel Time Tomography. **Barantseva, O. A.**, Vinnik, L. P., Farra, V., van der Hilst, R. D.
2. Developing and Validating Path-Dependent Travel Time Uncertainty Estimates for All Phases of the Regional Seismic Travel Time (RSTT) Model. **Begnaud, M. L.**, Anderson, D. N., Phillips, W. S., Myers, S. C., Ballard, S.
3. The 3D Crustal Velocity Structure Under the Changbaishan Volcanic Area in Northeast China Inferred from Ambient Noise Tomography. **Chen, Q. F.**, Wang, W.
4. Active Magmatic Underplating in an Intraplate Setting: Crust/Mantle Moho Transition in the Western Eger Rift, Central Europe. **Hrubcova, P.**, Geissler, W. H., Braeuer, K., Kaempf, H., Vavrycuk, V., Tomek, C.
5. The Effects of the Iceland Plume Track on the Greenland's Lithosphere. **Knezevic Antonijevic, S.**, Lees, J. M.
6. Velocity Model beneath the Reykjanet Array Derived from Rayleigh Wave Dispersion. **Brokesova, J.**, Malek, J., Novotny, O.
7. 3D Local Earthquake Tomography of the Cocos Ridge Subduction at the Southeastern End of the Middle American Trench. Arroyo, I., **Linkimer, L.**, Grevemeyer, I., Alvarado, G.
8. The Lower Crust and Upper Mantle beneath the Tien Shan from Full Waveform Tomography. Baker, B. I. B., **Roecker, S. W. R.**
9. Upper Mantle Layering in the North American Craton Using Short and Long Period Seismic Constraints. **Romanowicz, B. A.**, Caló, M., Roy, C., Clouzet, P., Yuan, H., Bodin, H., Maurya, S.
10. A Global Radial Anisotropic Model of the Upper Mantle from Surface Wave Observations. **Priestley, K.**, Ho, T., Debayle, E.
11. Student: Composite Stochastic Models for Fine-Scale Structure of the Crust and Upper Mantle. **Song, X.**, Jordan, T. H.
12. Seismic Structure of the Crust and Upper Mantle of Madagascar. **Wysession, M. E.**, Pratt, M. J., Andriampenomanana, F., Rakotondraibe, T., Ramirez, C., Aleqabi, G., Wiens, D. A., Nyblade, A. A., Shore, P. J., Rambolamanana, G., Tucker, R. J.
13. Assessing the Robustness of Seismic Imaging Methods: A Study toward Quantifying Resolution in Seismic Tomography. **Youssof, M.**, Mai, M.

Source Discovery Using Differential Methods: Applications to Explosion Monitoring (see page 650).

14. Characterizing Blast Wave Behavior at Solid-Gas Interfaces of Varying Curvature. **Chojnicki, K. N.**, Cooper, M. A., Guo, S.
15. Using Short-Period Surface Waves (Rg) as a Yield Estimator at Local Distances. **Napoli, V. J.**, Russell, D. R., Leidig, M.
16. Investigation of Seismic-Acoustic Coupling and MRg-Yield Relations through Surface Wave Analysis of Explosive Data in Different Geologies. **Phillips-Alonge, K. E.**, Napoli, V., Russell, D., Reinke, R.
17. Discriminating between Shallow, Natural Earthquakes and Blasts near Sussex, New Brunswick, Canada. **Bent, A. L.**, Lamontagne, M., Kolaj, M., McCormack, D. A., Adams, J.
18. Wave Propagation Effects on P/S Ratio at Local Distances for an SPE Explosion and Shallow Earthquake. **Pitarka, A.**, Walter, W., Chiang, A., Wagoner, J., Pyle, M.
19. Amplitude Difference Methods for Source, Site and Path Models Used in Explosion Monitoring Research. **Phillips, W. S.**, Fisk, M. D., Begnaud, M. L., Stead, R. J.
20. Coda-Wave Interferometry-Derived Source Separation between SPE-1 and -2 and Near-Source Medium Change between SPE-2 and -3. **Ford, S. R.**, Walter, W. R.
21. A Dry Alluvium Constitutive Model for Simulating the Source Physics Experiments (SPE). **Ezzedine, S.**, Vorobiev, O., Antoun, T., Glenn, L.
22. Numerical Simulation of near Field Ground Motions Observed during the Source Physics Experiments. **Vorobiev, O. Y.**, Ezzedine, S. M., Antoun, T. H., Glenn, L. A.
23. A Method for Yield Scaling FFT Velocity Amplitude Spectra from Chemical Explosions. **Steedman, D. W.**, Cashion, A. T., Bradley, C. R.
24. Seismic Wave Propagation from Underground Explosions: Influence of Topography on Wave Scattering and Ground Motions.. **Hirakawa, E. T.**, Ezzedine, S., Vorobiev, O., Pitarka, A., Glenn, L., Antoun, T., Walter, W.
25. Cross Borehole Change Detection Imaging for the Source Physics (SPE) at the Nevada National Security Site (NNSS). **Hoots, R.**, Knox, A., Abbott, E., Preston,
26. P-wave Attenuation of Yucca Flat, Nevada National Security Site. **Hoots, R.**, Abbott, E., Preston,
27. Towards Array Discrimination Using a Large-N deployment at the Nevada National Security Site. **Pyle, M. L.**, Euler, G. G.
28. Applying Insights from the Nevada Source Physics Experiments to the DPRK Declared Nuclear Test Seismic Signals. **Walter, W. R.**, Ford, S. R.
29. Relative Energy and Aperture Estimation of the Five Explosions in North Korea. **Li, L.**, Hao, C. Y.

30. Cross Comparison of Five DPRK Events Using Seismic Data of the International Monitoring System. **Villarroel, M.**, Bobrov, D., Kitov, I., Rozhkov, M.
31. Comparative Source Analysis of the DPRK Nuclear Events at Regional Scale: What We Can Learn About the Explosive Nature of the Events from Moment Tensor Inversions and MSVMAX. **Guilhem Trilla, A.**, Cano, Y.
32. Application and Validation of a Relative Relocation Technique for Explosion Monitoring. **Begnaud, M. L.**, Cleveland, K. M., Anderson, D. N., Pabian, F. V., Phillips, W. S., Rowe, C. A., Ballard, S.

Observations and Mechanisms of Anthropogenically Induced Seismicity (see page 639).

33. Tilt Trivia: A Multiplayer App Teaching Induced Seismicity Concepts. **Kilb, D. L.**, Yang, A., Garrett, N., Hilke, V., Pankow, K., Rubinstein, J., Linville, L.
34. Student: Identifying New Earthquake Templates Adds Valuable Information to Induced Seismicity Sequences. **Linville, L. M.**, Pankow, K. L., Kilb, D. L., Rubinstein, J. L.
35. Persistent Multiplets in EGS Reservoir: The Case Study of Soultz-sous-Forêts, France. **Cauchie, L.**, Lengliné, O., Schmittbuhl, J.
36. Student: Spectrogram-Based Detection of Small Earthquakes in Continuous Waveform Data. **Cheng, Y.**, Ben-Zion, Y.
37. Reservoir Delineation from Microseismic Events at the Blue Mountain Geothermal Site. **Templeton, D.**, Matzel, E., Myers, S., Cladouhos, T.
38. 2016 Observations and Mitigation Strategies for Hydraulic Fracture Induced Seismicity in Ohio. Friberg, P., **Dricker, I.**, Kozlowska, M., Brudzinski, M.
39. Microseismicity Recorded in the Geothermal Areas of the Central Apennines (Italy). **Braun, T.**, Caciagli, M., Carapezza, M. L., Famiani, D., Gattuso, A., Lisi, A., Marchetti, A., Mele, G., Pagliuca, N.M.
40. Evaluating the Efficacy of Oklahoma Corporation Commission Wastewater Disposal Reductions in Oklahoma. **Walter, J. I.**, Murray, K. E., Chang, J. C., Boak, J.
41. Performance of the Colombian Regional Seismic Network and of a Sparse Local Network for Detection and Characterization of the Seismic Activity in the Oil Zone of Puerto Gaitán, Llanos Orientales Basin (Colombia). Siervo, D., Reyes, M. D., **Dimate, M. C.**
42. The Milan Kansas Earthquake Fault: Narrow, Hydraulically Conductive and Critically-Stressed. **Hearn, E. H.**, Kolterman, C. E.
43. Student: Interpretation of Microseismicity Observed from Surface and Borehole Seismic Arrays During Hydraulic Fracturing in Shale - Bedding Plane Slip. **Stanek, F.**, Jechumtalova, Z., Eisner, L.
44. The Dallas-Fort Worth Airport Earthquake Sequence: Seismicity Beyond Injection Period. **Ogwari, P.**, DeShone, H., Hornbach, M. J.
45. A Half-Century of Induced Earthquakes in the Los Angeles Basin? **Hough, S. E.**, Page, M.
46. Comparison of Elastic Wavefield Simulations, Ray Tracing and Surface Array Data at the Groningen Gas Field: Implications for Induced Seismic Event Location and Characterization. **Wyer, P.**, Zurek, B., Burnett, W. A., Gist, G.

Assessment and Management of Hazards from Seismicity Induced by Hydraulic Fracturing (see page 627).

47. Induced Seismicity Above Crystalline Basement: An Example from Alberta, Canada. **Bao, X.**, Eaton, D. W.
48. Student: Improving Earthquake Catalog Locations in the Western Canada Sedimentary Basin Using the Double-Difference Method. **Palmer, S. M.**, Atkinson, G. M.
49. Student: An Overview of Ground Motion Characteristics from Potentially Induced Seismic Events in Alberta, Canada. **Kaski, K. M.**, Atkinson, G. M.
50. Student: Decision Analysis in Microseismic Surveys Using the Value of Information Technique: A Case Study from the Salton Sea Geothermal Field. **Jreij, S. F.**, Trainor-Guitton, W., Matzel, E., Pyle, M.
51. Delineation of Basement Faults in Oklahoma and the Relation to Induced Earthquake Sequences. **Shah, A. K.**, Crain, K.
52. Student: Actions and Regulatory Guidelines for Oklahoma Earthquakes Outside the "Normal" Areas of Seismic Activity. **Chang, J. C.**, Walter, J. I.
53. A Systematic Seismogenic Pattern of Injection-Induced Earthquakes in Northeast British Columbia and Western Alberta, Canada. **Kao, H.**, Visser, R., Smith, B., Babaie Mahani, A.
54. Student: Improved Seismological and Geological Characterization of Seismicity Induced by Wastewater Disposal Near Marietta, Ohio. **Leveridge, M. C.**, Brudzinski, M. R., Currie, B. S., Skoumal, R. J., Free, J. C.
55. Monitoring the Background Earthquake Activity on Anticosti Island, Quebec, Canada, Prior to Potential Hydraulic Fracturing Work. **Lamontagne, M.**, Lavoie, D., Kao, H.
56. Student: Monitoring Microseismicity in the Rome Trough, Eastern Kentucky: Year One Observations and Network Performance. **Holcomb, A. S.**, Carpenter, N. S., Woolery, E. W., Wang, Z.
57. QuakeMonitorTM: Utilizing a Surface-Based Automated Sensor Network to Monitor and Detect Induced Seismic Events in a Highly-Active Industrial Environment. **Mohamud, A. H.**, Jarpe, S., Taylor, S. R., Weir-Jones, I.

Recent Innovations in Geophone Array Seismology (see page 643).

58. IRIS Wavefields Community Experiment Using Nodal Arrays. **Sweet, J.**, Anderson, K., Woodward, R., Frassetto, A.
59. PH5 for Archiving and Translating Node and Other Geophysical Data: Examples from the IRIS Community Wavefield Demonstration Experiment. Azevedo, R. S., Hess, D., **Beaudoin, B. C.**
60. Huddle Tests of Fairfield Nodes and Texans on a UTEP Seismic Pier. **Harder, S. H.**, Karplus, M., Kaip, G. M.
61. The Source Physics Experiment Large N Array. **Mellors, R. J.**, Pitarka, A., Matzel, E., Walter, W., Snelson, C., Abbott, R.
62. Geophysical Structure at the SPE Site Using Surface Waves Recorded by the Large-N Seismic Array. **Chen, T.**, Snelson, C. M.
63. Student: Internal Structure of the San Jacinto Fault Zone at Blackburn Saddle from a Dense Linear Deployment across the Fault. **Share, P.**, Allam, A. A., Ben-Zion, Y., Lin, F., Vernon, F. L., Karplus, M., Schuster, G.
64. Student: Detection of Small Earthquakes with Dense Array Data on the San Jacinto Fault Zone. **Meng, H.**, Ben-Zion, Y.
65. Signal and Noise Coherence Lengths from 1Hz to 100Hz Using Large-N Deployments in Nevada and Oklahoma. **Euler, G. G.**, Pyle, M. L.
66. Student: Detecting Seismicity in a Prospective Geothermal Play, Using a 48 Geophone Array. **Trow, A.**, Linville, L., Pankow, K., Wannamaker, P.
67. Student: Preliminary Results from the Sevilleta Array in the Central Rio Grande Rift, NM: Virtual Source Reflection Imaging of the Socorro Magma Body. **Finlay, T.**, Worthington, L., Schmandt, B., Hansen, S., Bilek, S., Aster, R., Ranasinghe, N.
68. Student: Applying Cross-Correlation Methods to Broadband and Nodal Data to Detect and Locate Earthquakes Associated with the Socorro Magma Body. **Vieceli, R. E.**, Bilek, S. L., Worthington, L. L., Schmandt, B., Aster, R. C.
69. Student: Seismic Interferometry of the Bighorn Mountains: Using Virtual Source Gathers to Increase Fold in Sparse-Source, Dense-Receiver Active-Source Data. **Plescia, S. M.**, Sheehan, A. F., Haines, S. S., Cook, S. W., Worthington, L. L.
70. Student: 3D Basement Structure of Granite-Rhyolite Province in Midcontinent U.S. Using "Surplus" Data from Oil and Gas Explorations. **Kim, D.**, Brown, L. D.
71. Reflection Imaging with Earthquake Sources and Dense Arrays. **Quiros, D. A.**, Brown, L. D., Davenport, K. K., Hole, J. A., Cabolova, A., Chen, C., Han, L., Chapman, M. C., Mooney, W. D.

Regional Variations in Seismological Characteristics: Implications for Seismic Hazard Analysis (see page 646).

72. On the Regional Characteristics of the Components of Sigma Based on a Global Digital Strong-Motion Dataset. **Cauzzi, C.**, Faccioli, E.
73. USGS National Crustal Model for the Western United States, v1.0. **Boyd, O. S.**, Shah, A. K.
74. Ground-Motion Attenuation in the Sacramento-San Joaquin Delta, California from Seven Bay Area Earthquakes, Including the 2014 M6.0 South Napa Earthquake. **Erdem, J. E.**, Boatwright, J., Fletcher, J. B.
75. Student: The Relationship Between Site Conditions and Kappa: Some Recent Observation. **Palmer, S. M.**, Atkinson, G. M.
76. Student: Seismic Wave Propagation in Shallow Layers at the GONAF-Tuzla Site, Istanbul, Turkey. **Raub, C.**, Bohnhoff, M., Petrovic, B., Parolai, S., Malin, P.
77. The Effect of a Sedimentary Wedge on Earthquake Ground Motions: The Influence of Eastern U.S. Atlantic Coastal Plain Strata. **Pratt, T. L.**, Magnani, M. B.
78. Toward Estimating Site Effect in the Central United States from HVSR and Deep Borehole Recordings. **Carpenter, N. S.**, Wang, Z., Woolery, E. W.
79. Simulation of Hazard Consistent Site-Specific Time Histories Using Empirical Fourier Amplitude Spectrum Prediction Equations. **Traversa, P.**, Zentner, I.
80. Student: Applicability of Peak Frequency as a Site-Effects Indicator in California. **Hassani, B.**, Atkinson, G. M.
81. Student: Rupture Direction, Basin, and Distance Effects on Ground Motions from M7 Earthquakes on the Salt Lake City Segment of the Wasatch Fault, Utah. **Wang, N.**, Roten, D., Olsen, K. B., Pechmann, J. C.
82. An Equivalent Point-Source Stochastic Simulation of the NGA-West2 Ground Motion Prediction Equations. **Zandieh, A.**, Pezeshk, S., Campbell, K. W.
83. Examination of Ground Motion Simulation Modeling Uncertainty for the 2010 Mw 7.1 Darfield, New Zealand Earthquake. **Razafindrakoto, H. N. T.**, Bradley, B. A.
84. Student: Partially Nonergodic Region Specific GMPEs for Iran. **Sedaghati, F.**, Pezeshk, S.
85. Student: Evaluating Fundamental Seismological Parameters for Israel. **Giveon, M.**, Kamai, R.
86. Development of a New Strong Motion Database for Iran. **Farajpour, Z.**, Zare, M., Pezeshk, S.
87. Testing the Suitability of Global Ground Motion Models for the Western Balkan Region. **Gulerce, Z.**, Salic, R., Sandıkkaya, M. A., Milutinovic, Z.

Estimating Earthquake Hazard from Geodetic Data (see page 633).

88. Mitigating Postseismic Bias in Global Positioning System Secular Velocity Estimates for the Central California Coast Region. **Murray, J. R.**, Svarc, J.
89. 89 STUDENT: Geodetic Evidence for a Blind Segment of the San Jacinto Fault. **Tymofyeyeva, E.**, Fialko, Y.
90. Can Interseismic Geodetic Observations and Microseismicity Shed Light on Large Earthquake Behavior? Insights from Models of Long-Term Fault Slip. **Jiang, J.**, Fialko, Y., Lapusta, N.
91. Incorporating Geodetic Data into Seismic Hazard Assessment: Impact on Local Earthquake Risk. **Nyst, M.**
92. Power-Law Rheology Controls Aftershock Triggering and Decay. **Shcherbakov, R.**, Zhang, X.
93. The 2016 Earthquake Sequence and Associated Coseismic Deformation in Central Apennines in Italy. **Huang, M.**, Fielding, E. J., Liang, C., Milillo, P., Bekaert, D., Dreger, D.
94. Integrating Sentinel-1 InSAR and GNSS Data for Deformation Monitoring across the Alpine-Himalayan Belt. **Weiss, J. R.**, Wright, T. J., Walters, R. J., Hooper, A., Spaans, K., Hatton, E., Hussain, E., McDougall, A., Sandwell, D. T., Wessel, P., England, P.
95. STUDENT: National Seismic Hazard Maps for Ecuador. Beauval, C., Yepes, H., **Mariniere, J.**, Audin, L., Alvarado, A., Baize, S., Nocquet, J. M., Cotton, F., Drouet, S.
96. New Velocity Field for Northern Colombia and Western Venezuela and Implications for a Great Earthquake in the Southwest Caribbean. **Mencin, D. J.**, Bilham, R., Mora-Paez, H., Mattioli, G. S., La Femina, P., Audemard, F., Molnar, P.

The Mw7.8 Kaikoura Earthquake (see page 654).

97. Source Characteristics of the 2016 Kaikoura and Te Araroa, New Zealand, Earthquake Sequences from Regional Moment Tensor Analysis. **Ristau, J.**
98. Surface Rupture and Slip Distribution of the 2016 Mw7.8 Kaikoura Earthquake (New Zealand) from Optical Satellite Image Correlation Using MicMac. Champenois, J., **Klinger, Y.**, Grandin, R., Satriano, C., Baize, S., Delorme, A., Scotti, O.
99. Imaging the 2016 Mw 7.8 Kaikoura, New Zealand Earthquake with Teleseismic P Waves: A Cascading Rupture across Multiple Faults. **Zhang, H.**, Koper, K. D., Pankow, K., Ge, Z.
100. Rapid Aftershock Detection and Analysis Following the M7.8 Kaikoura Earthquake Using Matched-Filter Techniques. **Chamberlain, C. J.**, Warren-Smith, E., Fry, B., Townend, J.

Recent Advances in Earthquake Triggering and Aftershock Forecasting (see page 642).

101. Improving Iquique: How Detection Techniques Can be Used to Enhance Our Understanding of the 2014 Sequence. **Nealy, J. L.**, Hayes, G. P., Benz, H. M.
102. STUDENT: Visibility Graph Analysis of Southern California. **Azizzadehroodpish, S.**, Khoshnevis, N., Cramer, C.
103. Seismic Activity Analysis of Recent 15 Years Nearby Puerto Rico and Caribbean Region. Torres-Ortiz, D. M., **Huerta-Lopez, C. I.**

Earthquake Impacts on the Natural and Built Environment (see page 629).

104. STUDENT: Probabilistic Seismic and Liquefaction Hazard Analysis of the Mississippi Embayment Incorporating Nonlinear Site Effects. **Dhar, M. S.**, Cramer, C. H.
105. An Update on the Integration of Ground Failure Hazard and Loss Estimates with USGS Real-Time Earthquake Products. **Allstadt, K. E.**, Thompson, E. M., Nowicki Jessee, M. A., Zhu, J., Tanyas, H., Wald, D. J., Hearne, M.
106. Estimating and Communicating the Impact of Earthquake-Induced Ground Failures. **Thompson, E. M.**, Allstadt, K., Jaiswal, K., Marano, K., Wald, D. J., Bausch, D.
107. Rapid Estimates of Earthquake-Induced Ground-Failure Likelihood in Switzerland. **Cauzzi, C.**, Fäh, D., Wiemer, S., Clinton, J., Wald, D. J.
108. Expansion of the USGS ShakeCast System for Rapid Post-Earthquake Assessments of Critical Facilities. **Lin, K. W. L.**, Wald, D. J. W., Kircher, C. A. K., Jaiswal, K. J., Luco, N. L., Turner, L. L. T., Slosky, D. S.
109. Re-Evaluation of Seismic Hazards at the Central and Eastern United States Nuclear Power Plant Sites. **Heeszel, D. S.**, Munson, C. G., Ake, J. P.
110. STUDENT: Validation of Simulated Ground Motions via Measuring the Sensitivity of Structural Demands to Different Characteristics of Ground Motions. **Kiani, J.**, Camp, C., Pezeshk, S.
111. STUDENT: Linking Sample Structural Responses to Seismological Parameters Inferred from Population through Hierarchical Modeling. **Dhulipala, S. L. N.**, Flint, M. M.
112. Correlation of Building Damage with Spectral Aspects of Near-Source Motions - Cushing, OK Induced M5.0 Earthquake of November 7, 2016. **Celebi, M. K.**, Luco, N., McGarr, A., McNamara, D., Rubinstein, J., Stephens, C. D., Williams, R. A.
113. Location, Amount and Width of the 1906 San Andreas Fault Surface Rupture at the Upper and Lower Crystal Springs Reservoir Embankment, San Francisco Peninsula. **Hull, A.**, Johnson, C., Jackson, H., Madugo, C.

Earthquake Rapid Response (see page 631).

114. Student: Fault Structures Illuminated by the Aftershocks of the 2015 Mw 7.8 Gorkha Earthquake in Nepal as Captured by a Local Dense Seismic Network. Mendoza, M. M., **Ghosh, A.**, Karplus, M. S., Nabelek, J., Sapkota, S. N., Adhikari, L. B., Klemperer, S. L., Velasco, A.
115. Student: Local Seismic Amplification Measurements and Strong Motion Simulations in Port-au-Prince (Haiti). **St Fleur, S.**, Courboulex, F., Bertrand, E., Mercier de Lepinay, B., Deschamps, A., Hough, S. E., Boisson, D., Cultrera, G.
116. Assessment of the Pacific Tsunami Warning Center's Readiness to Assume Local Tsunami Warning Center Responsibilities for Puerto Rico and the Virgin Islands Based on Performance Statistics between 2004 and 2016. **Sardina, V.**, Koyanagi, K.
117. Geodetic Infrastructure, Data, Education and Community Engagement for Earthquake Rapid Response: An Overview of UNAVCO Support Resources and Earthquake Response Examples. **Phillips, D. A.**, Meertens, C. M., Mattioli, G. S., Miller, M. M., Charlevoix, , Hodgkinson, K. M., Bartel, B., Maggert, D., Henderson, D., Williamson, H., Puskas, C., Baker, S., Blume, F., Normandeau, J., Feaux, F., Galetzka, J., Pettit, J., Crosby, C., Boler, F.
118. Early Results from Testing and Deployments of a Cascadia, an Instrument with over 200dB of Dynamic Range, Specifically Built for Aftershock Studies. **Parker, T.**, Moores, M., Bainbridge, G., Townsend, B.

SSA-ESC Joint Session on Advances in Geotechnical Borehole Arrays, Data and Analyses (see page 654).

119. OTNX - A 3D Seismic Observatory for a Geothermal Drilling and Permeability Stimulation Experiment. Passmore, P. R., **Malin, P. E.**, Passmore, M. K., Valenzuela, S.
120. The Evolution of Excess Pore Pressure Generation and Dissipation: Observations from the Wildlife Liquefaction Array. **Steidl, J.**

Overcoming Challenges in Seismic Risk Communication (see page 642).

121. SAFRR Tsunami Scenarios and the Importance of Choosing the Right Source. **Ross, S. L.**, Wood, N. J., Cheung, K. F., Chock, G. Y. K., Cox, D. A., Jones, J. L., Jones, L. M., Lynett, P. J., Miller, K., Nicolsky, D. J., Richards, K. J., Wein, A. M., Wilson, R. I., Yamazaki Y.
122. 565 Earthquake Hazards Questions. **Wald, L. A.**

From Field Site to Data Center: Network Innovations for Earthquake Early Warning (see page 637).

123. ANZA Seismic Network: Real-Time Continuous Response Spectra Exceedance Calculation. **Vernon, F. L.**, Harvey, D., Lindquist, K., Franke, M.
124. Cybersecurity for Seismic Networks. **Bruton, C. P.**, Stubailo, I., Alvarez, M., Bhadha, R., Hauksson, E., Watkins, M. B.

Scaling and Empirical Relationships of Moderate to Large Earthquakes: Re-scaling or Re-thinking? (see page 649).

125. Student: A Critical Review of Empirical Earthquake Source Scaling Relationships. **Pace, B.**, Valentini, A., Ferrari, F., Visini, F.
126. Earthquake Scaling Relationship for Volcano-Tectonic Earthquakes: A Case-Study from Mt. Etna (Italy). Azzaro, R., D'Amico, S., **Pace, B.**
127. Family Tree of Magnitude Versus Rupture Size Relationships. **Peruzza, L.**, Fault2SHA, W. G.
128. Advanced Empirical Scaling Laws for Earthquake Sources. **Thingbaijam, K. K. S.**, Mai, P. M., Goda, K.

Machine Learning and its Application to Earthquake and Explosion Signal Analysis (see page 638).

129. Student: Supervised Machine Learning on a Network Scale: Application to Seismic Event Classification and Detection. **Reynen, A. M. G.**, Audet, P.
130. Single-Channel Based Earthquake Detection by Matching Spectrogram Images. **Skurikhin, A. N.**, Stead, R. J.
131. Student: Evaluation of Adaptive Sensor Tuning for Microseismic Event Detection Across Multiple Arrays and in Varying Noise Conditions at a Carbon Capture, Utilization, and Storage Site, Farnsworth Unit, Ochiltree County, Texas. **Ziegler, A. E.**, Knox, H. A., Balch, R. S., Draelos, T. J., Peterson, M. G., Van Wijk, J.
132. 132 Student: Analysis and Characterization of Hydroacoustic Data Collected by Autonomous MERMAID Floats. **Simon, J. D.**, Simons, F. J., Hello, Y., Nolet, G.

Ground Motions and GMPEs (see page 695).

133. Student: A Model for Estimating Amplification Effects on Seismic Hazards and Scenario Ground Motions in Southern Ontario. **Braganza, S. C.**, Atkinson, G. M.
134. Comparison among the Graizer-Kalkan (GK15) GMPE and Two NGA-West2 GMPEs. **Kalkan, E.**, Graizer, V.
135. Student: An Energy-Based Seismic Response Evaluation of Simple Structural Systems with Simulated Ground Motions. **Karim Zadeh Naghshineh, S. H. A.**, Askan, A. Y. S., Erberik, M. U. R.

136. Student: Data Processing with Non-Causal Zero-Phase Filters Under Predict NGA 2 GMPEs. **Roh, B.**, Buyco, K., Heaton, T. H.
137. Student: A New Generation of Ground-Motion Prediction Equations Using an Integrated Database for Iran. **Farajpour, Z.**, Zare, M., Pezeshk, S., Haji-Soltani, A.
138. Student: On the Bayesian Inference of Random Effects in the Recalibration of Ground-Motion Models to Icelandic Earthquakes. **Kowsari, M.**, Sonnemann, T., Halldorsson, B., Hrafnkelsson, B.
139. Student: Development of Source-To-Site Distance Conversion Equations for the Extended-Fault Sources. **Sedaghati, F.**, Tavakoli, B., Pezeshk, S.
140. Student: Implications of the Inter-Period Correlation of Strong Ground Motions on Structural Risk. **Bayless, J. R.**, Abrahamson, N. A.
141. Site Response of the Vertical Ground Motion and Its Correlation with Alternative Profile Proxies. Pe'er, G., **Kamai, R.**
142. Never Fear Velocity Reversals. **Yagoda-Biran, G.**, Kamai, R., Kerpel, B.
143. Student: Hybrid Empirical Ground-Motion Prediction Equations for the Gulf Coast Region. Pezeshk, S., **Haji-Soltani, A.**, Zandieh, A.
144. 144 Student: Relationships among Various Definitions of Horizontal Spectral Accelerations in Central and Eastern North America. **Haji-Soltani, A.**, Pezeshk, S.
145. Student: Comparison of Different Approaches to Incorporate Site Effects and Associated Uncertainties in Probabilistic Seismic Hazard Analysis: Application for a Liquid Natural Gas Tank. **Haji-Soltani, A.**, Pezeshk, S.

Presenting author is indicated in bold.

Thursday, 20 April—Oral Sessions

Time	Plaza D	Plaza E	Plaza F	Governor's Square 14
	Earthquake Complexities Revealed by Kinematic and Dynamic Modeling and Multiple Geophysical Data Sets Session Chairs: Wenyuan Fan, P. Martin Mai, David D. Oglesby (see page 659)	**Understanding and Modeling Ground Motions and Seismic Hazard from Induced Earthquakes** Session Chairs: Annemarie Baltay, Daniel McNamara, Eric Thompson, Mark Petersen (see page 682)	**The Future of Past Earthquakes** Session Chairs: David Schwartz, Ramon Arrowsmith, William Lettis, Koji Okumura, Daniela Pantosti, Thomas Rockwell (see page 678)	**Verification and Validation of Earthquake Occurrence and Hazard Forecasts** Session Chairs: Seth Stein, John Rundle, Mark Petersen (see page 684)
8:30 AM	Intraslab Rupture Triggering Megathrust Rupture Co-Seismically in the December 17, 2016 Solomon Islands Mw 7.9 Earthquake. **Lay, T.**, Ye, L., Ammon, C. J., Kanamori, H.	2017 One-Year Seismic Hazard Forecast for the Central and Eastern United States from Induced and Natural Earthquakes. **Petersen, M.**, Mueller, C., Moschetti, M., Hoover, S., Shumway, A., McNamara, D., Willaims, R., Llenos, A., Ellsworth, W., Michael, A., Rubinstein, J., McGarr, A., Rukstales, K.	INVITED: Geometric Complexity in Past Ruptures and Lessons for Hazard and Future Ruptures. **Biasi, G. P.**, Wesnousky, S. G.	Nowcasting Earthquakes: Applications and Sensitivity Testing. **Rundle, J. B.**, Donnellan, A., Luginbuhl, M., Giguerre, A., Turcotte, D. L.
8:45 AM	Imaging Complex Fault Slip History of 2016 Taiwan and Japan Earthquakes with Geodetic and Seismic Data. **Fielding, E. J.**, Huang, M. H., Liang, C., Yue, H., Simons, M.	Comparison between the 2016 USGS Induced-Seismicity Hazard One-Year Forecast and the 2016 "Did You Feel It?" Data Archive. **White, I.**, Liu, T., Luco, N., Liel, A.	INVITED: The Mechanics of Multifault Ruptures and the Keystone Fault Hypothesis. **Fletcher, J. M.**, Oskin, M. E., Teran, O. J.	INVITED: Insights from Population Forecasting for Earthquake Hazard Forecasting. **Spencer, B. D.**, Stein, S., Brooks, E. M., Salditch, L.
9:00 AM	Rupture Process of the 2016 Kumamoto Earthquake Revealed by Waveform Inversion with Empirical Green's Functions. **Nozu, A.**, Nagasaka, Y.	INVITED: A Better Understanding of the Seismic Hazard of Induced Earthquakes from High-Resolution Structure, Crustal Anisotropy, and Source Properties of the M_w 5.7 Prague Earthquake. **Cochran, E. S.**, Clerc, F., Sumy, D. F., Neighbors, C. J., Keranen, K. M.	INVITED: Multidisciplinary Paleoseismic Investigations of Complex Earthquake Ruptures: Characterising the Predecessors of the 2010 Mw 7.1 Darfield Earthquake in New Zealand. **Quigley, M. C.**, Van Dissen, R., Nicol, A., Hornblow, S., Sasnett, P., Cruden, A., Jiménez, A., Steacy, S., Duffy, B., Pettinga, J.	Probabilistic Framework and Experimental Concepts for Testing Earthquake Forecasting and Seismic Hazard Models. **Jordan, T. H.**, Marzocchi, W.
9:15 AM	Directivity and Rupture Velocity of Small Earthquakes. **Abercrombie, R. E.**, Poli, P., Bannister, S. C., Ruhl, C. J., Chen, X.	INVITED: Evaluation of the Fitting Accuracy for the Source Parameter Estimation of Potentially Induced Earthquakes in Oklahoma. **Yoshimitsu, N.**, Ellsworth, W.	Large Magnitude Earthquakes in New Zealand: What is the Norm? **Nicol, A.**, Van Dissen, R. J., Stirling, M. W., Gerstenberger, M. C., Khajavi, N.	How Good Should We Expect Probabilistic Seismic Hazard Maps To Be? Vanneste, K., **Stein, S.**, Camelbeeck, T., Vleminckx, T.

Time	Governor's Square 15	Governor's Square 16	Governor's Square 12
	Advances in Seismic Full Waveform Modeling, Inversion and Their Applications Session Chairs: Nian Wang, Xueyang Bao, Dmitry Borisov, Youyi Ruan (see page 655)	**Recent Advances in Very Broadband Seismology** Session Chairs: Adam Ringler, David Wilson, Robert Anthony (see page 673)	**Theoretical and Methodological Innovations for 3D/4D Seismic Imaging of Near-surface, Crustal, and Global Scales** Session Chairs: Marco Pilz, Nori Nakata (see page 680)
8:30 AM	STUDENT: 3D Ground Motion Simulation of the Ladysmith Earthquake for Kinburn Basin. **Esmaeilzadeh, A.**, Motazedian, D.	Physical Mechanisms of Seismometer Site Noise and Self-Noise. **Bainbridge, G.**, Upadhyaya, S., Townsend, B., Parker, T., Moores, A.	INVITED: Time-Lapse Changes in Seismic Velocity Log-Time Recovery of Earth Materials. **Snieder, R.**, Sens-Schoenfelder, C., Nakata, N., Li, X.
8:45 AM	Full Waveform Modeling with Mesh Refinement in SW4. **Petersson, N. A.**, Sjogreen, B., Rodgers, A. J.	INVITED: Installation Techniques Used to Maximize Data Quality at Global Seismographic Network Stations. **Davis, P.**, Berger, J., Ebeling, C., Hafner, K.	STUDENT: A New Approach to Constrain Near-Surface Seismic Structure Based Upon Body-Wave Polarization. **Park, S.**, Ishii, M.
9:00 AM	INVITED: Three-Dimensional Ground Motion Simulations of Moderate Earthquakes and Large Scenario Ruptures in the San Francisco Bay Area. **Rodgers, A. J.**, Petersson, N. A., Pitarka, A.	A Portable Fiber Optic Gyroscope - Performance and First Field Tests. **Braun, T.**, Wassermann, J., Ripepe, M., Bernauer, F., Guattari, F., Igel, H.	STUDENT: Analysis of Non-Diffuse Characteristics of the Seismic Noise Field in Southern California Based on Neighboring Frequency Correlation. **Liu, X.**, Ben-Zion, Y.
9:15 AM	Investigation of Scattered Wavefield by Using Full-Wave Simulations. **Bao, X.**, Shen, Y.	Progress in the Development of an Optical Seismometer. **Zumberge, M.**, Wielandt, E., Berger, J.	An Investigation on Time-Frequency Domain Phase Weighted Stacking and its Application to Phase Velocity Extraction from Ambient Noise Based Empirical Green's Functions. **Niu, F.**, Li, G., Yang, Y.

Time	Plaza D	Plaza E	Plaza F	Governor's Square 14
	Earthquake Complexities Revealed by Kinematic …	**Understanding and Modeling Ground…**	**The Future of Past Earthquakes**	**Verification and Validation of Earthquake…**
9:30 AM	Uncertainties in Teleseismic Rupture Models Using a Monte Carlo Approach: The Mw 7.3 Papanoa, Mexico Subduction Earthquake of 18 April 2014. **Mendoza, C.**, Martinez-Lopez, M. R.	STUDENT: Examining Earthquake Source Properties and Scaling of Recent Seismicity in Southern Kansas. **Trugman, D. T. T.**, Dougherty, S. L. D., Cochran, E. S. C., Shearer, P. M. S.	New Scenarios for Paleoseismological Ruptures Based on the 2016 Central Italy Earthquake Sequence. Civico, R., **Pantosti, D.**, Villani, F., Cinti, F. R., Pucci, S., De Martini, P. M.	INVITED: Improving Earthquake Forecasts with Crustal Deformation Observations. **Donnellan, A.**, Parker, J. W., Granat, , Rundle, J., Grant Ludwig, L., Arrowsmith, R., DeLong, S., Ben-Zion, Y.
9:45–10:45 AM	Posters and Break	Posters and Break	30-Minute Discussion	Posters and Break
	Earthquake Complexities Revealed by Kinematic and Dynamic Modeling and Multiple Geophysical Data Sets (continued)	**Understanding and Modeling Ground Motions and Seismic Hazard from Induced Earthquakes** (continued)	**The Future of Past Earthquakes** (continued)	**Verification and Validation of Earthquake Occurrence and Hazard Forecasts** (continued)
10:45 AM	INVITED: Multiscale Probabilistic Imaging of Tsunamigenic Seafloor Deformation During the 2011 Tohoku-oki Earthquake. **Jiang, J.**, Simons, M.	INVITED: STUDENT: Using Simulated Ground Motions to Constrain Near-Source Ground Motion Prediction Equations in Areas Experiencing Induced Seismicity. **Bydlon, S. A. B.**, Dunham, E. M. D.	Segmentation and Supercycles: Earthquake Cycle Complexities and the Sumatran Sunda Megathrust as a Behavior Catalog. **Philibosian, B.**, Meltzner, A. J., Sieh, K.	Seismic Hazard Prediction or Forecasting in the Central United States. **Wang, Z.**
11:00 AM	INVITED: The 2011 Mw 9.0 Tohoku Earthquake: Dynamic Rupture with Rupture Reactivation and Ground Motion Simulation. **Galvez, P.**, Dalguer, L. A.	Ground Motions from Induced Earthquakes in Oklahoma and Kansas. **Moschetti, M. P.**, Thompson, E. M., McNamara, D., Powers, P. M., Hoover, S.	Paleoseismology of the Collision Plate Boundary on the Himalayan Front. **Okumura, K.**, Malik, J. N.	INVITED: STUDENT: Assessing Earthquake Hazard Map Performance for Natural and Induced Earthquakes. **Brooks, E. M.**, McNamara, D., Petersen, M., Stein, S., Moschetti, M., Spencer, B. D., Shumway, A., Salditch, L.
11:15 AM	Dynamic Models of Large Ruptures on the Southern San Andreas Fault. **Lozos, J. C.**	INVITED: A Ground Motion Prediction Equation for Induced Oklahoma Earthquakes. **Yenier, E.**, Atkinson, G. M., Baturan, D.	Integrated Seismic Hazard Investigations and Progressive Reduction of Uncertainties: The North Anatolian Fault as a Case Example. **Kozaci, O.**	INVITED: STUDENT: Are Large Global Earthquakes Temporally Clustered? **Luginbuhl, M.**, Rundle, J. B., Turcotte, D. L.
11:30 AM	STUDENT: Pulse-Like Property and Complex Fault Geometry on Dynamic Rupture Models of the 2015 Mw7.8 Nepal Earthquake. **Wang, Y.**, Day, S. M., Denolle, M.	Are Ground-Motion Models Derived from Natural Events Applicable to the Estimation of Expected Motions for Induced Earthquakes? **Atkinson, G. M.**, Assatourians, K.	INVITED: Earthquake Cascade along Large Strike-Slip Faults, Rule or Exception? **Klinger, Y.**, Xu, X., Lefevre, M., Tapponnier, P., Liu, J., Le Béon, M.	STUDENT: Modeling Earthquake Clusters as Resulting From Long-Term Fault Memory. **Salditch, L. M.**, Brooks, E. M., Stein, S., Spencer, B. D., Agnon, A.

Time	*Governor's Square 15*	*Governor's Square 16*	*Governor's Square 12*
	Advances in Seismic Full Waveform Modeling, Inversion…	**Recent Advances in Very Broadband Seismology**	**Theoretical and Methodological Innovations for 3D/4D…**
9:30 AM	Detection of Voids Using 3D Elastic Full Waveform Inversion. **Borisov, D.**, Smith, J., Tromp, J., Miller, R., Peterie, S., Cudney, H., Sloan, S., Moran, M.	Seismogeodetic Instruments as Broadband Seismometers for Local Earthquake Early Warning and Rapid Response. **Bock, Y.**, Goldberg, D. E.	STUDENT: New High-Resolution 3D Imagery of Fault Deformation and Segmentation of the San Onofre Trend in the Inner California Borderlands. **Holmes, J. J.**, Driscoll, N. W., Kent, G. W.
9:45–10:45 AM	Posters and Break		
	Advances in Seismic Full Waveform Modeling, Inversion and Their Applications (continued)	**Recent Advances in Very Broadband Seismology** (continued)	**Earthquakes and Tsunamis** Session Chairs: Rich Briggs, Gavin Hayes (see page 663)
10:45 AM	INVITED: Structure and Physical Characteristics of the Southern Hikurangi Subduction Zone Derived from Seismic Full Waveform Imaging. **Arnulf, A. F.**, GNS Science Scientists	INVITED: Horizontal Seismometers - Determining Orientation and Self-Noise. **Hellweg, M.**, Taira, T., Uhrhammer, R. A.	Advancement of Seismological Datasets at ISC. **Storchak, D. A.**, Harris, J., Di Giacomo, D., Lentas, K.
11:00 AM	Lithospheric Foundering and Underthrusting Imaged beneath Tibet Revealed by Adjoint Tomography. **Chen, M.**, Niu, F., Tromp, J., Lenardic, A., Lee, C. T., Cao, W., Ribeiro, J.	INVITED: Coherence and Spectra Analysis of the USArray TA PY Posthole Test Array. **Vernon, F. L.**, Thomson, D. J.	Seismic Catalog of the Dominican Republic Period 2013-2016. **Polanco Rivera, E.**, Martinez, F., Pulliam, J., Huerfano, V.
11:15 AM	STUDENT: Full 3D Tomography Based on the Discontinuous Galerkin Method. **Wang, W.**, Chen, P.	Reliability and Repeatability in High Frequency Ground Motion Records. **Anthony, R. E.**, Ringler, A. R., Wilson, D. C., Hutt, C. R., Sandoval, L. D., Holland, A. A.	Seismic and Tsunami Hazard Assessment of Ecuador following Observations from the 2016 Mw7.8 Muisne Earthquake. **Malekmohammadi, M.**, Nikolaou, S., Toulkeridis, T.
11:30 AM	Advances in High Resolution Global Tomography of the Earth's Deep Mantle Using Numerical Wavefield Computations. **Romanowicz, B. A.**, Yuan, K., Masson, Y., Adourian, S., Karaoglu, H., French, S.	INVITED: Performance of Shallow Drill Emplaced Broadband USArray Seismic Stations. **Busby, R. W.**, Aderhold, K., Frassetto, A., Woodward, R. L.	"Sequencing" of Tsunami Waves, or Why the First Wave is Not Always the Largest. **Okal, E. A.**, Synolakis, C. E.

Time	Plaza D	Plaza E	Plaza F	Governor's Square 14
	Earthquake Complexities Revealed by Kinematic…	**Understanding and Modeling Ground…**	**The Future of Past Earthquakes**	**Verification and Validation of Earthquake…**
11:45 AM	STUDENT: Towards a Hybrid Broadband Ground Motion Simulation Model for Strong Earthquakes in the South Iceland Seismic Zone. **Sonnemann, T.**, Halldórsson, B., Hrafnkelsson, B., Mai, P. M., Papageorgiou, A. S., Jónsson, S.	Ground Motion Prediction Equation for Small-To-Moderate Earthquake Events in Texas, Oklahoma, and Kansas. **Zalachoris, G.**, Rathje, E. M.	INVITED: Using Displacement and Paleoclimate Data to Overcome Age Uncertainties in Rupture Histories of the Southern San Andreas Fault. **Scharer, K.**	Validation of Aftershock PSHA in Central Italy. **Gee, R.**, Peruzza, L., Pagani, M.
Noon–1:30 PM	Group Luncheon			
	Characterization of the Stress Field and Focal Mechanisms for Earthquake Source Physics and Fault Mechanics Session Chairs: Patricia Martínez-Garzón, Jeanne L. Hardebeck, Martha Savage, Marco Bohnhoff (see page 657)	**Recent Moderate Oklahoma Earthquakes: Widely Felt and Often Damaging** Session Chairs: William Yeck, Robert Williams, Justin Rubinstein (see page 675)	**Earthquake Geology and Paleoseismic Studies of the Intermountain West: New Methods and Findings on Seismic Hazard Characterization of Low Slip Rate Faults** Session Chairs: Seth Dee, Stephen Angster (see page 661)	**PSHA Source Modeling: Approaches, Uncertainty and Performance** Session Chairs: Peter Powers, Christie Hale (see page 671)
1:30 PM	INVITED: Heterogeneities of Stress and Strength and its Relationship With Induced Seismic Activities Associated With the Tohoku-Oki Earthquake. **Yoshida, K.**, Matsuzawa, T., Hasegawa, A.	INVITED: Local Effort for Global Contribution: Seismic Observations of Recent Oklahoma Moderate Earthquake Sequences and for Future. **Nakata, N.**, Chen, X., Chang, J. C.	Paleoseismic Investigation of the Teton Fault at Leigh Lake. **Zellman, M.**, DuRoss, C. B.	STUDENT: PEER PSHA Code Verification Project. **Hale, C.**, Abrahamson, N., Bozorgnia, Y.
1:45 PM	What Makes Seismic Events Grow Big?: Insights from the Analysis of *b*-Value and Fault Roughness Variations During Laboratory Stick-Slip Experiments. **Goebel, T. H. W.**, Kwiatek, G., Becker, T. B., Dresen, G.	Diverse Earthquake Responses to Wastewater Disposal near Fairview, Pawnee, and Cushing, Oklahoma. **McGarr, A.**, Barbour, A.	INVITED: Paleoseismology of the Corner Canyon and Alpine Sites: Insight into Normal Fault Segmentation of the Wasatch Fault Zone. **DuRoss, C. B.**, Bennett, S. E. K., Briggs, R. W., Personius, S. F., Reitman, N. G., Hiscock, A. I., Mahan, S. A., Biasi, G. P.	INVITED: Some Sources of Modeling Uncertainty for Area Source Zones in Probabilistic Seismic Hazard Analysis. **Blanco, J. E.**, Hale, C. D., Quittmeyer, R., Kimball, J.

Time	Governor's Square 15	Governor's Square 16	Governor's Square 12
	Advances in Seismic Full Waveform Modeling, Inversion…	**Recent Advances in Very Broadband Seismology**	**Earthquakes and Tsunamis**
11:45 AM	Global Adjoint Tomography. **Ruan, Y.**, Lei, W., Lefebvre, M., Modrak, R., Smith, J. A., Orsvuran, R., Bozdag, E., Tromp, J.	STUDENT: Estimating Noise and Wave-Propagation Effects from a 3D Array at the Sanford Underground Research Facility. **Bowden, D. C.**, Tsai, V. C., Mandic, V., Pavlis, G., Prestegard, T., Meyers, P., Caton, R., Walls, L., Coughlin, M., Harms, J.	Improving Earthquake Resilience in Developing Countries through Seismology. **Onur, T.**, Gok, M. R., Mackey, K.
Noon–1:30 PM	Group Luncheon		
	Intraplate Earthquakes: Central and Eastern North America and Worldwide Session Chairs: Lillian Soto-Cordero, Christine Powell, Will Levandowski (see page 669)	**Toppled and Rotated Objects in Recent, Historic, and Prehistoric Earthquakes** Session Chairs: Klaus-G. Hinzen, Rasool Anooshehpoor (see page 681)	**Emerging Opportunities in Planetary Seismology** Session Chairs: Sharon Kedar, Steve Vance, Nicholas Schmerr (see page 664)
1:30 PM	INVITED: A New Paradigm for Large Earthquakes in Stable Continental Plate Interiors. **Calais, E.**, Camelbeeck, T., Stein, S., Liu, M., Craig, T. J.	Engineering Seismological Aspects of Toppled and Rotated Objects in Past and Recent Earthquakes. **Hinzen, K. G.**, Reamer, S. K.	Emerging Opportunities in Planetary Seismology. **Kedar, S.**, Schmerr, N., Vance, S. D.
1:45 PM	INVITED: Repeating Large Holocene Earthquakes in the Central and Eastern U.S. Warrant Continuing High Hazard Characterization. **Williams, R. A.**	STUDENT: Could the Collapse of a Massive Speleothem be the Record of a Large Paleoearthquake? Valentini, A., **Pace, B.**, Vasta, M., Ferranti, L., Colella, A., Vassallo, M., Montagna, P., Pons-Branchu, E.	INVITED: InSight/SEIS: One Year Prior to Beginning the Seismic Investigation of Mars. **Banerdt, W. B.**, Lognonné, P., Giardini, D., Pike, W. T., Christensen, U., de Raucourt, S., Umland, J., Hurst, K., Zweifel, P., Calcutt, S., Bierwirth, M., Mimoun, D., Pont, G., Verdier, N., Laudet, P., Hoffman, T., Clinton, J., Dehant, V., Golombek, M., Garcia, R., Johnson, C., Kedar, S., Knapmeyer-Endrun, B., Mocquet, A., Panning, M., Smrekar, S., Teanby, N., Tromp, J., Wieczorek, M., Weber, R. C., Bozdag, E., Beucler, E., Daubar, I., Drilleau, M., Kawamura, T., Murdoch, N., the INSIGHT/SEIS Team.

Time	*Plaza D*	*Plaza E*	*Plaza F*	*Governor's Square 14*
	Characterization of the Stress Field and Focal…	**Recent Moderate Oklahoma Earthquakes…**	**Earthquake Geology and Paleoseismic Studies…**	**PSHA Source Modeling: Approaches…**
2:00 PM	Delineating the Seismic Record of Off-Fault Deformation near the Southern San Andreas Fault Using Crustal Deformation Models. **Cooke, M. L.**, Beyer, J. L.	InSAR Constraints on Recent Induced Earthquakes in the United States. **Barnhart, W. D.**, Yeck, W. L.	Forecasting Large Earthquakes along the Wasatch Front, Utah: Final Results from the Working Group on Utah Earthquake Probabilities. **Wong, I.**, Lund, W., DuRoss, C., Thomas, P., Arabasz, W., Crone, A., Hylland, M., Luco, N., Olig, S., Pechmann J., Personius, S., Petersen, M., Schwartz, D., Smith, R.	INVITED: Exploring Source Modeling in the GEM Hazard Models Database. **Pagani, M.**, Garcia, J., Poggi, V., Styron, R., Weatherill, G., Gee, R.
2:15 PM	INVITED: STUDENT: Spatiotemporal Variations of Seismic B-Value along the North Anatolian Fault Zone in Northwest Turkey. **Raub, C.**, Martínez-Garzón, P., Kwiatek, G., Bohnhoff, M., Dresen, G.	Geodetic Slip Model of the M5.8 3 September, 2016 Pawnee, Oklahoma, Earthquake: Evidence for Fault Zone Collapse. **Pollitz, F. F.**, Wicks, C. W., Schoenball, M., Ellsworth, W. L., Murray, M.	Time-Dependent Probabilistic Hazard along the Wasatch Front, Utah Using the Working Group on Utah Earthquake Probabilities Model. **Thomas, P.**, Wong, I.	INVITED: Slab Models for PSHA. **LaForge, R.**, Hale, C.
2:30 PM	Using Coseismic Slip Models, Focal Mechanisms, and Topography to Constrain Seismogenic Stresses. **Hetland, E.** A., Hines, T. T., Medina Luna, L., Styron, R. H., Wilcox-Cline, R.	INVITED: Hidden Faults: Rupture of an Immature Fault System in the 2016 Mw5.8 Pawnee, OK Earthquake. **Keranen, K.**, Savage, H., Lohman, R., Atekwana, E., Stevens, N., Coffey, G., Sickbert, T., Peterson, D., Rabinowitz, H., Garcia, J. C., Lambert, C.	STUDENT: Estimating Rates of Slip within the Central Walker Lane Using Multiple Geochronometers. **Angster, S. J.** A., Wesnousky, S. G. W., Owen, L. A. O.	INVITED: Parameterizing Directivity in PSHA. **Watson-Lamprey, J.**
2:45–4:00 PM	Pint and a Poster			
	Characterization of the Stress Field and Focal Mechanisms for Earthquake Source Physics and Fault Mechanics (continued)	**Induced Seismicity—The European Perspective** Session Chairs: Manfred Joswig, Joshua White, Mariano Garcia-Fernandez (see page 668)	**Seismotectonics** Session Chairs: Rich Briggs, Gavin Hayes (see page 676)	**PSHA Source Modeling: Approaches, Uncertainty and Performance** (continued)
4:00 PM	INVITED: Imaging Rupture Threshold Variations along Subduction Faults. **Bletery, Q.**, Thomas, A. M., Rempel, A. W.	INVITED: Hydrocarbon Induced Seismicity in Northern Netherlands. **Dost, B.**, Spetzler, J., Ruigrok, E.	Anthropogenic Influences in USA Intraplate Earthquakes. **Hagen, M. T. H.**	INVITED: Epistemic Uncertainty in the National Seismic Hazard Mapping (NSHM) Project Models. **Lee, Y.**, William, G., Hu, Z.

Thursday 20 April (*continued*)

Time	Governor's Square 15	Governor's Square 16	Governor's Square 12
	Intraplate Earthquakes: Central and Eastern North America and…	**Toppled and Rotated Objects in Recent, Historic…**	**Emerging Opportunities in Planetary Seismology**
2:00 PM	INVITED: The Geodynamics of Intraplate Stresses within Central and Eastern North America. **Holt, W. E.**, Ghosh, A., Wang, X.	Fragile Geologic Features in Coastal California. **Stirling, M. W.**, Rood, D. H., Caklais, A., Madugo, C. L. M., Abrahamson, N. A.	Investigating the Interior of Icy Worlds with Short Aperture Seismic Arrays. **Schmerr, N.**, Lekic, V., Panning, M., Hurford, T., Rhoden, A., Garnero, E., Yu, H.
2:15 PM	Evidence for Hydrous Mantle beneath the New Madrid Seismic Zone: A Potential Explanation for an Intraplate Enigma. **Powell, C. A.**, Levandowski, W.	INVITED: Earthquake Rotated Objects Associated with Ground Motion during the Mw 6.0 2016 Amatrice (Central Italy) Earthquake. **Cucci, L.**, Tertulliani, A., Lombardi, A. M.	INVITED: A Broadband Silicon Seismic Package for Planetary Exploration. **Pike, W. T.**, Standley, I. M., Calcutt, S., Kedar, S.
2:30 PM	INVITED: Control of the Lithospheric Mantle on Intracontinental Deformation: Revival of Eastern U.S. Tectonism. **Biryol, C. B.**, Wagner, L. S., Fischer, K. M., Hawman, R. B.	STUDENT: The Ruin of the Roman Temple of Kedesh, Israel; Example of a Precariously Balanced Archaeological Structure Used as a Seismoscope. **Schweppe, G.**, Hinzen, K. G., Marco, S., Reamer, S. K., Fischer, M.	INVITED: Development of a Planetary Broadband Seismometer for Geophysical Exploration of the Moon and the Ocean World. Chui, T. C. P., Griggs, C. E., Moody, M. V., Paik, H. J., **Kedar, S.**, Hahn, I., Williamson, P., Schmerr, N., Banerdt, W., Neal, C., Vance, S.
2:45–4:00 PM	Pint and a Poster		
	Intraplate Earthquakes: Central and Eastern North America and Worldwide (continued)	**Fault Mechanics and Rupture Characteristics from Surface Deformation** Session Chairs: Lia Lajoie, Kendra Johnson, Edwin Nissen (see page 665)	**Importance of Long-Period Ground Motions in Seismic Design of Structures** Session Chairs: Erdal Safak, Eser Cakti (see page 667)
4:00 PM	The January 2017 Barrow Strait Earthquake Sequence, Arctic Canada. **Bent, A. L.**, Ackerley, N., Kolaj, M., Adams, J.	Managing the Explosion of High Resolution Topography for Active Fault Research. **Arrowsmith, J. R.**, Crosby, C. J., Gross, B., Nandigam, V., Phan, M.	Observed and Calculated Response of Long-Period Structures to Surface Waves. **Safak, E.**, Cakti, E.

Time	Plaza D	Plaza E	Plaza F	Governor's Square 14
	Characterization of the Stress Field ...	**Induced Seismicity—The European Perspective**	**Seismotectonics**	**PSHA Source Modeling: Approaches...**
4:15 PM	Correlations Between Stress Orientation and Seismic Coupling in Subduction Zones. **Hardebeck, J. L.**, Loveless, J. P.	Modeling of Induced Seismicity in Producing Gas Fields in the Netherlands. **Wassing, B.**, Buijze, L., Kraaijpoel, D., Paap, B.	STUDENT: New Bedrock Evidence for Overall Offset on N-S Faults in the Vicinity of Historic Earthquakes in Little San Bernardino Mtns; Implications for Interactions Between the San Andreas Fault and the Eastern California Shear Zone. **Hislop, A.**, Powell, R. E., Moecher, D. P., Bemis, S. P.	Modeling Virtual Faults in PSHA. **Campbell, K. W.**, Gupta, N.
4:30 PM	Constraining Uncertainties of Stress Tensor Inversion with Data-Driven Focal Mechanism Cluster Analysis. **Specht, S.**, Heidbach, O., Cotton, F., Zang, A.	3D Mechanical Analysis of Complex Reservoirs for Induced Seismicity: A Novel Numerical Approach. **van Wees, J. D.**, Pluymaekers, M., Van Thienen-Visser, K., Osinga, S., Wassing, B., Fokker, P. A., Candela, T.	The Seismologically Detected Taan Fiord Landslide and Tsunami of 17 October 2015: Preliminary Findings. **Haeussler, P. J.**, Stark, C. P., Gulick, S. P. S., MacInnes, B., Shugar, D., Weiss, R., Higman, B., Larsen,, C., Bloom, C., Bilderback, E., Dufresne. A., Ekstrom, G., Geertsma, M., Gualtieri, L., Jaffe, B., Koppes, M., Labay, K., Loso, M., Lynett, P., McCall, N., Richmond, B., Reece, B., Venditti, J., Walton, M., Willis, M., Williams, H.	UCERF3 Implementation for Site-Specific Probabilistic Seismic Hazard Analysis. **Altekruse, J. M.**, LaForge, R., Ostenaa, D. A., El Menchawi, O.
4:45 PM	A Refined Methodology for Stress Inversions of Earthquake Focal Mechanisms. **Martínez-Garzón, P.**, Ben-Zion, Y., Abolfathian, N., Kwiatek, G., Bohnhoff, M.	INVITED: Recent Seismicity in the Northern German Gas Fields—Induced and Tectonic? **Joswig, M.**	Moho Temperature and Compositional Controls on Lithospheric Bending Strength in the Western United States. **Schutt, D. L.**, Lowry, A. R., Buehler, J. S.	Probabilistic Fault Displacement Hazard Analyses – Evaluation of Empirical Relationships for Fault Displacement. **Wells, D. L.**
5:00 PM	STUDENT: Spatio-Temporal Variations of Stress Parameters in the San Jacinto Fault Zone. **Abolfathian, N.**, Martínez-Garzón, P., Ben-Zion, Y.	INVITED: Monitoring an Underground Gas Storage in a Seismic Area: The Case of Collalto (Northeastern Italy). **Priolo, E.**, Romano, M. A., Garbin, M., Romanelli, M., Plasencia, M., Peruzza, L., Grigoli, F.	Meager Mountain Seismicity—Magmatic or Not? **Mulder, T.**	Incorporating Uncertainty in Kernel Density Models of Distributed Seismicity into Hazard Assessments. Montaldo Falero, V., Youngs, R., **Arcos, M.**, Hollenback, J.

Time	*Governor's Square 15*	*Governor's Square 16*	*Governor's Square 12*
	Intraplate Earthquakes: Central and Eastern…	**Fault Mechanics and Rupture Characteristics…**	**Importance of Long-Period Ground Motions in Seismic Design…**
4:15 PM	New Constraints on the Late Quaternary Slip Rate of the Cheraw Fault, Southeastern Colorado. **Zellman, M. S.**, Ostenaa, D. A., Mahan, S. A., Briggs, R. W., DuRoss, C. B., Reitman, N. G., Personius, S. F., Morgan, M. L.	Shallow Fault Physics Constrained by Active-Source Seismic Imaging, Fault-Zone Drilling, and Mechanical Testing. **Nevitt, J.**, Brooks, B., Catchings, R., Lockner, D., Moore, D., Goldman, M., Criley, C., Bennett, M., Sickler, R., Minson, S., Glennie, C., Ericksen, T., Chan, J.	Use of 3D Physics-Based Numerical Simulations in the Development of Long Period Ground-Motion Maps for Los Angeles. **Crouse, C. B.**, Jordan, T., Milner, K., Goulet, C., Graves, R.
4:30 PM	Faults and Lineaments of the St. Lawrence Rift System. **Lamontagne, M.**, Nadeau, L., Brouillette, P., Bédard, M. P., Grégoire, S.	Characterizing Near-Surface Fractures in Radar Interferograms. **Parker, J. W.**, Donnellan, A., Glasscoe, M. T.	Highlights of Recorded Responses of Two Tall Buildings to Long-Period Earthquake Motions from Distant Sources. **Celebi, M.**
4:45 PM	Eastern Tennessee Seismic Zone Paleoseismology—Alignment of Faults Displacing Quaternary Sediments, and Bedrock, and Liquefaction Features, Confirm Strong Earthquakes in the Past 15 ka. Cox, R. T., **Hatcher, R. D.**, Glasbrenner, J. C., Counts, R., Gamble, E., Warrell, K. F.	Statistically Preferred Hypocenter Location, Slip Variability, and Surface Rupture Patterns from Fractally Rough Fault Structure. **Allam, A. A.**, Kroll, K. A., Milliner, C. W. D., Richards-Dinger, K.	STUDENT: Effects of Simulated Magnitude 9 Earthquake Motions on Structures in the Pacific Northwest. **Marafi, N. A.**, Berman, J. W., Eberhard, M. O., Wirth, E. A., Frankel, A. D., Vidale, J. E.
5:00 PM	Discussion	Epistemic Uncertainty in Thrust Fault Slip as Revealed by 62 Vertical Offsets along the Cucamonga Fault. **McPhillips, D.**, Scharer, K., Lindvall, S. C.	Significant Duration of Earthquake Ground Motion for Subduction Zone Earthquakes. **Walling, M. A.**, Abrahamson, N. A.

Poster Sessions

Recent Moderate Oklahoma Earthquakes: Widely Felt and Often Damaging (see page 704).

1. Vs30 from Multi-Method Site Characterization Approach at Seismograph Locations in the Fairview, Oklahoma Region. **Stephenson, W. J.**, Odum, J. K., McNamara, D. E., Williams, R. A.
2. Brune Stress Parameter Estimates For The 2016 Mw5.8 Pawnee And Other Oklahoma Earthquakes. **Cramer, C. H.**
3. Regional Moment Tensor Inversion – Creation of a Defensible Velocity Model for Inversion. **Herrmann, R. B.**, Benz, H. M.
4. Student: MyShake: Smartphone-Based Detection and Analysis of Oklahoma Earthquakes. **Kong, Q. K.**, Allen, R. M., Schreier, L.
5. Poroelastic Properties of the Arbuckle Group in Oklahoma Derived from Well Fluid Level Response to the Mw5.8 Pawnee and Mw5.0 Cushing Earthquakes. **Kroll, K. A.**, Cochran, E. S., Murray, K. E.
6. Student: Understanding the Roles of Fluid and Faulting in Earthquake Sequences Using Data from Central Oklahoma. **Pennington, C. N.**, Chen, X., Abercrombie, R., Haffener, J. A., McMahon, N. D.

Induced Seismicity—The European Perspective (see page 698).

7. Mitigating Induced Seismicity While Optimizing Production/Injection Strategy of Gas Fields. Chitu, A., Leeuwenburgh, O., **Candela, T.**, Kraaijpoel, D., Wassing, B.
8. Modeling Induced Seismicity by Gas Depletion in a Postglacial, Prestressed Regime. **Li, G.**, Joswig, M.
9. Forecasting Magnitude Frequencies and Magnitude Occurrence Probabilities Using the Seismogenic Index Model—Application to Production and Injection Operations in Hydrocarbon and Geothermal Reservoirs. **Dinske, C.**, Shapiro, S. A.
10. Underground Seismic Monitoring and Seismic Hazard Assessment in Bobrek Coal Mine, Poland with the Use of Flameproof Seismic Observation System SOS. **Lurka, A.**, Mutke, G.

Understanding and Modeling Ground Motions and Seismic Hazard from Induced Earthquakes (see page 714).

11. Comparison of the USGS 2016 and 2017 One-Year Seismic Hazard Forecasts for the CEUS with a Focus on Oklahoma. **Hoover, S. M.**, Moschetti, M. P., Petersen, M. D., Mueller, C. S.
12. Access to "Did You Feel It?" Data for Induced Earthquake Studies. **Quitoriano, V.**, Thompson, E. M., Smoczyk, G., Wald, D. J.
13. Student: The Contribution of Uncertainty in Magnitude and Location to Near-Distance Variability in Ground Motions for Potentially-Induced Earthquakes in Oklahoma. **Holmgren, J. M.**, Atkinson, G. M.
14. Scaling Rotational and Translational Ground Motion Parameters from Induced Seismic Events. **Zembaty, Z.**, Mutke, G., Nawrocki, D.
15. Student: Empirical Ground Motion Characterization of Induced Seismicity in Alberta and Oklahoma. **Novakovic, M.**, Atkinson, G. M., Assatourians, K.
16. Processed Ground-Motion Records for Induced Earthquakes for Use in Engineering Applications. **Assatourians, K.**, Atkinson, G.

The Future of Past Earthquakes (see page 706).

17. A Late Cenozoic Kinematic Model for Fault Motion within the Greater Cascadia Subduction System. **McCrory, P. A.**, Wilson, D. S.
18. Increased Late Quaternary Slip Rates in the Southern Lower Rhine Graben, Central Europe. **Gold, R. D.**, Friedrich, A., Kuebler, S., Salamon, M.
19. Student: A New Slip Rate for the West Tahoe Fault and the Age of Glacial Deposits Using Cosmogenic 10Be Near Lake Tahoe, California. **Pierce, I. K. D.**, Wesnousky, S. G., Kent, G., Owen, L. A.
20. Quaternary Active Tectonic Deformation of the Transgressive Surface Offshore Ventura, CA, Constrained by New Geophysical Data. **Perea, H.**, Ucarkus, G., Driscoll, N., Kent, G., Rockwell, T.
21. A 200 Ka Paleoseismic Record of Earthquake-Triggered Slumps and Soft Sediment Deformation in the Dead Sea Basin. **Marco, S.**, Alsop, G. I., Levi, T., Kagan, E. J., Stein, M., Weinberger, R.
22. Paleoseismic Interpretation of Past Earthquakes Validated by Long Historical Records Argue for Large Scale Regional or Fault Interaction. **Rockwell, T. K.**, Biasi, G.
23. Century-Long Paleo-Seismic Hiatus in California and New Zealand. **Jackson, D. D.**
24. Variations in Surface Fault Rupture Recurrence and Seismic Moment Release in the San Francisco Bay Region During the Past Four Centuries. **Schwartz, D. P.**
25. Earthquake Forecast For The Wasatch Front Region by the Working Group on Utah Earthquake Probabilities: Final Results. **Wong, I.,** Lund, W., DuRoss, C., Thomas, P., Arabasz, W., Crone, A., Hylland, M., Luco, N., Olig, S., Pechmann, J., Personius, S., Petersen, M., Schwartz, D., Smith, R.
26. Constraining the Potential for Early Repeats and Clustering Using Historical and Paleoseimological Data. **Fitzenz, D. D.**, Nyst, M., Kane, D.

27. Evaluating the Relationship Between the Entiat Earthquake Cluster and the 1872 Chelan Earthquake, Central Washington State. **Brocher, T. M.**, Cakir, R.
28. Resolving 1906 Meihsan M7.1, Taiwan, Earthquake Using Historical Waveforms: Blind Thrust Faulting Mechanism with Observed Strike-Slip Surface Rupture. **Ma, K.**, Liao, Y., Hsieh, M.
29. The Future of the Past and Present Earthquake of Padangpanjang on June 28, 1926, West Sumatera, Indonesia. **Soehaimi, A. S.**, Wafid, M. W., Sulistyawan, I. H. S.
30. Student: Neotectonic and Seismicity Assessment of the 1961 Kara Kore Earthquake in the Marginal Grabens of the Afar Rift (Ethiopia). **Stockman, M. B.**, Polun, S. G., Gomez, F., Tesfaye, S.
31. Luminescence Dating for Paleoseismic Reconstructions: A Practical Guide to New Technology, Applications and Sampling Methods. **Rittenour, T. M.**
32. Fault Zone Landforms and Paleoseismology. **Arrowsmith, J. R.**, Salisbury, J. B., Zielke, O.
33. High Resolution DTM Reveals Tectonic Signal of the Dead Sea Fault at the Ateret Archaeological Site. Marco, S., **Hinzen, K. G.**
34. Student: Constraining the Holocene Extent of the Meers Fault, Oklahoma Using High-Resolution Topography and Paleoseismic Trenching. **Hornsby, K. T.**, Streig, A. R., Bennett, S. E. K., Chang, J. C.
35. Evidence for Prehistoric Earthquakes on the Southern Fairweather Fault in Trenches across the 1958 Surface Rupture, Glacier Bay National Park, Alaska. **Witter, R. C.**, Scharer, K., DuRoss, C. B., Bender, A. M., Haeussler, P. J., Lease, R.
36. Paleoseismic Results from Excavations across the Surface Rupture Associated with the 2014 South Napa Earthquake. **Prentice, C. S.**, Sickler, R. R., Scharer, K., DeLong, S. B., Hecker, S., Lienkaemper, J. J., Pickering, A.
37. Student: Testing the Shorter and Variable Recurrence Interval Hypothesis along the Cholame Section of the San Andreas Fault. **Williams, A. M.**, Arrowsmith, J. R., Rockwell, T. K., Akciz, S. O., Grant-Ludwig, L.
38. Investigating the History of Large Wasatch Fault Earthquakes along the Fort Canyon Fault at the Traverse Ridge Paleoseismic Site. **Toke, N. A.**, Langevin, C., Phillips, J., Kleber, E. J., DuRoss, C. B., Wells, J. D., Horns, D. M., McDonald, G., Carlson, J. K.

Earthquake Complexities Revealed by Kinematic and Dynamic Modeling and Multiple Geophysical Data Sets (see page 690).

39. Student: Mach Wave Coherence in the Presence of Source and Medium Heterogeneity. **Vyas, J. C.**, Mai, P. M., Galis, M., Dunham, E. M., Imperatori, W.
40. Student: The Spatial Interdependence of Kinematic Rupture Parameters as Evidenced by Dynamic Ruptures on Rough Faults. **Thingbaijam, K. K. S.**, Galis, M., Vyas, J. C., Mai, P. M.
41. Complex Slip Distributions on Complex Fault Geometries. **Herrero, A.**, Murphy, S.
42. Dynamic Models of Earthquake Rupture along Branch Faults of the Eastern San Gorgonio Pass Region in CA Using Complex Fault Structure. **Douilly, R.**, Oglesby, D. D., Cooke, M. L., Beyer, J. L.
43. Modeling Earthquake Rupture and Corresponding Tsunamis along a Segment of the Alaskan-Aleutian Megathrust. **Ryan, K. J.**, Geist, E. L., Oglesby, D. D., Kyriakopoulos, C.
44. Simulating Impacts of Rupture Variability on Near-Fault Strong Motions. **Graves, R. W.**
45. Strong Motion Simulation of the 2016 Kumamoto Earthquake (Mw7.0) Using Pseudo Point-Source Model and Empirical Green's Functions. **Nagasaka, Y.**, Nozu, A.
46. Joint Inversion of Continuous GPS, InSAR and Seismicity Data to Constrain the Spatiotemporal Evolution of Strain Release of the 2016 Kumamoto Earthquake Sequence: Implications for the Shallow Slip Deficit and the Role of Aseismic Slip. **Milliner, W. D.**, Burgmann, R., Wang, T., Inbal, A., Liang, C., Fielding, E.
47. Finite Rupture Process and Ground Shaking of the 2014 Mw5.1 La Habra Earthquake. **Wei, S. W.**, Fielding, E., Graves, R., Wang, T., Helmberger, D. V.
48. Student: Three-Dimensional Multi-Episode Directivity Analysis for Complex Ruptures. **Park, S.**, Ishii, M.
49. Student: Investigation of Back-Projection Uncertainties with M6 Earthquakes. **Fan, W.**, Shearer, P. M.

Earthquakes and Tsunamis (see page 694).

50. Student: Caribbean Regional Tsunami Early Warning Using W-Phase Source Inversion. **Casallas, I.**, Huérfano, V., Rivera, L.
51. Tsunamis Obey Snell's Law: Simulations and Real Data. **Okal, E. A.**, Synolakis, C. E.

Seismotectonics (see page 705).

52. Seismic Evidence for Splays of the Eureka Peak Fault beneath Yucca Valley, California. **Goldman, M. R.**, Catchings, R. D., Chan, J. H., Sickler, R. R., Criley, C. J., O'Leary, D. R., Christensen, A. H.
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Advances in Earthquake Early Warning

Oral Session · Tuesday 18 April · 2:15 PM · Plaza E
Session Chairs: Elizabeth Cochran, Angela Chung, and Douglas Given

How "Good" are Real-Time Ground Motion Predictions from Earthquake Early Warning Systems?

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Real-time ground motion alerts, as can be provided by Earthquake Early Warning (EEW) systems, need to be both timely and sufficiently accurate to be useful. Yet, how timely and how accurate the alerts of existing EEW algorithms are is often poorly understood. In part, this is because EEW algorithm performance is usually evaluated not in terms of ground motion prediction accuracy and timeliness, but in terms of other metrics (*e.g.* magnitude and location estimation errors), which do not directly reflect the usefulness of the alerts from an end-user perspective. Here we attempt to identify a suite of metrics for EEW algorithm performance evaluation that directly quantify an algorithms' ability to identify target sites that will experience ground motion above a critical (user-defined) ground motion threshold. We process 15,553 records recordings from 238 earthquakes (mostly from Japan and southern California) in a pseudo-real time environment, and employ two end-member EEW methods. We use the metrics to highlight both the potential and limitations of the two algorithms and to show under which circumstances useful alerts can be provided. Such metrics could be used by EEW algorithm developers to convincingly demonstrate the added value of new algorithms or algorithm components. They can complement existing performance metrics that quantify other relevant aspects of EEW algorithms (*e.g.* false event detection rates) for a comprehensive and meaningful EEW performance analysis.

The Effect of Ground-Motion Variability on the Accuracy of Earthquake Early Warning

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Because it is the earthquake ground motion that drives the damage and destruction of the built environment, not the earthquake per se, earthquake early warning (EEW) systems are only as good as their ground-motion predictions. Within an idealized cocoon that makes the location and magnitude of the (possibly still evolving) earthquake instantly known to us, we develop a ground-motion early warning (GMEW) scheme that issues alerts based on the expected exceedance of some threshold of ground motion at some user's location. By considering the problem in this way, we can translate the natural variability in ground-motion prediction, as encapsulated in ground-motion prediction equations (GMPE), into the resultant uncertainty in GMEW. This GMPE variability will lead to false alerts and missed warnings, creating a ceiling for EEW accuracy. The ceiling on EEW accuracy can be raised, however, by decreasing the variability in our GMPEs through including knowable site-, path- and/or region-specific effects into the GMPEs. We then estimate the accuracy that we can expect from an EEW system (given both a typical, factor-of-2 uncertainty in high-frequency GMPEs and the potential reduction of uncertainties that could be obtained if all knowable sources of ground motion variability were included) to calculate the resultant number of false alerts and missed warnings.

Comparing Operational Performance of the Virtual Seismologist and FinDer for Earthquake Early Warning

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An earthquake early warning (EEW) system can provide fast and accurate parameter estimations across wide ranges of source dimensions, event types and epicentral distances by integrating event or ground motion parameter estimations from different EEW algorithms, each of them optimized for specific tasks.

We have integrated two such independent EEW algorithms, Virtual Seismologist (VS) and FinDer in the popular open-source seismic monitoring framework, SeisComP3 (SC3).

VS(SC3) provides rapid magnitude estimates for network-based point-source origins using conventional triggering and association, while FinDer matches evolving patterns of ground motion to track on-going rupture extent, and hence can provide accurate ground motion predictions for finite fault ruptures.

SC3 is operated by a large number of regional seismic network across the world, many of which have a long term interest to develop EEW capabilities.

By combining real-time performance with playbacks from significant events, we report on the configuration and performance of VS and FinDer in various different tectonic and monitoring environments—Switzerland, Nicaragua and Southern California.

We discuss how real-time EEW reports from these complimentary algorithms can be combined in practice to provide a single EEW from the SC3 system.

G-FAST Earthquake Early Warning Performance for Simulated Cascadia Megathrust Events

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The G-FAST GNSS-based earthquake early warning module has been under development for several years and has undergone testing with several real earthquakes in Japan, Chile, and the western United States. G-FAST includes two modeling modules, peak ground displacement (PGD) scaling for a quick magnitude estimate and a CMT-driven finite fault slip inversion that estimates fault orientation and slip from rapidly determined coseismic displacements. In each test, the uniqueness in the earthquake sources and GNSS network geometries has led to varied performance metrics, making it difficult to understand the expected uncertainty in system performance. Seismic warning systems, such as ShakeAlert, also suffer from a dearth of large earthquakes recorded near dense seismic or geodetic networks, efforts are underway to create suites of synthetic events to fully exercise the systems. To this end, we test the performance of G-FAST with 1300 synthetic Cascadia earthquakes between M7.5 and M9.5 [Melgar *et al.*, 2016]. We fully explore the statistical properties of the two modeling modules for this suite of events, looking at magnitude biases, fault and CMT orientation, peak slip, location of slip and slip azimuth. For PGD scaling, magnitude estimates are stable roughly 60 seconds after origin time, bias is minimal, and the full range of estimates for the 1300 events is roughly one magnitude unit. The CMT has a tighter range of magnitude estimates than PGD scaling, but nodal plane orientation is highly variable due to complexities in the sources and network geometry. However, we show that slip distributions, peak slip, and slip azimuth are highly robust and immune to variability in the nodal plane. We finish by discussing the impacts of these results on ground motion prediction and assess the value of these observations in the context of operational earthquake early warning.

Fakequakes: Broadband Simulation for Hazards

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Scenario ruptures and ground motion simulation are important tools for studies of expected earthquake and tsunami hazards during future events. This is particularly important for large events for which observations are still limited. In particular synthetic waveforms are important to test the response to large events of earthquake and tsunami warning systems. This talk will discuss three topics: (1) We will show an application of the Karhunen-Loève expansion to generate stochastic slip distributions and kinematic ruptures on arbitrarily complex geometries such as 3D slab models of subduction zones or multi-segment faults. (2) We will discuss the generation of broadband synthetic ground motions by hybrid deterministic/stochastic methods and argue that they are still preferable, for these purposes, over fully deterministic and computationally intensive forward modeling approaches. Particularly, we will focus on portions of the seismogram typically ignored in broadband synthesis: P-waves and long period displacements that correctly capture static offsets. It is important to adequately model these, in addition to strong shaking, in order to study the response of currently operating early warning systems. Finally (3) we will discuss strategies for validating these waveforms. We propose that in addition to traditional earthquake engineering metrics such as PGA/PGV and SA, waveforms used for these purposes need to be validated by direct comparison to peak P-wave displacement (Pd) scaling laws and to PGD GMPEs obtained from high-rate GPS observations of large events worldwide.

Earthquake Early Warning for the West Coast of the U.S.

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A prototype production Earthquake Early Warning (EEW) system, ShakeAlert, has been operational in California since March, 2016. At the time of this writing, this system generates (non-public) alerts based on two point-source seismic algorithms, ElarmS and Onsite. Both these algorithms were tuned for use in California (CA).

In the summer of 2016, several ShakeAlert servers were deployed at the Pacific Northwest Seismic Network (PNSN) at the University of Washington in Seattle, WA. This provided an opportunity to test whether the two algorithms can be configured to work for the full West Coast (CA, OR, and WA). The algorithm configurations on the servers located at the PNSN are informed by previous work which had shown that ElarmS works well in OR and WA provided that a few changes to the configuration of its event associator are made to allow correct association of arrivals from distant stations to existing solutions and to better characterize offshore events.

At the PNSN, waveforms from OR and WA are processed and triggers from CA are received, thus creating a virtual West Coast wide seismic network. During this initial testing period, the prototype production systems in CA did not receive triggers from WA or OR since they currently provide alerts to beta users and various pilot projects.

For the large majority of earthquakes in CA, the differently configured algorithms generate identical, or very close, solutions, specially Onsite. We conclude that the configuration changes made to Onsite were not warranted. The configuration changes to ElarmS do perform better overall, in particular for a M_w 6.5 offshore northern California event. In WA and OR, Onsite produced large false alerts due to bad data, which points out the need for strict quality control of waveform data. Overall the experiment shows that the algorithms can be configured to work for the whole region, bringing West Coast wide EEW closer to reality.

Towards an Earthquake and Tsunami Early Warning in the Caribbean: The Puerto Rico Case

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The Caribbean region has a documented history of damaging earthquakes and tsunamis that have affected coastal areas (Jamaica ,1692; Virgin Islands, 1867; Mona Passage, 1918; Dominican Republic, 1946, and Haiti, 2010). There is evidence that tsunamis have been triggered by large earthquakes that deformed the ocean floor around the Caribbean Plate (CP) boundary. Seismic events originating in the NE (northeast) CP faults are considered to be a near-field hazard for Hispaniola, Puerto Rico and the Virgin Islands because tsunamis generated there can reach coastal areas within a few minutes after the earthquake. Sources for regional and teleseismic earthquakes have also been identified in the Caribbean and Atlantic Basins. The CP is monitored jointly by national/regional/local seismic, geodetic and sea level networks, all monitoring institutions are participating in the UNESCO ICG/Caribe EWS. The purpose of this initiative is to minimize loss of life and destruction of property, mitigate against catastrophic economic impacts via promoting research, real time (RT) data sharing, improving warning capabilities and enhancing education and outreach strategies. Currently more than, 100 broadband seismic, 65 tide gauges and 50 GPS high rate stations are available in near or real-time (Virtual Net, VN). These streams are used by detection and warning institutions to provide earthquake source parameters, and tsunami messages, in a timely manner. The regional cooperation is motivated by research and tsunami hazard monitoring, warning and education. It will allow the imaging of the tectonic structure of the CP to a high resolution which will permit further understanding of the source properties and the application of this knowledge to procedures of civil protection. The goal of this presentation is to describe the PRSN system, including the contribution to the VN, RT monitoring, local information protocols, and current advances in the imaging of the NE-CP tectonic structure.

Rapid Determination of P-Wave-Based Energy Magnitude: Insights on Source Parameter Scaling of the 2016 Central Italy Earthquake Sequence

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In this study, we proposed a novel methodology for the rapid estimation of the earthquake size from the seismic radiated energy. Two relationships have been calibrated using recordings from 29 earthquakes of the 2009 L'Aquila and the 2012 Emilia seismic sequences in Italy. The first relation allows obtaining seismic radiated energy ER estimates using as proxy the time integral of squared P-waves velocities measured over vertical components, including regional attributes for describing the attenuation with distance. The second relation is a regression between the local magnitude and the radiated energy, which allows defining an energy-based local magnitude (MLe) compatible with ML for small earthquakes. We have applied the new procedure to the seismic sequence that struck central Italy in 2016. Scaling relationships involving seismic moment and radiated energy are discussed considering the M_w 6.0 Amatrice, M_w 5.9 Ussita and M_w 6.5 Norcia earthquakes and their ML >4 aftershocks, in total 38 events. The M_w 6.0 Amatrice earthquake presents the highest apparent stress, and the observed differences among the three larger shocks highlight the dynamic heterogeneity with which large earthquakes can occur in central Italy. Differences between MLe and M_w measures allows to identify events characterized by a higher amount of energy transferred to seismic waves, providing important constraints for the real-time evaluation of an earthquake shaking potential.

Triggered Earthquake During the 2016 Kumamoto Earthquake (Mw7.0): Importance of Real-Time Shake Monitoring for Earthquake Early Warning

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Sequence of the 2016 Kumamoto earthquakes (M_w6.2 on April 14, M_w7.0 on April 16, and many aftershocks) caused a devastating damage at Kumamoto and Oita prefectures, Japan. During the M_w7.0 event, just after the direct S waves passing the central Oita, another M6 class event occurred there more than 80 km apart from the M_w7.0 event. The M6 is interpreted as a triggered earthquake; but it brought stronger shaking at the central Oita than that from the M_w7.0. We will discuss the triggered earthquake from viewpoint of Earthquake Early Warning.

In terms of ground shaking such as PGA and PGV, the M_w7.0 is much smaller than those of the M6 triggered earthquake at the central Oita (for example, 1/8 smaller at OIT009 station in PGA), and then it is easy to discriminate two events. However, PGD of the M_w7.0 is larger than that of the triggered earthquake, and its appearance is just before the occurrence of the triggered earthquake. It is quite difficult to recognize the triggered earthquake from displacement waveforms only, because the displacement is strongly contaminated by that of the preceding M_w7.0.

In many methods of EEW (including current JMA EEW system), magnitude is estimated from PGD, and then PGA and/or PGV are predicted through Ground Motion Prediction Equation (GMPE). However, magnitude from PGD does not necessarily mean the best one for prediction of PGA and PGV. In case of the triggered earthquake, PGD magnitude could not be estimated because of the strong contamination. Actually JMA EEW system could not recognize the triggered earthquake.

One of the important lessons from nine years' operation of EEW is an issue of the multiple simultaneous earthquakes. Because we want to predict ground shaking in EEW, we should more focus on monitoring of ground shaking rather than hypocenter or magnitude. Experience of the triggered earthquake also indicates the importance of the real-time monitor of ground shaking for making EEW more rapid and precise.

Towards Internet of Things Earthquake Early Warning: A Pilot Network in Chile

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The Internet of Things (IoT) is projected to comprise tens of billions of networked sensors by 2020. Many of these (*e.g.* MEMs-based accelerometers and GNSS chips) acquire data that can be used for earthquake and tsunami early warning (EEW, TEW). Because early warning depends on station density, harnessing IoT data should be a priority as warning systems evolve. We envision how IoT can be used in concert with scientific grade warning systems as well as stand-alone by using cloud-based infrastructure. We discuss resolution and detection thresholds for smartphone-based early warning efforts, in both fixed-network and crowd-sourced modes. We present results from a fixed-network, smartphone-based EEW and TEW pilot project in Chile. The Chilean network consists of sensor boxes containing a smartphone and an external consumer-quality GPS chip providing phase-based positioning with satellite-based differential corrections. In November 2015, we started installing units with a target network of 200. We built an Android app to analyze and transmit relevant data via SIM card to a server where we use the FinDer-BEFORES algorithm to detect events and produce real-time joint seismic-geodetic distributed slip models or near-field acceleration-based line source models. Either earthquake source model provides accurate ground shaking forecasts, while distributed slip models can be used to infer seafloor deformation and thus provide local tsunami warning. Although we utilize smartphone-based sensors in a fixed network, the approach can also be implemented in a crowd-sourced manner. Batch processing all of the data collected from the growing network shows that our analysis method successfully detected, located, and estimated the magnitude for three M_w>5 earthquakes, while producing no false alarms. In December 2016 we began live operation with 30-50 stations and since that time we have successfully detected three M_w>5 events and produced no false alarms.

Closing the Gap between Laboratory-based Damping Models and Observed Attenuation of Seismic Waves in the Field

Oral Session · Tuesday 18 April · 2:15 PM · Governor's Square 12

Session Chairs: Albert Kottke, Ashly Cabas

Insights into Small-Strain Damping from Borehole Array Recordings

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Seismic wave attenuation is a key parameter in site response models to predict ground motions and estimate site effects. Small-intensity earthquake recordings (PGA<0.1g) from two borehole arrays (Garner Valley and Treasure Island Downhole Arrays, CA) are investigated to quantify the small-strain material damping ratio (Dmin) using four approaches and the different results are compared. The methods used to estimate the damping ratio profile are: (1) matching of empirical (*i.e.*, from recordings) and theoretical acceleration transfer functions (TF), (2) matching of empirical and theoretical acceleration response spectrum amplification (AF), (3) matching of recorded and predicted surface time series parameters such as Arias Intensity, and (4) matching of the measured and theoretical change in high-frequency spectral decay parameter (delta kappa) between the borehole and surface sensors. For all of the approaches an initial Dmin profile is developed from the Stokoe and Darendeli (2001) relationship. The initial Dmin profile is scaled until the best match is obtained; the corresponding scale factor is called the Dmin multiplier.

When considering the TF and AF, the shapes of the theoretical and empirical curves are similar but the amplitudes of the peaks are larger for the theoretical curves. A Dmin multiplier of 3.0 to 4.0 best matches the empirical TF, but only 1.0 to 2.0 is needed to match the empirical AF. For the time series characteristics of the motion, the appropriate Dmin multiplier is 1.5 to 3.0. Finally, the delta kappa from the recordings imply a Dmin multiplier between 3.0 and 4.0. The derived Dmin multipliers are generally greater than 1.0 and can be considered as indicators of the effects of wave scattering due to spatial variability in the material properties across the site. The Dmin multipliers for Treasure Island are smaller than those for Garner Valley, which may indicate more lateral variability in soil properties at the Garner Valley site.

Adjustments to Small-Strain Damping and Soil Profile Assumptions to Improve Site Response Predictions

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Site response models have often been shown to be biased at high frequencies, where nonlinear soil behavior exerts its greatest influence on ground motions. Specifically, linear, equivalent-linear, and nonlinear site response models tend to underpredict high-frequency ground motions in the aggregate, and this bias persists for different types of constitutive models. We hypothesize that the reasons for this persistent bias are breakdowns in the one-dimensional (1D) site response assumptions and/or poorly characterized soil properties. Using 398 ground motions at 10 selected sites in Japan's Kiban-Kyoshin network (KiK-net), we test four physical hypotheses for this bias by performing a range of site response analyses in SHAKE and DEEPSOIL. Specifically, we (1) decrease the small-strain damping ratio, (2) increase the small-strain shear modulus, (3) apply a depth-dependent shear-wave velocity (V_S) gradient within layers, and (4) randomize the V_S profile. We find that the reduction of the small-strain damping ratio and the usage of a depth-dependent V_S gradient most greatly reduce the high-frequency bias; that the randomized V_S profiles sometimes improve predictions at the fundamental site frequency but often lead to greater issues at high frequencies; and that the adjustment of the small-strain shear modulus has a minimal effect. With regards to 1D site response model improvement, rather than solely focusing on the constitutive model type (*e.g.* equivalent-linear frequency domain vs. nonlinear time domain), this study suggests that greater attention should be paid to soil profiles and material parameters, as some of these physical adjustments are more successful at reducing model bias than changing the model type. The results of this study provide a framework for adjusting small-strain damping and soil profile input parameters to improve 1D site response model predictions.

Laboratory-Based Measurements of Material Damping of Soil and Rock

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Measurements of material damping in shear of soil and soft rock specimens are routinely performed in the laboratory using combined, resonant column (RC, dynamic) and torsional shear (TS, cyclic) equipment. With the RCTS equipment, the effects of parameters such as shearing strain amplitude (γ), mean effective confining pressure (σ_o'), number of loading cycles (N), soil type (granular or cohesive), rock type and/or stiffness, measurement frequency (f), total unit weight (γ_t) or void ratio (e), etc. can be studied. Examples of material damping, expressed as equivalent viscous damping (D) in RC testing or hysteretic damping (λ) in TS testing, are presented. Differences between viscous damping and hysteretic damping can be evaluated since both types of measurements are often performed sequentially in RCTS testing. For hard rock specimens, free-free (Fr-Fr) resonant column (dynamic) testing is performed. In this case, only unconfined, small-strain measurements can be made. However, equivalent viscous material damping in shear and unconstrained compression can be measured. The effects of rock stiffness and specimen size relative to the size of "defects" are discussed and material damping results are presented.

Seismic Wave Attenuation in the Shallow Geological Layer: Results from Different Approaches and Open Issues

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The estimation of the variability of ground shaking over short distances and its quantitative integration into seismic hazard assessment are major challenges in engineering seismology. When an empirical estimation of site response is not available, it is necessary either to compute it through numerical simulations or to describe it through proxies. In both cases, not only is knowledge of the underground S-wave structure necessary (or at least, its representation through integral parameters like Vs30), but a robust description of the wave attenuation is also required. Although over the last decade great effort has been invested in the development of non-invasive methods that have proved to be able to provide reliable estimation of S-wave velocity of the shallow geological layers, the estimation of the attenuation has attracted less attention. In this presentation, I will illustrate different approaches used for the empirical investigation of the attenuation of seismic waves, based on both earthquake and seismic noise recordings, collected by vertical arrays and 2D arrays, respectively. In particular, newly obtained results derived from the analysis of seismic noise appear to hint at the not straightforward relationship between S-wave velocity and attenuation. I will discuss the results, while paying attention to the influence on the estimation of the different contributions to attenuation caused by transmission losses due to variations in impedance (which, dependent upon the wavelength of the seismic waves with respect the dimensions of the heterogeneities, can be defined as scattering and lead to frequency dependence) and the intrinsic attenuation. This issue might therefore hamper the use of empirically estimated attenuation factors in numerical simulations of ground motion.

Capturing the Source and Site High Frequency Attenuation Properties (κ0)

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In their pioneering work Anderson and Hough (1984) modeled the high frequency fall-off of the acceleration spectrum by an empirical parameter κ. Originally, κ was attributed to the combined effect of whole path attenuation and a residual site term (distance independent) which is now often termed as κ0. Understanding the physical factors which are controlling κ0 remains a challenge. According to Ktenidou *et al.* (2014) there are probably three main factors controlling κ0: a source part, a contribution due to regional properties of the upper crust (deep and hard rock properties) and the contribution of superficial layers. In this study, we discuss the relative contributions of these three parts. We first quantify the source part of kappa and show that this source contribution remains rather small. We then present a new perspective to better understand the regional variations in κ0 that essentially utilizes concepts from classical seismological theory. The coda quality factor Qc is an often-used parameter to characterise attenuation properties in the crust as coda waves towards the tail of the seismogram are interpreted as backscattering waves from numerous heterogeneities distributed uniformly in the earth's crust. Therefore a potential link between hard-rock κ0 and Qc will be discussed. Finally, using crustal earthquake recordings extracted from RESORCE-2012 and NGA-west2 databases, we discuss the κ0 record-to-record variability (within-station) due to site-effects.

Computational Infrastructure and Data for Enhancing Earthquake Science

Oral Session · Tuesday 18 April · 8:30 AM · Governor's Square 16

Session Chairs: Lisa Grant Ludwig and Andrea Donnellan

Science Gateways for Enhancing Earthquake Science

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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, and users of Galaxy (a bioinformatics gateway) and NanoHUB (a nanotechnology gateway) number in the tens of thousands.

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. Looking forward, we also see important opportunities for coupling data to a range of machine learning techniques that can be used to identify features in data sets that are not readily discernible by human inspection.

The SCEC Software Ecosystem for Enhancing Earthquake System Science Research

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The Southern California Earthquake Center Community Modeling Environment (SCEC/CME) collaboration has developed a collection of independent, but inter-related, scientific software systems designed to support earthquake system science research. We describe this collection of software systems as a software ecosystem to emphasize that these codes are developed and co-evolve in a shared collaborative scientific and open-science computing environment. The SCEC software ecosystem includes California crustal velocity models (CVM-S, CVM-H, UCVM), advanced Probabilistic Seismic Hazard Analysis (PSHA) methods (OpenSHA), broadband ground motion methods (Broadband Platform), deterministic wave propagation codes (AWP, Hercules, RWG), a physics-based PSHA platform (CyberShake), and forecast testing centers (CSEP, CISM). The SCEC software ecosystem is based on open-source scientific software that can be compiled and run in standard Linux environments across multiple architectures. These scientific applications are typically developed as stand-alone codes that input, and output, standardized data formats. Selected computationally intensive codes have been parallelized, and in some cases, accelerated on many-core systems, to support large-scale ground motion simulations. Scientific codes in the ecosystem can often be combined into complex workflows to automate multi-stage research calculations, with the interfaces between programs defined in file-based exchange formats, or as database queries. This software ecosystem also supports scientific applications that perform equivalent calculations using alternative methods, thus providing a level of verification of the different methods for complex problems where theoretical and/or analytical solutions are not available. The SCEC software ecosystem development approach has enabled significant scientific and computing advances and important earthquake system science research results.

CIG Community Standards and Best Practices for Scientific Software

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Seismological research depends heavily on the ability to record, process, access, and analyze data. As the magnitude of available data and computer power has increased, so has the complexity of scientific problems addressed, creating a need to sustain existing scientific software and expand its development to take advantage of new algorithms and computational hardware. The Computational Infrastructure for Geodynamics (CIG) originated from community recognition that the efforts of individual or small groups of researchers to develop scientifically-sound software in this environment is impossible to sustain, duplicates effort, and impedes the adoption of state-of-the art computational methods that promote new discovery. Over the past decade, we have learned that successful scientific software development requires at a minimum throughout development: collaboration between domain-expert researchers, software developers and computational scientists; clearly identified and committed lead developer(s); well-defined scientific and computational goals that are consistently and regularly evaluated and updated; well-defined benchmarks and testing; attention to usability and extensibility; understanding and evaluation of the complexity of dependent libraries; and managed user expectations through education, training and support. From these experiences, CIG has established guidelines for best practices in software development and dissemination built on an open-source development model. These guidelines are continually informed through community efforts to improve the verification and validation of scientific software through benchmarking and ongoing efforts to promote reproducibility and credit through software attribution. Through these efforts the CIG community is better prepared to address scientific problems that require high performance computing including high-resolution seismic waveform and dynamo modeling at national leadership-class computing facilities Titan and Mira.

UNAVCO Computational Infrastructure Enhancing Earthquake Science

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UNAVCO has provided infrastructure and support for solid-earth sciences and earthquake natural hazards for more than three decades. This support includes both geodetic infrastructure for observations and the associated data management and archive services: sensor technology, software, models, heterogeneous data sets, cloud computing, management of huge data volumes, and development of community standards. Recent advances in GNSS technology and data processing now provide position solutions with centimeter-level precision at high-rate (>1 Hz) and low latency bridging the gap between traditional geodesy and seismology. These data have the potential to improve our understanding in diverse areas of geophysics including properties of seismic, volcanic, magmatic and tsunami sources, and thus profoundly transform rapid event characterization and warning.

Raw and processed Real-Time GNSS (RT-GNSS) data will require formats and standards that allow this broad and diverse community to use these data and associated meta-data in existing research infrastructure, with a burgeoning set of observables as new constellations navigation systems are launched. In addition, rapidly advancing sensor technology and integration present new data products that are derived from a combination of disciplines.

Stream Data and Cloud Computing have exciting potential but requires rethinking traditional data collection, meta-data and data analysis paradigms used in the geodetic community.

These advances critically highlight the difficulties associated with merging data and metadata between scientific disciplines. Even seemingly very closely related fields such as geodesy and seismology, which both have rich histories of handling large volumes of data and metadata, do not integrate easily in any automated way.

UNAVCO strives to address these critical issues on behalf of and at the direction of the broader geosciences community.

Simulation Based Earthquake Forecasting with RSQSim

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Within the SCEC Collaboratory for Interseismic Simulation and Modeling (CISM), we are developing physics-based forecasting models for earthquake ruptures in California. We employ the 3D boundary element code RSQSim to generate synthetic catalogs with millions of events that span up to a million years each. This code models rupture nucleation by rate- and state-dependent friction and Coulomb stress transfer in a complex, fully interacting fault system. The Uniform California Earthquake Rupture Forecast Version 3 (UCERF3) fault and deformation models are used to specify the fault geometry and long-term slip rates. The mean recurrence intervals in the resulting RSQSim model are then matched to those of UCERF3 by applying a normal-stress adjustment factor to each fault segment. From this calibrated model, we generate long catalogs of simulated California seismicity from which we calculate the forecasting statistics for large events. In particular, we have employed the Blue Waters Supercomputer to produce suites of million-year catalogs that allow us to investigate the epistemic uncertainties in the RSQSim physical parameters, including the rate- and state-friction parameters a and b, the initial shear and normal stresses, and the rupture slip speed. Although RSQSim is still in its nascent stage of development, our results illustrate how rupture simulators might assist forecasters in understanding the hazards due to multi-event sequences of complex faulting.

Collaboratory for Interseismic Simulation and Modeling (CISM)

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SCEC received a three-year grant from the W. M. Keck Foundation to construct a Collaboratory for Interseismic Simulation and Modeling (CISM). CISM provides a unique environment for developing large-scale numerical models that can simulate sequences of fault ruptures and the seismic shaking they produce. The goal of CISM is to equip earthquake scientists with HPC-enabled cyberinfrastructure that creates a new generation of comprehensive, physics-based earthquake forecasts using the California fault system as their primary test bed.

CISM provides a computational framework for combining earthquake simulations, which account for the physics of earthquake nucleation and stress transfer, with ground-motion prediction models derived from simulations of seismic wave excitation and propagation. CISM facilitates comparisons between models and against existing data. Once mature, models will be tested against observations within the Collaboratory for the Study of Earthquake Predictability (CSEP). Validated CISM forecasting models will be considered for USGS's operational earthquake forecasting.

First year CISM progress was concentrated in three areas: finalization of the UCERF3-ETAS model, RSQSim development and calibration, and development of visualization and cross-validation tools. RSQSim, a physics-based earthquake simulator, was extended to support triangular elements and now simulates earthquakes on the entire UCERF3 fault system. Calibration efforts are currently underway to match paleosiesmic and magnitude-frequency constraints. A new version of the SCEC-VDO visualization tool was released with support for animating both RSQSim and UCERF3-ETAS synthetic catalogs. A computational interface was developed between the OpenSHA software and RSQSim. This allows for direct comparisons between RSQSim simulated catalogs and the UCERF3 models, and for the coupling of RSQSim and ground-motion prediction equations to perform probabilistic seismic hazard analysis.

Software vs. Data: The FORCE11 Citation Principles

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Computers have been a part of seismology since the 1960s to enable in the recording, storage, analysis, and dissemination of data collected by worldwide seismic networks. These data and software tools are the foundation of sound, reproducible science and should be considered legitimate, citable research products. In recognition of their importance, FORCE11 working groups drafted parallel data and software citation principles as guidelines for citation within research objects. The principles address importance, credit and attribution, unique identification, persistence, specificity, and access(ibility). The data principles include evidence, verifiability, and interoperability and flexibility while the software principles do not, but discuss them within software's context.

The principles differ since software is different from scientific data: software is executable, data is not; data provides evidence, software provides a tool; software is a creative work, data are facts or observations; software can have complex dependencies; and software's lifetime is generally shorter than data. Hence, software is subject to copyright, and results can depend on version number, revisions, compiler, and platform. In addition, software may fall into obsolescence over time or suffer rot impacting its availability and (re)usability.

Due to the immediacy of seismological data, little attention has been given to data and software as citable, creative works. Research credibility is promoted by transparency and reproducibility through citation. Developers should deposit their code into a repository, instruct users in how to cite their software, and obtain a unique identifier such as a DOI. Users should look for developer instructions on how to cite. If no instructions are included, they should use the citation principles as a guideline, look for prior citation examples, and contact the authors. Leveraging the computational infrastructure will enable us to rapidly move towards this goal.

Using GPU Clusters to Detect Millions of Small Earthquakes in Southern California with Template Matching

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Seismic networks routinely record small earthquakes that are not detected by standard automated network processing. To detect and locate these small earthquakes, we apply a template matching technique to nine years of continuous data recorded by the Southern California Seismic Network (2008-2016). The waveforms of nearly 300,000 past events are used as templates to search for similar signals in the continuous data and calculate magnitudes. A large GPU cluster is used to perform the calculations. We identify approximately 20 times as many events as the original SCSN catalog, resulting in millions of events total in this new seismicity catalog. These events are associated with billions of differential times that will be used for precise relative relocation. New observations associated with the high-resolution catalog will be presented in the meeting.

Using GeoGateway to Explore Off-Fault Deformation along the San Andreas Fault in the Carrizo Plain, CA

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Several studies have examined apparent discrepancies between geologically measured slip rates, slip-per-event measurements, and average recurrence intervals of paleoearthquakes on the San Andreas fault in the Carrizo Plain. To resolve discrepancies it is necessary to understand the role of off-fault deformation in the seismic cycle. Crustal deformation is spatially and temporally non-uniform as strain accumulates over long time scales, is rapidly released in earthquakes, and readjusts post-seismically. Because earthquake processes occur over such widely varying temporal and spatial scales, many types of data— each of which probe a different aspect of the earthquake cycle— are required for analysis. Prior studies used short aperture, long time period geological studies, or broad aperture, short time period geodetic methods. In our current work we use NASA's GeoGateway tool to access, analyze and model GPS and UAVSAR data along the San Andreas fault in the Carrizo Plain, and incorporate optical imagery, fault models, and paleoseismic data from geologic studies. GeoGateway is a convenient and powerful tool for analyzing these heterogeneous data sets for enhanced understanding of the earthquake cycle.

Tsunami Early Warning through Earthquake, Tsunami, and Ionosphere Simulation

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Tsunami early warning is a high priority for at-risk regions due to the scale of both economic and human costs in these disasters. A large array of sensors exist in the form of the Global Navigational Satellite System (GNSS). Recent work has shown that perturbations in the Total Electron Content (TEC) of the ionosphere, which can be detected with GNSS signals, can be used to observe changes in the Earth's surface height, including those caused by tsunamis. We use long-term synthetic seafloor uplift histories from the Virtual Quake earthquake simulator as initial conditions for a tsunami simulation, the results of which are then used to model ionospheric response. Observed real-time TEC perturbations can then be quickly referenced against large precomputed catalogs of tsunami scenarios, allowing for rapid determination of hazard for at-risk regions in the event of a tsunamigenic earthquake.

Earthquake Interaction and Triggering: From Near Field to Far Field, From Natural to Induced

Oral Session · Tuesday 18 April · 2:15 PM · Governor's Square 15

Session Chairs: Wenyuan Fan, Andy Barbour, Xiaowei Chen.

What Really Triggers Earthquakes?

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For more than 20 years the static stress-change hypothesis has provided a basis for explaining the spatial distribution of triggered earthquakes in evolving sequences with varying success rates. To date several questions remain unanswered: Are earthquake occurrences related by a stress threshold? Do earthquakes always rupture maximum stressed faults? How we can best determine which faults are near failure? How do oversimplified stress field approximations influence the determination of optimally-oriented failure planes? Here, we present a methodological improvement for estimating fault triggering potential that builds on the joint effect of the pre-existing and the co-seismic stress field in complex fault geometries. We sample a complete range of possible failure planes, while varying kinematic and frictional parameters, and we incorporate the spatial variation in crustal stress that results from non-uniform principle stress axis orientations to identify potential rupture planes. We implement our method for analyzing triggering patterns following the M=7.2 2010 El Mayor-Cucapah (EMC) event. We use a high-accuracy focal mechanism catalog and the stress field characteristics derived from Community Stress Model to predict the rupture style of triggered seismicity for the period between April 2010 and December 2013. We evaluate different approaches for their ability to reproduce consistent rupture styles considering the uncertainties of individual focal mechanisms. We find that (1) Optimal Oriented for Failure planes are successful at 35.8%, (2) Potential Planes that represent maximum total stress faults succeed at a 27.5% rate, and (3) Potential Planes with informed priors from pre-EMC focal mechanisms at 91%. Although earthquakes do not coincide with maximum stresses, the probabilistic determination of all potential ruptures is far more informative when compared to deterministic approaches for stress estimation.

Preparation Phase of a M4.2 Earthquake below the Eastern Sea of Marmara Offshore Istanbul Observed from GONAF Downhole Recordings

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The main branch of the North Anatolian Fault Zone below the Sea of Marmara is facing a high probability for a M>7 earthquake. Recently implemented monitoring efforts such as the downhole GONAF observatory nor allow for detecting low-magnitude seismicity along the eastern Marmara section offshore of Istanbul. The June25, 2016, M4.2 earthquake off the Armutlu peninsula was the largest local earthquake in years. Low-noise recordings from the closest vertical seismic GONAF array allowed to detect a series of earthquakes preceding and following the mainshock down to M~0. In the 64 hours before the M4.2 event, a total of 18 M>0 earthquakes with S-P times within 0.1 sec of the M4.2's S-P time took place. They reflect a type of self-organization and preparatory phase of the mainshock. In the subsequent 48 hours at least 3 to 4 times as many similar size-and-S-P time events were also detected. The relative magnitudes of the detected events span from the detection limit of the array at M~0 to M~3.5 as measured on the same scale as the M4.2. Based on their close hypocenter locations the entire series of detected events appear to fill a local seismic gap, whose dimensions are on the same order as the M4.2 rupture. A large fraction of the preceding and following events have similar waveforms. Average cross-correlation coefficients of foreshocks show a clear increase during the ten hours before that mainshock possibly reflecting a preparation process in direct vicinity to the mainshock hypocenter. If processed in near-real time this might support approaches in earthquake forecasting.

Modeling Repeating Earthquake Interactions: Triggering Effect from Nearby Microseismicity

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We build on more than a decade of work establishing a record of repeating microearthquakes with data from the borehole HRSN network and surface NCSN network sites at Parkfield, CA. By the end of 2015, 217 repeating-earthquake sequences ranging from M = -0.4 to M = 3 with up to 83 recurrences of near-identical ruptures of isolated asperities were identified within this partly creeping transition segment of the San Andreas fault (SAF). We used this large earthquake population to examine, model and test if fault interaction in the form of static stress changes and transient postseismic fault creep produces much of the observed aperiodicity in the occurrence of these events. Using the large number, precisely known locations, and frequent repeats of these events, we (1) examined the catalog for empirical evidence of earthquake triggering and event sequences and (2) explicitly modeled the mechanics of such interaction. This has allowed us to evaluate the role of fault-interaction stresses in the timing of observed event sequences. We developed physical models of the slip events and afterslip on the surrounding SAF and their interactions building on existing boundary element methods that allow for consideration of time-dependent stress changes. And we explicitly considered the role of the 2004 earthquake in the spatio-temporal development of the repeating earthquake sequences. Using the models, we have also venture to explicitly examine if fault interaction through stress transfer determines recurrence history and aperiodicity of earthquakes among sub-populations of the Parkfield repeating earthquakes.

Regional and Stress Drop Effects on Aftershock Productivity of Large Megathrust Earthquakes

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The total number of aftershocks increases with mainshock magnitude, resulting in an overall well-defined relationship. Observed variations from this trend prompt questions regarding influences of regional environment and individual mainshock rupture characteristics. We investigate how aftershock productivity varies regionally and with mainshock source parameters for large (MW ≥ 7.0) circum-Pacific megathrust earthquakes within the past 25 years, drawing on extant finite-fault rupture models. Aftershock productivity is found to be higher for subduction zones of the western circum-Pacific than for subduction zones in the eastern circum-Pacific. This appears to be a manifestation of differences in faulting susceptibility between island arcs and continental arcs. Surprisingly, events with relatively large static stress drop tend to produce fewer aftershocks than comparable magnitude events with lower stress drop; however, for events with similar co-seismic rupture area, aftershock productivity increases with stress drop and radiated energy, indicating a significant impact of source rupture process on productivity.

Remote Triggering of Microearthquakes and Deep Tectonic Tremor in New Zealand Following the 2016 M7.8 Kaikoura Earthquake

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We conduct a systematic search for remotely triggered seismicity in New Zealand following the 2016 M7.8 Kaikoura earthquake. This complex event has triggered numerous aftershocks, as well as deep and shallow slow-slip events along the Hikurangi subduction zone in North Island. We first examine continuous waveforms recorded by New Zealand GeoNet for evidence of dynamic triggering during the passing of waves from the Kaikoura earthquake. To avoid contamination from the mainshock coda and early aftershocks, we apply a high-pass filter at 10 or 20 Hz to the data, and visually inspect spectrogram of the high-passed waveforms to identify high-frequency signals during and immediately following the large-amplitude surface waves. Although most nearby broadband stations were clipped during the mainshock, we are able to identify many widespread sites with evidence of dynamic triggering. These include triggered long-duration high-frequency signals at stations OUZ and GRZ in low strain-rate regions, station DCZ, near the Puysegur subduction zone in the southern South Island, and many sites within the Taupo volcanic zone. We interpret many of the signals as deep tectonic tremor signals associated with nearby subduction zones or major inland faults. In addition, we also observe many triggered shallow microearthquakes, mostly within the Taupo volcanic zone, following the instantaneously triggered deep tremor signals. Our next step is to use a waveform matching method to scan through the continuous waveforms to better quantify spatial-temporal evolution of triggered seismicity and its relationship with the triggered slow-slip events. Updated results will be presented at the meeting.

Testing for the 'Predictability' of Dynamically Triggered Earthquakes in Geysers Geothermal Field

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Dynamic triggering studies provide clues about conditions under which failure occurs as a result of passing seismic waves and can aid our understanding of the predictability of earthquake activity. Geysers Geothermal Field, a well-instrumented region known to be highly susceptible to transient stresses generated by passing seismic waves, is ideal for investigating the conditions necessary for dynamic triggering, whether instantaneous or delayed. In this study, we form more complete earthquake catalogs around the time of known triggering mainshocks and several $M \geq 5$ mainshocks from the Mendocino Triple Junction region by applying the matched filter technique. Based on our detections, we find that dynamic stress positively correlates with magnitude, such that a larger dynamic stress triggers a large event early on in the triggered sequence. When projecting Coulomb stress changes caused by each mainshock onto the dominant faulting styles for Geysers, we find that mainshocks with statistically significant triggering have, on average, higher stress changes than those without statistically significant triggering. Our efforts are now focused on understanding the local stress state around the time triggering occurs, which includes the investigation of Gutenberg-Richter b-values in space and time and the magnitude of tidal stresses projected onto Geyser's dominant fault planes determined from focal mechanism solutions.

Investigating Earthquake Stress Release from Triggered Seismicity in Geothermal and Induced Seismicity Regions

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Earthquake triggering has been shown to occur in a variety of tectonic settings and with a suite of inferred mechanisms. Large earthquakes have been shown to promote the triggering of small earthquakes, non-volcanic tremor, and volcanic responses due to static stresses in the near field caused by physical movement along the fault (static triggering), and remotely due to stress loading and passage of seismic waves (dynamic triggering). Recent induced seismicity, earthquakes caused by human activity, results from industrial practices such as deep wastewater injection. In sum, dynamic, static, and induced seismicity result from stress changes that trigger faults and/or volcanic activity. We target regions where natural, induced, and dynamically triggered events occur in order to gain insight into the faulting process, magmatic responses, and stress mechanisms for failure. We explore dynamic triggering in documented regions of induced seismicity and productive geothermal areas to examine the role of fluids and wave type in the triggering process. Specifically, we document dynamic triggering and analyze the attributes of triggering. We examine relationships between wave type, wave orientation to local stress field, and peak dynamic stress in order to assess whether fluid is the only factor with triggered seismicity in these regions. Our investigation indicates dynamic triggering, in some cases, may be enhanced in regions where the incoming, triggering seismic wave aligns with the local stress field.

On the Importance of Surface Deformation for Understanding Time-Dependent Seismic Hazard Due to Fluid-Injection

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Increasing seismicity in the central USA since 2009 coincides in space and time with wastewater injection. However, observations of the surface deformation and physical models to constrain the extent to which fluid migrates and to unequivocally link the seismicity and wastewater injection are scarce. In a recent work, Shirzaei *et al.* (2016) presented an example from Texas showing the wastewater injection causes uplift at a few mm/year, detectable using radar interferometric data. They also showed that the crustal strain and pore pressure constrained using the measured uplift and reported injection data increased stress in rocks with low

compressibility, which triggers earthquakes including the M_w4.8, 17 May 2012 event, the largest earthquake recorded in east Texas. Here, I report on 8 injection sites in Oklahoma, where high volume (> 10^6 m^3) fluid injection has possibly caused detectable surface uplift of > 2 mm/yr. To this end I compile large sets of SAR images acquired by ALOS L-band satellite over the Oklahoma during period 2006 and 2011 and apply an advanced multitemporal InSAR algorithm to measure mm-level changes in surface elevation. In the following, I use the obtained deformation data in conjunction with the time series of injected fluid at each site to constrain: 1) rate of change in volumetric strain, 2) temporal evolution of rocks vertical hydraulic conductivity, and 3) horizontal hydraulic conductivity within injection layer. Availability of these parameters allows obtaining more accurate estimates of the pore fluid pressure, which in turn enhances the evaluation of earthquake potential in the vicinity of injection sites.

A Physical Mechanism for Earthquake Dynamic Triggering in Fluid Regions

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Weak dynamic seismic stress waves from distant earthquakes can dynamically trigger seismicity, abruptly change the fluid permeability of a hydrologic system, or cause liquefaction and volcanic eruptions.

Many proposed mechanisms to explain these phenomena require large fluid pressure gradient to induce fluid flow during the passage of the waves, yet the exact mechanism on how the fluid pressure can change is unclear.

Using full-waveform numerical modeling, we found that the transient seismic-wave fluid pressure in a fluid-filled fracture could increase more than two orders of magnitude relative to the pressure of the incident wave. We call this Pressure-Surge Phenomenon (PSP). The PSP depends on incident wave frequency, the size of the fracture, as well as the aperture. Our modeling showed that this pressure increase could be much more pronounced for low-frequency transient wave incidence than for high frequencies and could develop large pressure gradient to drive the fluid to flow inside the fracture.

In particular, the PSP showed that the dynamic triggering of earthquakes may not necessarily be due to the purported belief that the system is at a critical state such that a perturbation of stress such as a weak incident wave can cause the catastrophic failure. Instead, the PSP provides a new mechanism for the triggering—the fluid pressure magnification which reduces the normal stress on the fracture/fault to cause the fault to slip.

Our modeling showed that the PSP is a fundamental phenomenon that can pay important roles in all above mentioned natural phenomena in fluid-fracture systems.

What Water Pressure is Needed to Trigger Earthquakes?

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We are proposing an experiment to understand the initiation of large earthquakes by inducing seismic events on a shallow fault with water injection. Increasing the fluid pressure near an active fault will reduce normal pressure on a fault and bring it closer to failure, according to the classic Coulomb failure criterion. A study to monitor the water pressure and subsequent triggered earthquakes can help answer some fundamental questions in seismology about the stress levels that cause earthquakes and the physical conditions that are necessary for a large earthquake to occur.

Possible sites for such an experiment would be transform faults near mid-ocean ridges, such as the East Pacific Rise. Seismicity in these regions is quite shallow and accessible with ocean boreholes of 2 to 3 km depth. In such settings, moderate (M5 to M6) earthquakes occur at repeat intervals of 5 to 15 years. We would like to conduct a water injection experiment at one of these sites a few years before the expected earthquakes recurrence, to try to trigger an early occurrence of the event.

What is the water pressure needed to trigger an earthquake? Assuming a recurrence time of about 15 years and a stress drop of about 2 MPa for an M5 earthquake, to trigger an earthquake 2 years early, we would need to increase the shear stress 0.3 MPa. Using the Coulomb failure criterion, this would correspond to a decrease of normal stress (or increase of pore pressure) of about 0.5 MPa. This increase is relatively small, however, the absolute pore pressure at 1 km depth is about 8 MPa. So pumping pressure of about 8.5 MPa would be necessary to reduce the normal stress on the fault. Such pumping pressures are possible using the current riser drilling technology.

Earthquake Source Parameters: Theory, Observations and Interpretations

Oral Session · Tuesday 18 April · 8:30 AM · Plaza F

Session Chairs: Vaclav Vavrycuk, Grzegorz Kwiatek, German Prieto

A New Strategy for Earthquake Focal Mechanisms Using Waveform-Correlation-Derived Relative Polarities and Cluster Analysis: Application to a Fluid-Driven Earthquake Swarm

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In microseismicity analyses, reliable focal mechanisms can typically be obtained for only a small subset of located events. We address this limitation here, presenting a framework for determining robust focal mechanisms for large populations of very small events. To achieve this, we resolve relative P- and S-wave polarities between pairs of waveforms using their signed correlation coefficients—a byproduct of previously performed precise earthquake relocation. We then use cluster analysis to group events with similar patterns of polarities across the network. Finally, we apply a standard mechanism inversion to the grouped data, using either catalog or correlation-derived P-wave polarity datasets. This approach has great potential for enhancing analyses of spatially concentrated microseismicity such as earthquake swarms, mainshock-aftershock sequences, and industrial reservoir stimulation or injection-induced seismic sequences.

To demonstrate its utility, we apply this technique to the 2014 Long Valley Caldera earthquake swarm, which is interpreted to have been initiated and sustained by an evolving fluid pressure transient. In our analysis, 85% of events (7212 out of 8494 located by Shelly *et al.* [JGR, 2016]) fall within five well-constrained focal mechanism clusters, more than 12 times the number with network-determined mechanisms. Of the earthquakes we characterize, 3023 (42%) are smaller than magnitude 0.0. We find that mechanism variations are strongly associated with corresponding variations in hypocentral structure, yet mechanism heterogeneity also occurs where it cannot be resolved by hypocentral patterns, often confined to small-magnitude events. Small (5-20°) rotations between mechanism orientations and earthquake location trends for each cluster persist when we apply 3D velocity models. Although this discrepancy might still be a velocity-model artifact, it could also be explained by a geometry of en echelon, interlinked shear and dilational faulting.

Ambient Noise Moment Tensor (ANMT) Estimation

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One challenge in estimating seismic moment tensors, and improving on their ability to determine focal parameters including the source type, is the effect of 3D velocity structure on the waveforms. Commonly, moment tensor solutions are found by assuming well-calibrated 1D velocity models to compute Green's functions. While this is effective, there are always problems with some paths being affected by strong 3D propagation effects or with events that occur in complex geologic environments where the assumption of 1D velocity structure is not valid. Denolle *et al.* (2013) developed the concept of the Virtual Earthquake utilizing ambient noise cross-correlation Green's functions, showing that it was possible to project a unit-force Green's tensor to seismogenic depth and determine the tensor of single-couple and force-dipole Green's functions, assuming the theoretical equations for fundamental mode surface waves. Using this approach, they simulated the synthetic ground motions for earthquakes of a given scalar moment, strike, rake and dip, and demonstrated correlation with actual earthquake records in 3D basin environments, demonstrating viability for ground motion amplification studies. We are using the Virtual Earthquake approach to develop an ambient noise moment tensor (ANMT) method. In this paper, we present numerical tests documenting the accuracy of both the approximation for the depth projection of the surface force and the approximate derivatives. We then construct a synthetic dataset using frequency wavenumber single-couple/dipole Green's functions and apply various levels of noise, which will be inverted with the approximate Green's functions from surface focus unit-force Green's functions. We will present the work in terms of the ability to determine the seismic moment tensor, the uncertainties in the moment tensor, and the ability to constrain the source-type for cases in which there are non-double-couple components in the synthetic data.

Estimating Moment Tensors Using Virtual Seismometers

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We are developing methods to monitor tectonically active features so that we can identify faults at risk of slipping. The virtual seismometer method (VSM) is an interferometric technique that provides fast, precise, high frequency estimates of the Green's function (GF) between earthquakes. VSM works by effectively replacing each earthquake with a "virtual seismometer" recording all the others. The technique isolates the portion of the data that is sensitive to the source region and dramatically increases our ability to see into tectonically active features, such as at depth in fault zones. This allows us to measure the evolution of seismicity over time, including changes in the style of faulting.

An advantage of VSM is that it considerably reduces the modeled numerical domain to the region directly around the cloud of events. This lowers computational cost, permits higher frequency resolution, and suppresses the impact of the Earth structural model uncertainties outside the tectonically active region.

Here, we show that the cross-correlated signals from seismic wavefields triggered by two events and recorded at the surface are a combination of the strain field between these two sources, times a moment tensor. Based on this relationship, we demonstrate how we can use these cross-correlated signals to estimate the full moment tensor.

Analysis of the 2016 Seismic Sequence in Central Italy

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On August 24, 2016, a M_w6.0 earthquake struck Central Italy near the town of Amatrice and claimed the lives of 300 people. Two months later, the intensity of the aftershock sequence suddenly increased, when on its northern sector two seismic events of M_w5.9 and M_w6.5 indicated the activation of a new fault system. The latter event of October 30, 2016, was the strongest in Italy since the M_w6.9 Irpinia earthquake of November 23, 1980, destroying almost all the pre-damaged buildings. The aftershock sequence of more than 40,000 localized events extends actually in an area of circa 80 km x 25 km.

We relocalized seismic events with M>3 by applying master-event waveform stacking. This method combines some features of relative location techniques (such as the source specific station correction term [Richards-Dinger and Shearer, 2000]) with a waveform based location method [Grigoli *et al.*, 2016], reducing the dependency on the velocity model and improving location accuracy.

In this work, we used also seismic data from INGV, improved the hypocentral depth by modeling P – pP signals at teleseismic distances, analyzed the moment tensors of the strongest events by modeling broadband data at regional distances, calculated the Apparent Source Time Functions (ASTF) and the slip distribution for the M_w5.9 event of August 24, 2016, using some aftershocks as Empirical Green Functions (EGF), and finally applied the Source Scan Algorithm for the calculation of the rupture propagation direction. The combined interpretation of seismological analysis of seismic data at local, regional and teleseismic distances sheds light on the complexity of the rupture process for the 2016 Central Italy seismic sequence.

P-Waveform Inversion for Moment Tensors Using the Principal Component Analysis

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We present a moment tensor inversion of waveforms of P waves using the principal component analysis (PCA). The method is based on the point source approximation, characterized by the direct P wavelets identical at all receivers irrespective of azimuths and take-off angles of the corresponding rays. The PCA inversion for moment tensors consists of the following steps. First, the records of P waves are aligned for all stations using the cross-correlation analysis. Second, the principal component decomposition is applied to extract the common waveform of the P wave and to calculate the respective PCA coefficients. Third, the PCA coefficients are used as the P-wave amplitude factors in the standard amplitude inversion for the moment tensors. The robustness and accuracy of the proposed inversion method is analyzed on numerical tests and on real observations of 2014 earthquake swarm activity in West Bohemia, Czech Republic. It is shown that even though the method works in a semi-automatic regime, it yields very accurate results which are comparable or even better than those obtained by the standard waveform inversion or the inversion of P-wave amplitudes picked manually. The method is particularly suitable for analysis of extensive datasets of local natural or induced microseismicity, where manual processing of individual earthquakes is not feasible.

Radiated Energy Enhancement and Rupture Complexity of Large Subduction-Zone Earthquakes

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The rupture characteristics of large earthquakes on subduction zone plate boundaries vary substantially. The asperity model, proposed in the early 1980s, related variations of the largest earthquake size and complexity in a region to stress heterogeneity. Repeating earthquakes and geodetic measurements of inter-seismic strain accumulation support the notion of asperities being surrounded by creeping regions with different frictional properties. The surge of large earthquakes over last decade and the advance in observations and analysis techniques allow us to evaluate whether asperities differ from region to region. To quantify variable rupture complexity, we introduce a new energy radiation parameter, the radiated energy enhancement factor (REEF): the ratio of directly measured broadband radiated energy to the calculated minimum radiated energy (for an event of equal seismic moment and duration with parabolic shape moment-rate function). For large earthquakes, REEF is closely related with complexity in the observed moment-rate function. We find that (1) REEF variation among different subduction zones is consistent with the level of segmentation proposed in the asperity model; and (2) REEF values are similar for earthquakes with different magnitudes in each region. Both observations indicate that the regional "asperity" structure observed at scales of tens to hundreds of kilometers is similar to that at smaller scales. Asperities thus differ from region to region, likely due to variable stress conditions on the plate boundaries.

Another Look at the Foreshocks of the 1999 Mw 7.1 Hector Mine, California, Earthquake

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Foreshock sequences provide an important window into the nucleation process of some large earthquakes. The October 16, 1999, M_w 7.1 Hector Mine earthquake in southern California was preceded by 18 cataloged foreshocks during the 20 hours before the mainshock (Hauksson *et al.*, 2002). Visual inspection of continuous seismic data for these 20 hours at the 6 nearest stations in the Southern California Seismic Network (SCSN) revealed 42 foreshocks, indicating that small foreshocks occur more often than are observed in the catalog (Zanzerkia *et al.*, 2003). A combination of increased computing capability and recent developments in seismological techniques motivated us to revisit this foreshock sequence. Brown *et al.* (SSA meeting, 2012) used autocorrelation to produce 446 detections in the 20 hours of continuous data leading up to the mainshock, but we find that most of these events were similar noise signals rather than earthquakes. In this study, we systematically detected foreshocks with similar waveforms in continuous data at the 7 nearest stations in the SCSN, using an extension of the Fingerprint And Similarity Thresholding (FAST) method (Yoon *et al.*, 2015) to multiple seismic stations. Although the number of foreshocks detected in the 20 hours before the mainshock increases to 52, we do not find evidence for hundreds of small events. For those foreshocks we detect, we compute precise double-difference locations (Waldhauser and Ellsworth, 2000), as well as source parameters for the largest foreshocks, to analyze their space-time evolution and their relationship to the mainshock.

Complex Spatiotemporal Evolution of Seismicity and Source Parameters of the 2008 Mw 4.9 Mogul Earthquake Swarm in Reno, Nevada

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After approximately 2 months of swarm-like earthquakes in the Mogul neighborhood of west Reno, NV, seismicity rates and event magnitudes increased over several days culminating in an M_w 4.9 (ML 5.1) dextral strike-slip earthquake on 26 April 2008. Although very shallow, the M_w 4.9 main shock had a different sense of slip than locally mapped dip-slip surface faults. We relocate 7549 earthquakes, calculate 1082 focal mechanisms, and statistically cluster the relocated earthquake catalog to understand the character and interaction of active structures throughout the Mogul, NV earthquake sequence. Rapid temporary instrument deployment provides high-resolution coverage of microseismicity, enabling a detailed analysis of swarm behavior and faulting geometry.

Double-difference waveform-based relocations reveal an internally clustered sequence in which foreshocks evolved on multiple structures surrounding the eventual main shock rupture. The relocated seismicity defines a fault-fracture mesh and detailed fault structure from approximately 2–6 km depth on the previously unknown Mogul fault that may be an evolving incipient strike-slip fault zone. The seismicity volume expands before the main shock, consistent with pore pressure diffusion, and the aftershock volume is much larger than is typical for an M_w 4.9 earthquake. We group events into clusters using space-time-magnitude nearest-neighbor distances between events and develop a cluster criterion through randomization of the relocated catalog. Identified clusters are largely main shock-aftershock sequences, without evidence for migration, occurring within the diffuse background seismicity. Finally, we estimate well-constrained, independent P- and S-wave corner frequencies for 148 earthquakes (2.2ML≤5.1) using EGF-derived spectral ratios. Resulting stress drops vary over two orders of magnitude and enable investigation of stress drop variation within a well-recorded sequence.

Seismic Source Parameters of the Induced Seismicity at The Geysers Geothermal Area, California, by a Generalized Inversion Approach

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The accurate determination of stress drop, seismic efficiency and how source parameters scale with earthquake size is an important for seismic hazard assessment of induced seismicity. We propose an improved non-parametric, data-driven strategy suitable for monitoring induced seismicity, which combines the generalized inversion technique together with genetic algorithms. In the first step of the analysis the generalized inversion technique allows for an effective correction of waveforms for the attenuation and site contributions. Then, the retrieved source spectra are inverted by a non-linear sensitivity-driven inversion scheme that allows accurate estimation of source parameters. We therefore investigate the earthquake source characteristics of 633 induced earthquakes (ML 2-4.5) recorded at The Geysers geothermal field (California) by a dense seismic network (*i.e.*, 32 stations of the Lawrence Berkeley National Laboratory Geysers/Calpine surface seismic network, more than 17.000 velocity records). We find for most of the events a non-selfsimilar behavior, empirical source spectra that requires ωγ source model with γ > 2 to be well fitted and small radiation efficiency ηSW. All these findings suggest different dynamic rupture processes for smaller and larger earthquakes, and that the proportion of high frequency energy radiation and the amount of energy required to overcome the friction or for the creation of new fractures surface changes with the earthquake size. Furthermore, we observe also two distinct families of events with peculiar source parameters that, in one case suggests the reactivation of deep structures linked to the regional tectonics, while in the other supports the idea of an important role of steeply dipping fault in the fluid pressure diffusion.

Source Parameters for Events in the Central and Eastern United States

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We report on the robust determination of source parameters of over 60 recent events in the Central and Eastern United States (CEUS). Source parameters, including seismic moment Mo, apparent stress sigma, and high-frequency falloff eta, are determined using the coda recorded by regional stations. The amplitudes of coda waves are notably more stable than those from direct phases. We achieve the highest quality source spectra over a broad frequency band by correcting the observed coda amplitudes for propagation effects. We observe significant differences in the coda envelope shapes between the stable CEUS and the Western U.S. which indicates strong differences in scattering and attenuation. Lateral attenuation variations are calculated using a recently-developed method that explicitly includes a scattering term and we obtain coda Q values that are consistent with those determined using direct amplitudes (Pasyanos *et al.*, 2016, BSSA). The method has shown great improvement in interstation variations, particularly at higher frequencies (> 1 Hz), allowing one to examine the source effects of smaller events (M<3.5). With this dataset of events ranging from M 2.6-6.5, we look for differences in stress drop due to factors such as earthquake size, source depth, and tectonic region. We also look for any observed differences in the source spectra among tectonic events, possibly-induced earthquakes, and other sundry events (*e.g.* mining events, offshore explosions).

Earthquake Stress Drop: Source Scaling, Uncertainties, and Complexity of Small Earthquakes

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Earthquake stress drop is fundamental to understanding the physics of the rupture process. Unfortunately, it is far from simple simple to calculate reliable and precise measurements of stress drop from the spectrum of the radiated energy. The large number of studies of earthquake stress drop, the high variability in results, the large uncertainties, and the ongoing scaling controversy are evidence for this.

I have developed an EGF-based approach that involves strict selection criteria for EGFs, and stacks over the best quality recordings to stabilize the results. I use this approach to investigate the uncertainties of stress drop measurements, and identify the most significant problems in source parameter calculation. This method has been applied to hundreds of earthquakes (M~2-6) from a diverse range of tectonic settings, including the Hikurangi subduction zone, New Zealand (Abercrombie *et al.*, 2017), induced earthquakes in Oklahoma, and the tectonic Mogul sequence in Nevada. The focus is on obtaining precise and accurate measurements of corner frequency and stress drop for the best-recorded earthquakes. For each stacked ratio, a grid-search is performed to obtain quantitative uncertainty measurements, and the analysis is restricted to the well-constrained corner frequency measurements.

I find that there is significant real variability in earthquake sources; the variation of stress drop within individual sequences is larger than between different sequences. The uncertainties remain large, and I discuss likely reasons for this, compared to ground-motion variability. For example, the finite frequency bandwidth makes it harder to separate source and path effects, and limits the frequency range over which a corner-frequency (or ratio asymptotes) can be resolved, potentially causing an artificial scaling. Also, a significant number of earthquakes are clearly complex, and attempting to model them with a simplistic source model furtherincreases the errors.

Improving Earthquake Source Parameters Estimation with Adaptive Window Spectral Analysis

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Since the 1960s, the scaling relationships of source parameters has been debated. The behavior of corner frequency, stress drop, and radiated seismic energy as a function of size, tectonic setting or depth provide fundamental information on the static and dynamic behavior of the earthquake rupture. Multiple approaches have been put forward to estimate these parameters, including source time function estimation, spectral analysis or coda wave envelopes. Each approach has advantages, but also have disadvantages that may introduce bias in the source parameter estimates and need to be understood and considered. For example, spectral analysis provides an overall view of the seismic radiation as a function of frequency, but the analysis requires to make a-priori decision on the window length to be analyzed. If the window is too small, spectral resolution is poor, if it is too long, signal-to-noise ratio (SNR) considerations may be an issue. Coda wave envelope methods avoid this problem, by estimating the envelope functions for band-limited signals, allowing for different window lengths at different frequencies. In many studies, the maximum frequency of analysis of coda waves is limited to about 20 Hz, with some exceptions of course. In this contribution, I show an adaptation of the multitaper spectral analysis method that allows for spectral estimation over a wide frequency range using adaptive time windows, such that the user is not required to predetermine the window size to be analyzed. I show that such a method allows for a much better SNR at all frequencies, and can be adapted for empirical Green's function or spectral ratios for collocated earthquakes. Examples are show for earthquakes over a wide magnitude range and uncertainty estimation of the corresponding source parameters. Ideally such an adaptive method is used in future source parameter studies.

Self-Similarity of M1 to 8 Earthquakes through Ground-Motion Modeling, and Special Attributes of Small Magnitude Earthquakes

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Ground-motion records of small (<~M3) earthquakes are strongly controlled by attenuation, and much less so by stress drop, due to the corner frequency being greater than the largest observable frequency. We illustrate the essential consequences of this effect using over 15,000 near-source (R<20 km) small-magnitude records in conjunction with data from moderate to large (M 3 to 8) earthquakes in the NGA-West2 dataset, and the model of Baltay and Hanks [2013]. For this ensemble dataset covering magnitudes 1 to 8, a single stress drop of ~5 MPa and single attenuation parameter kappa=~0.04 models the median ground motion well at R=10 km. This strongly supports earthquake self-similarity, in that a magnitude-dependent stress drop is not required by the data when the effect of kappa attenuation is properly accounted for.

In the small-magnitude regime, strong high-frequency attenuation implies direct scaling of ground motion with moment. This same physical description yields a systematic difference between moment and local magnitude. By definition, moment magnitude, **M** ~ 2/3 log M0, is uniformly valid for all earthquake sizes [Hanks and Kanamori, 1979]. However, the relationship between local magnitude and M0 is itself magnitude dependent. For moderate events (M 3 to 7) **M** and ML are coincident; for earthquakes smaller than M3, ML ~ log M0 [Hanks and Boore, 1984]. This implies that ML and **M** differ by a factor of 1.5 for these small events, and yields the scaling of ground motion as 1.5***M**, or 1.0* ML, as observed in the small-magnitude data.

We lastly consider how this affects b-value. The oft-cited b-value of 1 should hold for small magnitudes, given **M**. Use of ML necessitates b=2/3 for the same dataset; use of mixed, or unknown, magnitudes complicates the matter further. This is of particular import when estimating earthquake given limited data on their recurrence, as is the case for induced earthquakes in the central US.

Stress Drop and Source Scaling of Recent Earthquake Sequences in the Central and Eastern United States

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Knowledge of source scaling and variation in stress drop are essential to a better understanding of source physics and strong ground-motion prediction. Due to the large uncertainties in stress drop measurements, many previous studies have found results showing both self-similar and non-self-similar scaling relationships between large and small earthquakes. Moreover, the validity of the recently proposed idea that induced earthquakes in the central and eastern United States (CEUS) have low stress drops needs to be tested in a reliable and systematic way. In this study, we investigate the stress drop and source scaling of recent important earthquake sequences in the CEUS including the 2011 M_w 5.7 Mineral, Virginia earthquake and several M_w 5+ induced earthquakes in Oklahoma. We apply a multi-window coda spectral ratio method, which enables us to separate the source effect from the path propagation and site response effects, to obtain reliable estimates of corner frequencies and stress drops. We demonstrate that the use of the coda spectral ratio method can produce more stable estimates than the use of the direct S-waves in the conventional empirical Green's function (EGF) or spectral ratio method. Our results shed light on the yet un-resolved question whether potentially induced earthquakes are different from tectonic earthquakes in terms of stress drop and source scaling in the CEUS.

On the Variation of Strong-Motion Parameters in the Context of the Specific Barrier Model

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Reliable simulations of high-frequency earthquake strong ground motion time histories are based on seismological models that have been calibrated on the basis of recorded data. As a result, peak ground motion parameters such as PGA, PSA, etc. derived from suites of synthetic strong-motion time histories capture the median trend of data as a function of *e.g.* distance and frequency, respectively, for a given earthquake magnitude. However, the variability associated with peak parameters from earthquake strong-motion data is generally not captured in time history simulations from simple seismological models if their key parameters are not allowed to vary from their mean values. A feasible way of incorporating such variability into simulations is to use a simple, yet physically consistent seismological model. Therefore, we model the earthquake source using the specific barrier model (SBM) in the context of the stochastic modeling approach. The mean value of the key SBM parameter, the local stress drop, has been estimated for earthquakes in Greece. Variations of the corresponding theoretical earthquake source spectra are introduced quantifying the effects of various subevent populations on the earthquake source and empirical models accounting for directivity effects. The variations in site conditions are accounted for using actual borehole data. By varying other physical parameters of the model, we show to what extent the seismological model can incorporate the variability of the earthquake source, path and site conditions to match the observed variability of strong-motion. Finally we discuss the corresponding implications on the level of source complexity (subevent populations) of earthquakes of different magnitudes. That in turn has important implications for using the specific barrier model in modeling the earthquake as an extended source for hybrid near-fault simulations.

Forecasting Aftershock Sequences in the Real World

Oral Session · Tuesday 18 April · 8:30 AM · Plaza E

Session Chairs: Andrew Michael, Matt Gerstenberger, Warner Marzocchi

Forecasting Aftershocks and the Complexity of Implementing Simple Models

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The USGS is working to operationalize aftershock forecasting using the method of Reasenberg and Jones (Science, 1989) as updated by Page *et al.* (BSSA, 2016). This simple model only includes triggering by the mainshock. The creation of an automatic system and development of recent manual forecasts have highlighted some of the pitfalls of making forecasts with this approach: poorly modeling secondary sequences due to large aftershocks, artificially having to change mainshocks if a larger earthquake occurs, neglecting background rate changes during swarms, and underestimating natural variability. Most of these problems can be solved by using the more complex epidemic (ETAS) model. It is still necessary to artificially define the areal extent of a sequence using a sequence-specific ETAS model. For instance, after the M_w 5.8 Pawnee, Oklahoma, earthquake of September 3, 2016 the USGS issued a series of aftershock forecasts for the next month and year for a specified aftershock zone. While the observed number of earthquakes has fallen within the range of the forecast, during the first 4 months after the mainshock, the 12 largest earthquakes in Oklahoma occurred outside of the Pawnee aftershock zone and the focus of our public statements. Those events are within the forecasts of the 2014 National Seismic Hazard Maps, which focus on natural events and remove areas of presumed induced seismicity, and the 2016 One-Year Seismic Hazard Forecast for the Central and Eastern United States from Induced and Natural Earthquakes (soon to be updated for 2017). However, those forecasts do not include clustering and would have been a poor forecast within the Pawnee area. A full forecast, including both ETAS-triggered events and a spatially varying background rate, while computationally complex, avoids artificial choices that complicate developing operational systems based on sequence-specific models and would provide an integrated view of all sources of seismicity.

A Prototype Operational Earthquake Loss Model for California Based on UCERF3-ETAS—A First Look at Valuation

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We present a prototype operational loss model for California based on UCERF3-ETAS, which represents the first earthquake forecast to relax fault segmentation assumptions and to include multi-fault ruptures, elastic-rebound, and spatiotemporal clustering, all of which seem important for generating realistic and useful aftershock statistics. UCERF3-ETAS is nevertheless an approximation of the system, so usefulness will vary and potential value needs to be ascertained in the context of each application. We examine this question with respect to statewide loss estimates, exemplifying how risk can be elevated by orders of magnitude due to triggered events following various scenario earthquakes. Two important considerations are the probability gains, relative to loss likelihoods in the absence of main shocks, and the rapid decay of gains with time. For example, the probability of exceeding $50 billion in losses is elevated by a factor of 716, and 140, and 7.1 in the first day, week, and year, respectively, following an M 7.1 scenario on the Hayward fault. We hope this study inspires similar analyses with respect to other risk metrics in order to help determine whether operationalization of UCERF3-ETAS would be worth the considerable resources required, including on-demand access to high-performance computing.

Characterizing the Triggering Susceptibility of Characteristic Faults

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Statistical averages of earthquake triggering behavior, namely Gutenberg-Richter magnitude scaling, can produce foreshock probabilities that differ by orders of magnitude from fault-specific methods that employ characteristic magnitude distributions. Following a M4.8 earthquake near Bombay Beach in 2009, estimated probabilities for a subsequent M≥7 event varied by ~100-fold depending on whether or not characteristic magnitude distributions were used (Michael, 2012). In the September 2016 swarm, the public advisory included a range of probabilities (a factor of 30) to capture model uncertainty.

The characteristic model may be most easily tested in terms of its foreshock predictions. First of all, due to the spatial reach of aftershock triggering, these tests are not sensitive to the assumed width of the fault zone. Even more importantly, the predictions of the characteristic model with respect to foreshock triggering are dramatic. The UCERF3-ETAS (Field *et al.*, 2017) model, for example, predicts that a potential foreshock near the southern end of the quiet San Andreas fault is 23 times more likely to trigger a M≥7 mainshock than a similar earthquake near the active San Jacinto fault. A model with Gutenberg-Richter scaling would predict the same foreshock probability for these two scenarios.

While the foreshock-related consequences of the characteristic model are sizable and have been used in public earthquake advisories, they have, to our knowledge, never been directly observed. We search for evidence of this effect both in California and global subduction zones. The global dataset allows us to maximize the data power of our tests, and while it is a different tectonic environment than where the characteristic model has been routinely applied to foreshock probabilities (namely, California), the essentials of the problem are the same—we look to see if fault activity rate, normalized by slip rate, has a linear effect on the triggering of large earthquakes.

Operational Earthquake Forecasting of Aftershocks for New England

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Although the forecasting of mainshocks is not possible, recent research demonstrates that probabilistic forecasts of expected aftershock activity is possible. Previous work has shown that aftershock sequences in intraplate regions behave similarly to those in California, and thus the operational aftershocks forecasting methods that have been developed for California can be adopted for use in areas of the eastern U.S. such as New England. We have developed estimates of the average rate of aftershocks for earthquakes as a function of magnitude for New England and vicinity. In our operational aftershock forecasting system, immediately after an earthquake of magnitude 3.0 or greater, a forecast of expected aftershock activity for the next 7 days will be generated based on our generic New England aftershock activity model. Approximately 24 hours after the mainshock, the parameters of the aftershock model may be updated using the observed aftershock activity observed to that point in time, and if so a new forecast of expected aftershock activity will be issued. The forecast will estimate the average number of weak, felt aftershocks and the average expected number of aftershocks. The forecast also will estimate the probability that another earthquake, including one that is stronger than the first mainshock, might take place during the next 7 days somewhere in New England. The aftershock forecast will specify locations of the expected aftershocks s well as the areas over which aftershocks of different magnitudes could be felt. The system will use web pages, email and text messages to distribute the aftershock forecasts. For protracted aftershock sequences, new forecasts will be issued periodically. Initially, the distribution system of the aftershock forecasts will be limited, but later it will be expanded as experience with and confidence in the system grows.

The Time-History of a Forecast: The Case Study of Central Apennines

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In real world the detection capability of seismic networks varies and this influence the performance of catalog-based earthquake forecasts. Also, realistic physics-based models require slip distributions that are available within few hours to days following a large earthquake. Acknowledging the limitations our preliminary forecasts during the early post-earthquake disaster environment is critical for improving any future operational efforts. In our case study, the 2016 Central Apennines sequence, three earthquakes of magnitude larger than M=5.9 occurred within a 50 km distance within almost two months. The first occurred on 24th August (M=6.0) near Amatrice, then on October 26th two large shocks (M=5.4 and M=5.9, 32 minutes after) struck almost 30 km further north. Four days later, on 30th October, the largest (M=6.5) occurred near Norcia, close to the location of the largest early aftershock. We present the first forecast diary aiming to (1) document the scientific effort (2) describe the timeline of preliminary forecast development and (3) compare initial vs more informed model(s), available few days to weeks after each mainshock. We compare between physics-based models available within the first few hours/days and we quantify their predictive skills compared with existing statistical models. The early physics-based forecast considers: (1) a uniform slip model with empirically determined fault length and (2) a wide range of fault constitutive parameters whereas the informed version incorporates: (1) geodetic and seismic source models and (2) constrained fault constitutive parameters based on the initial seismicity response. For the interseismic period between the August and the October events that occurred in Visso and Norcia the results of the early physics-based forecast support at least 3 events with M>4 and app. 2 events with M> 3.5 for the respective fault arrays.

Forecasting the 2016 Bombay Beach, CA Swarm

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Earthquake swarms, often modeled as time-varying background seismicity driven by external processes, present challenges for operational earthquake forecasting, in terms of both methodology and communication. We present some of the issues that were encountered during the 2016 Bombay Beach, CA swarm of 100 2≤M≤4.3 earthquakes, which began on Sept. 26 and lasted ~a week. The swarm's proximity to the southern end of the San Andreas Fault (SAF) caused concern that a larger event could be triggered on it. Within 1-2 days, different forecast models were used to evaluate this likelihood. An Epidemic-Type Aftershock Sequence (ETAS) model (Ogata, 1988) could account for the higher background rate during the swarm while the UCERF3-ETAS model (Field *et al.*, 2017) accounted for a characteristic magnitude distribution on the SAF. The ETAS model resulted in probabilities that were >3 times higher than the UCERF3-ETAS estimate, but while the time decay of aftershock sequences can be modeled, it is difficult to forecast how long the swarm's change in background rate will last.

The California Earthquake Prediction Evaluation Council convened on Sept. 27 to review the forecasts and advised the California Office of Emergency Services (CalOES) of a 0.03%-1% chance of a M≥7 earthquake on the southern SAF over the next week, the probability range reflecting model uncertainties. Later that day the USGS released the information in a public statement, and CalOES issued a 7-day earthquake advisory. The USGS updated its forecast on Sept. 30, with decreases in the probabilities that reflected the decrease in swarm activity. A final update was made on Oct. 6, stating that the earthquakes had subsided and the likelihood had returned to the long-term level. The response to the swarm highlighted areas in need of improvement, including developing and validating forecast models that can be applied to swarms and major fault zones, and communication between organizations and with the general public.

Earthquake Forecasting for the November 2016 Kaikoura, New Zealand Mw 7.8 Earthquake

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The November 14th, 2016, M_w 7.8 Kaikoura earthquake generated significant shaking and damage throughout a large part of central New Zealand. The recovery effort has been distributed over a very large area and the dissemination of information about the potential for future shaking has been an integral part of the GNS Science response. Through the nature of the event and the varied recovery efforts we have been required to provide model results that spanned from aftershock probability tables through to detailed and specific engineering information. Additionally, the main shock triggered three slow slip events (SSE) on the Hikurangi subduction zone that were unique in character in our approximately 20 years of observations; these SSE provided a difficult challenge to the on going forecasting efforts.

As is typical in such events, data quality issues, including changes to the main shock magnitude, have provided a challenge to forecasting efforts. Similar to past earthquakes we have used a hybrid of the STEP and EEPAS models to produce the forecasts. An important change has been the use of the negative binomial distribution, constrained by ETAS simulations (Harte, 2013), to describe the uncertainty in the STEP rates. These uncertainties were also used to produce stochastic events sets for use in hazard calculations for engineering decisions (*e.g.*, forecast design spectra as compared to the design standard or probabilities of landslide). To date the aftershock productivity has been low when compared to the STEP model based on average New Zealand aftershock sequence behavior.

Here we will described the various models used and engineering outputs developed, including the efforts to estimate the impact of the SSE on the potential for triggered earthquakes.

Challenges and Successes of Communicating the M7.8 Kaikoura Earthquake Operational Earthquake Forecast

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In New Zealand, the operational earthquake forecast has been communicated for six different earthquake sequences with large mainshocks since 2010. During that time, each sequence represented a unique set of challenges for the social science researchers, the seismologists developing the forecasts, and the communicators involved.

Despite the previous experiences of communicating earthquake forecasts, communicating the M7.8 Kaikoura earthquake was complex. One prominent issue was the triggering of multiple slow-slip events on the nearby subduction interface beneath the North Island of New Zealand by the M7.8 earthquake. This was a new unknown; researchers and communicators alike were challenged with communicating a highly complex and changeable event. Based on social science research, the team worked to develop a strategy to calculate and communicate the new forecast, so that it included the slow-slip events. This included expert elicitation with scientists around the country, as well as validation with an international panel to determine the change in the forecast to include the slow-slip events.

Other communication challenges included navigating political and emergency management concerns, as well as pressure from a variety of publics to provide certainty in an uncertain event. Further issues included trauma in the affected public, concerns about "WHAT" in the international community, and information requests from both overseas and local media. The communication strategy included tactics such as empathetic messaging, coordination of communication across agencies, humour, and two-way communication techniques.

Operational Earthquake Forecasting Six Years into the Canterbury Sequence: Lessons for Initial and Ongoing Communications

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Six years after the Canterbury sequence began on September 4, 2010 we held one interview and three focus groups with 21 emergency managers, public health officials, and hazard researchers that live and work in the area. Preliminary findings include evidence that: (1) Some audiences can operate from an effectively communicated concept of an aftershock sequence without consulting revised quantitative earthquake forecasts, although a damaging aftershock may renew interest in more details. Participants reiterated: "over the next decade earthquakes will occur further apart with spikes of activity". This indicates the importance of describing an earthquake sequence in a memorable way early on when audiences are attentive. (2) Coordination of earthquake forecast messages across roles continues to be necessary throughout an earthquake sequence; informed public emergency and health communicators underestimated the effects of the 2016 M5.7 Valentine's Day aftershock on some population groups and missed a communication opportunity by not reinforcing the scientist's message with their messages through their channels. Affected populations included people new to the area that were upset by the heavy shaking and people who had prior experience with the sequence and re-traumatized by it. (3). Social media was a popular source of earthquake information and residents used it to support each other. Those who have become accustomed to frequent earthquakes were able to extend support to others online and in-person. (4) Communicating uncertainty in the earthquake forecast instills trust in scientists. Useful representation of uncertainty includes ranges for probabilities and numbers of earthquakes, and distributions of forecasted shaking at locations. (5) For some, there is a shift in focus from the current sequence to a potentially more devastating earthquake sequence from a rupture of the Alpine fault. We will relate findings to risk communication literature.

Japanese New Guidelines for the Seismic Forecast Information after Big Earthquakes

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A big earthquake of M6.5 occurred at 21:26 on 14 April, 2016 (JST) in Kumamoto Prefecture. Japan Meteorological Agency (JMA) issued information about aftershock probability after this earthquake. The information was based on guidelines determined by the Headquarters of Earthquake Research Promotion (HERP) in 1998. However, after 28 hours of the M6.5 earthquake, a bigger earthquake of M7.3 occurred in the same region and triggered distant earthquakes. The seismically active area was finally spread up to about 150km long. As this seismic activity, "The 2016 Kumamoto Earthquake", was revealed that it was not a simple mainshock–aftershock patterns, JMA stopped issuance of the following information and called attention to people to high seismic activity and strong motion by big earthquakes.

With lessons learned from this, seismologists and JMA discussed under a framework of the HERP, and new guidelines were published in August 2016. The points of the guidelines are followings.

(1) JMA calls attention to strong motion which is similar level to the first big earthquake for about one week after big earthquakes.

(2) If there were prior cases of foreshock–mainshock–aftershock series or earthquakes with similar magnitude which occurred in short period near the big earthquakes, JMA calls attention to such cases.

(3) If active faults and assumed source regions of big thrust-type subduction-zone earthquakes existed near the big earthquakes, JMA explains the characteristics and calls attention to them.

(4) After one week, if the active seismic activity continues, JMA issues aftershock probability. The probability is shown by magnification ratio which compares to the probability just after the biggest earthquake and before the big earthquakes.

(5) When JMA calls to attention to strong motion by aftershocks, JMA uses a word "earthquake" instead of "aftershock", because the word of "aftershock" gave some impression to people that bigger earthquakes would not occur.

Geoacoustics: Infrasound and Beyond

Oral Session · Tuesday 18 April · 4:30 PM · Governor's Square 16

Session Chairs: Daniel Bowman, Stephen Arrowsmith, Omar Marcillo

Quantifying River Turbulence: New Insights into the Fluvial Seismo-Acoustic Field

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A controlled study at the Harry W. Morrison Dam (HWMD) on the Boise River, Idaho was conducted to study the mechanism that controls observed spectra and time-dependent amplitude variations in seismic and acoustic signals collected near the river hydraulics. The HWMD's multiple facets are systematically adjusted to change the behavior of the standing wave generated beneath the dam. This behavior is defined by a dimensionless parameter called the Froude number. A correlation between the Froude number and the spectral content of the seismo-acoustic field generated by the HWMD is identified. This correlation is corroborated by cross spectra and semblance coherency results. Insights and methodology gained from the HWMD controlled experiment have been applied to the Big Falls Rapid (BFR) of the South Fork Payette River, Idaho.

BFR is a 12 m semi-vertical waterfall, characterized by four bathymetric steps that each create a hydraulic jump. The seismo-acoustic field generated by the BFR was monitored from May and June of 2016 using a network of Gems microphones and 2 Nanometrics Meridian seismographs. The monitoring period coincides with the annual median peak discharge and largest discharge variance. These conditions lead to variable Froude regimes generated at each of the four hydraulic features. Spectrograms indicate that variable turbulence is generated by hydraulic jumps oscillating in distinct cycle throughout the flood period. The changing turbulent oscillations couple appreciable energy into the seismo-acoustic field, with the dominant frequencies being time-dependent. Semblance results indicate the locations of highest likelihood infrasound generation and provide further insights into the mechanisms behind infrasonic signals observed next to turbulent river systems. Results from this study emphasize the benefits for a catalog that characterizes standing river waves and other surficial river features by their generated seismo-acoustic fields.

Prospects for Enhanced Infrasound Sensitivity from a Balloon-Borne Platform

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We present results of an experiment to test the efficacy of balloon-borne infrasound sensors. Balloon-borne sensors should have two important advantages over ground-based infrasound stations: there should be virtually no wind noise on a free-floating platform, and a sensor in the stratosphere should benefit from its location within the stratospheric duct. Balloon-borne sensors have the disadvantage that the amplitude of infrasound waves will decrease as they ascend with altitude. To assess the sensitivity of balloon-borne sensors, we arranged three large explosions (2400 ±100 lb equivalent TNT) from Socorro, NM to take place while we flew several infrasound sensors on a NASA high-altitude (35 km) balloon that was launched from Ft Sumner, NM. Two of the three explosions were detected from the balloon at distances of over 330 km. Three separate wavefront arrivals were detected from the first explosion, spanning a 25-s interval. A small solar balloon was also launched near Ft. Sumner in time to listen for the second explosion, which it detected from its float altitude of 15 km. The peak-to-peak amplitude at 35 km was 0.06 Pa, and this wave was sensed with a SNR that was better than 20. The balloon-borne platform does exhibit extremely low wind noise. We will compare the signals detected from both balloons and a dozen ground-stations with wave propagation models.

Socorro and Wanaka: Balloon Borne Infrasound Expeditions

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A balloon borne infrasound sensor circumnavigating Antarctica over the Southern Ocean shows significant broad band signals recorded on a simple microphone. For 14 days a NASA gondola, floating at 35km elevation, recorded remarkable signals including consistent microBarom that vary in time and space. A 10 hour portion of the flight traversed South American Andes, in southern Chile just north of the active Villarrica Volcano. We present signals recorded during this expedition and suggest that the high frequency observations represent transmissions from the earth, including impulsive signals possibly from volcanoes or extraterrestrial bolides. While the source of the high frequency signals is yet unknown we provide a statistical analysis of the content during the flight. Verification of similar, ground sourced signals using chemical explosions in New Mexico, demonstrate that infrasound signals are well recorded on stratospheric stations floating hundreds of km from the source. Comparison of stratospheric floating balloon platforms with ground based (IMS) infrasound stations shows considerable improvement in system noise floors, suggesting that balloon borne signals offer a high fidelity alternative to traditional acoustic installations.

Three-Dimensional Local Infrasound Simulation Capability with In Situ Atmospheric Measurements

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Finite-difference waveform modeling techniques are increasingly popular for infrasound propagation simulation in the atmosphere due to their capability for handling all relevant wave propagation effects, including sound diffraction and scattering in complex media. Predicting infrasound amplitudes by physics-based modeling is also critical to estimating explosion energies of natural and/or man-made explosions. The accuracy of finite-difference modeling is, however, often compromised by the uncertainty of background parameters used to specify atmospheric conditions. Mesoscale numerical weather forecast models are commonly used for infrasound simulations, but they often fail to capture highly variable local winds due to their limited spatio-temporal resolutions. We investigate the impacts of local atmospheric conditions on infrasound propagation and how much the accuracy of physics-based infrasound simulations can be improved with local atmospheric observations. Field data from a series of above-ground chemical explosion experiments are used in this study. We selected experiments that produced dense recordings of acoustic wavefields and local atmospheric measurements of ambient pressure, temperature, and wind. The atmospheric specifications were provided by one or a combination of 1) local radiosonde soundings, 2) Atmospheric Sounder Spectrometer for Infrared Spectral Technology (ASSIST), 3) surface weather stations, and 4) a wind LIDAR profiler. The wind LIDAR can map wind speed and direction on a slice in the atmosphere up to ~ 10 km range depending on the air conditions. The combination of these independent measurements can complement atmospheric profiles for numerical simulations and capture local atmospheric variability. We perform full 3D finite-difference simulations of infrasound propagation with the local atmospheric data and evaluate the accuracy of the numerical modelings with the field observations.

Applying a Revised Attenuation Versus Distance Stratospheric Wind Correction to Infrasound Data

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Previous studies have shown that stratospheric wind, during specific times throughout the year at very near distances, influence the amplitude pressure wave by creating 'theoretical ducting' or 'no ducting' on the wave-front [Mutschlecner and Whitaker, 1999; Clauter and Blandford, 1997; Pierce and Posey, 1971; Balachandran *et al.*, 1971; Reed, 1969]. We have derived two distance attenuation relationships of infrasound amplitudes at longer range distances, one for yield-normalized amplitudes (A_n=-0.96x+2.19), and one that incorporates the stratospheric wind corrected yield-normalized amplitudes (A_{cs}=-0.93x+2.07) using the Horizontal Wind Model, 2014 (HWM14) data set. This was accomplished by replicating the relationships derived from the applied research on a largely used attenuation versus distance relationship by Mutschlecner and Whitaker, 1999, who observed amplitude attenuation at short range distances and much smaller periods compared to the long-range distances and longer periods used to determine the attenuation versus distance equation used in this study. Using the Mutschlecner and Whitaker, 1999 methodology an attenuation constant *k* is derived integrating the meridional and zonal winds across the wave-front propagation path from source to receiver. We discover that at long-range distances the uncorrected-wind amplitude data with respect to distance is not statistically different than the corrected-wind amplitude data, having a standard error of ±1.06 and ±1.03 respectively. We integrate this derived attenuation constant into the analysis of infrasound data to determine the usefulness of the attenuation versus distance equation in more recent data sets.

Integrated and Geophysical Investigations for Site Characterization of Critical Facilities and Infrastructure

Oral Session · Tuesday 18 April · 2:15 PM · Governor's Square 14

Session Chairs: Jamey Turner, Jeffrey Bachhuber, Osman El Menchawi, Daniel O'Connell

Measurement- and Proxy-Based VS30 Estimates

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I present a review of the state-of-practice for estimating VS30, the time-averaged shear-wave velocity of the upper 30 m, as well as select developments for advancing measured or proxy-based VS30 methods. VS30 values have traditionally been derived directly from on-site array-based records of seismic travel-times. As a result of cost and/or environmental factors that restrict the mobilization of on-site recording arrays, remotely-derived proxy-based methods have been used to estimate VS30 values. Thus, proxy-based methods—commonly using map information: geology, slope, terrain, or their hybrids—serve as a stopgap solution until on-site measurements are available. Because of the indirect nature of these map-based methods, proxy-based VS30 estimates are known to have substantial uncertainties, whereas inter- and intra-method variability of measured VS30 values is typically 5-10%. To reduce uncertainties, Iwahashi *et al.* (2016) used a large data set of recently available measured VS30 values and an improved terrain framework to recalibrate their proxy-based VS30 model. For sites where cost isn't a factor, there are advancements in the analyses of earthquake and microseismic data from seismic monitoring stations that allow estimations of VS30. Herrick *et al.* (2017) found P-wave-based VS30 estimates from earthquake sources correlate with array-based VS30 measurements in the VS30 range of 500-1500 m/s, while earthquake-based VS30 estimates outside of this range differ by more than 10 percent. Hassani *et al.* (2017) expanded the Hassani and Atkinson (2016) study, which compared VS30 to earthquake-based estimates of the dominant site frequency (fd), to fd based on microseisms and found the earthquake and microseismic fd estimates scale linearly. Lastly, Yong *et al.* (2017) found measured VS30 values correlate well with array-based VR40 (Rayleigh-wave phase velocity at the 40-meter wavelength) estimates, thus indicating VR40 is a potential proxy for estimating VS30 values.

Direct Evaluation of S-Wave Amplification Factors from Microtremor Horizontal-to-Vertical Ratios: Empirical Corrections to "Nakamura" Method

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The Horizontal-to-Vertical spectral ratios of microtremors (MHVRs) have been utilized as a convenient tool to extract a predominant frequency at a target site. The so-called "Nakamura" method (Nakamura, 1980) assumed that MHVR provides us directly the S-wave amplification factor of earthquake in the horizontal components (*i.e.*, HHR), although the validity of the method had never been proved,. However, based on the diffuse field theory (Sánchez-Sesma *et al.*, 2011) MHVRs correspond to the square root of the ratio of the imaginary part of horizontal displacement for a unit harmonic load and the corresponding one in the vertical direction, while Horizontal-to-Vertical spectral ratios of earthquake (EHVRs) correspond to the ratio of the horizontal motion for a vertical incidence of S wave with respect to the vertical correspondent of P wave (Kawase *et al.*, 2011). Thus there should be a systematic difference between EHVRs and MHVRs because of the difference in their primary contribution of wave types. We first calculated the ratios of EHVRs with respect to MHVR (EMR) at 100 strong motion stations in Japan. Then frequency is normalized by the fundamental peak frequency at each site and calculated the average of the EMRs for five categories of sites based on the fundamental frequency. Once got empirical EMRs for five categories we translated MHVRs into pseudo EHVRs. Finally we calculated the average Vertical-to-Vertical spectral ratios (VVRs) for the same sites determined by the generalized spectral inversion (Nakano *et al.*, 2015), Then the S-wave amplification factor HHRs of earthquake at the site can be calculated from MHVRs with double corrections using EMRs and VVR for corresponding categories. We compare the final empirical prediction with the observed HHRs to find the quite high correlation. The proposed method to get HHRs from MHVRs with these double corrections can be considered as extension of the so-called Nakamura method.

State-of-Practice of Site Characterization: The Role of Seismic Investigation and Land Management Policies

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A large amount of research has been conducted during the last decades on site characterization and on the effects of local geology on earthquake ground motion. We provide a description of the regulatory framework for seismic microzonation (SM) and an overview of the use of seismic measurements, with particular regard on the use of ambient vibration in Europe. In particular, we describe the Guidelines for Seismic Microzoning, implemented in Italy, which is basis for a proper evaluation of seismic risk applicable to land, urban, cultural heritage conservation and emergency planning, as well as to technical design standards. These guidelines were necessary to harmonize SM studies distributed over the whole Italian territory and performed by different local technical bodies and practitioners with the support of research and academic institutions. SM Guidelines were implemented into three levels. The first aims at developing the general geological model of the study area by identifying geometry of areas with similar seismic effects. The 1D effects are quantified in the second level via simplified approaches based on the measurement of average velocities in the shallow sedimentary layers and resonance period of local sediments. The third level focuses on peculiar situations unsuitable for simplified approaches and requiring advanced numerical simulations, laboratory tests, etc. Due to the importance of resonance phenomena in SM, the extensive identification of major impedance contrasts is a key aspect for all the SM levels. To this purpose, ambient vibration measurements (both in single station and array configurations) revealed to be of major importance due to their cost effectiveness and wide applicability. Different interpretation protocols have been codified (qualitative, semi-quantitative and quantitative) each supporting specific SM levels. Recent experiences during last damaging earthquakes allowed testing in the field effectiveness of the proposed approach.

Site Characterization for Safety-Related Nuclear Facilities: ASCE 1 Update

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Comprehensive site characterization is an essential step for the siting and design of nuclear safety-related structures. As a part of ASCE 1, which is a national standard for geotechnical analysis and design of nuclear safety-related structures, standards are being developed for site characterization involving field investigation and in-situ and laboratory testing. The standard requires that a phased approach is adopted for site characterization, which proceeds from initial high-level screening to detailed site-specific investigations. Investigations are aimed at identification of potential geohazards and characterizing the engineering parameters and properties of surficial and subsurface material at the site.

Geotechnical investigations must be conducted to allow quantification of variability of the site soil and rock properties in both horizontal and vertical directions. Investigation methods and procedures that will result in adequate site characterization are covered by this standard. For foundations of nuclear structures, founding strata stiffness and its variability within the zone of influence shall be characterized and quantified in both horizontal and vertical directions.

The standard emphasizes an integrated approach using a full range of geologic, geophysical, and geotechnical exploration and testing techniques and incorporation of new technologies. Determination of soil and rock properties requires at least two independent testing methods, encompassing both field and laboratory procedures. Each soil and rock layer must be sampled and characterized to an appropriate depth, and with sufficient number of tests, to evaluate variability throughout the foundation influence zone.

Specific emphasis has been made to capture the spatial, parametric, and investigation and testing method uncertainties, and integration of data from various techniques to develop a reliable geologic-geotechnical site model.

Update of Regulatory Guide 1.132

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The U.S. Nuclear Regulatory Commission (NRC) uses Regulatory Guides (RGs) to inform the public and provide guidance to applicants, licensees, and certificate holders of acceptable methods to comply with the Commission's rules and regulations. Some RGs additionally identify acceptable techniques to evaluate specific problems or postulated accidents; others provide standard formats that applicants and licensees can follow to submit documents to the Commission. The

methods, processes, and formats identified in RGs substantially reduce the review time for a license application or license amendment.

Regulatory guides RG 1.132, "Site Investigations for Foundations of Nuclear Power Plants" and RG 1.138, "Laboratory Investigations of Soils and Rocks for Engineering Analysis and Design of Nuclear Power Plants" provide key guidance on site characterization and subsurface material engineering properties determination for design and analysis of nuclear power plants. The latest version of RG 1.132 was published in October 2003. During the past 13 years, site investigation methods have improved, new technologies and equipment developed, new generation of nuclear power plants designed and built/under construction, and regulatory requirements updated. To reflect those changes and better serve the public, NRC is now revising RG 1.132 to update guidance for site investigation to meet today's needs.

This presentation describes major revisions of RG 1.132 including emphasis on conducting site investigations using a phased approach progressing from literature search and reconnaissance investigations to detailed site investigations, construction mapping, and final as-built data compilation to provide a strong basis for site suitability, foundation design and construction; utilization of state-of-art technologies and state-of-practice procedures and methods; use of multiple methods to determine important subsurface material properties, and consideration of small modular reactor design.

Inversion of Irregular Vibroseis Data For 3D Shallow Velocity Structure

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Vibroseis data acquired at the Diablo Canyon Power Plant had irregular source and receiver geometries due to large buildings that limited access to many areas. Daily movement of 5-10 m spaced arrays of 200-500 receivers gave 3D surface-wave coverage in areas where few Vibroseis source points were feasible. First-arrival data were combined with gravity data to develop a high-resolution 3D P-wave velocity model to 300 m depth. Shallow complex infrastructure produced irregular amplitude variations that precluded amplitude inversion of the 3D Vibroseis data. However, far-field phase and group dispersion were well resolved within receiver subarrays. An initial 3D S-wave model was developed to ~60 m depth by interpolating and extrapolating 1D S-wave-elevation inversions of phase-dispersion estimated at centroids of 104 3D subarrays of 10-25 receivers that recorded 20-200 far-field Vibroseis source points surrounding each receiver subarray. The 3D S-wave model was iteratively updated in two regions with sufficient 3D source-receiver coverage to invert for S-wave updates using Rayleigh-wave group delays in the 8-28 Hz frequency band of the Vibroseis sweep. FLAC 3D forward calculations provided synthetic data to calculate waveform misfits and group-delays used with 2D tomographic back-projection to update the 3D S-wave velocity model. This 3D waveform inversion approach only requires forward 3D synthetic calculations for the number of source positions instead of full adjoint 3D synthetic calculations for all source and receiver positions. Consequently, many 3D models can be explored with this approach with only modest memory and CPU requirements to ensure appropriate starting models are used when full amplitude data are available for 3D waveform inversion. The final 3D P- and S-wave model accurately reproduces complex waveforms with clear multipathing arrivals and is consistent with previous surface and downhole seismic data within their measurement uncertainties.

Advancements in Identifying Subsurface Abandoned Mine Voids: Integration of Historic Data, LiDAR, Multi-Method Surface Seismic, Borehole Imaging, and Remediation, Wyoming USA

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Active-source swept frequency vibratory and impulsive signal 2D and Square Array Void Mapping (SAVM) seismic were acquired at dozens of sites in Wyoming in support of the Abandoned Mine Lands (AML) program. Many towns and critical structures in WY are extensively undermined by abandoned shallow (<200 ft bgs) mine workings up to 100+ years old which pose ongoing risks. Over time abandoned mines can progressively collapse, causing subsidence-related surface deformation that can affect buildings, infrastructure, and property values. Void conditions vary from air-filled to water-filled and open to completely collapsed and rubble-filled. Additional hazards may be present, such as pressurized combustible gases and active mine fires, which complicate intrusive investigations and remediation efforts. Integration of 2D IMASW Vs and 2D finite-frequency first-arrival Vp tomography, reflection, group velocity, and relative amplitude processing delineates voids and collapse zones at depths up to ~180 feet. A custom, modular, integrated acquisition design combined with multiple processing approaches is able to adapt to a range of subsurface conditions often poorly constrained prior to seismic data acquisition. The integration of 4 to 5 processing techniques is often required to identify voids based on multiple co-located geophysical anomalies. Initial seismic surveys are targeted based on historic mine maps and borings with variable location accuracies, LiDAR and satellite imagery, and geomorphic features. Anomalies are interpreted and ranked by number of co-located types in XYZ space to prioritize drilling targets. Subsurface investigations use various drilling methods, downhole geophysics, borehole sonar/laser and camera/video to image void spaces, providing data for georeferencing historic mine maps, and assessing volumes and conditions. Remediation efforts ensue, *e.g.* grout or foam injection operations. This integrated approach is applicable to all shallow voids, *e.g.* karst.

Slip Rate of the Hosgri Fault Based on the Sedimentary Record of Plio-Quaternary Sediments within a Right-Stepping Extensional Pull-Apart

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In 2015, Pacific Gas & Electric (PG&E) completed a seismic source characterization to assess the seismic hazard at the Diablo Canyon Power Plant (DCPP), in which the Hosgri fault was identified as the dominant seismic source. PG&E characterized the fault primarily from submarine mapping from seismic reflection images and single-channel, high-resolution sparker data. In support to the U.S. Nuclear Regulatory Commission's review of PG&E's probabilistic seismic hazard analysis (PSHA) for the DCPP, we evaluated the slip rate on the Hosgri fault by analyzing the growth of sediments within an extension pull-apart that formed a few kilometers offshore, where slip is transferring from the Hosgri to the San Simeon fault. As the pull-apart developed, sediments accumulated along the bounding "Half Graben fault," infilling the available volume created by the extension generated by the horizontal component of Hosgri fault displacement. For the analysis, we relied on four previously identified Plio-Quaternary unconformities in the sedimentary section that were based on correlations to the global eustatic sea-level cycles. We analyzed these unconformities on 24 profiles of seismic images along the Half Graben fault. Our results show an increase in slip rate for the Hosgri fault from 0.21 mm/yr in the Pliocene to 2.17 mm/yr in the late Quaternary. The late Quaternary rate is consistent with the slip rate of the Hosgri fault used in the PG&E PSHA. The increase in slip rate from the Pliocene to the late Quaternary may simply represent an increase in activity on the Hosgri fault in the late Quaternary, or it may represent increasing cooperation and fault-linkage between the Hosgri and San Simeon faults as these faults grow, propagate laterally such that their fault tips overlap, and begin to behave as a single linked fault system.

This abstract is an independent product of the CNWRA and does not necessarily reflect the view or regulatory position of the NRC.

Empirical Characterization of Extreme Ground Motion at Soft-Sediment Sites

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It is widely recognized that seismic waves can be locally amplified due to soil layering and basin geometry. Such empirical site responses are usually evaluated by calculating the spectral ratios between simultaneous recordings on sediments and on a nearby rock site. As reliable reference sites close enough are not always available, vertical arrays, with the downhole sensor corrected for the downgoing wave field serving as the reference, can overcome the difficulty.

In this study, we analyze the impact of the soil behavior on site response at 170 sites of the Japanese KiK-net strong motion network. The sites were selected from the entire network through comparison of the fundamental frequencies estimated from recordings and through indirect modeling techniques.

To account for amplification phenomena, it is shown that a correlation exists between the quarter-wavelength velocity and the frequency-dependent seismic impedance contrast at a site and the surface-to-downhole ground-motion ratio. Such correlation allows the construction of a predictive equation, which can be used for reconstructing the expected site response. As it is well recognized that the site effects can be significantly different for a strong event compared to

small ones, we further extend this approach to account for nonlinear soil behavior.

Although the linear theory is valid in a large number of seismological problems, nonlinear behavior should also be taken into account in order to produce accurate ground-motion predictions. Based on the findings for linear ground motion, we investigate the key soil and event parameters that allow a parameterization of the nonlinear modification of site response (*i.e.*, an increase in the site response amplitude at relatively low frequencies and a decrease in the high-frequency amplification).

Constraining Shallow Shear Wave Velocities Using the Initial Portion of Local P Waves Recorded at ANSS and EarthScope Transportable Array in the CEUS.

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USARRAY and ANSS seismic stations provide an invaluable waveform dataset for studying ground motion attenuation in the Central and Eastern United States. However, the dataset is useful only after the site effects at each station are well understood. Since there are many stations in USARRAY and ANSS, it would be costly to accurately determine sub-surface velocity structure beneath every station using geophysical exploration techniques involving arrays, such as ReMi and SASW. It would be more economical to estimate the site effects with waveforms recorded at the seismic stations. Such approaches have been widely applied, but most of them involve the frequency dependent ratio between the horizontal and vertical component of either ambient noise or S waves from earthquakes. The horizontal component of P waves can also be used to infer subsurface velocity structure. It is demonstrated that the ratio of radial to vertical P waves is mostly sensitive to sub-surface shear velocity, so the radial/vertical ratio of the P wave is a good indicator of subsurface shear velocity. Therefore, the subsurface velocity structure can be estimated using an approach similar to teleseismic P receiver functions, but at much smaller scale and higher frequency that matches well with results from ReMi and Refraction/Reflection techniques (Ni *et al.* 2014). We used the approach introduced by Ni *et al.* (2014) and calibrated our models with findings from Ni and Somerville (2013) to obtain data on shallow shear-wave structure in the Central and Eastern United States. A rich database of local earthquakes from 2009 to 2013 recorded at ~560 seismic stations was analyzed and associated receiver functions were inverted. The results are in reasonable agreement with local geology and with the results of Ni and Somerville (2013), Ni *et al.* (2014) and Kim *et al.* (2014). The data are made publically available for future refinement.

Novel Approaches to Understanding Active Volcanoes

Oral Session · Tuesday 18 April · 8:30 AM · Governor's Square 12

Session Chairs: Ninfa Bennington, Stephen McNutt, Jeremy Pesicek, Richard Aster, Matthew Haney

Volcanic Tremor and Plume Height Hysteresis from the March 2016 Eruption of Pavlof Volcano, Alaska

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Seismic and acoustic volcanic tremor is routinely used to monitor and characterize volcanic eruptions. The source of volcanic tremor during eruptions is the subject of extensive active research, yet it is difficult to determine. On March 28, 2016, Pavlof Volcano, Alaska erupted with no warning. The eruption lasted for ~40 hours and produced a sustained ash plume up to 9 km altitude that forced the cancellation of over 100 flights. This eruption produced significant seismicity and infrasound and was the first to be recorded on the recently deployed EarthScope Transportable Array (TA) in Alaska.

Here we analyze tremor amplitudes from Pavlof and compare them to observations of the ash plume height. Seismic and acoustic amplitudes strongly correlate with each other during the eruption. However, the relationship between tremor amplitude and plume height shows a clear time dependence (hysteresis). Specifically, tremor amplitude and plume height are directly correlated early in the eruption, during the period of increasing eruption intensity. Once the eruption begins to wane, plume heights remain high while the tremor levels drop rapidly. We propose that this time-varying relationship arose from changes in the tremor source related to volcanic vent erosion, and propose a 3-stage conceptual model. Also of note is that a similar hysteresis is observed between seismic river noise and discharge during storms, suggesting flow and erosional processes in both rivers and volcanoes can produce irreversible structural changes. Future eruption monitoring and interpretations of volcanic tremor, including their relationship to plume height and eruption intensity, should take into account the stage of the eruption and state of the upper conduit and vent, as well as insight from other studies of flows.

We also present preliminary analysis of the relationship between tremor and plume heights from the 2008 Okmok Volcano, Alaska eruption.

Ground-Coupled Air Waves at Pavlof Volcano, Alaska During the 2007 Eruption and Their Potential for Eruption Monitoring

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An abnormally high number of explosion quakes were noted during the monitoring effort for the 2007 eruption of Pavlof Volcano on the Alaska Peninsula. In this study we manually catalogued the explosion quakes from their characteristic ground-coupled air waves. This study investigates how the ground-coupled air waves might be used in a monitoring or analysis effort by estimating energy release and gas mass release. Over $3x10^4$ quakes were recorded over the month long eruption, with rates as high as 19 explosions per minute. The energy release from the explosions is approximated to be $3x10^{11}$ J, and the total gas mass (assuming 100% water) released was 450 metric tons. The tracking of explosion quakes has the potential to estimate relative eruption intensity as a function of time, and is thus a useful component of a seismic monitoring program.

Detecting Magmatic Activity over Multiple Volcanic Eruption Cycles via Ambient Noise Interferometry: A Study of Veniaminof Volcano, Alaska

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Veniaminof volcano is one of the largest and most active volcanoes in the Aleutian Arc. It is a stratovolcano located on the Alaska Peninsula and ~700 km SW of Anchorage, AK. Recent eruptions include Strombolian events in 1983, 1993, and 1994 as well as smaller, predominantly phreatic eruptions in 2002, 2005 (two separate eruptions), 2006, 2008, 2009, and 2013. The volcano has displayed a range of pre-eruption seismic activity leading into its four most recent eruptions, including: anomalous seismicity, increasing volcanic tremor, increasing volcanic tremor and seismicity, or an absence of volcanic tremor or anomalous seismicity. Frequent activity at this volcano poses major hazards to the heavily trafficked north Pacific air routes that overly it. Given this substantial hazard, it is imperative that we improve our ability to detect precursory activity leading to active volcanism at Veniaminof. We take advantage of continuous waveforms recorded on the volcano's seismic network to identify such precursory activity at the volcano. Seismic interferometry using ambient noise is carried out in order to probe the subsurface of this volcano and determine temporal changes in relative seismic velocity from pre- through post-eruption, specifically for 2002 through 2013 Veniaminof eruptions. Ambient noise interferometry is an emerging geophysical technique that allows us to probe the subsurface of a volcanically active region and determine temporal changes in seismic velocity related to magmatic activity (*e.g.* preeruption inflation and coeruptive deflation of a volcanic edifice, lava dome collapse). Preliminary analysis of eruptions between 2002 and 2013 show decreases in seismic velocity preceding some, but not all of the eruptions occurring here.

Seismic Evidence for a Cold and Hydrated Mantle Wedge beneath Mount St Helens

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Mount St Helens has been the most active volcano within the Cascade arc historically, however, its location is unusual because it lies 54 km trenchward (west) of Mount Adams and the main axis of arc volcanism. This region of the arc (the Rainier to Hood segment) displays an anomalously wide east-to-west distribution of volcanism and contrasts with the adjacent segments north and south which have a narrow axis of volcanism subparallel to the subduction trench. Heat flow data and thermal modeling indicate that the slab is decoupled from the mantle wedge beneath the forearc, resulting in a cold wedge that is unlikely to generate melt. Consequently, the close proximity of Mount St Helens to the forearc raises questions regarding the extent of the cold mantle wedge and the source region of melts that are ultimately responsible for volcanism.

High-resolution active-source data collected during the iMUSH experiment shows that Mount St Helens sits atop a sharp lateral boundary in Moho reflectivity; a strong PmP arrival is observed from shots on the east side of the volcano and western shots show little-to-no PmP energy. Passive-source results from USarray confirm this observation and indicate that the reduced Moho velocity contrast is caused by a combination of fast lower-crust and slow upper-mantle. Preliminary receiver function results from the iMUSH broadband array also show this feature. A weak forearc Moho has been observed by several previous seismic studies and has been interpreted as low-velocity serpentinite in the mantle wedge, consistent with regional gravity and magnetic data. Our observation is unusual because it occurs directly beneath an active volcano which requires melting and high temperatures in the mantle wedge (>~1200°C), inconsistent with cold temperatures required for serpentine or chlorite stability (<~800°C). We suggest that the mantle wedge beneath Mount St Helens is cold and hydrated and that the melt source region lies east towards Mount Adams.

The iMUSH (imaging Magma Under mount St. Helens) Project

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The iMUSH project integrates active and passive source seismic experiments with magnetotelluric (MT) observations and petrology to better understand the structure and dynamics of the Mount St Helens (MSH) magmatic system from the subducted plate to the surface. The geophysical experiments included a 70-element broadband array with 10-km station spacing within about 50 km of the MSH edifice from summer 2014 through 2016, 23 shots recorded in 2014 by geophones at 6000 sites including 900 Nodal stations, and ~150 MT stations within ~100 km of MSH in 2013-2015. A few papers are already published on the active-source seismic experiment, and data from all the highly successful geophysical experiments are actively being processed. Preliminary results include new 3D images of P-wave, S-wave and P/S-wave velocity as well as 3D electrical conductivity models. Mid-lower crustal velocities are generally fast to the west of MSH, consistent with the presence of the accreted Siletz terrain, and slow to the east consistent with generally higher temperatures. P-wave speeds are generally slow in the upper crust (~5-15 km depth) in a narrow zone coincident with the St, Helens seismic Zone (SHZ) that cuts through MSH with a NNW-SSE orientation. This may correspond to fluids rising from the eastern edge of an inferred hydrated mantle wedge. There is also some evidence from MT data for high electrical conductivity in places along this trend. High Vp/Vs and high electrical conductivity extend under the Indian Heaven volcanic field at depths of 5-15 km potentially associated with regions of partial melt and/or fluids. The area above this strong electrical conductor has low P-wave speeds, and the lower crust beneath Indian Heaven has high P-wave speeds. The area of high conductivity also extends north between MSH and Mount Adams almost as far as Mount Rainier.

Revisiting Seismicity Prior and during Cotopaxi´s 2015 Eruptive Activity, Ecuador

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Cotopaxi is one of the more dangerous volcanoes in Ecuador. In order to enhance the IGEPN´s monitoring capabilities, with the support of JICA a network of 5 broadband 3-component stations with collocated infrasound mics was installed in August 2004. A monthly average of 0.57 local seismic events with amplitudes larger than 2 x 10^{-4} m/s was observed until December 2008. A subtle increase was recorded after early 2009 when the average seismic count during January, 2009 to March 2015 rose to 1.5 events/ month. A clear increase of seismic activity was detected in April 2015, 4 months before initiation of eruptive activity as 14 seismic events larger than 20 x 10^{-4} m/s were recorded between April and May 2015. In total, around 3000 events were counted in May 2015. At the end of May, and particularly in June, spindle-shaped tremor episodes became the dominating feature (it reached 150 tremor episodes a day). It suggested a perturbation of the hydrothermal system as a lake was observed in the crater´s interior in July.

A decrease of seismic activity from the end of July 2015 was interpreted as a drying out phase of the hydrothermal system. Seismic activity resumed with a swarm of volcano- tectonic events on August 13, hours before the occurrence of explosions on the dawn of August 14. Three other explosion signals with an infrasound component were recorded that day. High frequency tremor increased in the following days and they were related to ash emissions. A large number of VT events detected since mid September accompanied a second period of ash emissions in Oct. 2015. Afterwards, the number of seismic events showed a decreasing trend through January 2016, although the number of sizable events remains at a monthly rate of 5.7 events from April 2015 until the present; some of these events have energy contents below 2 Hz and are accompanied by an infrasound resonance. IGEPN keeps an exhaustive monitoring this volcano.

The Use of Low-Amplitude Non Harmonic Tremor to Estimate Long-Term Gas Emission at Pacaya Volcano

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Since 1961, Pacaya volcano, Guatemala, has been in an open-vent state. The dominant activity during this time has been strombolian style bubble bursts from the summit vent. These small events are often so closely spaced in time that their codas overlap at even the closest permanent station 1.6 km NNW of the summit so that the seismicity is essentially nonharmonic tremor. In October 2013, we deployed an infrasound array and four broadband seismometers to investigate this signal in more detail. Although events were clearly visible in the infrasound data, most were indistinguishable in the seismic data, even at 550 m from the source. At some volcanoes, larger strombolian explosions produce VLP events that can be compared with gas emission data to demonstrate a linear relationship between gas mass and seismic moment. No VLP events were recorded at Pacaya, but the moment tensor solution of the seismic expression of these small events is consistent with small volume changes in the uppermost conduit. Here we expand on previous work to investigate the relationship between gas emission and seismicity.

We identified strombolian explosions in the infrasound using a template matching approach. With a conservative correlation threshold of 0.9, we found an average of 1 event every 13 seconds during the 5-day deployment. We then generated a phase-weighted stack of the seismic manifestation of these events, using the times (adjusted slightly by correlation to account for small changes in sound speed due to wind and temperature variations) from the infrasound. Lastly, we constructed a synthetic seismogram based on the timing and amplitude of the infrasound events.

Due to the limited local network, this method of using the seismic tremor to estimate gas emission at Pacaya is used to retrospectively compute the gas budget for Pacaya over much longer time periods. This method could easily be adapted to other open systems, such as Kilauea and Villarrica volcanoes.

Magma Migration at Active Volcanoes in the North Kivu Region Tracked Using Seismic Techniques and Space-Based Sulfur Dioxide Emission Estimates

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The Kivu rift belongs to the Western branch of the East African Rift system and hosts two of Africa's most active volcanoes, Nyiragongo and Nyamulagira. At the same time, the Kivu region is one of the most densely populated areas in Africa, making the continuous monitoring of these volcanoes and the better understanding of the volcanic processes a top priority.

Magma movements at active volcanoes are commonly associated with changes in volcanic tremor and long-period (LP) seismic events, as well as accompanied by modifications in SO2 degassing levels and patterns. We use data from the recently deployed broadband seismic network (KivuSNet) in combination with space-based SO2 emission estimates from the Ozone Monitoring Instrument (OMI) to develop a multidisciplinary continuous tracking methodology for magma migration over the past 2.5 years in the Kivu region. Ambient noise interferometry techniques are used to track the variations of tremor source zones, combined with the detection and location of LP events using a cross-correlation based approach. For time periods of limited data availability, template matching technique provides further insights, even with only two available stations. These data are combined both with the time series of SO2 emission variations and its spatial variations, the latter in time periods of favourable wind conditions allowing for the separation of the contribution of each volcano to the total emissions.

We find that this methodology allows for a robust discrimination of magma migration in and out of the shallow plumbing system, improving our ability to interpret signs of volcanic unrest on a daily time scale.

Magma Imaging with Seismic Dense Array: A Case Study from Krafla, Iceland

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The distribution and movement of magma in the earth's crust has been a critical concern of geochemical and geophysical investigations for much of the past century. The K-39 and the IDDP-1 wells in Krafla, Iceland provide a unique opportunity for calibrating geophysical methods against a known magma target at depth. In this study, we show how body waves from microearthquakes can be used for reflection imaging beneath the geothermal field of Krafla, Iceland. The suggested method we refer to is Virtual Reflection Seismic Profiling (VRSP) and it technique takes an advantage of recent advances in both seismic instrumentation (dense arrays) and seismic analysis (seismic interferometry). The VRSP image produced by the pilot dataset from Krafla contains prominent reflections that correspond to the depth of a magma body encountered by the IDDP-1 well. Additional features indicated by other coherent reflections could correspond to additional intrusions, including feeder chambers, buried extrusive layering or even fluid pockets. However, true 3D recording is needed to properly position many of these features. Ambiguities notwithstanding, these results confirm virtual reflection techniques as a promising new method for detecting and mapping subsurface structure at sites characterized by high levels of microseismicity.

Using Dense Geophone Arrays to Image Subsurface Hydrothermal Structure in the Upper Geyser Basin, Yellowstone National Park

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In November 2015 and 2016, we deployed three-component 5 Hz geophones at a total of 133 and 519 locations, respectively, in the vicinity of Old Faithful Geyser. In 2015, the geophones were left on the ground to record continuous seismic data for two weeks. In 2016, besides 33 backbone stations, which remained in the same locations throughout the entire experiment, the rest of the geophones (~100) were moved every 24-48 hours as a transportable array. Despite the shorter duration for each station location in 2016, the array was considerably denser compared to 2015. Moreover, with the 343 active hammer shots, the 2016 experiment was designed to provide a higher resolution shallow subsurface image focusing on Old Faithful.

A tremendous amount of hydrothermal tremor is observed, likely due to collapsing bubbles within the subsurface plumbing system. For Old Faithful, tremor starts 45 minutes prior to an eruption. Tremor amplitudes increase with time until they reach a peak 25 minutes prior to the eruption and then decrease until the eruption begins. The seismic signal related to the buildup of the Old Faithful subsurface reservoir is missing on stations to the northwest. This suggests a shallow subsurface feature that strongly attenuates the seismic signal immediately NW of the cone of Old Faithful.

We will also show examples of noise cross-correlation functions and demonstrate their spatial and temporal relationships with known hydrothermal activity. We will demonstrate how the cross-correlation based velocity measurements can be used to image the subsurface, delineate background geological structure, and understand localized hydrothermal formation. Clear correlations are observed between noise cross-correlation variation and the Old Faithful eruption cycle on the short time scale and ambient air temperature on the long time scale. We will discuss how these can lead to a better understanding of the geyser recharging cycle and its sensitivity to external factors.

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

Oral Session · Tuesday 18 April · 8:30 AM · Governor's Square 14

Session Chairs: Peter Moczo, Steven Day, and Jozef Kristek

Broadband Synthetic Seismograms for Magnitude 9 Earthquakes on the Cascadia Megathrust Derived From 3D Finite-Difference Simulations and Stochastic Synthetics

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We have produced broadband (0-10 Hz) synthetic seismograms for magnitude 9 Cascadia earthquakes to be used to assess building performance and ground failure, and to help improve community resilience, as part of the M9 Project. We computed 3D finite-difference simulations with kinematically-specified rupture models consisting of broadly-distributed slip up to about 20m with relatively low dynamic stress drop and deeper M8 sub-events with higher stress drops. These long-period synthetics were combined with short-period stochastic synthetics with a crossover period of 1.0 s. The synthetic response spectra at periods of 1-10 s are significantly affected by the average rupture velocity, slip velocity, spatial variations of the rupture velocity and slip, hypocenter, down-dip edge of rupture, and the magnitude, position, and slip distribution of the sub-events. The ranges of plausible rupture parameters are assessed based on comparison of synthetic response spectra with predictions of the BC Hydro ground-motion prediction equations and on parameters used to model the 2010 M_w 8.8 Maule, Chile earthquake. Using a local rupture velocity that is spatially correlated with co-seismic slip produces increased ground motions at periods of 1-3 s and higher variability of response spectra at close-in stations, compared to constant rupture velocity. A key finding is the amplification of 1-10 s ground motions by factors of 2 to 5 for sites in the Seattle and Tacoma sedimentary basins, relative to sites just outside the basin, similar to observations from local earthquakes. Areas of focusing within the basins are sensitive to the slip distribution and rupture timing of the nearest sub-event. We added a small random component to the shear-wave velocity of sediments in the basins to model small-scale variations not captured in the original 3D model. Randomness in shear-wave velocity with 5% standard deviation can reduce the amplitude of peaks of spectral response at 1-3 s by 30%.

Various Modes of Rupture Directivity as Inferred from Joint Source Inversions and Ground Motion Simulations

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Rupture directivity is a combined effect of rupture propagation, the earthquake source radiation pattern, and particle motion polarization on seismic ground motions (Spudich and Chiou, 2008). This effect is known to cause directional variations in seismic ground motion and damage (*e.g.*, Archuleta and Hartzell, 1981; Heaton *et al.*, 1995), and to occur if a strike-slip or dip-slip rupture propagates to a site in the along-strike or updip direction, respectively (Somerville *et al.*, 1997). However, recently, quite different cases from these regular modes of rupture directivity have been found in Nepal and Japan.

For the 2015 Gorkha, Nepal, earthquake (GCMT M_w 7.9), we performed a joint inversion of teleseismic, strong motion, GPS, and InSAR datasets, finding dip-slip faulting and rupture propagation along the fault strike. We also found large ground velocity pulses and large seismic intensities in the direction along the fault strike. Although this is not a case of the regular rupture directivity modes, we confirmed from ground motion simulations that it could occur for a dip angle as low as of the Gorkha earthquake.

The 2016 Kumamoto, Japan, earthquake (GCMT M_w 7.0) was a strike-slip event and large ground velocity pulses were found in the fault-parallel component at stations close to the source fault. Again, this is not a case of the regular rupture directivity modes, because the rupture directivity of a strike-slip earthquake usually generates large fault-normal pulses in a widespread area. We performed a joint inversion of teleseismic, strong motion, and GPS datasets, finding near upward rupture propagation rather than usual lateral one. We then confirmed from ground motion simulations that a concentrated distribution of fault-parallel pulses could occur in the mode of near upward propagation.

A Blind Test of the Local-Scale Adjoint Tomography

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We have developed a multiscale full-waveform adjoint-tomography method for local surface sedimentary structures with complicated interference wavefields.

The local surface sedimentary basins and valleys are often responsible for anomalous earthquake ground motions and corresponding damage in earthquakes. In many cases only relatively small number of records of a few local earthquakes is available for a site of interest. Consequently, prediction of earthquake ground motion at the site has to include numerical modeling for a realistic model of the local structure. Though limited, the information about the local structure encoded in the records is important and irreplaceable. It is therefore reasonable to have a method capable of using the limited information in records for improving a model of the local structure.

We have developed our inversion suitable for local surface structures with this goal in mind.

A local surface structure and its interference wavefield require a specific multiscale approach.

In order to verify our inversion method, we performed a blind test. We obtained synthetic seismograms at 8 receivers for 2 local sources, complete description of the sources, positions of the receivers and material parameters of the bedrock. We considered the simplest possible starting model—a homogeneous halfspace made of the bedrock.

Using our inversion method we obtained an inverted model. Given the starting model, synthetic seismograms simulated for the inverted model are surprisingly close to the synthetic seismograms simulated for the true structure in the target frequency range up to 4.5 Hz. We quantify the level of agreement between the true and inverted seismograms using the L2 and time-frequency misfits as well as using the goodness-of-fit criteria based on the earthquake-engineering characteristics of seismic motion.

We also verified the inverted model for other source-receiver configurations not used in the inversion.

Validation of a 3D Geological Model for the Numerical Simulation of Earthquake Ground Motion in Emilia (Italy)

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We use 3D numerical modeling of seismic waves to explain the ground motion observed in the Po Plain (Italy) during the Emilia 2012 earthquake sequence, which could not be predicted adequately by classical ground motion prediction equations (GMPE).

The investigated area is a 70 km wide square bounded at North and South by the Po river and the Apennines range, respectively. The area includes the epicenters of the 2012 seismic sequence started on May, 20 with a ML 5.9 event. The geology of the area is characterised by a NNE-verging fold-and-thrust system, almost completely buried under late Pleistocene-Holocene deposits of the Po Plain.

On the basis of published data and by using GeoModeller software, we have built a 3D visco-elastic, geological-structural model with details suitable for seismic waveform simulations in the frequency range up to 2 Hz. We simulate two ML 4.2 events located at the NE and NW ends of the seismogenic area. The numerical simulations are performed by a well-established implementation of the Fourier pseudospectral method developed by the authors. The model is validated by comparing quantitatively the simulated seismograms to those recorded by about 20 stations, which were active in the area during the 2012 sequence.

Simulations predict correctly the most significant features observed in the waveforms, which may be caused by several factors as: the presence of anticlines, the basin margin and the variable thickness of sediments. The validated 3D model can now be used for the numerical estimation of the ground motion in the Po plain and represents a starting point for implementing more detailed, 3D local models and performing earthquake simulations in a wider frequency range.

Using CyberShake 3D Ground Motion Simulation Workflows to Advance Central California PSHA

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As part of its program of earthquake system science, the Southern California Earthquake Center (SCEC) has developed a simulation platform, CyberShake, to perform physics-based probabilistic seismic hazard analysis (PSHA) using 3D deterministic wave propagation simulations. CyberShake performs PSHA by first simulating a tensor-valued wavefield of Strain Green Tensors. CyberShake then extends an earthquake rupture forecast by varying the hypocenter location and slip distribution on finite fault models, resulting in about 500,000 rupture variations. Seismic reciprocity is used to calculate synthetic seismograms for each rupture variation at each computation site. These seismograms are processed to obtain intensity measures, such as spectral acceleration, which are combined with probabilities from the earthquake rupture forecast to produce a hazard curve. Hazard curves are calculated at seismic frequencies up to 1 Hz for hundreds of sites in a region and the results are interpolated to obtain a hazard map.

The CyberShake platform uses scientific software and middleware to integrate parallel and high-throughput research codes into scientific workflows. Scientific workflow tools manage input and output data, support remote job execution, provide error recovery, and enable the automation required for the multi-week CyberShake studies on open-science supercomputers that are used to calculate regional hazard maps.

In developing and verifying CyberShake, we have focused our modeling in the greater Los Angeles region. We are now expanding the hazard calculations into Central California, using both a 3D central California velocity model created via tomographic inversion, and a regionally averaged 1D model. We will describe the CyberShake computational methodology and SCEC's workflow-based software infrastructure that have enabled CyberShake to expand into Central California. We will compare hazard estimates from the 1D and 3D models, and describe our future CyberShake plans.

On the Fast and Efficient Broadband Simulation of Earthquake Strong-Motion with Basin Generated Surface Waves

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The comprehensive estimation of the earthquake response of structures, in particular nonlinear response, for design purposes requires the use of physically realistic synthetic time histories of earthquake strong-motion. In this study, we simulate the high-frequency motions from a simple, yet physically realistic model of the earthquake source, the specific barrier model by first calibrating its far-field spectrum, as an example, to source spectra of Greek earthquakes. We complete the seismological model by adopting regional path attenuation functions proposed in the literature, and frequency dependent site amplification functions derived from Greek borehole data. The model provides good agreement with both stochastic and empirical regional ground motion models of peak strong-motion parameters such as peak-ground acceleration and pseudo-spectral acceleration. Thus, the model can be applied for the generation of synthetic time histories of earthquake strong-motion in Greece, useful *e.g.* for response analyses purposes. However, the model does not address the long period surface waves that may arise when the seismic waves encounter sedimentary basins, affecting structures of long natural period of oscillation, such as long-span bridges, high-rise structures and liquid storage tanks. We therefore extend the applicability of the seismological model into the long-period range based on key physical basin parameters that are used to scale the probability density functions of the amplitude and group delay spectra, respectively, albeit to different extents. The resulting broadband time histories provide realistic earthquake strong-motion that include basin-generated (Rayleigh) surface waves. We discuss various applications of this simple model and ongoing work, for example its calibration to observed surface wave data, and the potential use of the nonstationary spectral envelope in predicting peak structural response parameters due to surface waves.

Salvus: A Flexible Open-Source Package for Waveform Modeling and Inversion from Laboratory to Global Scales

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Recent years have been witness to the application of waveform inversion to new and exciting domains, ranging from non-destructive testing to global seismology. Often, each new application brings with it novel wave propagation physics, spatial and temporal discretizations, and models of variable complexity. Adapting existing software to these novel applications often requires a significant investment of time, and acts as a barrier to progress. To combat these problems we introduce Salvus, a software package designed to solve large-scale full-waveform inverse problems, with a focus on both flexibility and performance.

Currently based on a continuous high order finite (spectral) element discretization, we have built Salvus to work on unstructured quad/hex meshes in both 2 or 3 dimensions, with support for P1-P3 bases on triangles and tetrahedra. A diverse (and expanding) collection of wave propagation physics are supported (*i.e.* viscoelastic, coupled solid-fluid, weak non-linearities). Interfaces with the PETSc suite of system solvers are included for future applications demanding stronger non-linearities. Additionally, with a focus on the inverse problem, functionality is provided to ease integration with internal and external optimization libraries. Finally, to ensure that the code remains accurate and maintainable, we use modern software testing practices and ensure conformance with a suite of analytical wave equation solutions.

Salvus bridges the gap between research and production codes with a design based on templated C++ mixins which separate the physical equations from the optimized numerical core. This allows domain scientists to add new equations using a high-level interface, without having to worry about implementation details. Our goal in this presentation is to introduce the code, show several examples across the scales, and discuss some of the extensible design points

Off-Fault Deformation and Shallow Slip Deficit from Dynamic Rupture Simulations with Fault Zone Plasticity

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Kinematic source inversions of major ($M_w \geq \sim 7$) strike-slip earthquakes reveal significantly smaller slip in the uppermost 2-4 km than at greater depth. The slip inferred geodetically at depth also exceeds surface displacements observed in the field after these events, and it has been suggested that this shallow slip deficit (SSD) is caused by inelastic failure near the surface. Here, we aim to reproduce the depth-dependence of slip observed during past earthquakes by performing 3D simulations of dynamic rupture in plastic media. Simulations are carried out with the AWP-ODC finite difference code using a slip-weakening fault friction law, a Drucker-Prager (DP) yield condition and depth-dependent stress. We experiment with different rock strength models, with friction angles and cohesions derived from the Hoek-Brown criterion for fractured rock masses of good, moderate and poor quality. We simulate a part of the fault system that ruptured during the 1992 M 7.3 Landers earthquake, using a ~30 km planar fault segment approximating the Homestead Valley and SE end of the Emerson Valley fault segments. No significant SSD is produced by our simulation in the linear case and in the nonlinear case for a good quality rock mass. However, nonlinear simulations performed with moderate and poor quality rock masses yield a SSD of ~60 and ~80%, respectively, consistent with values reported during previous M ~7 earthquakes. We also compare simulated off-fault deformations (OFD), defined as the normalized difference between on-fault displacement and total displacement, with published values derived from sub-pixel image correlation (COSI-Corr) results and field observations for the Landers earthquake (Milliner *et al.*, 2015). OFDs obtained from the linear and good quality rock models are less than 10%, but range between 20-70% and 40-80% in the moderate and poor quality rock mass, respectively, consistent with observed values.

EDGE: Extreme-Scale Discontinuous Galerkin Environment

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We present our newly developed software EDGE, targeting at high performance and extreme scalability when solving hyperbolic partial differential equations with the Discontinuous Galerkin (DG) method.

EDGE includes an ADER-DG solver for the elastic wave equations and relies on unstructured tetrahedral meshes to cope with complex model geometries (*e.g.* topography, fault geometries or material heterogeneities).

First, we discuss advantages and limitations of EDGE's concept of fused simulations.

Here, given "similar enough" input data, we are able to run multiple simulations in a single execution of the solver.

This approach not only increases the potential parallelism and the amount of shared data between different fused simulations, but is also applicable to many other numerical methods.

High-dimensional problem settings, *e.g.* uncertainty quantification in the context of seismic hazard analysis or tomographic inversion, are a prime candidate for EDGE's unique fusing capabilities.

We conclude the talk by presenting performance results for seismic simulations on the recently released Intel Xeon Phi processor.

For a sixth order forward simulation, we achieved a performance of 10.4 PFLOPS in hardware on 9,000 nodes of Cori Phase II.

In terms of throughput, EDGE's fused seismic simulations are able outperform their non-fused counterparts by 1.8x-4.6x, depending on the chosen convergence rate.

Toward Exascale Seismic Simulations with SW4

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Current and future generations of supercomputers enable seismic simulations with 100,000's to 1,000,000's of cores with mixed CPU & GPU architectures. However, direct application of current algorithms on these large machines will not achieve satisfactory performance. In order to move toward Exa-scale computing (billion billion calculations per second) we are modifying the SW4 seismic simulation code for the latest and future machines. In this talk we report on the porting of SW4 to the Cori-II supercomputer at the National Energy Research Scientific Computing Center (NERSC), located at LBNL. The Cori-II machine has 9,300 nodes, each having a 68-core Intel Xeon Phi processor. While each node on this machine has more cores that previous (Intel based) supercomputers, each individual core is slower. To achieve good computational performance it is thus necessary to make the spatial decomposition finer, *i.e.*, assign fewer grid points to each core. We have implemented a hybrid programming model in SW4 where a MPI-task decomposition in the horizontal directions is augmented by an OpenMP-threaded decomposition in the vertical direction. We report on the performance of the hybrid programming model for some smaller test cases, and then demonstrate how this technique has enabled a significant increase in frequency content for regional ground motion simulations in the San Francisco Bay Area.

Paleoseismology of Subduction Earthquake Cycles

Oral Session · Tuesday 18 April · 8:30 AM · Plaza D
Session Chairs: Rob Witter, Ian Shennan

Implications of the Kaikoura Earthquake on Hikurangi Subduction Seismogenesis, New Zealand: Insights from Paleoseismology

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The 14 November 2016 M_w 7.8 Kaikoura earthquake was associated with multiple fault ruptures that progressed in a southwest to northeast direction, including the Kekerengu and Needles faults. These faults are adjacent to a complex set of faults in Cook Strait which serve to transfer motion from the Marlborough fault system to the Hikurangi subduction zone. The Kaikoura earthquake resulted in positive coulomb stress changes on faults in Cook Strait and the subduction interface. An accelerated episode of slow-slip movement on the plate interface occurred at multiple locations on the Hikurangi subduction interface soon after the Kaikoura earthquake which is also raising concerns as to further earthquake activity. Paleoseismic and historic information provide some insights into past temporal relationships between crustal faults and great earthquakes on the southern Hikurangi subduction interface. The most recent major event (MRE) on the plate interface was 520–470 years before present (B.P.), which overlaps with the pre-penultimate event (PE) on the Kekerengu fault. The PE on the interface was 880–800 years B.P., which overlaps with the PE's on both the Wairarapa and Wellington faults. Thus, a partial temporal correlation exists between past upper crustal fault rupture and great subduction events, but the dating does not have the resolution to assess whether the subduction events followed or preceded or were coeval with the upper plate fault ruptures. Since the MRE on the subduction interface at least four large upper plate earthquakes in the southern Hikurangi margin have not coincided with a great subduction earthquake. While a great subduction earthquake may yet follow the Kaikoura earthquake, there is, as yet, insufficient understanding of the mechanical interactions and current levels of accumulated stress, to assess the likelihood of cascading failures with any accuracy.

The Application of Diatoms to Reconstruct the History of Subduction Zone Earthquakes and Tsunamis

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Earthquake and tsunami records on centennial and millennial temporal scales are necessary to understanding long-term subduction zone behavior and the occurrences of large, but infrequent events. Microfossils, such as diatoms, incorporated into coastal stratigraphy provide some of the most detailed reconstructions of the history of earthquakes and tsunamis. We explore qualitative and quantitative techniques that employ the relation between diatoms and salinity, tidal elevation, and life form to: (1) reconstruct records of vertical land-level change associated with large earthquakes; and (2) identify anomalous sand and silt beds deposited by tsunamis. A global database shows that diatoms have been successfully employed in the reconstruction of earthquake and tsunami histories in Chile, the Indian Ocean, Japan, New Zealand, the North Sea, the Pacific Northwest of North America, and the South Pacific. We use case studies from some of these locations to highlight advancements in the field and new capabilities that diatoms have enabled. In Alaska and Chile, diatoms have documented both uplift and subsidence at proposed segment boundaries, expanding our knowledge of the variability of slip in megathrust ruptures. In tsunami studies in Alaska and Chile, allochthonous marine and brackish diatoms along with high fragmentation of diatom valves within sand deposits signaled repeated, high-energy marine incursions into coastal lowlands. To conclude, we provide an example of a marsh monitoring experiment along the Cascadia subduction zone to emphasize the importance of studying the modern diatom response to changing environmental conditions to refine estimates of coseismic deformation.

Limits of Coastal Evidence for Large Subduction Earthquakes: How Big is Still Too Small to Detect?

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Seismic hazard analyses require realistic source models—earthquake locations, sizes, and rupture frequencies—but building these models is intrinsically challenging along subduction zones where instrumental records are short and geologic records are indirect and incomplete. Giant M >9 earthquakes in the past 12 years have set the bar for maximum seismic potential, but great (M ≥8) earthquakes that rupture shallow portions of the megathrust have received less attention. Such shallow ruptures may not be detected in the coastal geologic record. The 2015 Illapel, Chile M_w 8.3 earthquake vividly illustrates the potential for ambiguous coastal records of large shallow interface slip. The Illapel rupture produced only decimeters of coastal uplift in a region presumed to subside coseismically, and the spatial extent of tsunami inundation did not clearly overlap the region of coseismic land level changes due to coastal configuration. As a result, in coming centuries the magnitude and location of the Illapel event will be difficult to decipher from coastal evidence.

We revisit the problem, "How big is still too small to detect," by posing the question: What slip distributions and magnitudes create vertical deformation patterns that are at or below the thresholds of coastal evidence for land-level change? Coseismic vertical land-level change is highly dependent on slip distributions, the vertical and lateral extents of ruptures, and the geometries and coastal configurations of individual subduction zones. Despite this variation, we conclude that in most subduction zones, shallow interface ruptures as large as M 8.5 displace the coast by <30 cm and likely leave equivocal or no geologic evidence along continental coasts. This implies that marine turbidite and lacustrine records of coseismic shaking, and records of seemingly 'orphan' tsunamis (not stratigraphically tied to local land-level change) may be essential for assessing the record of subduction earthquakes up to M 8.5.

Sedimentary Records from Lakes: How They Can Help Improve Our Understanding of Subduction Earthquake Cycles in Alaska

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The sedimentary record of subaquatic landslide deposits and turbidites in lakes has been used as a proxy of past earthquakes in a variety of tectonic settings (*e.g.* in Chile, New Zealand and Switzerland). The reasoning behind this approach is that seismic shaking in lake basins can cause widespread and coeval failure of sediment-covered slopes, leaving a distinct imprint in the sedimentary record. Also, the study of lake sediments can provide shaking intensity information, which offers a quantitative method to reconstruct the magnitude and epicenter of past earthquakes. In the Alaska-Aleutian Subduction Zone (AASZ), however, lakes were never before studied for paleoseismology purposes.

We studied the sediments of three south-central Alaskan lakes using seismic stratigraphy and sediment cores. The landslide record not only reveals the presence of sublacustrine landslides related to the historic 1964 megathrust earthquake, but also a succession of older landslide deposits. These are all inferred to have been caused by multiple, coeval slope failures, which can be attributed to past seismic shaking. Sediment cores (up to 15 m in length), taken in each lake basin on sites away from landslide deposits, show a varved background sedimentation, occasionally interrupted with turbidites. These turbidite records represent an independent seismometer of past earthquake events.

The continuous and varved sedimentation of the Alaskan lakes corroborates our paleoseismic records (landslides and turbidites) with a high-resolution age framework. In the future, these multi-lake records can thus provide insights into the temporal and spatial variability of paleo-earthquakes in the eastern AASZ. This can be relevant for defining the extent of past ruptures and for inferring information on rupture pattern variability and interplate coupling.

3D Simulations of Megathrust Earthquakes in Cascadia—Implications of Paleoseismic Evidence for the Down-Dip Rupture Extent and Along-Strike Rupture Variability

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The M9 Project is a multi-disciplinary effort aimed at reducing the catastrophic potential of large Cascadia earthquakes on the social, built, and natural environments. This work relies on developing a suite of synthetic ground motions for various M9 rupture scenarios in Cascadia, which are then used to probabilistically evaluate the ensuing consequences from a megathrust event. We generate long-period synthetic ground motions using 3D finite difference simulations and an updated version of the Cascadia velocity model. Slip consists of multiple high-stress drop subevents (~M8) with short rise times on the deeper portion of the fault, superimposed on a background slip distribution with longer rise times. A key parameter in defining the earthquake source is the down-dip limit of slip, which controls the proximity of the rupture to major cities. We focus on three choices for the down-dip rupture extent used by the 2014 National Seismic Hazard Maps: the top of the non-volcanic tremor zone, the 1 cm/yr locking contour, and the midpoint of the fully locked boundary and the 1 cm/yr locking contour. Our simulations show that allowing the rupture to extend to the up-dip limit of tremor (*i.e.*, the deepest considered rupture extent), even when tapering slip to zero at the down-dip edge, results in multiple areas of coseismic coastal uplift. This is inconsistent with paleoseismic evidence, which suggests predominantly coastal subsidence in past great earthquakes. In contrast, defining the down-dip limit of rupture as the 1 cm/yr locking contour results in primarily coseismic subsidence at coastal sites. We also find that the presence of deep subevents can produce along-strike variations in subsidence and ground shaking along the coast. We show that coastal geologic evidence for coseismic displacement can be used to inform the down-dip limit of M9 earthquake ruptures in Cascadia, and thus, improve our understanding of seismic hazard associated with the Cascadia megathrust.

Recording and Preservation Sensitivities for Paleoseismic Data on the Cascadia Margin

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Sensitivities always apply to the generation, recording, and preservation of geologic data (*e.g.*, Nelson *et al.*, 2006). The resolution of the recording of subsidence events in the coastal marshes of Cascadia, was estimated to be > 0.5 m in some of the original work. This estimate was improved by Engelhart *et al.* (2013) who demonstrated that this could be improved to 0.2 m or better; however, these modern methods have only been applied in a few places. Tsunami washover deposits are subject to land barriers and the state of the tide. Bradley Lake for example, is subject to overtopping a 5.5 m berm for tsunami to enter the lake. Given these realities, coastal records are subject to a higher threshold of both preservation and resolution of earthquake evidence that is a convolution of three factors: 1) the slip model of the earthquake; 2) the state of the tide; and 3) the vertical motion induced at the site. While the degree of subsidence and "boldness" of the soils are important clues, they are just a small part of the larger picture. The coastal subsidence data also represent a 1d dataset, and thus are a weak constraint on the position of the locked plate boundary and the size of the earthquake. By comparison to the land record, the requirements for generation and preservation of submarine and sublacustrine paleoseismic evidence are simpler, requiring a favorable depocenter, modest ground shaking, and nearby slopes that will fail under seismic loadings. We suggest the recording threshold is lower for paleoseismic turbidites. The slope stability requirement is quite low, requiring only tenths of a g or less for failure. Magnitude thresholds for recording and preservation of submarine landslides in Cascadia were estimated as M ~7.1 and may be as high as M ~8.3-8.5 for onshore sites. We conclude that the turbidite record is likely more sensitive and more complete than the land record in most cases, as long as spatial sampling and resolution are sufficient.

Temporal Variability of Interseismic Strain Accumulation along Subduction Megathrusts, on Timescales of Decades to Centuries

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It has long been assumed that once the postseismic phase of the earthquake cycle is complete, deformation and strain accumulation during the interseismic phase of the seismic cycle are uniform. Although postseismic transients have been widely documented, they are commonly observed to decay to a "background" deformation rate. The belief was that, subsequently, this "background" interseismic strain rate remained steady over most of the seismic cycle [Savage and Thatcher, 1992, JGR]. More recently, researchers discovered processes and phenomena previously unappreciated along subduction zones, including slow slip at a range of timescales, changes in the width of the locked region, and changes over time in plate coupling. Yet our understanding of the range of behavior during the interseismic period is generally limited by the brevity of modern geodetic networks.

Taking advantage of high-resolution paleogeodetic data from coral microatolls in Sumatra, we show that it is the rule, not the exception, that interseismic rates vary over the course of a seismic cycle, and from one seismic cycle to the next. Although interseismic vertical deformation rates (uplift or subsidence) may be linear for decades to a century, the rate may shift abruptly and remain fixed at a new rate for decades more. The coupling pattern before one great earthquake may be different from the pattern leading up to a similar, co-located earthquake. Some sections of a megathrust may be nearly uncoupled for a century or more, yet appear nearly fully coupled at other times and sustain large displacements during an ensuing earthquake. In general, the coral records suggest that our observations and understanding of fault behavior between earthquakes are still incomplete. They call into question the very meaning of an interseismic coupling pattern determined from a modern geodetic network, when that coupling pattern may reflect deformation during only the most recent few decades.

The December 25, 2016, M7.6, Southern Chile Earthquake and its Relation to the 1960 Rupture

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On December 25, 2016 at 11:22 a.m. (local time) a M_w=7.6 earthquake took place along the coast of the southern Chile, with epicentral coordinates 74.391°W and 45.517°S at a depth of 30 km (National Seismological Center, www.sismologia.cl). This earthquake is the largest recorded in the country since September 16, 2015 when the Illapel, M_w=8.4, event took place. The geometry of the fault and the location of the recent event, are consistent with the subduction of the Nazca plate beneath the South American plate. Preliminary estimates, based on scaling relationships and early aftershock distribution, indicate that the rupture length reaches about 60 km with an average fault slip of around 2 m. Maximum accelerations of the order of 27% g have been recorded in the east-west component of the GO07 station located in the southern part of the island of Chiloe, near Quellon. A GNSS device placed at the same location was subjected to a co-seismic displacement of 17 cm to the west, 4 cm to the south and 7 cm of subsidence.

The previous large event taking place in this region was the May 22, 1960, M_w 9.5 giant earthquake. Coastal elevation changes and inland leveling lines as well as the few observations of horizontal deformations associated to this earthquake reveal that the rupture zone extends from the Arauco Peninsula in the north (~37°S) to the Taitao Peninsula (~46°S) in the south (Plafker and Savage, 1970). The average displacement of the earthquake generating fault reached 20 m, with maximum values of more than 40 m. The December 2016 event took place in a region of relatively low slip during 1960 however, GPS and sea level data indicate that the 1960 earthquake influence might have been over by the beginning of the new millennia.

Paleoseismology of Large Earthquakes Resulting from Continental Subduction along the Himalayan Frontal Thrust of Nepal

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It is along the Himalaya where the potential exists to collect a full suite of geodetic, geologic, and seismologic observations across the entirety of a major convergent plate boundary. We report here our most recent efforts to conduct paleoseismology along the Himlayan Frontal Thrust (HFT) of Nepal and place these results in the context of available geodetic and seismological data bearing on the potential for great earthquakes along the arc. The recent 2015 Gorkha earthquake

earthquake produced displacement on the lower half of the shallow decollement that is the HFT. We most recently emplaced trenches across the HFT where it has produced scarps in young alluvium at the mouths of major rivers at Tribeni and Bagmati, each respectively located directly up dip and ~200 km to the west of the Gorkha earthquake rupture plane. The most recent rupture at Tribeni occurred 1221–1262 AD to produce a scarp of ~7 m vertical separation. Vertical separation across the scarp at Bagmati registers ~10 m, possibly greater, and formed between 1031–1321 AD. The temporal constraints and large displacements allow the interpretation that the two sites separated by ~200 km each ruptured simultaneously, possibly during 1255 AD, the year of a historically reported earthquake that produced damage in Kathmandu. In light of geodetic data that show the equivalent of ~20 mm of crustal shortening across the HFT occurs on an annual basis, the sum of observations is interpreted to suggest that the HFT extending from Tribeni to Bagmati may rupture simultaneously, that the next great earthquake near Kathmandu may rupture an area significantly greater than the section of HFT up dip from the Gorkha earthquake, and that it is prudent to consider that the HFT near Kathmandu is approaching or in the later stages of a strain accumulation cycle prior to a great thrust earthquake, most likely much greater than occurred in 2015. The study continues and should add more to the picture.

Possible Sedimentary Evidence for Paleoearthquakes and the 2016 November M 7.8 Kaikoura Earthquake along the Hikurangi Subduction Zone

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The Hikurangi margin straddles the convergent boundary between the Pacific and Australia tectonic plates and is New Zealand's potentially largest earthquake and tsunami hazard. The 3 km-deep Hikurangi Trough marks the location where the Pacific plate is subducting beneath the eastern continental margin of the North Island and NE South Island. This region has a very short historical earthquake record relative to the likely recurrence of great earthquakes and tsunami. In October 2016 an international 5-year project commenced to evaluate the prehistoric earthquake history here.

In November 2016 an RV Tangaroa voyage acquired 50 sediment cores up to ~5.5 m long from sites on the continental margin between the Kaikoura coast and Poverty Bay. Core sites were selected using available 30 kHz multibeam bathymetric and backscatter data, sub-bottom acoustic profiles, archived sediment samples, and results from numerical modeling of turbidity currents. Sites fell into 3 general categories: turbidite distributary systems; small isolated slope-basins; and Hikurangi Channel, levees, and basin floor. The terrigenous-dominated sequence included layers of gravel, sand, mud, and volcanic ash. Many of these layers are turbidites, some of which may be seismogenic.

During the voyage the 13th November 2016 M_w 7.8 Kaikoura Earthquake occurred. Using a multicorer within 5 days of the earthquake, we recovered what appeared to be a very recently emplaced, still-fluidized, co-seismic turbidite ~10-20 cm thick, overlying the pre-earthquake seabed (evidenced by an oxidized layer), in up to 5 cores. This deposit appears to extend at least 300 km along the Hikurangi Channel and offers a rare opportunity to calibrate our paleoseismic data and to test hypotheses of turbidite triggering and emplacement. Further laboratory characterization of the stratigraphy, physical properties, and benthic assemblages along with radionuclide analyses will test this hypothesis further.

Seismology Software Tools That Improve What We Do and How We Do It

Oral Session · Tuesday 18 April · 2:15 PM · Governor's Square 16

Session Chairs: Michelle Guy and Eric Martinez

The ANSS Station Information System: A Centralized Station Metadata Repository for Populating, Managing and Distributing Seismic Station Metadata

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Maintaining and archiving accurate site metadata is critical for seismic network operations. The quality of all products of a network, such as the earthquake catalog or ShakeMaps etc. depend on using accurate site locations and channel response. Regional seismic networks can accomplish this task by using the Advanced National Seismic System (ANSS) Station Information System (SIS). It is a repository of seismic equipment inventory, equipment response, and other site information. This poster will give an overview of the system as well as highlight recent developments.

SIS has a web-based user interface that allows network operators to enter information about seismic equipment and assign response parameters to it. It allows users to log entries for sites, equipment, and data streams. Users can also track when equipment is installed, updated, and/or removed from sites. SIS also has an interface for editing information so that metadata can be updated when more accurate information becomes available.

When seismic equipment configurations change for a site, SIS computes the overall gain of a data channel by combining the response parameters of the underlying hardware components. Users can then distribute this metadata in standardized formats such as FDSN StationXML or dataless SEED. One powerful advantage of SIS is that new instruments can be assigned response parameters from the Incorporated Research Institutions for Seismology (IRIS) Nominal Response Library (NRL), or from a similar instrument already in the inventory, thereby reducing the amount of time needed to determine parameters when new equipment (or models) are introduced into a network.

SIS is also useful for managing field equipment that does not produce seismic data (eg power systems, telemetry devices or GPS receivers) and gives the network operator a comprehensive view of each field site. Thus, operators can also use SIS reporting capabilities to improve planning and maintenance of the network.

The Global Earthquake Model (GEM) Suite of Tools for Seismic Hazard Modeling

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Since 2009 the Global Earthquake Model Foundation actively develops an all-inclusive suite of open-source software tools supporting the construction of hazard models and their calculation. The tools created for the processing of basic information (*e.g.* earthquake catalogues) and for the construction of the PSHA input model is organized in a number of toolkits comprising: the OpenQuake (OQ) Hazard Modeler's Toolkit (oq-hmtk), the OQ Strong Motion Toolkit (oq-smtk), the OQ Catalogue Toolkit (oq-cattk) and its lightweight version and the OQ Model Building Toolkit (oq-mbtk). This set of toolkits provides the essential methodologies needed for creating state-of-practice PSHA input models starting from common datasets such as earthquake catalogues, information from earthquake geology, and results obtained from the modeling of tectonic processes. The models produced with this set of toolkits can be later used for computing hazard, and ultimately risk, using the OpenQuake-engine, the primary hazard and risk calculation engine developed by GEM.

This software, entirely hosted on Github, is developed using a common set of tools and (almost) standard development approach, which comprises the construction of a large set of tests. Personnel of the GEM Foundation and a small global community of scientists and engineers, have contributed the development of the software. Some of the main challenges for the near future will be therefore to enlarge the community of contributors in order promote an more collaborative development, to increase the number of methodologies available and, promote collaboration with other projects sharing similar goals and approaches not necessarily just within the seismological community.

Product Distribution Layer

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The Product Distribution Layer (PDL) is an enterprise message bus used to exchange earthquake data products. U.S. Geological Survey (USGS), the Advanced National Seismic System (ANSS), and other collaborators publish data using command line and java interfaces. These data include Quakeml messages, ShakeMap grids, and many other derived data products. PDL clients receive push notifications when new data is published and configure whether and how to download and process that data. Redundant paths and reliable notification provide robust delivery even after there are network outages.

PDL is used to connect independent but related systems. For example, ShakeMap receives Hypocenter, Strong Motion, and Did You Feel It? data inputs via PDL and, after processing, sends its output via PDL for subsequent processing by other systems like ShakeCast and PAGER. At the same time backend systems are processing data, the USGS Earthquake Hazard Program web site is also connected to PDL and updates near-real time data feeds, the ANSS Comprehensive Catalog, and related event pages as soon as new data is published.

Libcomcat: Tools for Automated Earthquake Information Extraction

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The U.S. Geological Survey (USGS) National Earthquake Information Center (NEIC) and Advanced National Seismic System (ANSS) locates on average 27,000 earthquakes every year. To organize this information, the NEIC has in the past created a number of catalogs, which were designed to only capture limited information relating to an earthquake. However, many more types of earthquake data products are now being generated, including maps and grids of modeled ground motions (ShakeMaps), results of loss models (PAGER), and community-generated intensity data (Did You Feel It?). These products have been generated for historical (*e.g.* back to 1900) and new near real-time events, all of which need to be/are associated, archived, and searchable. The USGS Earthquake Hazards Program created the ANSS Comprehensive Catalog (ComCat) to provide a mechanism to organize and search these increasingly diverse data products, and to provide a means to browse and search the data contained within it.

In addition to providing a user interface, ComCat provides a web service Application Programming Interface (API), which presents data in a JavaScript Object Notation (JSON) format. The NEIC has created a set of Python libraries around this API called libcomcat. Libcomcat is used by scientists and developers to write custom applications to interact with ComCat. Recognizing that not all scientists are also developers, the NEIC also built command line tools around the libcomcat interface. These tools include: getcsv, which retrieves basic earthquake information in spreadsheet friendly formats; getfixed, which retrieves earthquake information in fixed width formats familiar to the seismology community; and getcomcat, which automatically downloads data products for selected earthquakes. The libcomcat libraries and tools are open source for community access and involvement. Community contributions to this point include extending some tools to other languages such as MatLab.

Using a Fast Similarity Search Algorithm to Identify Repeating Earthquake Sequences

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Repeating earthquakes (REs) are regular or semi-regular failures of the same patch on a fault. Therefore they produce near-identical waveforms at a given seismic station. Quasi-periodic sequences of REs are commonly interpreted as slip on small locked patches consistently loaded by large areas of surrounding fault that are creeping (Nadeau and McEvilly, 1999). Detecting them, therefore, places important constraints on the extent of fault creep at depth. In addition, the magnitude and recurrence interval of these RE sequences can be related to the creep rate and used as constraints on slip models.

Detecting REs is a time consuming process that requires calculating pairwise cross-correlation coefficients (CCCs) between recorded waveforms at common stations targeting events in a specific area. To expedite our search, we use a fast and accurate similarity search algorithm developed by the computer science community (Zhu *et al.*, 2016). Our initial tests on a data set including ~1500 waveforms suggest it is around 40 times faster than the regular pairwise CCC algorithm.

In this study we test our implementation of the algorithm by searching for REs in northern California fault systems (*e.g.* Rodgers Creek, Maacama, Bartlett Springs, etc) upon which creep is suspected, but not well constrained. We identify event pairs with CCC>0.85 and cluster them based on their similarity. As an independent location based check, we use cross spectrum analysis to calculate precise differential S-P times for each event pair at 5 or more stations. We consider a cluster of events a RE sequence if the source location separation distance for each pair is less than the estimated circular size of the source. Currently we can identify 34 RE families and many more RE candidates that need to be tested by our location based method. In future, we plan to use this information in combination with geodetic data to produce a robust creep distribution model for all of the faults in this region.

The Subduction Zone Observatory

Oral Session · Tuesday 18 April · 2:15 PM · Plaza D

Session Chairs: Diego Melgar, Lee Liberty, and Jeff Maguire

Updates on The Subduction Zone Observatory Workshop

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On September 29-October 1 2016 an International Workshop was held in Boise Idaho to discuss what a Subduction Zone Observatory initiative could accomplish and what form it might take.

Discussion on what SZO could be were organized around four themes: Deformation and the Earthquake Cycle; Volatiles, Magmatic Processes and Volcanoes; Surface Processes and the Feedbacks between Subduction and Climate; and Plate Boundary Evolution and Dynamics. Attendees had abundant opportunity to weigh in on the most important scientific opportunities, the key obstacles holding back discoveries, and the types of future community scale efforts that would best advance subduction zone science. Participants were asked: "What is new, exciting, and doable?" "What can't we do now?"

Much of the scientific enthusiasm at the workshop resulted from recent examples of spectacular new types of datasets that provide a window towards a next generation approach to understanding Subduction Zones. Many phenomena that were previously captured as static snapshots are now starting to be shown as movies, in 4D. From the locking of the plate boundary fault, to the gases expelled from volcanoes prior to eruption, to the surface mass transport between forearc mountains and the trench, to geological records of past ruptures spanning back thousands of years, newly available observational time series are revealing dynamically evolving processes. Synergistically, the sensors deployed for basic research are finding evermore practical applications. Earthquake and tsunami early warning, volcanic ash observatories and dispersion models linked with global air traffic control, eruption warnings based on volcanic unrest, incipient landslides detected by satellites, all rely on sensor suites that now serve the dual purpose of a greater scientific understanding and a reduction in societal hazards.

In this talk we will give an overview of the SZO workshop report and discuss possible next steps.

Crustal Deformation Following Great Subduction Earthquakes Controlled by Mantle Rheology and Earthquake Magnitude

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After a great subduction earthquake, while ongoing fault slip (afterslip) continues to cause seaward motion of the surface, viscoelastic relaxation causes opposing crustal motion, with the dividing boundary located roughly above the downdip edge of the rupture. As the effect of viscoelastic relaxation decays with time, effect of the relocking of the megathrust becomes increasingly dominant to cause the dividing boundary to migrate away from the rupture zone, eventually leading to wholesale landward motion of the surface. The duration of the postseismic opposing motion represents the system relaxation time, which is basically the material relaxation time of the upper mantle scaled by earthquake magnitude. A higher mantle viscosity leads to a longer relaxation time and hence longer-lived opposing motion. Larger earthquakes induce greater coseismic stress perturbation, and their often longer rupture length results in inefficient postseismic viscous mantle flow in the strike direction. Both factors lead to longer system relaxation times. To quantify this process, we employ 3D spherical-Earth finite element models of Burgers rheology to study ten M 8-9.5 subduction earthquakes. As end-member examples, our models explain the long-lived opposing motion following the 1960 M 9.5 Chile earthquake which is still continuing today and the very short-lived opposing motion following the 1995 M 8 Antofagasta earthquake which lasted for only one year. We show that the magnitude-dependent system relaxation times of the other 8 events define a trend between these end members. Our models also suggest somewhat different viscosities for different margins, likely associated with the different thermal conditions of their arc and back-arc regions. Other factors, such as locking distribution and the amount of afterslip, are found to affect deformation details.

Ocean Bottom Pressure Measurements for Detecting Vertical Seafloor Deformation

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Ocean bottom pressure can be used to detect seafloor vertical deformation since small seafloor height changes produce measurable pressure changes. Pressure sensors can reliably resolve deformation that occurs on short timescales—less than a few days. However, inherent sensor drift makes resolving small, slow signals that occur over longer periods difficult. One solution is to use a deadweight calibrator as an in situ reference pressure source. In one method, a continuous drift-corrected pressure time series can be produced using the reference pressures as intermittent calibration values. The reference pressures are required to be stable over time to be used as calibration points. A self-calibrating pressure recorder (SCPR) that uses this mechanism was developed and deployed at Axial Seamount in 2013. The drift-corrected record showed uplift of 60 cm over a 17-month period. In an alternative configuration, campaign-style absolute determinations of seafloor pressure can be achieved. The absolute self-calibrating pressure recorder (ASCPR) uses the deadweight calibrator as an absolute reference whose NIST-traceable pressure value is known. The reference pressure and all measurement parameters must be known to a high degree of accuracy. The true, absolute seafloor pressure value is measured from the difference of the known reference pressure and observed seafloor pressure. Once measured absolutely, the pressure data will be valuable for studies in the future, irrespective of the instrument used. The ASCPR has been deployed in the Cascadia subduction zone once a year since 2014. To reliably resolve the secular deformation rate many years of observation will be required. The measurement accuracy is on the order of 3-5 cm at 1-3 km depth, but we expect a final accuracy of ~10 ppm (1 cm at 1 km depth) with further improvements.

Geometrical Effects of Megathrust Faults on Slow Slip Events and Seismic Ruptures

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Mega-thrust fault geometry has long been postulated to influence the seismic and aseismic slip processes in subduction zones. In this study, we present numerical simulations in the framework of rate-state friction of earthquake cycle slip on megathrust faults with non-planar geometry, represented using triangular element meshes. We apply the model to investigate the fault geometrical effects on slow slip events (SSE) in northern Cascadia and earthquake rupture patterns along the Manila subduction zone. In both cases, we find that the "geometry parameter", defined to encapsulate the spatial variations in fault local dip and local strike angles, is critical in controlling the along-strike segmentation of slow slip (Cascadia) and seismic slip (Manila).

For the northern Cascadia model, without introducing any other type of along-strike heterogeneity, the central ~ 150 km segment beneath Port Angeles acts as a repetitive slip patch, with SSEs appear every ~ 1.5 years and a maximum slip of ~ 2.5 cm. Two minor slip patches with less cumulative slips straddle the central patch. The modeled slip patch distribution captures the major SSE characteristics revealed by GPS inversions. Earthquake cycle simulation for the Manila subduction zone demonstrates that first-order fault geometry heterogeneity, *i.e.*, transition from the steeper south segment to the flatter north segment due to the subducting Scarborough seamount chain, controls earthquake rupture behavior. Fault shear stress evolution (presented by S-ratio) and coseismic rupture propagation speed are both clearly correlated with the along-strike profile of the geometry parameter. Modeled interseismic coupling state also is spatially consistent with the thrust fault seismicity distribution along the Manila Trench. Our modeling results suggest that megathrust fault geometry plays a key role in seismic and aseismic slip processes and needs to be incorporated in the mechanism studies of subduction zone deformation.

Rupture Segmentation and Variable Coupling along the Sunda Megathrust: The Case from Geodesy for an Ocean-Bottom Seismometer Array Offshore Sumatra

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Recent studies using geodesy and paleogeodesy suggest that offshore observations along the Sumatra subduction zone, including OBS, would help to answer important questions regarding megathrust behavior. These observations could help us to better understand persistent barriers to rupture and why we see partial rupture of fully locked and loaded patches. They would also allow us to better search for slow-slip events (SSEs), and to assess the behavior of the updip sections of the megathrust.

The Sunda megathrust has a history of generating great earthquakes that are segmented by persistent barriers. The barriers are located at structural features of the downgoing slab, are estimated to have strong spatial variations in coupling, and themselves generate moderate earthquakes. Between the larger barriers, some segments have a history of throughgoing rupture in similar seismic events. Others, such as the Mentawai segment, sometimes rupture in great earthquakes but sometimes rupture in a piecemeal fashion. Coupling patterns along the megathrust are spatially and temporally variable. We have not identified any SSEs in a decade of GPS data, but corals recorded a 15-year SSE. The Aceh and Mentawai backthrusts are potential sources of hazard, but little is known about their structure or behavior. The interseismic nature of the shallow megathrust is poorly understood, but the shallow fault close to the deformation front has shown itself capable of generating rare "tsunami earthquakes."

A valuable component of the SZO towards understanding these observations could be to deploy an OBS network, in conjunction with marine geophysics surveys and seafloor geodesy. For example, better information on slab geometry may help to explain partial ruptures of fully locked patches of the fault, microseismicity data may help to better outline the persistent barriers, and identification of areas of tremor and repeating earthquakes would guide our search for SSEs and to identify creeping region

The Alaska-Aleutian Megathrust Fault System: Upper Plate Response to Plate Boundary Conditions

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The 1964 Great Alaska M_w 9.2 earthquake resulted from rupture of three asperities and included splay fault surface ruptures that produced local tsunamis. Here, we integrate bathymetric, seismic, gravity and magnetic data to show how rupture patterns from the earthquake compare with Holocene and older faults, forearc structures, and subducted Pacific plate features along the Alaska-Aleutian megathrust. The northeastern Prince William Sound asperity resulted in the largest horizontal surface displacements (20m) and coseismic uplift (10m) related to reactivation of a series of faults along the Patton Bay and Middleton Island megathrust splay fault systems. Not all active faults ruptured in 1964, but all faults splay from a relatively horizontal megathrust where rheological changes in the accretionary prism produce duplexing, underplating and rapid exhumation. The central, Kenai, asperity shows a complex pattern of sea floor ruptures, is bound by a subducted fracture zone, and shows a steeper megathrust dip. Here, sea floor scarps and related faults along the continental shelf obliquely cut the Eocene and younger Stevenson forearc basin where the northward migrating Portlock anticline is spatially coincident with a subducted fracture zone. The southwestern Kodiak Island asperity was activated in 1964 as tsunami modeling indicates rupture of two megathrust splay faults. The Kodiak shelf faults show multiple Holocene ruptures that extend across the southwestern limits of 1964 slip patch, suggesting a complex relationship of rupture to the Kodiak asperity. Paleoseismic and geophysical data provide growing evidence that (1) asperities along the Alaska-Aleutian megathrust activate tsunamigenic splay faults on the continental shelf, (2) splay faults can cross existing forearc structures, and (3) asperities can trigger or be triggered by adjacent segment ruptures.

Plate Boundary Transitions in SZO—Learning from Processes at the Mendocino Triple Junction

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The Mendocino Triple Junction (MTJ) region straddles the transition between two of the most important segments of the North American plate boundary, separating Cascadia subduction from the translational tectonics of the San Andreas plate boundary. The region is seismically active, undergoes rapid and spatially varying deformation, and involves many key plate boundary elements. Although the MTJ itself is not a primary focus of SZO, its location and function at the transition from one of the key subduction zone study areas to an associated major plate boundary structure provides insights into fundamental processes as a subduction zone undergoes a transition. Its location linking two of the major targets of both the PBO and USArray components means that a wealth of relevant new data have been acquired under EarthScope. All these data bear directly on the processes at work as the North American lithosphere undergoes a transition from being the long-lived upper plate of a megathrust system to a participant in the formation of a new lithosphere-cutting transform plate boundary. How that transition occurs has implications for both the behavior of the southern third of the Cascadia system and the development of the San Andreas plate boundary fault system. A recent EarthScope synthesis workshop was held to explore the potential to develop the MTJ region into a focus site for improved understanding of key subduction related processes. Additionally the on-land access to the actively deforming accretionary wedge of the southern Cascadia subduction system makes the MTJ location an ideal laboratory for SZO related educational activities.

Defining the Temporal Relationship between Afterslip and Aftershocks Using Dense Seismic and Geodetic Networks in Nicoya, Costa Rica

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The Nicoya Peninsula in Costa Rica, extending within 60km of the trench, presents a rare opportunity to study a megathrust seismogenic zone using land-based techniques. Postseismic processes from the 2012 M_w 7.6 Nicoya earthquake are ongoing, and have been captured with seismic and geodetic techniques. Sparse campaign GPS observations, however, result in low model resolution throughout much of the time period considered.

In this study we fit continuous GPS recordings with functions to examine relaxation times over 4 years of postseismic recordings. This includes at least 2 slow slip events and the largest aftershock (24 Oct 2012, M_w 6.5). Modeled offsets at progressively larger time windows are used as input to predict corresponding displacements at campaign GPS sites using GMT gpsgridder [Sandwell and Wessel, 2016, *GRL*]. By inverting for slip with consistent resolution using predicted deformation at all 40 GPS sites we create a temporally and spatially dense characterization of afterslip evolution.

A waveform matched filter technique has been employed to identify aftershocks until end 2012, with completeness down to M_c 1.3 [Yao *et al.*, 2017, *JGR*]. By extending this catalogue beyond the first 4 months we will create a multi-year aftershock catalogue. This can be compared with the detailed afterslip evolution to best characterize the relationship between contemporaneous post-seismic processes. Such work is particularly intriguing given the posited relationship between small repeating earthquakes and afterslip. Uchida and Matsuzawa [2013, *EPSL*] use magnitude-slip relations for repeating earthquakes to map afterslip following the 2011 M_w 9.0 Tohoku earthquake. In Nicoya, 2012 repeating earthquakes exhibit an anticorrelation to GPS-determined afterslip. Further study should be conducted to understand if or when it is appropriate to use repeating earthquakes as in-situ "strainmeters".

Three-Dimensional Velocity Models from the iMUSH Active-Source Seismic Experiment

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The iMUSH (imaging Magma Under St. Helens) project is a multidisciplinary study involving the collection and analysis of active- and passive-source seismic, magnetotelluric, and petrologic data near Mount St Helens. Using a subset of the active-source data set, our previous 2D velocity models indicated regions of magma migration and storage beneath Mount St. Helens (MSH) and nearby Indian Heaven Volcanic Field (IHVF). Building upon these results, we have produced 3D Vp and Vs models down to depths of 12 km using direct P and S waves from all of the active-source shots recorded at ~ 6000 seismograph locations. These models show shallow anomalies that correlate well with known geologic features, including the Spirit Lake and Spud Mountain plutons north of MSH. As indicated in the 2D analysis, high Vp/Vs regions are observed beneath MSH and IHVF, and a large north/south trending region of high Vp/Vs is seen west of the volcano that agrees well with the approximate eastern boundary of the accreted terrane Siletzia. In addition, low Vp anomalies are observed near the margins of a previously identified high conductivity subsurface feature that extends between Mount St. Helens, Mount Adams, and Mount Rainier. With the exception of MSH and IHVF, these low Vp features are not accompanied by anomalous Vp/Vs values. The integration of these velocity models with results from other components of the iMUSH project will provide a comprehensive view of the magmatic system. Applying similar approaches to volcanic regions and active fault systems associated with the SZO would provide high-resolution, time-dependent subsurface information that would be valuable for assessing regional hazards.

Strategies for Developing Capacity Building, Education, and Outreach in Conjunction with a Subduction Zone Observatory

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The initial planning stages of a Subduction Zone Observatory (SZO) (however it is defined geographically and from a scientific research perspective) must include the integration of capacity building (CB) and education and outreach (E&O) to ensure the broadest impact possible of the scientific discoveries. The workshop report of the SZO Workshop held September 2016 asserts that the goal of E&O will be "to communicate current scientific understanding of subduction zones and the associated hazards to the general public and policy makers, and to train the next generation of scientists…" An SZO provides a natural laboratory for education of a wide audience. An SZO also offers unique opportunities for "science diplomacy," in which the observatory is leveraged to develop local and regional capacity to deal with hazards associated with subduction, including earthquakes, tsunamis, and volcanoes.

As science goals of the SZO are articulated, their societal implications will also emerge and the CB and E&O goals will become more apparent. Local outreach in the vicinity of an SZO is important to connect local communities with emerging science. Capacity building is critical to ensure strong connections to the local community and to facilitate the transfer of knowledge, skills, data and technology. To be successful, CB/E&O efforts must be sustained over decades, so sound planning, integration with subduction zone science, and consistent funding are critical.

This presentation will describe the process of developing a focused plan for CB and E&O in concert with the formalization of an SZO. We will outline the process for developing a framework for CB and E&O that is flexible enough to evolve as the SZO evolves (science plan, geographic region(s), etc.). Within the CB/E&O framework we will share strategies for identifying audiences, key resources, potential outputs and short- and long-term outcomes that will align with the overall SZO mission.

Theoretical and Practical Advances in Ambient Noise and Coda Studies

Oral Session · Tuesday 18 April · 4:30 PM · Governor's Square 12

Session Chairs: Julien Chaput and Hsin-Hua Huang.

Estimating the Effect of Non-Diffuse Noise on Ambient Seismic Noise Cross-Correlations in Southern California

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We study both random errors and the effect of non-diffuse noise components for stacked ambient noise cross-correlations. For random errors, we estimate the frequency-dependent amplitude and phase uncertainties of ambient noise cross-correlations based on the method of Liu *et al.* (2016) for different normalizations. We compute the stacked cross-spectrum of noise recorded at station pairs in southern California by averaging the cross-spectrum of evenly spaced windows of the same length, but offset in time. Windows with signals (*e.g.* earthquakes) contaminating the ambient seismic noise are removed as statistical outliers. Standard errors of the real and imaginary parts of the stacked cross-spectrum are estimated by assuming each window is independent. For frequencies below 0.2 Hz, we find temporal correlation in the noise data, which can be accounted for using a block bootstrap resampling method. In addition, the temporally correlated signals are linked to the non-diffuse wave components found in Liu and Ben-Zion (2016). To study the possible bias from non-diffuse waves on stacked noise cross-correlation functions, we simulate ambient noise data by adding non-diffuse components to otherwise diffuse noise in southern California using the same correlated neighboring frequency noise statistics from real data and 1D velocity model. The non-diffuse noise sources are in the ocean and they are assumed to have temporal correlation. We cross-correlate the simulated noise data and estimate how much it deviates from the cross-correlation of fully diffuse noise when combined with the random error estimations.

We propose to use the characterizations of random fluctuation and non-diffuse noise in noise cross-correlation to constrain uncertainties in ground motion predictions and surface wave tomography based on ambient-field observations.

Seismic Interferometry at a Large, Dense Array: Imaging the Source Physics Experiment

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We use several methods of seismic interferometry to obtain highly detailed images at the site of the Source Physics Experiment (SPE). The objective of SPE is to obtain a physics-based understanding of how seismic waves are created at and scattered near the source. In 2015, a temporary deployment of 1,000 closely spaced geophones was added to the main network of instruments at the site. We focus on three interferometric techniques: Shot interferometry (SI) uses the SPE chemical explosions as rich sources of high frequency, high signal energy. Coda interferometry (CI) isolates the energy from the scattered wavefield of distant earthquakes. 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 between the two. The power of these inter-station techniques increases rapidly as the number of seismometers in a network increases. For large networks the number of correlations computed can run into the millions and this becomes a "big-data" problem where data-management dominates the efficiency of the computations. The large network of mixed geophone and broadband instruments at the SPE allows us to calculate over 500,000 GFs, which we use to characterize the site and measure the localized wavefield. Within the geophone network we obtain high quality signals between 2-40 Hz.

The Large-N array at SPE reveals a complex structure in the alluvium south of the shot point. We measure large variations in seismic velocities and amplitudes in the top 100 meters. The structure gets much smoother at depth. This heterogeneous shallow layer scatters seismic energy as it moves across the array, resulting in the complex waveforms seen in records of the SPE shots.

On the Application of Super-Resolution Array Processing Methods for Characterizing Earth's Short-Period Seismic Noise Field

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We report on the application of the Multiple Signal Classification (MUSIC) algorithm to seismic array data of the International Monitoring System (IMS) to map the short-period ambient noise field and its evolution. The MUSIC algorithm is based on the eigen-decomposition of the spectral covariance matrix, and can provide estimates of the number and characteristics of multiple, simultaneously arriving wavefronts at a sensor array. The ability of MUSIC to retrieve waveform parameters of co-existing wavefronts is exploited to map the short-period seismic noise field, which is composed of multiple coexisting wave types—teleseismic P waves, regional distance P waves, and regional surface waves (Rg and Lg). We show preliminary results for year-round noise field mapping for seismic arrays PS49 (Alaska, US) and PS09 (Yellowknife, Canada). Initial results at PS49, also known as ILAR, show that the phase velocity of persistent Rg and Lg noise sources varies as a function of season. This may be caused by natural variation of the noise sources, which are related to ocean waves, or by a subtle seasonal dependence to the intra-array velocity structure. If the latter case is true, it might be possible to improve the location capabilities of PS49 by deriving season-specific slowness azimuth station corrections (SASCs). We also present a framework to complement previous efforts to map the seismic noise based only on the most energetic/coherent components, and to extend this study to 27 seismic arrays of the IMS.

Short Period Surface-Wave Tomography in Central and Eastern US

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As a crucial step in defining crustal models for regional moment tensor inversion, we focus on fundamental-mode surface-wave dispersion at periods greater than 2 seconds for the US east of 110W. The measured dispersion consists of over 3 million Rayleigh- and Love-wave group velocities measured from earthquake recordings and group and phase velocities obtained from ambient noise cross-correlations. To be able to obtain the dispersion at short periods, the 40 Hz BH channel data from the TA deployment were used. The derived ambient-noise empirical Green's functions were analyzed interactively and tomographic maps were developed using a code that inverted a complete data set at all periods to provide smooth dispersion curves as a function of period and location. While the tomographic images at short periods clearly define shallow and upper crustal features, *e.g.*, basins and the mid-continent Rift, short period dispersion from ambient noise could not be obtained uniformly at all locations east of 110W, even when short period noise sources were nearby, such as the Gulf Coast. To understand the limitations of ambient noise techniques, year-long data sets of synthetic noise were simulated to understand the effects of surface structure on the empirical Green's functions. To summarize, earthquake data are good but may not excite short periods because of source depth, explosions that excite short periods are rare, and ambient noise techniques are very useful if a good empirical Green's function can be obtained which is often not the result of the lengthy processing.

Using Discrete Wavelet Transforms to Discriminate Between Noise and Phases in Seismic Waveforms

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Polarization metrics such as the horizontal-to-vertical ratio are currently used to discriminate between noise and event phases in three-component seismic waveform data collected at regional (and larger) distances. Accurately establishing the identity and arrival of these waves in adverse signal-to-noise environments is helpful in detecting and locating the seismic events. In this work, we explore the use of multiresolution decompositions to discriminate between noise and various event phases. A segment of the waveform lying inside a time-window that spans the coda of an arrival is subjected to a discrete wavelet decomposition; the cumulative distribution functions (CDF) of the wavelet coefficients at the various wavelet levels constitute the predictors/factors for the classification task. We develop summaries of the wavelet coefficients' distributions *e.g.*, wavelet power metrics, to reduce the dimensionality of the predictor-space while preserving their predictive skill. Statistical tests and clustering analysis are used to establish that CDFs at intermediate and fine levels have substantial discriminating power, whereas the coarser scales are of little use. We design and test a classifier to segregate noise/P/S phases using data from stations in Argentina (Coronel Fontana, CFAA) and Iceland (Stora Kjalalda, STKA). All waveforms, including those generated by events at teleseismic distances are included in the study.

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To Tweet or Not To Tweet: Effective Use of Social Media for Citizen Science and Science Communication

Oral Session · Tuesday 18 April · 4:30 PM · Plaza F
Session Chairs: Susan Hough, Julian Lozos, Christine Goulet, Paul Earle

Social Media in the Wake of a Quake: A Science Journalist's Perspective

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In the immediate aftermath of a devastating earthquake, accurate information is vital for journalists covering the situation. Social-media tools such as Twitter can provide valuable input to news stories in near-real-time. Using my 20-plus years as an earth science reporter, I will describe how such tools can strengthen journalistic coverage of earthquakes and other natural disasters. Twitter can provide rapid-response input from top scientific experts and observers on the scene, while Facebook sometimes proves the fastest and most reliable method for obtaining official information from government and other organizations. That being said, I will also explore how to avoid falling into the trap of false information in the midst of a fast-moving news situation.

USGS Social Media Strategy

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The USGS was an early adopter of social media beginning in 2007. Since those early days, we have grown to around 150 profiles across almost a dozen different services based upon a strong, but simple, social media strategy. By focusing our efforts around that strategy and encouraging the public to engage with our science through services such as Twitter, Facebook, and Instagram, we have been looked upon as a leader in Federal Government social media outreach. In our presentation, we'll review the focus of our social media strategy, how we encourage our employees to be a part of our social media management efforts, and how we've set the tone for employees to interact with the public about the science they perform. In addition, we'll discuss the methods and various ways by which we interact with our social media managers to support our efforts and continue growing our social media presence.

Social Media for Scientists: Why, Where and How

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Social media (SM) has emerged as a cost effective, high impact tool for science communication and is already widely used by the media, educators, scientific organizations and individual scientists. However, to fully capitalize on the educational potential and communication capabilities of social media, science organizations and individual scientists must formulate and apply a SM strategy. An effective strategy must define goals, determine an audience, create and share appropriate content, perform routine engagement and periodically complete quantitative and qualitative evaluations of metrics. This talk will outline a theoretical framework for effective online communication and then present practical guidelines for building or improving social media presence. As proof of concept, we will examine the IRIS EPO Facebook and Twitter platforms before and after the adoption of a SM strategy and show how metrics can be used to improve SM statistics and performance. In the first year after the implementation of the SM strategy, followers of the IRIS EPO Facebook page increased by 153% and the weekly reach increased by 500%. The IRIS EPO Twitter page following increased by 196% and experienced an 800% increase in monthly impressions. These are significant increases in growth as compared to the preceding 5 years. The implementation of a defined strategy with clear goals, content creation and posting, and metrics evaluation allows scientific organizations and individual scientists to fully harness the communication and educational potential offered by social media networks.

To Tweet or Not To Tweet: Is it Even a Question?

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Social media has revolutionized information provisioning to citizens. Today, there are many countries where social media, notably Facebook or Twitter, is the main communication tool for rapid public earthquake information. This choice is often driven by the very pragmatic consideration that it is much simpler to publish information on social media than to develop and operate a website able to cope with massive traffic surges that is compatible with desktops, tablets and smartphones!

Today the question is not whether seismologists should use social media but which social media should be used for a given objective in a multicomponent (websites, social media, apps) earthquake information system. The answer depends on many parameters such as the information to be disseminated (earthquake prevention messages, rapid earthquake information, guidance after violent shaking…), the size and expertise of the team or the capacity and willingness to interact directly with the public.

The information system developed by the EMSC (Euro-Mediterranean Seismological Centre) is centered on a Twitter bot called LastQuake and an eponymous smartphone app. This system also allows the rapid collection of felt reports at a global scale. It has proven very efficient, for example, on Dec. 27th 2016, 1 000 felt reports were collected within 10 minutes of the M5.6 Romania earthquake, more than 90% of them being collected through the app. The key to such performance is to provide very rapid (typically within less than 90s) confirmation to eyewitnesses of the existence of the earthquake using automated systems.

We will show that despite its role in collecting felt reports, the app alone is not sufficient and that the other components of the information systems are essential. We will assert the importance of visual communication for a global service and introduce our app's post-earthquake visual guidance aimed at reducing inappropriate behavior after violent shaking.

Shaping the Earth, One Tweet at a Time

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Geodesy, an unfamiliar term for many, can be difficult to explain in a tweet or other social media tool. Yet geodesy, the study of Earth's shape, gravity, and rotation and their changes over time, and geodetic tools, such as GPS, have societal impacts that are important to communicate. UNAVCO uses multiple social media channels to convey our community's science as well as the services we provide, and their societal implications. The multiple channels reach different audiences, with different strengths for each one. Twitter serves the community best for announcements, especially regarding hazards and where to find more information. Facebook is effective for telling formal and informal science stories, either about research results or about the technology behind them. YouTube provides a very cost effective channel for showing videos about science for research and education. Instagram shares field efforts, with the opportunity for more staff participation. Pinterest is an ideal venue for reaching educators. Despite the challenges of communicating technical materials in limited space, social media offers the opportunity to reach a broad audience, convey news in a timely manner, correct misinformation, enhance open access to data, share research, and provide more information about scientific applications of familiar tools like GPS to the public.

Varied Modes of Fault Slip and their Interactions—Slow Earthquakes, Creep to Mega Quakes

Oral Session · Tuesday 18 April · 8:30 AM · Governor's Square 15
Session Chair: Abhijit Ghosh

Interaction between Slow and Fast Slips in the Japan Trench: Prospect from near Field Ocean Bottom Seismic and Geodetic Observations

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Slow earthquakes as a transient acceleration of plate motion are now being identified as ubiquitous phenomena in subduction zones. They are distributed around the strong interplate coupling area or near the asperity of megathrust earthquakes in several subduction margins; consequently, they have triggered megathrust earthquakes. Recent seismic and geodetic facilities have successfully captured some slow-earthquake activity leading up to large earthquakes and triggering the megathrust events, especially in subduction zones. Specifically, in the Japan Trench, slow earthquakes, such as tremors and slow slip events, have been identified by near-field seismic and geodetic observations before the occurrence of the 2011 Tohoku-Oki earthquake. Both seismic and geodetic observations suggest that the low-frequency tectonic tremor and slow slip event prior to the occurrence of the mainshock were located near the trench, where huge coseismic-slip exceeding 30 m was observed. A recent laboratory rock experiment on the frictional properties of slow earthquakes by using gouge samples from the plate boundary in the Japan Trench subduction zone shows that an increase in sliding velocity on the slow-earthquake's fault could induce frictional weakening behavior, and in particular, slip-weakening. These suggest that the slow earthquake may have facilitated the large coseismic slip of the mainshock on the plate boundary fault, as well as having triggered the initiation of the mainshock rupture.

Aleutian Array of Arrays (A-Cubed): Simultaneous Imaging of Continuous Activity of Slow Earthquakes and Volcanic System in the Aleutian Islands

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Alaska-Aleutian subduction zone is one of the most seismically and volcanically active plate boundaries in the world. The subduction fault shows a wide variety of frictional behavior along its strike and dip from fast megathrust earthquakes to creeping and slowly slipping sections. How they interplay, if at all, remains enigmatic. Rupture areas of large damaging earthquakes in recent past are reasonably constrained. Characteristics of slow earthquakes including their spatiotemporal distribution, however, are largely unknown. We deploy an array of arrays and capture seismic activities in high fidelity. It consists of three well-designed mini seismic arrays in Unalaska Island, west of mainland Alaska. The arrays are strategically placed to simultaneously image subduction fault and plumbing system of nearby Makushin volcano. We apply a beam backprojection technique to detect and locate tremor. It detects near-continuous and prolific tremor activity under Unalaska and Akutan Islands. We are able to delineate the patches that generates majority of the tremor and identify tremor migration patterns with a wide range of propagation velocities. In addition, we identify many families of low frequency earthquakes. Characterization of these slow earthquakes using array techniques and their spatiotemporal distribution is providing first detail picture of the slow earthquake activity under the Aleutian Islands.

Seismic Coupling of Fast and Slow Ruptures on a 760 mm Laboratory Fault

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Much of the fault that slipped coseismically in the 2011 Tohoku earthquake slipped stably both before and after the **M** 9 earthquake, as inferred from both repeating earthquake sequences and geodetic data. This indicates that a single fault may slip either slowly and silently or fast and seismically in different circumstances. We report laboratory experiments on a 760 mm-long granite sample that may shed light on this type of behavior. We generated sequences of laboratory slip events that switch back and forth between fast stick-slip events (~100 mm/s peak slip rates) and slow slip events (20 microns/sec–10 mm/s). Dilatant hardening or another type of strongly velocity dependent friction property is not required to explain the slow events. Instead, the mechanical interaction between a steady-state-velocity weakening rock/rock fault and a -velocity strengthening Teflon bearing causes slow slip events to remain slow rather than accelerate to fully seismic slip rates. The mode of faulting (fast or slow) can be dictated solely by changes in loading conditions, either through the rate of applied load or by allowing the fault to heal in stationary contact. The spectrum of slip rates under otherwise identical conditions allows us to measure its effect on seismic coupling coefficient. We find that stick-slip events exhibit constant seismic coupling, but when slip rates fall below about 70 mm/s seismic coupling decreases with decreasing slip rate. The slow slip events we observe are primarily aseismic but produce swarms of very small **M** -6 to **M** -8 events. These mechanical and seismic interactions shed light on the mechanics of seismic asperities, repeating earthquakes, and tremor.

Very Low Frequency Earthquakes (VLFEs) in Cascadia during Episodic Tremor and Slip (ETS) Events and Inter-ETS Period

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VLFEs are a long duration type of slow earthquake with a typical moment release of M_w 3.0-4.0. VLFEs are thought to be caused by the shearing of rate weakening patches in a rate strengthening background from the passage of slow slip in the transition zone. The overwhelming majority of previous VLFE studies show a clear spatiotemporal correlation between tremor and VLFEs [Ghosh *et al.*, 2015]. However, Hutchison and Ghosh [2016] found VLFE activity that was spatiotemporally asynchronous with tremor during the 2014 ETS event. To better understand the relationship of VLFEs to tremor and ETS events and create a more robust VLFE catalog, we apply a match filter algorithm using the VLFEs from the 2011 ETS event detected using centroid moment tensor inversion as template events [Ghosh *et al.*, 2011]. We analyze nearly two years of seismic data, which includes both the 2011 and 2012 ETS events and an inter-ETS time period of approximately one year. Using the match filter method we are able to detect hundreds of additional events during the ETS events and inter-ETS period. The resulting catalog suggests increased VLFE activity during ETS events and diminished activity during the inter-ETS period, broadly similar to tremor activity. Interestingly, VLFE activity persists throughout the inter-ETS time period even when tremor is not detected in the vicinity. This study reflects the effectiveness of match filtering for the detection of VLFEs in Cascadia, while also revealing the ongoing nature of VLFEs during the inter-ETS period and reflecting increased activity coincident with ETS events.

Repeating and Triggered Slow Slip Events in the Near-Trench Region of the Nankai Trough Detected by Borehole Observatories

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Slow slip events (SSE), non-volcanic tremor, and very low-frequency earthquakes (VLFE) are well documented down-dip of the seismogenic zone of major faults, yet similar observations for the shallowest reaches of subduction megathrusts are rare. We document a family of repeating strain events in the Nankai subduction zone, updip of rupture zone of great (M8) earthquakes. We report on data from two borehole observatories which penetrate the hanging wall accretionary prism: IODP Site C0002, located 36 km landward of the trench; and Site C0010, located 25 km landward. We focus on a time window from Dec. 2010–Apr. 2016, for which we recovered records of formation pore pressure at both sites.

After filtering oceanographic noise using a local hydrostatic reference at each site, the pressure records reveal seven transient signals that are synchronous at the two holes. Of these, six arise spontaneously, and occur at ~1 yr intervals with durations of ~7-21 days. All are positive in sign at C0010, with consistent magnitudes of ~0.3-0.9 kPa; at Site C0002 three are negative in sign and two are positive, with magnitudes of ~0.3-0.7 kPa. The remaining two events are larger (1.7-2.7 kPa), exhibit a negative sign at both sites, and occur immediately following: (1) the Mar. 2011 M 9 Tohoku earthquake; and (2) the Apr. 16 M 7 Kumamoto earthquake. In most cases, the pressure transients are accompanied by swarms of VLFE on the shallow plate interface. We interpret the pressure signals to reflect volumetric strain in response to SSEs. The data are well fit by slip of ~1-2 cm on a patch at the plate interface that extends 20-40 km in the dip direction, and is centered beneath Site C0002 (spontaneous events) or slightly updip (triggered events). The repeating nature of the events, taken together with apparent triggering by regional earthquakes, indicates that the outermost reaches of the megathrust are highly sensitive to perturbation and are perched near a state of failure.

Large Earthquakes and Creeping Faults

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Most shallow continental crustal faults remain predominantly locked during the long periods of time between large earthquakes, however some slowly slip, or creep. The related microseismicity helps reveal faults that might not otherwise be observed, but there is also the question of whether or not the presence of fault creep prevents large earthquakes, or if they do occur, how these large earthquakes behave compared to similar-sized events on locked faults. I show that well-recorded creeping fault earthquakes of up to magnitude 6.6 that have occurred in shallow continental regions produce similar fault-surface rupture areas and similar peak ground shaking as their locked fault counterparts of the same earthquake magnitude. The behavior of much larger earthquakes on shallow creeping continental faults is less well known, because there is a dearth of comprehensive observations.

For more information, please also see the review article: Harris, R.A., Large earthquakes and creeping faults, Reviews of Geophysics, 2017.

Late-Interseismic State of the Alpine Fault and the Australia–Pacific Plate Boundary in the Central South Island, New Zealand— Constraints from Scientific Drilling, Low-Frequency Earthquakes, and Microseismicity

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The Alpine Fault is inferred on paleoseismic grounds to produce large (M_w~8) earthquakes approximately every 300 years and to have last ruptured in 1717 AD. The fault is thus late in its average interseismic cycle, providing a rare opportunity to study conditions in the seismogenic crust ahead of an anticipated large earthquake. In the last decade, the seismogenic characteristics of the Alpine Fault at different scales have been investigated using complementary scientific drilling, field, laboratory, and geophysical means. This presentation reviews results obtained during the Deep Fault Drilling Project (DFDP), focused on the structure and present-day state of the fault zone, and with regional seismic networks targeting low-frequency earthquakes (LFEs) and microseismicity in the wider plate boundary. DFDP drilling conducted in the Whataroa Valley in 2014 revealed a very high geotherm (>120°C/km), which arises from the advection of rock and groundwater, and moderate fluid overpressures (~9% above hydrostatic levels). Measurements made nearby in 2011 showed that the fault's principal slip zone is impermeable (~10^{-20} m^2) and associated with a 20–30 m-wide zone of phyllosilicate alteration across which permeability varies by approximately six orders of magnitude, within a higher-permeability damage zone. The implications of these observations for the fault's rheology at different stages of the earthquake cycle remain to be fully explored, but rheologically important changes such as the brittle–ductile and illite–smectite transitions may occur at depths of only a few kilometers. In contrast, the spatiotemporally complex responses to regional seismicity of microearthquake swarms and LFEs constrain the local proximity to failure and imply that triggering involves a combination of extrinsic (related to the dynamic stresses associated with seismic waves) and intrinsic factors (controlled by the ambient state of stress and hydrogeology).

Systematic Search for Repeating Earthquakes in New Zealand

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Repeating earthquakes are clusters of microseismic events occurring virtually at the same region with very high waveform similarities. Because they likely represent asperities surrounded and loaded by aseismic creep, they can be used as an in-situ creep meter to quantify fault creep at depth. Here we conduct a systematic search for repeating earthquakes in New Zealand, focusing on the transition zone from fully locked to creeping section of the Hikurangi subduction zone in the North Island, as well as the aftershock zone of the 2016 M7.8 Kaikoura earthquake. The analysis procedure generally follows our recent studies [*e.g.*, Yao *et al.*, 2017] and is briefly described here. We first request event-based waveforms from the GeoNet since 2010. Then we apply a 2-8 Hz band-pass filter to the vertical-component data, and compute waveform cross-correlations using a 16s time window starting 0.5 s before the analyst-picked P arrivals. Next, we select those stations with cross-correlation (CC) values larger than 0.5, and compute a mean value for all possible station pairs. Event pairs with mean CC values larger than 0.9 are considered as potential doublets, and further grouped into potential repeating clusters using an equivalency class (EC) algorithm. Our preliminary results have shown abundant repeating clusters in both regions, suggesting that they are likely driven by episodic slow-slip or ongoing afterslip of the Kaikoura mainshock. Our next step is to systematically relocate these potential repeating clusters to ensure that they occur in the same region, and compare their spatio-temporal behaviors with geodetically inverted slow-slip. Updated results will be presented at the meeting.

Enhanced Detection of Earthquake Swarms in Southern Mexico and Relationships to Slow Slip

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The degree to which the family of slow fault slip behaviors is related to more traditional earthquakes is an outstanding question, although theoretical predictions indicate slip in the transitional zone promotes failure in the seismogenic zone. The Oaxaca segment of the Middle American Subduction zone is a natural laboratory for studying the spectrum of fault slip due to the shallow subduction angle and short trench-to-coast distances that bring broad portions of the seismogenic and transitional zones of the plate interface inland. We deployed broadband seismometers in 2006 to improve the network coverage to ~70 km station spacing. While characterization of tectonic tremor was a focus of this deployment, the seismicity catalog generated by this network also revealed 24 earthquake swarms. We identify swarms by inspecting every burst of seismicity for 3 empirical traits of swarm sequences: no clear triggering mainshock, many events near the maximum size, and relatively constant seismicity rate throughout the sequence. A productive earthquake swarm in July 2006 occurred during a geodetically-detected slow slip episode (SSE). To better understand the temporal patterns of the swarms, we used multi-station waveform template matching to scan for similar events over a 6 year time frame. This revealed the family of similar events associated with the July 2006 swarm were active during other relatively shallow (~20-35 km) SSE. This pattern is similar to how families derived from the aftershocks of the 2012 M_w 7.4 Ometepec earthquake were active during the shallow SSE that occurred in the months leading up to the mainshock. In contrast, a SSE ~15 months prior occurred at ~25-40 km depth and was primarily associated with an increase in tectonic tremor. Observations in this region indicate that shallower SSEs promote elevated seismicity rates, and deeper SSEs promote tectonic tremor.

Shallow and Deep Creep Events Observed and Quantified Arrays of Creepmeters and Strainmeters

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The five-decade history of creep on surface faults undertaken with creepmeters with high resolution (10 µm) but limited range (≈1 cm), is steadily being supplemented by a new generation of extensometers and strainmeters that in addition to monitoring interseismic creep with 3 µm precision, can also measure surface rupture and immediate afterslip of up to several meters. Extensometer dynamic range has been extended by the adoption of 360° rotary Hall effect transducers as sensors. On the San Andreas fault and North Anatolian the new sensors compliment space based geodesy in that they record a rich time history of slow slip interrupted by creep events whose temporal evolution can be used to constrain fault zone rheology at near surface (<100m) and shallow depths (<3 km). An unexpected finding is that the depth of surface creep on the North Anatolian fault appears to have shallowed by 25% in the 70 years since the Bolu M_w=7.3 earthquake, and that parts of the southern San Andreas fault reversed in slip direction for four years following the El Major earthquake. PBO Borehole strainmeters, which now produce 100 Hz data near these creeping faults permit us to identify the location, direction and rate of propagation of subsurface creep events. Over 50 creep events have been detected on the creeping section of the San Andreas with depths at least as great as 4 km and have been correlated to nearby surface extensometers. Typically the amplitude of creep events recorded by surface extensometers is less than that inferred from strainmeter or InSar data due to near-fault deformation. Several indicators suggest that the deformation near the flanks of creeping faults may be partly non-recoverable plastic deformation.

Advances in Earthquake Early Warning

Poster Session · Tuesday 18 April ·

Earthquake Early Warning Feasibility Study for the New Madrid Seismic Zone

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Research in the last decade on Earthquake Early Warning Systems (EEWSs) has undergone rapid development (in terms of theoretical and methodological advances in real-time data analysis, and improved telemetry and computer technology) and is becoming a useful tool for practical real time seismic hazard mitigation. The New Madrid Seismic Zone (NMSZ) covers a wide area with several heavily populated cities, vital infrastructures, and facilities located within a radius of less than 70 km from the epicenters of the 1811-1812 earthquakes. One of the challenges associated with the NMSZ is that while low to moderate level of seismic activity is common, larger earthquakes are rare, *i.e.* there is no instrumental data for earthquakes with magnitudes between M5.5 and M7.0 in the NMSZ, hence, in order to analyze any event within this magnitude range synthetic seismograms are required. The main focus of this study is to undertake a feasibility study of an EEWS for the NMSZ. We examine the stations within the NMSZ in order to answer the question "What changes should be applied to the NMSZ network to make it suitable for earthquake early warning (EEW)". We explore the optimization of the NMSZ network in order to maximize warning times and identify target areas where it is beneficial to make modifications to the spatial distribution of stations to improve its adaptability for early warning purposes. The stations within the NMSZ do not globally meet the technical requirements proposed by Auclair *et al.*, (2015), *i.e.* there are no redundancies in data sensors and acquisition system, or power supply systems but some redundancy has been implemented in communication systems. The data processing system currently in place is robust but still requires a dedicated server for an EEW algorithm. In a performance analysis, the telemetry data latency average is 2.8 s in the NMSZ network of 31 high-gain, high-sample-rate weak and strong motion, vertical channels used in this study.

Earthquake Early Warning System for Schools in the Campania Region, Southern Italy

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We present a feasibility study about Earthquake Early Warning System (EEWS) aimed at providing alert in schools of the Campania Region in Southern Italy. Data provided by the Italian accelerometric network, are analyzed and processed by the software platform PRESToPlus, while seismogenic zones, specific for the studied area, are assumed as sources of earthquake threat. The study is performed analyzing the lead-time distribution associated with all possible seismic sources. This parameter corresponds to the time interval between the alert issuing and the arrival of the potential most damaging seismic waves to the target site, and represents a crucial parameter to be considered for the mitigation of people exposure to seismic risk.

Lead-times are evaluated at each municipality in the Campania Region and the lead-time values for the 5th, 10th, and 25th are then extracted from the obtained distributions. We present results for the 5th percentile which corresponds to the worst-case scenario, since, for any given site of interest, the lead-time is expected to be larger than this value in the 95% of the possible cases. Due to the peculiar characteristics of the Campania Region, we conclude that most of the schools might benefit from an efficient EEWS. In fact, the population in the Campania Region is mostly distributed along the coast, while the most threatening earthquakes generally occur along the Apennine chain, on average 50-80 km far from the coastline. Thus, most of the schools in the Campania Region could have enough time to undertake automatic mitigation actions. We present also an application of the EEWS procedures in the high school ITIS E. Majorana, located at Somma Vesuviana, about 80 km far from the seismogenic Irpinia area. The testing school was equipped with a small seismic accelerometric network, the PRESToPlus EEW software platform, and an actuator we named Sentinel. The whole system was tested by blind tests performed during the normal school activities.

Analysis of Ambient Pre-Seismic Noise for Short-Term Advance Warning of Large Earthquakes

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Ambient seismic noise with spectral peaks at about 0.07 Hz and 0.2 Hz, due to primary and secondary microseisms, respectively, is observed everywhere at stations on hard basement rock. We examined pre-earthquake ambient seismic noise from five large earthquakes recorded at 14 three-component stations. Spectral characteristics of seismic noise within the frequency range of 0.1 to 0.2 Hz, which included the secondary spectral peak frequency f_p were found to be significantly altered by pre-earthquake activity when monitored by stations near the earthquake epicenter. We analyzed the spectra of several segments of time and examined temporal variations within each segment by obtaining spectra of consecutive windows, each 256 sec long. We also computed standard deviation, a measure of complexity, by considering variation in spectral amplitudes within each 256 sec window. Our analysis of seismic noise within a few hours of the earthquake origin time provided the following indications of short-term precursory activity: (1) decrease of f_p with time, (2) increase of mean amplitude within 0.1–0.2 Hz with time, and (3) increase of complexity with time. A comparison of these temporal variations at stations at various epicentral distances showed larger amounts at smaller epicentral distances, confirming that these variations are due to a pre-earthquake source and not due to external factors such as seasonal variations in seismic noise. It seems therefore that pre-earthquake activity within or near the hypocentral region causes perturbation of the fairly stable ambient seismic noise by a progressively stronger and more complex component rich in low frequencies. Our analysis provides a relatively simple methodology for obtaining advance warning of a few hours or more before at least some impending large earthquakes.

Reducing Alert Times for ShakeAlert's ElarmS Earthquake Early Warning Algorithm

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ElarmS, the Earthquake Early Warning (EEW) algorithm developed by UC Berkeley Seismological Lab (BSL), has been in operation since 2007 and has been part of the US West Coast ShakeAlert production prototype system since it began operating in February 2016. Over the past year ShakeAlert has successfully detected hundreds of earthquakes of magnitude $M \geq 2$ along the west coast of the US and has delivered real-time notifications to beta users including: municipalities, emergency response groups, county officials, lifelines, schools, utilities and private industry. The method uses a network of seismic instruments to detect first motions at surface stations near the epicenter, determine source parameters, and then predict ground shaking at more distant locations. As instruments close to the epicenter quickly detect the seismic energy, station spacing will determine the system's ability to rapidly and accurately detect and predict strong shaking. We present an analysis of the "blind zone" for ElarmS in California, comparing the existing network and telemetry delays with the expected performance after network and telemetry improvements. Currently, the best performance (<5 s) is only reached at a very few locations in the San Francisco Bay and Los Angeles areas. EEW improvements are planned across the US West Coast, with funding from the USGS, the State of California, CGS, and agencies in Washington and Oregon. The goal is to have 10 km station spacing in population centers and regions with high earthquake hazard, to achieve rapid detection and reporting. In less populated and lower hazard areas, station spacing will be ~20 km. For Northern California, about 400 new and upgraded stations are targeted to be deployed over the next 3 years by USGS, CGS, UC Berkeley and other organizations. When those deployments are complete, alert times will be drastically reduced in all areas of the state. The initial station installation effort at the BSL is currently underway.

Evaluating the Geodetic Alarm System (G-larmS) Performance Using Synthetic Earthquakes

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The Geodetic Alarm System (G-larmS) is a collaboration between the Berkeley Seismological Laboratory and New Mexico Tech to integrate real-time GNSS into Earthquake Early Warning (EEW). G-larmS has been in continuous operation since 2014 using event triggers from the ShakeAlert EEW system and real-time position time series from a triangulated network of GPS stations along the west coast. G-larmS has been extended to include southern California and Cascadia, providing continuous west-coast wide coverage since 2016. G-larmS currently uses high rate (1 Hz), low latency (<~5 s), accurate positioning (cm level) time series data from a regional GPS network and P-wave event triggers from the ShakeAlert EEW system. It extracts static offsets from real-time GPS time series upon S-wave arrival and performs a least squares inversion on these offsets to determine slip on a finite fault. A key issue with geodetic EEW approaches is that unlike seismology-based algorithms that are routinely tested using frequent small-magnitude events, geodetic systems are not regularly exercised. Scenario ruptures are therefore important for testing the performance of G-larmS. Synthetic long-period 1Hz displacement waveforms were obtained from a new stochastic kinematic slip distribution generation method (Fakequakes). Waveforms are validated by direct comparison to peak P-wave displacement scaling laws, peak ground displacement GMPEs obtained from high-rate GPS observations of large events worldwide, and NGA-West2 spectral acceleration GMPEs at 10s period. We develop a catalog of 1300 Cascadia megathrust scenarios as well as ~4000 individual ruptures on 25 large faults (capable of M>6.5) in California built from realistic 3D geometries. We use simulated real-time displacement streams to systematically test the recovery of slip, fault length, and magnitude by G-larmS. We characterize the overall performance of G-larmS and discuss recommendations and implementations for improving the algorithm.

Closing the Gap between Laboratory-based Damping Models and Observed Attenuation of Seismic Waves in the Field

Poster Session · Tuesday 18 April ·

Estimation of Site-Specific Kappa (κ_0)-Consistent Damping Values at Selected Stations from the KiK-net Database

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Selected stations from the KiK-net database have been used to compare field estimates of the attenuation of seismic waves near the surface, as obtained through measurements of site-specific κ (*i.e.*, κ_0), with laboratory-based values of minimum shear strain damping (ξ_{min}). Integrated models of κ_0 and ξ_{min} are proposed and found to provide an upper limit for low-strain damping profiles when compared to laboratory-based models used in geotechnical site response analysis. Typical damping models developed by testing small-scale soil samples in the laboratory can only characterize material damping. Other attenuation mechanisms, such as scattering of the wavefield, are impossible to capture by this type of dynamic laboratory testing. In addition, we evaluate the difference in damping at the surface and at borehole stations to determine the contribution of shallow layers to attenuation as captured by κ_0 values at the surface. Thus, values of κ_0 are computed at the surface and at the downhole instrument depth of each study site. The difference between both values, what we refer to as $\Delta\kappa$, is found to correlate well with the averaged shear wave velocity (V_s) over the top 30 m of the profile, V_{s30}, and also with the depth to bedrock. Estimates of κ_0 for hard rock and stiff sites in Japan are also examined and compared to other regional κ_0 values proposed for high V_{s30} materials in New Zealand, Greece, and Switzerland.

Utilizing California Vertical Array Data to Study Methods for Estimation of Small-Strain Damping in 1D Ground Response Analysis

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We utilize a database of surface and downhole recordings from 21 vertical array sites in California to study the bias and uncertainty in prediction of site effects by one-dimensional (1D) ground response analyses (GRA). We use three methodologies for estimation of small-strain damping: (1) Using empirical models by Darendeli (2001) and Menq (2003) which are based on laboratory testing of soil damping under small strains; (2) Using an empirical model by Campbell (2009) for estimating the quality factor (Q) based on shear-wave velocity (VS), and converting Q to small-strain damping; (3) Using the difference between spectral decay parameter (κ) computed from Fourier Amplitude Spectra for surface and downhole recordings, and adjusting the geotechnical model damping from (1) so as to produce the observed difference in κ.

Studying the misfits between the observed site response and GRA predictions enables us to evaluate the performance of each methodology for estimating damping. We quantify the misfits in terms of bias and dispersion of response spectral acceleration at various oscillator periods. We quantify dispersion by performing mixed-effects analysis, and decomposing prediction residuals into between- and within-site components. We take the between-site standard deviation as a quantification of epistemic uncertainty. Our primary results show laboratory-based damping produces less biased predictions for short spectral periods (shorter than ~0.5 sec) compared to VS-based damping which has less bias at longer periods (longer than ~0.5 sec). Results for approach (3) are under development as of this writing but should be ready at the time of the conference.

Investigating the Low-Strain Dynamic Properties of Late-Glacial Silts and Clays in the Lab and the Field

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Late-glacial marine silt and clay sediments found along the highly populated St Lawrence and Ottawa River valleys are known to amplify ground motions during weak shaking, but knowledge of the dynamic properties governing their behaviour at higher strain levels is limited. A joint study is investigating the frequency- and strain-dependence of material damping, shear wave velocity (Vs), and cyclic shear strength properties at a site near Ottawa, Ontario, Canada. Accordingly, one theme within this project is examining low strain comparisons between field and lab measurements of Vs and damping. A thin-walled Osterberg hydraulic piston sampler was used to collect 127mm-diameter samples at a test site adjacent to a 95m borehole cased for geophysical testing. A new technique for a modified Stokoe-type resonant column is used to measure the transfer function and dynamic properties of the samples as a function of frequency at constant strain levels. These lab tests will be compared to downhole measurements conducted using a mono-frequency approach to the spectral ratio technique. A vibratory source generating signals between 10 and 100Hz, and two identical downhole 3-component geophones were used for the field tests. Field results indicate a very low-loss material (damping<0.5%, strain<10^{-6}%) with negligible frequency dependence in massive muds, although layering can produce some scattering effects at higher frequencies.

The integrated field and lab results are indicating that a more complete understanding of site response is provided by surface and downhole geophysical investigations to image the "large scale" geological features at a site (*e.g.* seismically distinct deposits, bedrock topography) which provide a better context for the laboratory-analyzed samples.

The Contribution of Scattering to Near-Surface Attenuation

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The rapid decrease of the acceleration spectral amplitude at high frequencies has widely been modeled by the spectral decay factor kappa (κ). Usually, the path-corrected component of κ, often called κ0, is believed to be a local and frequency-independent site characteristic, in turn representing attenuation related to waves propagating vertically through the very shallow layers beneath the study site. Despite the known relevance of κ0 in a wide range of seismological applications, most methods for its calculation do not fully consider the influence of the scattering component. To account for the scattering component, we present a summary of statistical observations of the seismic wavefield at sites of the Swiss seismic networks. The intrinsic properties of the wavefield show a clear dependency on the local shallow subsoil conditions with differences in the structural heterogeneity of the shallow subsoil layers producing different scattering regimes. Such deviations from the ballistic behavior (*i.e.*, direct waves that sample only distinct directions) are indicative for local structural heterogeneities and the associated level of scatter. Albeit the attenuation term related to scattering depends nonlinearly on the instrinsic term, the results indicate that the commonly used explanation for the high-frequency decay spectrum might not be appropriate but involving the amount of scattering might allow better constrained estimates of κ0.

Exploration of Kappa Using 2D Numerical Simulation of Wave Propagation

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The high-frequency attenuation κ introduced by Anderson and Hough (1984) is related to the attenuation of the seismic wavefield emitted by the source and travelling to the recording site. 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.

Anderson and Hough (1984) decomposed κ in local (κ0) and regional attenuation (κR), respectively. Furthermore, Parolai and Bindi (2015) have studied the influence of intrinsic attenuation and scattering of waves on κ0 estimation though 1D numerical simulation of S wave propagation. In this study we propose to explore the dependency of κ (κ0 and κR) to intrinsic attenuation and scattering through 2D numerical simulation of wave propagation. To do so, we model a point source at depth and study the waves recorded at the free surface for different properties (homogeneous and random) of the propagation media. We follow the procedure depicted by Sato, Fehler and Maeda (2012) to generate random media in the heterogeneous Earth.

Physical Consistency of Seismic Q for near Surface

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Several measures of mechanical damping within Earth materials are used for the shallow subsurface: damping ratio (ξ) in geotechnical engineering, spectral decay parameter (κ) in site characterizations, and inverse quality factor 1/Q and t* in observational and laboratory seismology. Each of these parameters measure the rate of attenuation of oscillations in the form suitable for the respective applications. Parameter Q is also closely linked to the viscoelastic model, which allows making fundamental predictions, such as relations between bulk and shear attenuations, relations between attenuation of different wave types, and accumulation of attenuation over ray paths. However, it is important to see that all of these parameters are empirical and require justifications by physical principles. Parameter ξ appears to be the most robust, as it describes mechanical damping force or a resonator expressed by differential equations of mechanics. By contrast and despite what is often assumed, the seismic parameter Q is poorly justified physically and only based on a perceived analogy of a seismic wave with a resonator. Nevertheless, wave-propagating media are not analogous to resonators, and the internal friction acts in them differently. In consequence, seismic Q is an uncertain, apparent property sensitive to measurement procedures and wave types used.

To overcome this uncertainty of the seismic Q (and to a lesser degree, also of κ), one needs to directly use mechanical models of wave propagation. These models must also be sufficiently specific and detailed in order to include the effects of subsurface structure, scattering, and finite sizes of samples and boundary conditions used in the laboratory. Models based on hydro-mechanics of fluid-saturated soil and porous rock (Biot's, squirt, WIFF, solid and fluid viscosity, numerical simulations) suggest ways for bypassing the Q in engineering seismology and evaluation of ξ and κ directly.

High Frequency Attenuation of Regional Phases and Applications to Event Discrimination

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Seismic event amplitude measurement plays a critical role in underground explosion monitoring and the discrimination between earthquakes and explosions. In order to improve amplitude estimation at small event-to-station distances, an accurate 2D model of attenuation is important. As part of the Source Physics Experiment (SPE), we develop a detailed attenuation model for a portion of the western U.S. centered around southern Nevada. The SPE consists of a series of chemical explosions at the Nevada National Security Site (NNSS) designed to improve our understanding of explosion physics and enable better modeling of explosion sources. A high-resolution attenuation model will aid in the waveform modeling efforts of these experiments, and enable us to take a more detailed look at how a 2D model helps to improve local and regional P/S amplitude ratios typically used in event discrimination. We invert amplitudes from regional crustal phases in the frequency range 0.5-16.0 Hz, with an emphasis on improving the model at high frequencies. We consider observed amplitudes as the frequency-domain product of a source term, a site term, a geometrical spreading term, and an attenuation (Q) term (*e.g.* Walter and Taylor, 2001). Initially we take a staged approach to first determine the best 1D Q values; next we calculate source terms using the 1D model, and finally we solve for the best 2D Q parameters and site terms considering all frequencies simultaneously. Our resulting model correlates quite well with the regional geology and suggests that the empirically observed power law relating Q to frequency holds up in this region, at least to frequencies of 16 Hz.

A Comparison of Frequency-Dependent Attenuation in the Piedmont and Coastal Plain of the Southeastern US

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The M_w 4.1 Edgeville, South Carolina, earthquake of February 15, 2014 was well-recorded by the Earthscope transportable array (TA), present at the time in the southeastern United States. In addition, the earthquake was well-recorded by 84 Earthscope flexible array stations deployed primarily in Georgia by the Southeastern Suture of the Appalachian Margin Experiment (SESAME). The SESAME deployment consisted of stations sited on 3 profiles. The earthquake epicenter was located near the junction of a profile trending to the northwest across the northeastern Georgia Piedmont, and a south-trending profile extending from near the Fall Line of eastern Georgia into northern Florida. A third south-trending profile was located to the west in central Georgia, spanning the Piedmont and Coastal Plain. The goal of the SESAME experiment was to better understand the development of Pangea during continental collision and subsequent continental breakup leading to the development of the Atlantic passive margin. The local earthquake data from the TA and SESAME arrays are important for quantifying frequency-dependent attenuation between 1 and 25 Hz, and the profile geometry allows comparison of near-receiver attenuation in the hard-rock environment of the Piedmont with stronger attenuation due to the sediments of the Coastal Plain. Preliminary analysis has focused on high-frequency coda spectra at fixed lapse times along the Piedmont and Coastal Plain profiles. The slope of the log spectral ratio (Coastal Plain/Piedmont) versus frequency function from respective stations at a fixed coda lapse time provides an estimate of the difference in the near-receiver attenuation parameter kappa in the two geologic provinces. Preliminary estimates of the difference range from 20 to 70 msec, and appear to increase with the thickness of Coastal Plain sediments.

Computational Infrastructure and Data for Enhancing Earthquake Science

Poster Session · Tuesday 18 April

UCVM: From Supercomputers to Laptops, Querying and Visualizing 3D Seismic Velocity Models

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Three-dimensional (3D) seismic velocity models provide the underlying material properties and structural geometry needed to conduct earthquake ground motion simulations. The Southern California Earthquake Center (SCEC) has developed the Unified Community Velocity Model (UCVM) software package in order to facilitate access to these models. The UCVM software framework provides a suite of tools for querying and visualizing models, and for generating discretized versions of the models that can be readily used for simulations. We present a Python 3 version of UCVM that supports the southern California velocity models: CVM-S4, CVM-H 15.1.0, and CVM-S4.26. It also supports the latest model built for central California (CCA). The UCVM software framework makes it easy to extract material properties (seismic P and S velocities, and density) for specific data points by providing a common interface through which researchers can query seismic velocity models for a given location and depth. UCVM has a built-in digital elevation model to facilitate queries by depth or elevation. It includes visualization tools that can generate 2D cross-sections, horizontal slices, and basin depth maps; and we recently added the capability to generate Vs30 maps and 1D depth profiles as well. Since the platform is written in Python, users can import UCVM functions, modules, and classes for use in their own software. UCVM is currently being used to generate 3D regular grids and unstructured octree-based meshes for several SCEC wave propagation finite difference and finite element codes, including AWP-ODC and Hercules. UCVM is currently being used to generate large-scale data products for use in high frequency forward wave propagation simulations. The program is also used to provide the initial input used in the SCEC CyberShake platform.

Testing the Density of Seismic Networks with ShakeMap

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ShakeMap, developed by the U.S. Geological Survey, is an important tool used to assess the extent of ground motions after an earthquake, which can be used for loss estimation, public information, and emergency management efforts. Thus, the more accurately the ground shaking and damage can be captured by ShakeMap, the more effectively it can be used in these efforts. While the seismic station distribution in seismically active locations in the US provide a wealth of data that are used to generate ShakeMaps after an earthquake, instrumentation gaps are present. In order to generate ShakeMaps for regions under-represented by stations, Ground Motion Prediction Equations (GMPEs) are currently used to fill in the gaps. However, GMPEs introduce a great deal of uncertainty into the ShakeMap due to their smooth nature. Here, we use 'data' extracted from detailed dynamic rupture-based simulations of large earthquakes in selected areas (including southern California and the Salt Lake Valley) to test the ability of the current networks to reproduce detailed shaking patterns. Preliminary results show that ShakeMap reproduces the major features in the simulated ground motions for a M7.8 scenario on the southern San Andreas fault, including wave-guide effects near the Los Angeles basin using the current network of stations. This result is maintained even when up to 70% of randomly selected stations are disabled (simulating malfunction) in the LA basin. For the areas where the scenario ground motions are poorly resolved, we use ShakeMap to propose additional station locations. Furthermore, we explore the feasibility of increasing the resolution of ShakeMap for large events by replacing the empirical attenuation relation estimates with physics-based, 3D scenario-specific ground motion estimates to improve damage assessment and emergency response.

Web-Based Database of Active and Passive Surface Wave Investigation Results for Site Classification

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Demand on the development of database for investigation results is increasing as non-invasive site-investigation methods, active and passive surface wave methods, horizontal to vertical spectral ratio, and refraction, are getting popular for evaluating site response of earthquake ground motion. Seismic ground motion not only depends on 1D velocity structure but also on 2D and 3D structures so that spatial information of S-wave velocity must be considered in ground motion prediction. The database can support to construct the 2D and 3D underground S-wave velocity structures. Inversion of surface wave processing is essentially non-unique so that other information must be combined into the processing. The database of existed geophysical, geological and geotechnical investigation results can provide indispensable information to improve the accuracy and reliability of investigations. Most investigations, however, are carried out by individual organizations and the investigation results are rarely accumulated in the unified and organized database. To study and discuss appropriate database and digital standard format for the non-invasive site investigations, we developed a prototype of web-based database to accumulate observed data and processing results of active and passive surface wave investigations that we have performed at more than 400 sites in U.S. and Japan. The database was constructed on a web server using MySQL and PHP so that users can access to the database through the internet from anywhere with any device. All data is registered in the database with location and users can search geophysical data through Google Map. The database stores dispersion curves, horizontal to vertical spectral ratios and S-wave velocity profiles at each site that was saved in XML files as digital data so that users can review and reuse the data. The database also stores a published 3D deep basin and crustal structures and users can use them during surface wave data processing.

A Detailed Automatic Seismicity Catalog (1998-2015) for the San Jacinto Fault Zone Region

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Earthquake catalogs are foundational datasets for numerous studies on structures and dynamic processes. Retroactive processing of historic data archives is warranted by the development of new methods and the need for consistent objective analysis of heterogeneous data volumes. The San Jacinto Fault Zone (SJFZ) has been monitored by a combination of regional and local networks from 1998 through 2015. The coverage is provided primarily by the Anza and Southern California networks and augmented by several temporary dense arrays. The volume of data from the SJFZ renders manual processing prohibitively expensive. An automatic workflow yields a consistent and detailed catalog of hypocenter parameters, earthquake magnitudes, and P/S wave arrival observations. The main methods include: i) recently developed S-wave detection algorithm, ii) hypocenter parameter inversion considering a detailed 3D velocity model via differential evolution optimization, iii) double difference relocation, and iv) moment magnitude estimation via multi-taper spectral analysis. An increase in catalog completeness is achieved when compared with existing catalogs in the San Jacinto fault zone. This provides increased opportunities for analyses of structural and earthquake source properties, spatio-temporal seismicity patterns and additional topics. Detailed results of the catalog will be presented at the meeting.

Earthquake Interaction and Triggering: From Near Field to Far Field, From Natural to Induced

Poster Session · Tuesday 18 April ·

Enhanced Dynamic Triggering in Waste-Water Injection Sites near Woodward, Oklahoma

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Regions with high pore pressure can be more susceptible to dynamic triggering from transient stress by surface waves of distant earthquakes.The triggering stress threshold can help us understand the stress state of seismogenic faults.Recent dramatic seismicity increase in central US provides a rich database for assessing dynamic triggering phenomena.We begin our study by conducting a systematic β search in 1° by 1° bins for dynamic triggering for the continental US using ANSS catalog(Mc=3) from 49 global mainshocks(Ms>6.5, depth<100km, estimated dynamic stress>1kPa). Then we generate a stacked map with β≥2, which represents significant seismicity increase.As expected,the geothermal and volcanic fields in California show clear response to distant earthquakes.We note areas in Oklahoma with ongoing wastewater-injection induced seismicity also show enhanced triggering.

Next we focus on Oklahoma and use local Oklahoma Geological Survey catalog(Mc=2.8) to calculate beta map with finer grid size 0.1° by 0.1° for each mainshock.Ten mainshocks show repeated triggering(β ≥ 2.0) in an event cluster in Woodward,Oklahoma. Using the nearby station,we apply matched filter detection to continuous waveform 1day before and 1day after each mainshock to generate a more complete catalog.The detected catalog shows that 9 and 6 local events are triggered during surface waves from April 25 2015 M7.8 Nepal earthquake and the M7.3 aftershock, respectively. The 2 mainshocks also cause significant seismicity increase up to 12hours after the mainshock.From the spatial distribution of seismicity in the cluster, we characterize the seismogenic fault in this area as a vertical, strike-slip fault with a strike of 60°.The incident angle from Nepal earthquakes on the fault is 57° relative to the strike,which is close to the direction of peak triggering potential(61°) for Rayleigh wave.The triggering dynamic stresses are as low as 1kPa,which suggests the fault in this region is likely critically loaded.

Triggering Mechanisms in Large Iranian Earthquake Sequences from Calibrated Relocations

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We examine the patterns of the mainshock-aftershock activity across Iran to unravel the dominant type of earthquake triggering mechanism. We exploit the premise that for unilateral ruptures, dynamic stress changes should promote an increase in the seismicity rate in the direction of rupture propagation, whereas static stress changes should show no such directional bias. In this regard, Iran offers a rich potential to study the kinematics of rupture propagation and subsequent triggering with (1) region's intense seismicity (> 40,000 events from the ISC Bulletin since 1960), (2) more than thirty mapped surface ruptures associated with M 6-7.5 earthquakes, (3) nearly thirty events with fault dimensions mapped with InSAR and (4) rapidly-improving station coverage from the mid-1990s onwards. However, due to the unknown Earth structure and uneven station coverage, catalog earthquake locations are subject to up to ~50 km of location bias. To overcome this limitation, we developed a new two-tiered multiple-event relocation approach that exploits near-source arrival times or independent location constraints. The first step uses mloc—an implementation of the Hypocentroidal Decomposition relocation technique—to relocate small clusters at local spatial scales. In the second step, these absolute locations are used as prior constraints in BayesLoc—a Bayesian relocation technique that can handle much larger datasets—to yield region-wide calibrated hypocenters. Later, the seismicity rate change is quantified, and static stress changes are calculated for events where detailed slip distributions are known from InSAR. Our results from early instrumental and modern earthquake clusters—including Ahar, Rigan, Silakhour and Zirkuh—mostly show aftershock distributions concentrated in the rupture propagation direction, favoring a significant role for dynamic triggering. However, control by static stress changes cannot be ruled out due to the legacy of nearby historical events.

Long-Term Seismic Behavior around the Epicenter of the 2008 Mw7.9 Wenchuan Earthquake

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The 12 May 2008 M_w7.9 Wenchuan earthquake ruptured ~300 km unilaterally along the Longmenshan Fault Zone that straddles the eastern Tibetan Plateau and Sichuan Basin. Currently the triggering relationship between the Wenchuan mainshock and the impoundment of Zipingpu reservoir in September 2005 is still under debate. One way to evaluate whether the reservoir recharge/discharge is connected to the mainshock is to examine long-term seismic behavior and reservoir heights. Ruan *et al.* [2016] applied a waveform matching technique to obtain a more complete catalog from 01/01/2008 to 05/12/2008, and found no correlation between the seismicity rate and water level. Here we investigate a much longer duration seismic behavior before and after the mainshock, including the seismicity rate change from earthquake detection, seismic velocity change from possible repeating earthquakes and from ambient noise cross-correlation. We first conduct a systematic waveform detection of microseismicity using catalog events and available continuous data from Oct 2004 to Dec 2009 recorded by 7 short-period stations in the Zipingpu Reservoir Seismic Network (ZRSN). We further relocate all events to examine whether there is any spatio-temporal evolution of long-term seismicity and its relation to the water level change. We also identify repeating earthquakes with high waveform cross-correlations and use to monitor temporal variation of seismic velocity before, during and after the mainshock. We hope to better understand whether the impoundment and subsequent changes in water level of the Zipingpu reservoir affected the local stress state, which advanced the timing of the Wenchuan mainshock. Updated results will be presented at the meeting.

Possible Activation of Splay Faults During the 2006 Java Tsunami Earthquake

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The 2006 M_w 7.8 Java earthquake was a tsunami earthquake. The earthquake was deficient in high-frequency seismic radiation and 8 m tsunami run-ups in Java resulted in over 800 fatalities. The earthquake lasted ~180 s, extended ~200 km from west to east, and exhibited large variations in rupture speed along strike. High-frequency (0.3-1 Hz) global back-projection suggests a unilateral two-stage rupture. The first stage lasted ~65s with a rupture speed of ~1.2 km/s, which agrees well with finite-slip fault models. By contrast, the second stage ruptured from 65s to 140s with a rupture speed of ~2.5 km/s, approximately twice as fast as the first stage rupture. Intriguingly, high-frequency radiators during the second stage rupture spatially correlate with splay fault traces that have been imaged by active source seismic profiles and can be mapped along-strike using residual free-air gravity anomalies. Although back-projection does not have the depth resolution to discriminate between radiation from the subduction interface and radiation from splay faults in the overthrusting plate, the significant change in the rupture character observed near 65 s and the strong spatial correlation of the stage-two radiation with the splay fault traces suggests that the splay faults may have been activated during the megathrust earthquake generating the observed high-frequency radiation of the second stage. Similar reactivation of splay faults has been suggested in the Nankai Trough during the 1944 M_w 8.1 Tonankai earthquake (Moore *et al.*, 2007). For the Java earthquake, the possibly activated splay faults may have hosted near-instantaneously triggered early aftershocks that ruptured at a much higher speed during the coseismic rupture. The residual gravity anomalies reveal the splay faults extending well over 200 km along strike and slip along these faults could potentially have contributed to the devastating tsunami.

Induced Intraplate Earthquakes in Colorado from Extreme Seismic Waves from the End-Cretaceous Asteroid Impact

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The end-Cretaceous impact in the Yucatan/Caribbean region generated extreme seismic waves larger than those produced by ordinary earthquakes. Shaking with periods of tens of seconds with particle velocities of ca. 3 m/s continued for hundreds of seconds. One would expect that such extreme shaking induced earthquakes and that it caused ground damage. (1) With regard to induced earthquakes, we found two outcrops of syn-impact fault displacement near Trinidad, Colorado. The nearby ~1 km apart localities at Long's Canyon and Madrid Canyon roadcut may represent the effect of a single event. The normal displacement was ca. 1 m. The faults appear to have slipped just once, cutting strata below the impact horizon but not above it. The event was crudely magnitude 6. (2) The dynamic strains of ca. 10-3 were large enough for shallow sedimentary rock to fail nonlinearly, but too small to produce strain markers that survived subsequent sediment compaction. However, grain-scale cracks associated with nonlinear failure likely increased permeability. Sulfate-bearing water mixed with sulfate-free barium-bearing water at the swampy land surface. Heavy mineral separation to obtain chromite from the impact horizon, revealed numerous barite grains from this process. (3) We found ca. 30 cm long and ca. 1 cm wide vein entering the impact horizon from below. Local dewatering of the shallowest sediment likely occurred. The vein subsequently buckled from sediment compaction. In general with regard to induced seismicity, extreme shaking tends to induce earthquakes that relax ambient tectonic stress. Intraplate tectonic stresses and interplate earthquakes are ubiquitous, however; the ubiquitous plate boundary earthquakes do not produce sufficiently strong waves to trigger intraplate earthquakes thus relieving the intraplate tectonic stresses.

Numerical Investigation of Interactions between Dynamic Stress and Pore Fluids in Earthquake Triggering

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The phenomenon of triggered earthquakes resulting from seismic sources at distances where dynamic stress dominate has become well documented in recent years. Effects on pore fluids from distant sources have been similarly well documented, with tidal fluctuations well demonstrated in borehole fluid levels, and coseismic changes in fluid discharge rates having been noted since ancient times.

We review available analytical representations of dynamic stress imparted by both body and surface waves. We also review methods for representing stress induced permeability changes, drawing from examples published in both scientific and engineering literature. Applicability is evaluated considering the intended environment and assumed conditions of each formulation.

A practical test is provided by means of finite element analysis simulation of the coupled system. The synthetic example is drawn to represent conditions in the Central United States, and considers various faulting regimes, fault depth, and degrees of material and fluid property heterogeneity. Within our simulated zone of interest, we observe the result provided by the model that accounts for poroelastic properties in a dynamic fashion as compared to a baseline example with static properties, and an example that does not considering fluid at all. For all simulated cases, we apply Mohr-Coulomb failure criteria for hazard assessment.

Seismicity in the Mineral Mountains, Utah and the Possible Association with the Roosevelt Hot Springs Geothermal System

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Seismicity in and near the Mineral Mountains of south-central Utah is being investigated as part of the seismic characterization for the Utah Frontier Observatory for Research in Geothermal Energy (FORGE) site. Using a local scale seismic array, Zandt (1982) proposed that seismic activity in the region primarily occurs in swarms. Seismic swarms in this area may be associated with fluid migration within the Roosevelt Hot Springs geothermal system along local faults. In addition, seismicity in this area may be associated with thermal contraction of rocks at depth as a result of heat transfer for geothermal production. The 34-megawatt Blundell Geothermal Plant came online in 1984 and has been producing continually since that time. From 1981 to 2011, the University of Utah Seismograph Stations (UUSS) has detected and located 58 earthquakes (M 0.31 to 2.53) in this area. While there are a few small swarms of seismic events in this time period, not all seismicity occurs in swarms. Comparing the current catalog to the plant's production rates, there is also no clear correlation with geothermal production. This study's focus is on using the catalog events for this area as templates for a subspace detection analysis to reduce the magnitude of completeness. The dataset being analyzed is continuous data from January 2010 through December 2016 from four UUSS regional seismic stations. The newly detected events will be located and added to the current Mineral Mountains earthquake catalog. With the more comprehensive catalog, reinvestigation of swarm activity and geothermal production rates will be completed. This data and the continuous collection of data will provide the baseline for analyzing microseismic events related to the stimulation and heat flow testing at the FORGE site.

InSAR MSBAS Time-Series Analysis of Induced Seismicity in Colorado and Oklahoma

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Since 2009, the number of earthquakes in the central and eastern United States has dramatically increased from an average of 24 M ≥ 3 earthquakes a year (1973-2008) to an average of 193 M ≥ 3 earthquakes a year (2009-2014) (Ellsworth, 2013). Wastewater injection, the deep disposal of fluids, is considered to be the primary reason for this increase in seismicity rate (Weingarten *et al.*, 2015). We use Interferometric Synthetic Aperture Radar (InSAR) to study six potential regions with injection induced seismicity: Greely and Platteville in Colorado and Edmond, Cushing, Pawnee, and Jones in Oklahoma. Currently, Platteville is not seismically active; however, it serves as a baseline since its high-volume injection wells have the potential to induce future earthquakes.

InSAR data complements seismic data by providing insight into the surface deformation potentially correlated with earthquake activity. To study the ground deformation associated with the induced seismicity and injection well activity, we develop full-resolution interferograms using data from Radarsat-1/2, ERS-1/2, Envisat, ALOS, and Sentinel-1. We pair the SAR images using the small perpendicular baseline approach (Berardino *et al.*, 2002) to minimize spatial decorrelation. The paired SAR images are processed into interferograms using JPL ISCE software (Gurrola *et al.*, 2010). Using the MSBAS algorithm (Samsonov *et al.*, 2013, Samsonov and d'Oreye, 2012) and the JPL GIAnT software (Agram *et al.*, 2013), we construct a time-series of displacement integrating all interferograms for the region.

To correlate the relationship between surface deformation and wastewater injection, we compare the well locations, depths, and injection rates with the spatial and temporal signature of the surface deformation before and after induced earthquakes, filling in the spatiotemporal gap lacking from seismicity.

Temporal Changes in Seismicity and Seismic Velocities in Salton Sea Geothermal Field

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Stress perturbations from seismic waves hundreds to thousands of kilometers away are capable of triggering micro-earthquakes in volcanic and geothermal regions, resulting in surface deformation and temporal changes of sub-surface seismic velocities. Due to its close proximity to major active faults, including the Southern San Andreas Fault, Imperial Fault, Brawley Seismic Zone (BSZ) and San Jacinto Fault, the Salton Sea Geothermal Field (SSGF) is one of the most seismically active and geothermally productive fields in California. An improved understanding of temporal changes in seismicity and seismic velocities in SSGF not only provides important clues to the underlying physical processes that drive earthquake swarms here, but also improves earthquake hazard assessment in Southern California. Here we present a systematic investigation of triggered seismicity in SSGF from 2007 to 2014 utilizing the Calenergy Borehole Network (EN). We apply a GPU-based waveform matched-filter technique (WMFT) to obtain more complete catalogs and analyze the seismicity rate change in SSGF around regional and remote earthquakes with predicted dynamic stress above 5 KPa. We find triggered seismicity following several regional earthquakes, such as the 2009 M_w6.9 Baja California and 2010 M_w5.7 Ocotillo Earthquakes. We also utilize the ambient noise cross-correlation method to quantify the temporal velocity changes in SSGF. Our result shows clear velocity reduction following the 2010 M7.2 El-Mayor earthquake, and the co-seismic reductions are larger for ray paths outside the geothermal regions. Our next step is to relocate newly detected triggered events, and to conduct a detailed investigation on the spatial and depth extent of seismic velocity changes associated with the occurrence of the 2010 M7.2 mainshock and other regional earthquakes.

Earthquake Source Parameters: Theory, Observations and Interpretations

Poster Session · Tuesday 18 April

Estimating the Magnitude of Laboratory-Generated Seismic Events Using a Ball Drop Empirical Green's Function (EGF) Method

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We estimate the seismic moment of laboratory-generated seismic events using a ball drop empirical Green's function (EGF) method. This method does not require the modeling of wave propagation or sensor response. Rather, it uses a ball impact as a reference source or EGF. We follow the mathematical framework developed in McLaskey *et al.* (2015 Bull. Seis. Soc. Am. 105, 257-271), which links the seismic moment M_0 of seismic sources to the impulse of the ball impact since they both have a flat source spectra below some corner frequency f_0. Using this technique, we determined the seismic moment, corner frequency, and stress drop of three different types of seismic events generated from three different test conditions. The largest events (**M** -3) were generated from the dynamic shear rupture of a saw-cut simulated fault in a 3-meter-long slab of Barre gray granite loaded in a large-scale biaxial apparatus with 7 MPa (7 MN) of stress (force). **M** -6 events were generated from tensile fractures in a reinforced concrete beam under flexural testing (four-point bending). The smallest events recorded (**M** -7 to **M** -8) were generated during the closure of a 100 mm-long fracture in Barre gray granite block loaded in uniaxial compression at 5 MPa. These tiny events (acoustic emissions) likely resulted from brittle processes associated with the interacting surface topography of the naturally fractured rock surfaces. We also attempt to link the seismic parameters to physical models of tensile, shear, and implosive source processes.

Multichannel Deconvolution for Earthquake Apparent Source-Time Functions

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Previous studies of earthquake apparent source-time functions (ASTFs) have removed propagation effects through seismogram deconvolution with a smaller earthquake known as an empirical Green's function (EGF). We develop a multichannel deconvolution (MCD) algorithm for recovering ASTFs that does not require an EGF, but instead the availability of two or more earthquakes that share a common Green's function. Under this condition ASTFs satisfy $U_i * S_j - U_j * S_i = 0$, where U_i and S_i are the seismogram and ASTF for a given earthquake. This system can be augmented with a scaling equation and written as $\mathbf{Ax} = \mathbf{b}$, where matrix $\mathbf{A}$ comprises the seismograms in a block-Toeplitz structure and $\mathbf{x}$ contains the target ASTFs. We minimize an objective function for this linear system with a Newton-Projection algorithm that honors positivity, causality, and duration constraints. If the earthquakes have a suitable range in magnitude, EGF deconvolution may be used to estimate differences in duration of the events, and to obtain a starting model for the larger ASTF(s). We demonstrate the effectiveness of MCD using synthetic tests and apply it to five ~M5 earthquakes from the Kamaishi sequence, Japan, related to the 2011 Tohuku-Oki M9 event. We demonstrate that MCD is an effective way to recover earthquake ASTFs, and

that the details of rupture revealed by MCD ASTFs will be useful in furthering our understanding of the earthquake source.

Estimating Lg Wave Source Time Functions with Multiple Green's Function Events

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We have employed two algorithms to study the Source Time Function (STF) of the regional phase Lg in central Asia: Frequency Domain deconvolution and projected Landweber deconvolution (Vallee, 2004), which applies the causality and positivity constraints to the STF. These algorithms are implementations of the Empirical Green's Function (EGF) method (Hartzell, 1978). The EGF method uses waveforms from a pair of similar events that are well-separated in magnitude. When the STF of the smaller event is sufficiently brief, its waveform can be treated as the EGF of the larger event waveform, allowing for the retrieval of the finite STF of the larger event via deconvolution. After applying these algorithms to events in central Asia, we have found that the estimated durations of the STFs obtained using the individual algorithms are similar, indicating that the duration of the STF can be robustly estimated. Strictly speaking, these estimated STFs are relative to the STF of the small event, which has a finite duration itself. In order to retrieve the absolute STF, the relative STF should be corrected by a convolution with a pulse of finite duration representing the small event STF. In principal, the estimation of the larger event's STF is more reliable when more than one small EGF event is used. It is a challenge to find the appropriate durations of the small events' STFs. We have begun to develop a procedure to find these appropriate durations. This procedure assumes the durations of the small STFs are near the values predicted by the widely accepted source scaling relationship. It then conducts a grid-search for small STF durations by allowing them to depart from the predicted values. The optimal durations should yield estimates of the large STF, whose duration and stress parameters are independent of the small EGF used. We are applying this procedure to moderate earthquake sources in central Asia to estimate STFs. This procedure should yield more robust STF estimates.

Diverse Seismic Signals Associated with the Sinkhole at Napoleonville Salt Dome, Louisiana

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Moment tensor inversion of discrete seismic events prior to the appearance of a sinkhole at Napoleonville Salt Dome with Green's Functions computed using a 3D velocity model allows us to build a time history of centroid locations and source-types of these events. We interpret the sequence of events after a rigorous analysis of uncertainties associated with centroid locations and source-types on the basis of residuals between observed and synthetic low-frequency displacement waveforms. While the moment tensor solutions of most events are dominated by an isotropic volume-increase component, there is considerable variability in the time evolution and frequency content of these events. During the most vigorous phase of the sequence, the seismic events had a spectral peak at ~0.4 Hz and were occurring at a near-steady rate. The 0.4 Hz spectral peak is possibly associated with resonance of a crack filled with methane-charged water, consistent with the isotropic moments in the low frequency moment tensors and the large volume of natural gas released during the formation of the sinkhole. We also perform various synthetic tests to check the possibility of the 0.4 Hz resonances being generated by seismic waves trapped in shallow low velocity sediments. Few of the steady sequences of events culminated in longer duration and larger magnitude events occurring in quick succession. We also find episodes of long period ground uplift as inferred from pseudo-tilt signals recorded by the broadband sensors and high-frequency harmonic tremor, synchronous with many of these larger magnitude long duration events. The similarity between these seismic signals and seismic signals commonly recorded in volcanoes indicates common fluid-driven mechanisms. After the appearance of the sinkhole, we are unable to detect any similar events with the 0.4 Hz spectral peak. However, there are new shallow long duration events with volume-decrease mechanisms.

Towards Automated Estimates of Directivity and Related Source Properties of Small to Moderate Earthquakes with Second Seismic Moments

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We develop a method for automated estimation of directivity, rupture area, duration, and centroid velocity of earthquakes with second seismic moments. S phase picks are given by an automated picking algorithm with a 1D model and cataloged event locations. These are refined for deconvolution using a grid search within a short time window around the automated S picks. Source time functions of target events are derived using deconvolution with stacked Empirical Green's Function (EGFs) selected by spatial and magnitude criteria as well as performances in the deconvolution. Smoothing and non-negative constraints are imposed to stabilize the linear time domain deconvolution. The use of stacked EGFs helps to reduce non-generic source effects such as directivity in individual EGFs. The method is suitable for analysis of large seismic dataset and works for target events with magnitudes as small as 3.8. Applications to small to moderate earthquakes in southern California indicate that most have significant directivity. Updated results will be presented in the meeting.

Uncertainties in Spectral Models from Empirical Green's Function Analyses

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Removing wave propagation effects from seismic observations is necessary to examine the properties of the earthquake source. The empirical Green's function approach is a popular technique among seismologists for removing path effects. The essence of the approach is that the impulse response of the Earth, known as the Green's function, is similar for co-located large and small events, and therefore cancels when one takes the spectral ratio of the waveforms. Spectral ratios are then fit using parametric models of the earthquake source spectrum, such as the omega-square models of Aki (1967) and Brune (1970) to recover the individual models of the large and small earthquake source spectra. The parameters of these models are then used to infer the earthquakes' stress drops, and to some degree, radiated energy, conditional on various assumptions. While many studies acknowledge that there are large uncertainties in obtaining source parameters, there has yet to be a significant focus on quantifying them. This study focuses on quantification of uncertainties, which is critical understanding how meaningful and interpretable the obtained the source parameters are. Parameters in classic source models, such as high-frequency falloff rates, corner frequencies, sharpness, are strongly correlated. It is also shown that the properties of the lognormal distribution are not usually considered in the calculation of radiated energy, which biases published energy estimates. These uncertainties and biases are demonstrated using teleseismic data from global strike-slip earthquakes with moment magnitude greater than 7, including the recent Kumamoto and Kaikoura earthquakes.

An Alternate Noise Parameterization for Moment Tensor Estimation

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Recently Tape and Tape (2015) devised a uniform moment tensor parameterization. This provides the opportunity to systematically interrogate the model space and to further assess resolution and parameter trade-offs that are not easily quantifiable within standard frameworks for moment tensor inversions. Nominally, the goal of our estimation is to optimize an objective function that is expressed in terms of a residual and data covariance matrix. However, outlier data can dominate some portion of the residuals and unduly bias the parameter estimates. To remedy this we could treat the data covariance matrix as a weighting matrix and, in a somewhat subjective fashion, manually adjust the relative importance of any waveform to the solution. Instead, we attempt to be more quantitative and parameterize the noise so that it can be treated as an unknown in the inversion. To mitigate the computational burden introduced with sophisticated noise parameterizations we instead attempt to express the noise as a reduced rank superposition of eigenvector/eigenvalue pairs taken from the waveform's normalized noise autocorrelation matrix. These pairs are then subsequently scaled by some uniformly distributed random variable. The effect of this random perturbation can then be marginalized with an analytic integration of the probability density function for each waveform. The integration reduces the model parameter space for each waveform to an unknown data variance, unknown event depth, and, for small seismic events where the source time function is approximately a unit impulse, an unknown moment tensor. We apply this methodology to the Pawnee, Oklahoma 2016 earthquake and the January 2016 North Korean nuclear test with a particular interest in assessing the viability of the noise discretization as well as the trade-off between noise in the observed signal and magnitude estimation.

Automated Estimation of Rupture Directivity in Small to Moderate Earthquakes

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Resolving the extent of rupture directivity in small to moderate earthquakes is a challenging problem due to having finite bandwidth, limited data availability, and lack of knowledge about subsurface structure. We discuss both parametric and non-parametric techniques for resolving directivity signals in the frequency domain, using empirical Green's functions to correct for propagation and site effects. The methods build on a previously developed algorithm for resolving earthquake source properties from body wave spectra, using two stages to produce reliable spectral ratios for one target event at a time. We compare an approach that analyzes spectral ratios for azimuthal splitting to one which identifies directivity signals from azimuthal variations in the seismic energy. The methods are applied to a test dataset of earthquakes occurring primarily in the San Jacinto fault zone region.

Seismic Moment Tensor Catalogue for the Central Mediterranean Area

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The study has been conducted under the framework of the project led by the Istituto Nazionale di Geofisica e Vulcanologia (INGV) to update the Italian seismic hazard map with the main goal to provide a catalogue of moment tensor solutions for crustal earthquakes in the central Mediterranean area focusing on earthquakes occurred in the Italian peninsula and surrounding regions. We estimate the focal mechanisms of more than 800 earthquakes of moment magnitude greater than 3 and occurred between 2005 and 2016. We used waveforms recorded by the Italian National Seismic Network managed by INGV, CAT-SCAN (Calabria Apennine Tyrrhenian–Subduction Collision Accretion Network) project and recent data of the Malta Seismic Network managed by the Department of Geosciences at University of Malta. We computed the moment tensor solutions using the Cut And Paste (CAP) method which allowed to determine source depth, moment magnitude and focal mechanisms using a waveform modeling. It has been proven that the CAP method is quite efficient for earthquakes over a wide range of magnitudes and it provides also stable solutions for low-magnitude events. In order to check the stability and robustness of the final focal mechanisms solutions several tests have been conducted. Comparisons with already published solutions (when available) and with seismological and geological information allowed us to properly interpret the moment tensor solutions in the framework of the local geodynamic. Focal data were inverted to obtain the seismogenic stress in the study area.

Constraining Earthquakes Source Properties Using Depth Phases

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The mechanism for intermediate depth and deep earthquakes is still under debate. The temperatures and pressures are above the point where ordinary fracture ought to occur. Key to constraining this mechanism using seismological observations is the precise determination of hypocentral depth and the robust estimation of source parameters. It is well known that depth phases can provide important information, they sample the upper hemisphere of the focal sphere and have the potential of providing unique constrains on rupture directivity and velocity, they also allow us to precisely determine hypocentral depth. Nevertheless, routinely and systematically picking such phases at teleseismic or regional distances is problematic due to poor signal-to-noise ratios around the pP and sP phases. To overcome this limitation, we take advantage of the wide availability of dense seismic arrays. We use array processing to unambiguously identify such phases and present a set of techniques that allow us to perform robust estimates of sources properties using pP phases arrivals. We focus our attention on well constrained Double Seismic Zones (DSZ) in South and Central America. We contrast the source properties of event pairs that are confidently relocated to the upper and lower plane of the DSZ, respectively, and try to find statistically significant differences between the two planes of seismicity.

Source Inversion Using Regional and Teleseismic Data: Using a Multi-Objective Optimization to Constrain the Source of the M5.4 2016 September 12 South Korea Earthquake.

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Moderate seismic events generate seismic waves that are observed at regional and teleseismic scales. Nonetheless, they are too rarely combined in a single source analysis. We propose here a new approach for source inversion using a multi-objective optimization scheme combining teleseismic body wave and regional surface wave observations, and we apply it to determine the source parameters of the 2016 September 12 South Korea earthquake (M_w 5.4).

Teleseismic short-period and regional broadband seismograms from the IRIS-FDSN web service are processed, then selected following two criteria. First, 0.3-1.5Hz teleseismic data with signal-to-noise ratio above 2 are selected and a 'cepstrum' function is blindly applied to help detect reflected waves arrivals inside a P-coda. We show that this method allow the identification of recordings with weak P-coda and clear depth phases (pP,sP) arrivals, and can be used to select the optimal set of teleseismic seismograms for the inversion. Second, regional seismograms are selected according to the fit between their observed and theoretical dispersion curves extracted from the local 1D velocity model. Two frequency bands are proposed: 15-50s for epicentral distance smaller than 2°, 30-80s otherwise.

Finally, we explore the space parameters from exhaustive grid searches for the two objective functions, Tf and Rf for telesismic and regional data, respectively. We study the parameters sensitivities to Tf and Rf. We show that seismic moment parameters can be exclusively derived from Rf and are fixed for Tf, when the depth parameter is not sensitive to Rf and can be inverted from both. The selection of the optimal solution satisfying both cost functions uses the optimum Pareto Front, that, by combining these two independent cost functions, allows to decrease epistemic uncertainties. We finally discuss the advantage of this approach for increasing resolutions of moderate earthquake sources in areas with limited regional instrumentation.

The 2016 Grand Wash, Arizona Earthquake Swarm

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An earthquake swarm occurred during April and May, 2016 in the area west of the Grand Wash fault in northwest Arizona. A total of 62 events were located ranging from Md 0.4 to Ml 3.8 magnitude. The range in magnitudes and the location of the swarm in an area with a historically low frequency of events presents an opportunity to better understand the physical characteristics of the Grand Wash area. Preliminary analysis of the seismic data was conducted with application of the Wadati Ratio, Poissons Ratio, and the b-value obtained from the slope of the FMD plot. Both the Wadati Ratio and the Poissons Ratio values from the swarm data are close to the average worldwide values for shallow crust (1.73, 0.24). The b-value of 0.64 falls within the range of most worldwide values calculated in other studies, but somewhat below that for swarms in continental extensional terranes. Further analysis of the Grand Wash swarm will build upon these preliminary results and focus on a comparison of the three parameters in this study to the same parameters derived from other studies on both the southern Colorado Plateau and the southern Basin and Range provinces.

Source Mechanisms of Induced Earthquakes In The Geysers Geothermal Reservoir

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In this study, we use broadband data acquired by a local surface network of 33 broadband stations to determine the source mechanisms of the induced earthquakes in The Geysers geothermal field. The broadband network was deployed throughout the Geysers area and operated from February 2012 to July 2013. More than 35,000 events with ML>1.0 were detected in the reservoir during the operating period. A semi-automatic approach based on the principal component analysis (PCA) is applied in the moment tensor inversion of P-wave amplitude. This approach can extract P-wave amplitude fast and robustly and make it possible to estimate source mechanisms of extensive dataset. In this study, we analyze the source mechanisms of about 1500 events with ML>2.0 in The Geysers area. The strikes of fault planes show clear correlation with the trending of regional maximum horizontal stress (NNE-SSW). This suggests that the tectonic stress is an important controlling factor of the focal mechanisms. In addition, considerable portions of non-double-couple components are observed. The Non-DC components are closely associated with fluid injection and the medium properties around the focal area.

Investigation of Source Parameters of the Gyeongju Earthquake Sequence of 2016

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At 12 September 2016, earthquakes with magnitudes up to M=5.8 occurred at the southeastern of the Korean Peninsula. The seismic activity began on 10:44:32 UTC on September 12 with magnitude of 5.1 and the main shock with magnitude of 5.8 occurred at 11:32:55. Small size of events, considered as aftershocks, still continued although nearly 4 months had passed since then. The largest aftershock with magnitude of 4.5 occurred on September 19, after one week after the main shock. In this study, seismic source parameters of main shock, foreshocks and aftershocks of the Gyeongju earthquake sequence are investigated. We estimate source parameters of 54 earthquakes with magnitudes greater than 2.5 occurred around the source region from September 12 to December 25. The seismic source parameters are measured from S-wave source spectra, based on Brune's source model (1970). It is found that the main shock had stress drop of 132 bar, which is generally higher than stress drops of earthquakes in the peninsula. Spatial and temporal variation of source parameters of the Gyeongju earthquake sequence would also be discussed.

Source Parameter Validations Using Multiple-Scale Approaches for Earthquake Sequences in Oklahoma: Implications for Earthquake Triggering Processes

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The rapid increased seismicity rate in central US has drawn significant attention to the associated earthquake hazards in intraplate regions. Several important scientific questions arises: whether they have similar stress drops to tectonic events, whether they are self-similar ruptures, and whether the spatial-temporal variations reflect the underlying pore pressure and fault strength variations. To address these questions, we study several well-recorded earthquake sequences in Oklahoma.

For this cluster, we apply both a stacking-based empirical Green's function method and an individual-pair based method. For the stacking approach, significant effort has been devoted to improve the stability and reliability. We apply a series of different stacking approaches: (1) calculating empirical correction function by averaging difference between observations and model predictions for different magnitude bins; (2) using the smallest magnitude bin as EGF, and assess the event source parameters from both individual stations and all stations averaged. For both approaches, we test with traditional source models and modified source models to include intermediate fall-off rate of 1. For the individual approach, considerable effort is dedicated towards understanding of effect of source complexity in effecting the source parameter estimations, and consistency with stacking approach. In this study, we will report new results on source parameter validation, which will eventually lead to improved workflow in spectral analysis.

For each sequence, we also compare the stability of spatial-temporal variations of resolved source parameters, and relationship between localization of high stress drop clusters and large magnitude earthquakes, in order to better understand the controlling factors on large earthquake occurrence.

Insights into Volcanic Processes in the East Africa Rift Using Small, Temporary Seismic Networks

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The East African Rift System (EARS), an active continental rift zone, contains a number of active and inactive volcanoes that are potential sites for geothermal energy production. The University of Texas at El Paso and the Kenyan Geothermal Development Company (GDC) collaborated to monitor several volcanic centers by deploying 14 seismic stations around the Menengai Caldera and nine stations at the volcanic centers: Silali, Paka, and Korosi. We perform double-difference relocations to obtain high precision earthquake locations, and identify three major seismic swarms located in two volcanic systems. Two of them occur at the center of Menengai, one with a pipe-like shape and one on the northwestern flank reveals a circular pattern of seismicity. Korosi volcano shows no seismic activity, partially due to lack of seismic coverage, and Silali had no seismic activity present during this study. We also estimate the stress conditions of the swarms using Gutenberg-Richter b-value analyses to interpret the variation in stresses accompanying the migration of fluids and the tectonic stress state. We further use focal mechanisms to approximate the orientation of stress and whether faulting is modulated by local stresses. We find that P-axis strikes NE-SW for two seismic swarms beneath the Menengai and Paka volcano. To further resolve the geometries and locations of the magmatic reservoirs at the four volcanic centers, we develop a 3D high-resolution S-wave velocity model, which delineates the locations and shapes of the sources of the magmatic reservoirs as well as the stress perturbations due to these processes. The tomography model extends throughout the four volcanic systems, and we identify four magma chambers at approximately 6 km in depth, consistent with the seismicity results. We conclude that active fluid movement under Menengai and Paka indicated by seismicity and low S-wave velocity suggest potential for geothermal production at these sites.

Analysis of the 30 July 1972 MW 7.6 Sitka Earthquake Aftershock Sequence

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The 1972 M_w 7.6 Sitka earthquake is the largest earthquake to have occurred along the Alaska portion of the Queen Charlotte fault (QCF) in historic time. The QCF system forms the plate boundary between the Pacific and North American plates within southeastern Alaska and has accumulated enough slip since 1972 to produce a comparable sized event in the near future. Thus it is important to better understand the controls on the rupture process of the 1972 mainshock and its aftershocks. Following the mainshock, the U.S. Geological Survey installed a network of 11 portable seismographs that recorded over 200 aftershocks of the sequence. These locations were never published and the digital phase data were misplaced; however, we were able to scan paper-based copies of the data, convert the data to digital form and successfully relocate 93 of the aftershocks.

The relocations show two clusters of aftershocks along the QCF, one to the north of the mainshock and the other one to the south with a small gap between the mainshock rupture zone and the clusters. More aftershocks are found in the northernmost cluster and some of the events appear to line up on structures at angle to the QCF. These off-fault lineations are similar to aftershock patterns observed in the 2013 M = 7.5 Craig, Alaska earthquake. We are currently examining recent seismicity patterns, local geology and geophysics to better determine the structures controlling these aftershock patterns and mainshock rupture process.

Moderate Sized Events (3 Mw 5.4-5.6) and Aftershock Relocations of the 2016-2017

Nine Mile Ranch Earthquake Sequence near Hawthorne, Nevada

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On December 28th, 2016 three moderate sized earthquakes (M_w 5.6, 5.4, and 5.5) occurred within the Walker Lane in a remote area southwest of Hawthorne, Nevada. The first of these (M_w 5.6) occurred at 08:18 UTC and was followed 4 minutes later by an M_w 5.4. The third (M_w 5.5) occurred at 09:13 UTC, 55 minutes after the initial earthquake. Moment tensor solutions show high-angle strike-slip faulting within a generally E-W extension direction. These events resulted in surface cracks and damage to historical 1800s URMs at Nine Mile Ranch (fortunately they were not inhabited). To date, the Nevada Seismological Laboratory (NSL) has relocated ~800 events from the sequence. Initial relocations using GrowClust (Trugman *et al.*, 2016) indicate several structures are involved in the sequence with right-lateral strike slip faulting on the main fault plane striking ~N45W and dipping at a high angle to the NE. The three main events are located very near one another at the intersection of the main fault plane and a SW-striking alignment of aftershocks within a depth range of ~9-12 km. The main fault plane extends for about 5 km. Our aim is to improve locations with additional events as they are processed, characterize the spatio-temporal evolution of the sequence and place it within the context of the the Walker Lane region near Hawthorne. In 2011, 5 km to the east, a swarm occurred with 42 earthquakes of magnitude 3.0 and larger with the largest event at M_w 4.6. The 2011 and 2016 sequences occur in close proximity to Aurora Crater and other local volcanic centers, with the most recent volcanism estimated at 250 Ka.

Variations in Earthquake Source Properties along a Developing Transform Plate Boundary

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The Solomon Islands-Vanuatu composite subduction zone represents a complex tectonic region along the Pacific-Australia plate boundary. Here the Australia plate subducts under the Pacific plate in two parts—the Solomon Trench and the Vanuatu Trench—with the two segments separated by the 280 km long San Cristobal Trough (SCT) transform fault produced by a tear in the approaching Australia plate. The tearing Australia plate provides an opportunity to study the evolution of a newly created transform plate boundary. Over the past few decades, there have been several instances of large magnitude strike-slip earthquakes migrating westward along the SCT through a rapid succession of events. These earthquakes rupture the eastern two-thirds of the SCT, however, they fail to reach the tear. This pattern was most recently observed in May 2015 with a sequence of three ~MW 7 strike-slip earthquakes.

Utilizing b-value and Coulomb Failure Stress analyses, we have observed that both the magnitude and frequency of earthquakes increase along the transform with greater distance from the tear. These patterns likely reflect the coalescence of fault segments into a through-going structure via a displacement-driven plate boundary maturation process. We have also found that both the 2015 and a similar 1993 sequence exhibit a distinct east-to west decrease in normalized centroid time shifts (τc), likely indicating along-strike earthquake source property variations. The τc trend for the propagating earthquakes may reflect additional plate boundary development. Using empirical Green's functions (eGf) and the spectral ratio method, we have calculated the corner frequencies and stress drops for the 2015 strike-slip earthquakes and associated eGfs. Preliminary analysis indicates a slight increase in stress drop from east to west, possibly reflecting varying rupture complexity along the SCT resulting from the displacement-driven plate boundary maturation process.

A Comparison of Different Methods of Calculating Source Spectra and Stress Drop in Southern California

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The large uncertainties and variability in studies of earthquake stress drop affect strong ground motion prediction and limit our understanding of earthquake physics. With multiple researchers using a variety of different methods to compute and model source spectra, it is hard to compare results, or understand the origin of any discrepancies. To improve the quality and reliability of stress drop measurements in Southern California, we compare in detail two different approaches that analyze P-wave spectra.

Shearer *et al.* [2006] developed a large-scale, regional approach involving stacking and averaging P-wave spectra to obtain parameters for large catalogs of events. Abercrombie *et al.* [2017] developed a smaller-scale, EGF approach in an attempt to obtain the best possible results for the best-recorded earthquakes. To compare these methods, we focus on two test regions with dense seismicity, one near the Landers earthquake epicenter and one around Cajon Pass. The Landers region contains over 1000 aftershocks of the 1992 mainshock, and we are able to calculate P-wave corner frequency and stress drop estimates for several hundred of these using both methods. Initially, we applied the two approaches independently. There is a strong correlation between the results, but there is also significant scatter with differences up to a factor of ~1.5 in corner frequency. The results from the smaller-scale approach have a larger range of corner frequency and stress drop compared to the large-scale stacking approach, which is consistent with the averaging involved in the methods. We analyze the results to determine whether the differences are mainly for the less-well recorded events, or ones for which the methods included different data. To investigate the effects of specific steps in the procedures, we repeat the two analyses side by side, to test for differences in data selection criteria, spectral calculations, and EGF modeling.

Source Spectra and Magnitude Scaling of Induced Earthquakes in Oklahoma and Kansas

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Recent studies have questioned long-held assumptions about the functional form of the far-field body-wave spectrum and the self-similarity of earthquakes under magnitude scaling. The vast majority of studies of earthquake source spectra assume a Brune-type spectral model with a single corner frequency. However, some studies have proposed an alternative parameterization of the source spectrum which employs two corners. We examine assumptions of the form of the far-field body wave spectrum and its scaling with magnitude for suspected induced earthquakes in Oklahoma and Kansas (M≥3.0). We employ a coordinated approach to addressing this problem by spectral analysis and ground motion analysis, using methods defined in previous studies. Earthquake source spectra, estimated from well-recorded, far-field observations, are fit with one- and two-corner spectral models. The earthquake catalog is parsed and processed to account for and minimize the influence of path and site effects that may distort the source spectrum. In parallel, we model earthquake ground motions using the apparent moment rate functions of Archuleta and Ji (2016) for a large database of induced earthquakes in the region in order to examine the requirement for two-corner spectral models. Here, we present preliminary results from our on-going studies to explore the earthquake source dynamics and source scaling with magnitude. The form of the source spectrum we derive and its scaling with magnitude have important implications for understanding earthquake rupture dynamics and characterizing seismic hazard.

Reference

Archuleta, Ralph J., and Chen Ji. "Moment rate scaling for earthquakes 3.3≤ M≤ 5.3 with implications for stress drop." *Geophysical Research Letters* 43.23 (2016).

A Local Magnitude Formula for Western Canada Sedimentary Basin

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A local magnitude (ML) relation for Western Canada Sedimentary Basin (WCSB) is developed using a rich ground-motion dataset compiled from local and regional networks in the region. The assessment of amplitude decay with distance suggests that joining of direct waves by post-critical reflections from Moho discontinuity modify the attenuation pattern in the 100 km–200 km distance range. Accordingly, the regional ML distance correction is parameterized using a trilinear function. The standard ML relations derived for California fail to capture the rates and shape of amplitude attenuation in WCSB, resulting in overestimated magnitudes by 0.3 to 0.6 units. The overestimation is larger for local networks due to the increased discrepancy between standard ML relations and the actual attenuation properties at close distances. The derived relationship results in unbiased ML magnitude estimates in WCSB over a wide distance range (2 km–600 km), which ensures consistent magnitude estimates from local and regional networks.

ML-Mw Magnitude Relationship: Western Alberta Case Study

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Local magnitude (ML) is one of widely reported magnitude scales in earthquake catalogs due to its ease of calculation in real-time. ML is often used as a proxy of moment magnitude (M_w) for small events, for which moment tensor solution is limited by low signal-to-noise ratios. In this study, we examine the empirical relationship between the two magnitude scales for M_w<4 events in western Alberta. M_w magnitudes are determined by spectral matching on the low-frequency end of observed displacement spectra. A comparison of ML magnitudes, determined from regionally-calibrated local magnitude formula, to M_w values indicate that ML attains smaller values than M_w for M_w<3. This contradicts with the common assumption of M_w≈ML for small events. The discrepancy between the two scales increases with decreasing M_w, which is in agreement with recent findings of others (*e.g.*, Ross *et al.* 2016; Munafò *et al.* 2016).

Forecasting Aftershock Sequences in the Real World

Poster Session · Tuesday 18 April ·

Real-Time Completeness of the USGS ComCat Earthquake Catalog and Implications for Operational Aftershock Forecasting

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Aftershock forecasts often depend on the characteristics of the ongoing aftershock sequence up to the time of the forecast. The observed aftershocks may be used to fit sequence-specific parameters for clustering models and to seed simulations of future aftershocks. Immediately following a large mainshock, the catalog magnitude of completeness may be elevated due to decreased detection of smaller events, complicating the use of the early aftershocks. Recently, Page *et al.* (BSSA, 2016) introduced a simple function describing the time-dependent magnitude of completeness for the USGS Comprehensive Catalog (ComCat) catalog following global M≥6 earthquakes. As a further complication, the real-time earthquake catalog typically has omissions and errors not present in the final catalog. This real-time catalog incompleteness must also be quantified to avoid underestimating the probability of future aftershocks in real-time forecasts. We study the real-time catalog completeness of the ComCat catalog using snapshots downloaded periodically following selected M≥6 global and M≥5 U.S. earthquakes. Preliminary results for recent events, including the M5.8 Pawnee, Oklahoma, earthquake, show that during the first month, the real-time magnitude of completeness can be as much as one magnitude unit higher than the final catalog magnitude of completeness. We will quantify the real-time catalog completeness for global and U.S. earthquakes, following Page *et al.* (BSSA, 2016) and/or Hainzl (SRL, 2016), including dependencies on the time that the catalog was sampled. This parameterization can then be used in operational aftershock forecasts based on the ComCat catalog to account for the real-time catalog incompleteness. This should increase the accuracy of forecasts based on ongoing aftershock sequences.

Geoacoustics: Infrasound and Beyond

Poster Session · Tuesday 18 April ·

Dispersed Acoustic Waves: Implications for Atmospheric Inversion and Source Location

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The October 28, 2014 explosion of the Antares rocket at Wallops Island, Virginia produced a strongly dispersed acoustic wave. Twenty Transportable Array infrasound stations detected this phase as it propagated almost a thousand kilometers along the Eastern seaboard from Virginia to Maine. The extensive station coverage provides an opportunity to quantify the characteristics and areal extent of this unique wave form. We invert the time/frequency evolution of the dispersive phase to determine the atmospheric conditions that gave rise to it, and compare the results with those produced by weather observatories and forecast models. We also investigate the forward problem of estimating source location and size based on sparse observations of dispersed acoustic waves in a known atmosphere.

The Acoustic Signature of Underground Chemical Explosions during the Source Physics Experiment

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Phase I of the Source Physics Experiment (SPE) was a series of six underground chemical explosions in granite. The experiment focused on improving the nuclear monitoring community's understanding of the seismo-acoustic signatures of buried explosions. We discuss the amplitude, impulse, and peak frequency of each shot with respect to explosive yield and depth of burial. The wave forms of each are compared and contrasted, and the influence of ground motion, spall, and gas venting are considered. While the acoustic sensors were relatively close to the source (<5 km), atmospheric perturbations were non-negligible. Thus, the influence of the atmosphere on acoustic wave forms across the network are quantified. Predictions for the last explosion in the series are compared to the recorded time series. Finally, three acoustic source modeling approaches are presented: the Rayleigh integral, explosive source-time function inversion, and a boundary element model.

Acoustic Yield Estimation Using Full Waveforms

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We outline a new method for estimating the yield of explosions from shock-wave and acoustic-wave measurements. The method exploits full waveforms by comparing pressure measurements against an empirical stack of prior observations using scaling laws to perform a grid search over a range of trial yields. A major advantage of this approach is that it can be applied to measurements across a wide range of source-to-receiver ranges. The method is applied to data from different explosion experiments, demonstrating that stacks from one region can be exported to reliably estimate yields in new regions.

Combining Seismic and Acoustic Event Catalogs to Better Understand the Nature of Individual Events

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We present a combined catalog of seismic and acoustic events within the vicinity of Utah in 2011. Focusing on the Bingham Copper Mine, an area with many mining blasts, we group seismoacoustic events. For events detected at multiple acoustic arrays, grouping is based on origin time and location. For events detected at only one acoustic array, grouping is based on trace velocity and backazimuth. Here we quantify differences in origin time and location, comparing these to event type and magnitude estimated from seismic data. Ultimately, we show that the use of a combined seismoacoustic catalog leads to a better understanding of the nature of individual events.

Improved Nearfield Dispersion Measurements from Analytic Representation of Time-Warped Acoustic Modes

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Time-warping is a unitary transformation designed for separating interfering normal modes via nonlinear resampling based on the predicted traveltime of a waveguide. Non-stationary signals in the time domain become approximately stationary in the warped domain, where individual modes can be separated by bandpass filtering around the stationary warped frequencies. The inverse warping transformation is then performed on the filtered modes to yield separated normal modes in the time domain.

Measuring dispersion from unwarped modes is typically performed via Short-Time Fourier Transform (STFT), where time/frequency measurement resolution is limited by the Gabor uncertainty principle. Because the separated normal modes are monocomponent and nearly monochromatic in the warped domain, their instantaneous frequency can be determined stably from the time derivative of instantaneous phase. Therefore, by simply taking the Hilbert transform of the separated warped modes, group velocity dispersion can be directly measured as a continuous function in the warped domain, avoiding the time/bandwidth tradeoff associated with STFT measurements.

I analyze time-warped synthetic acoustic Green's functions computed for a coastal ocean model at ranges from 2-10km, and compare dispersion measured by traditional spectrogram analysis to the analytic representation method. I find that dispersion curves recovered for 4 normal modes using both methods agree with analytically-determined model dispersion to within the spectrogram uncertainties. Where group velocities at the earliest times are lost in the spectrogram measurements (due to finite STFT window length), the analytic representation method recovers dispersion for the entire duration of the unwarped signal, and its measurement uncertainties do not depend on the arbitrary choice of STFT window length.

Integrated and Geophysical Investigations for Site Characterization of Critical Facilities and Infrastructure

Poster Session · Tuesday 18 April ·

Fault-Zone Exploration in Highly Urbanized Settings Using Guided Waves: An Example from the Raymond Fault, Los Angeles, California

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Locating faults in the near-surface beneath highly urbanized settings is challenging because urbanization obscures geomorphic evidence of the faults in relatively short time periods. Yet, urban faults can represent major hazards because they directly underlie large populations. Such is the case along the western Raymond Fault in Los Angeles, where it steps over to the Hollywood Fault. It is important to identify the main and auxiliary traces that may underlie homes and buildings. Paleoseismic trenching and other invasive techniques offer the clearest evidence of faulting, but long trenches cannot be economically excavated in highly urbanized areas or zones where faulting is widely distributed, such as fault step overs. In May 2016, we used an alternative, non-invasive approach to locate faults between the Raymond and Hollywood faults. This technique involves using peak ground velocities (PGV) measured from guided-wave energy generated within a known fault trace, as recently done elsewhere (Catchings *et al.*, 2013). From a known site (from trenching) of the Raymond Fault, we used an accelerated weight drop to input seismic energy into the fault zone. The seismic energy was recorded by seismic arrays located about 400 to 700 m from the source and aligned approximately perpendicular to the expected trend of the Raymond Fault. Although the area was bisected by a four-lane highway and numerous busy streets, our recorded seismic energy was largely noise free as a result of stacking more than 200 shots. We observed four distinct zones of high PGV values along the array, none of which coincided with roadways or other local noise sources. Instead, these zones of high PGV coincided with fault traces inferred from geologic mapping, borings, and pre-urbanization (1923; 1928) aerial photos. We find that the guided-wave PGV method is highly effective in locating faults in both urban and rural areas.

Characterization of Earthquake Site Amplification in Alberta, Canada, for Induced-Seismicity ShakeMap Applications

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We aim to characterize earthquake site amplification in Alberta, Canada, both for individual sites and on a regional basis. This will aid in the interpretation of ground motion recordings and improve our understanding of induced-seismicity hazards. For 18 seismograph stations, we collected geophysical data via passive and active seismic surveys (multichannel analysis of surface waves and microtremor array methods). Empirical amplification functions are derived from correlating earthquake and microtremor recordings with site descriptor variables such as the time-averaged shear-wave velocity in the upper 30 meters (V_{S30}), depth-to-bedrock and surficial geology. Dispersion curves calculated using the high-resolution frequency-wavenumber and spatially averaged coherency spectrum processing methods, along with horizontal-to-vertical spectral ratios (HVSRs) were inverted to estimate V_{S30} for the 18 seismograph station locations. The site classes range from NEHRP C to D with D being the predominant site class. We observe excellent agreement in peak frequency and amplitude between earthquake and microtremor HVSRs at the same station. This provides confidence in the robustness of rapid low-cost microtremor methods as a measure of earthquake site amplification in Alberta's geologic setting.

Estimation of Kappa for Gyeongju Area in South Korea and Kappa Scaling Factors for NGA-West2 Ground Motion Prediction Equations

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The spectral decay parameter, kappa, was estimated for individual sites of temporary seismic array which had been operated from October 2010 to March 2013 in Gyeongju Area of South Korea. We used 342 earthquake waveform data recorded at Gyeongju seismic array for kappa estimation based on Anderson and Hough (1984) method. The estimated κ values show distance dependence characteristics. The site-specific kappa for each site was determined from the intercept of the least-squares line between kappa and a distance. The estimates of site kappa range between 0.0149 and 0.0317 sec, and the arithmetic average of kappa of all sites in the array is 0.0233 sec. From the regressed line of all data regardless of the sites, kappa is determined 0.0231 sec. The site kappa of Gyeongju Area is suggested as 0.023 sec based on those two estimates. The site, HDB, which is located nearby the Gyeongju seismic array was also estimated for purpose of comparison, since HDB consists of borehole seismometers and accelerometer installed at the depth of 20 m. The estimated kappa of 0.0182 sec for HDB is smaller than it of Gyeongju seismic array which were installed at the surface. It indicates that spectral decay at the high frequency of acceleration spectrum is influenced by characteristics of surficial sediment layers. For the same events, regional variation of kappa is observed through the different sites. It, however, was also observed that several specific events derived much different kappa than others at most of the sites. It could be concluded that both site effects and source effects contribute the spectral decay at the high frequencies. Finally, kappa scaling factors for the five NGA-West2 GMPEs were calculated using inverse random vibration theory suggested by Al Atik (2014) so that those equations can be applied to Gyeongju Area in consideration of the difference in kappa between Gyeongju Area and WUS. The estimated kappa for Gyeongju can be used in PSHA and development of GMPEs.

Comparing Earthquake-Based P-Wave and Traditional Array-Based Methods for Obtaining VS30

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The U.S. Geological Survey (USGS) is expanding a national compilation of VS30, the time-averaged shear-wave velocity in the upper 30 m of the crust (Yong *et al.*, 2016). More than 500 VS30 values, as well as geologic settings, are being assessed and added. We are able to expand the database and provide more VS30 estimates using a recently-developed method for determining VS30 values based on the initial portion of recorded P-waves from local earthquakes. The original database already had 2,997 sites and made use of 14 different geophysical array-based methods. Following sufficient validation, we will incorporate results from the new P-wave method into the national dataset.

A recent study by Hosseini *et al.* (2016) applied the P-wave receiver function method to many local small earthquakes and yielded 514 VS30 estimates for the National Science Foundation Earthscope Transportable Array and USGS Advanced National Seismic System sites located largely in the Central and Eastern United States. Of those 514 values, 23 are co-located at sites for which VS30 estimates based on array-based measurements were previously available. We observe differences of greater than 10 percent in VS30 values for 75 percent of these sites, which span all National Earthquake Hazards Reduction Program (NEHRP) Site Classes (A—E). The greatest differences in VS30 estimates are between the P-wave receiver function and array-based methods (body-wave reflection-refraction methods and the multi-channel analysis of surface waves).

We describe the potential conditions that lead to differences between the P-wave and array-based results, as well as the character of the surface (geology and topography) and subsurface (depths to bedrock and water table). Our preliminary findings support the continued application of the P-wave method for calculating VS30 values for NEHRP Site Classes B and C sites.

Shear-Wave Velocity Analysis by Surface Wave Methods in the Boston Area

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Shear modulus is one of the most pivotal parameters in engineering problems involving the mechanical behavior of rock and soil. Shear-wave velocity (Vs) is the best seismic indicator of shear modulus. Previous research of surface-wave methods, such as Spectral Analysis of Surface Waves (SASW) (Nazarian *et al.*, 1983), Multichannel Analysis of Surface Waves (MASW) (Park *et al.*, 1999), and Refraction Microtremor (ReMi) (Louie, 2001), has shown that inverting surface waves for subsurface shear-wave velocities is a good way to obtain subsurface shear-wave velocities. Compared to body-wave methods, surface-wave methods are noninvasive and can be employed more rapidly and economically. In order to determine which surface-wave method gives the best estimation of the shear-wave velocity structure of near-surface soils, we collected seismic data at three sites in the greater Boston area. The stability and uncertainty of each method is evaluated by plotting a series of Vs models found from each dataset together with the standard deviations of the sets of models. The standard deviation varies not only with different methods, but also with different geophone intervals, survey line locations, and source types (active or passive). Overall, the MASW and the ReMi methods (forward modeling) have relatively low standard deviation, whereas the standard deviation of the SASW method is generally higher. In addition, because ambient noise that is rich in low frequency components is used as the source signal of the ReMi method, this passive method appears to yield a better resolution at deeper depths than the other two active methods. However, if in the use of inverse modeling in the processing of ReMi data, the Vs models resulting from

the inversion sometimes turn out to have an unreasonable shape and a high standard deviation, apparently indicating some instability in the inversion algorithm.

Comparison of Site Dominant Frequency from Earthquake and Microseismic Data in California

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An important predictive variable for site amplification is the site dominant frequency (fd), which is roughly a function of the thickness and shear-wave velocity of the soil layer. At permanent (or long-term) seismic monitoring stations, fd can be calculated from the peak of the horizontal-to-vertical spectral ratios (HVSR) obtained from earthquake recordings (eHVSR). For site characterization projects, fd is commonly estimated from HVSR obtained from microseismic (mHVSR) observations recorded by short-term three-component single-station arrays—note that in the mHVSR case, the fd is generally derived from the Fourier spectrum rather than the response spectrum. In this study, we compare the fd values derived from eHVSR with those derived from mHVSR. For the eHVSR, we use the response spectra from the Next-Generation-Attenuation-West2 database (Ancheta *et al.*, 2014). We calculate eHVSR for seismic stations in California having at least three earthquake records and measure fd from the eHVSR. For the mHVSR, we use data acquired from the Yong *et al.* (2013) VS30 (time-averaged shear-wave velocity in top 30 m) site characterization project. The database includes mHVSR estimated from multiple closely-located single-station recordings conducted within approximately 150 m of each of 187 seismic stations in California. Comparing the fd values from the eHVSR response spectra data to those from the mHVSR data for the sites in common shows that eHVSR fd values for response spectra scale linearly with mHVSR fd values. The eHVSR fd values from response spectra are on average 0.80 times the fd values from mHVSR Fourier spectra, with a standard deviation of 0.25. The relationship holds for microseismic surveys at distances up to 300 m away from the seismic stations. The results of this study have potential for better characterizing the site response in modern ground-motion prediction equation models as well as in building codes.

A Dual-Approach Analysis of Lg Wave Site Amplification Using Site Response Ratios

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Site response ratios of the Lg wave amplitude can be measured using the reverse two-station method (Chun *et al.*, 1986). Deterministically solving for site response logarithms at individual stations using these ratios results in an underdetermined problem. In the ideal case (when all sites are well-sampled by the ratios) the problem is rank-deficient by 1. Adding an assumption that the average logarithm of responses is zero makes the problem full-rank, and the individual responses can be determined. However, a typical site response ratio dataset does not provide sufficient samples for all stations, so additional rank-deficiency occurs, preventing an inversion of all individual responses. In this case a statistical analysis of the responses can be conducted to evaluate their gross behaviours, such as their distribution function, mean and standard deviation. The statistical analysis can be used to (1) predict responses of any new stations with a specified uncertainty at any confidence level, and (2) evaluate the validity of the assumption that the average log-response is zero. Both these jobs cannot be done with a deterministic inversion. As an example, we conduct a deterministic inversion of the site responses of 217 stations in China. These stations are well-sampled by response ratios so that there is only a slight rank-deficiency, which is tackled by a minor damping. Separately, we conduct a statistical analysis of these responses, which can be modelled as following a normal distribution with a zero mean and a standard deviation. The results of statistical analysis are consistent with the deterministically resolved response values.

Site Response Assessment in Two Geological Contexts, France

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Particular shallow geological configurations introduced by significant lithological and/or geometrical variations may cause ground motion amplification. For the safety assessment of critical facilities, site effects associated with such geological conditions have to be quantified.

In this prospect, seismic campaigns were conducted for two sites in France with different shallow geological conditions. The first site is located along the Rhône River, flowing above a deep and elongated Plio-Quaternary paleo-valley (+-500 m thickness) incised in Cretaceous limestones. The second is located in the Gironde estuary, presenting a hundred-meter pile of both Quaternary and Tertiary loose sediments lying and gently dipping over Mesozoic limestones.

For each area, we performed seismic measurements in summer 2016, namely horizontal-to-vertical spectral ratio technique (HVSR), and ambient vibration array measurements (AVA). The obtained results provide soil column parameters such as the fundamental resonance frequency f0 and S-wave velocity profiles through the inversion of the surface waves dispersion. We also performed seismic monitoring of distant earthquakes during several months in 2016 in order to estimate empirical amplification of seismic waves by comparing records on basement rocks and on the sediment cover using Standard Spectral Ratio technics (SSR).

Amplifications derived from numerical modeling based on soil properties obtained through the aforementioned experiments and from the empirical estimation of seismic waves amplification provide crucial information for the assessment of site response to weak motion.

Detection of Underwater Seismic Sources with T-wave Signals and Array Analysis

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In the recent decades, the use of the Ocean Bottom Seismometer (OBS) has largely improved the comprehension of seismicity and focal mechanism in the offshore convergent plate boundary, where is considered to generate disastrous earthquakes causing significant damages at the onshore area. In practice the relatively low signal-to-noise ratio (SNR) of the OBS seismograms limits the potency of OBS experiment when we proceed seismic analysis with seismic-phase-dependent algorithms. In this study, we apply the beamforming array analysis upon the T-wave signals acquired in the OBS experiments in the South China Sea and the Philippine Sea. As a particular form of seismic waves propagating in ocean water, T waves can provide insight into underwater seismic sources and oceanic environment. First we locate the T-wave events by means of the beamforming array analysis. We plan to retrieve the underwater seismicity as complete as possible. Beside the excitation by tectonic earthquakes, various sorts of seafloor geological process (*e.g.* volcanism, hydrothermal activity, landslide, etc.) are also T-wave generators. The analysis conducted from T-wave duration and amplitude variation can render further information for the characteristics of seafloor geological process. With the near-field observation of the T waves, we can establish a better comprehension of the underwater seismic sources. It is important for the offshore seismic risk mitigation. In fact, our study can further extend to discuss the seismic energy conversion in-between ocean water and the solid earth. It is an interdisciplinary research with multiple folds.

Soil Effects in the City of Lorca (SE Spain) and Damage Distribution of the M 5.2 11 May 2011 Earthquake

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A M_w 5.2 earthquake shook the city of Lorca, in Murcia region (SE-Spain) on 11 May 2011. The event caused 9 fatalities and more than 300 people were injured in a town with a population of around 60000 in an area of 7 km2. Around 1000 buildings, including residential, cultural heritage, schools, government buildings, healthcare, security facilities, etc., were damaged with different degree. Damage was concentrated in several areas of the town where around 40% of buildings were affected. In the historical centre 16% of buildings were damaged and historical heritage was severely affected. Within the two years following the earthquake, single-station ambient-vibration records were obtained at 79 sites in Lorca, mainly in its urban area and at 13 sites, 9 three-directional digital tromographs were deployed in 2-D array configurations (dimensions of the order of 100 m). Measurements in the vertical component were used to retrieve the relevant effective dispersion curve of Rayleigh waves by considering ESAC and f-k approaches. Furthermore, at each measurement point within the array, horizontal-to-vertical average spectral ratios (HVSR) were also computed. The dispersion and HVSR curves obtained at each site were jointly inverted by considering a genetic algorithm approach, assuming that the monitored ambient vibration wavefield is dominated by surface waves including both Love and Rayleigh waves with relevant higher modes. S-wave velocity profiles, along with the relevant uncertainties, were estimated at each site up to depths of the order of hundreds of meters. The obtained results, including HVSR amplitude mapping, reveal that possible ground motion amplification by local soils is not significant in most of the Lorca urban area and they also suggest the presence of significant lateral heterogeneities in the subsoil structure, resulting from past tectonic activity of major faults present in the region.

On the Bayesian Inference of Shear Wave Velocity Structure from Horizontal-To-Vertical Spectral Ratio

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The shear-wave velocity (Vs) model is known as a key component in any reliable seismic site response analysis and ground motion amplification studies. The Vs model can be retrieved either with invasive (*e.g.* conventional geophysical methods) or non-invasive techniques (*e.g.* surface-wave methods or refraction tests). Although the non-invasive methods provide practical and cost efficient alternatives, the inversion problems are highly nonlinear and can be influenced by non-uniqueness solution which principally results in high level of uncertainties. It is well established that the Horizontal-to-Vertical Spectral Ratio (HVSR) results represent the subsoil characteristics, particularly when there is a significant impedance contrast between layers. In this paper we model the seismic body waves in the layered medium and simulate the HVSR on the basis of an approximate initial soil structure model. We then apply a robust and computationally efficient Bayesian inversion technique which provides an estimate of the corresponding soil structure. We test the proposed technique using microseismic recordings from IzmirNet stations in Turkey. The Markov Chain Monte Carlo (MCMC) technique with Metropolis steps is employed in order to obtain the best fitting family of Vs profiles along with their uncertainties. The theoretical HVSRs are calculated through body-wave approximation as a reliable estimate for subsoil structure of the sedimentary layers overlaying the half-space. A blind test is conducted over the number of layers to consistently investigate the best resolution of model parametrization. The good agreement between the obtained results and available soil properties information confirms the applicability of the proposed approach in this study. Perhaps more importantly, it highlights to what extent the S-wave velocity profile estimate can be trusted from the parameter variations and unavoidable trade-offs.

Using Routine Multi-Method Shear-Wave Velocity Data (Vs30) as a First Approximation of

Seismic Hazard Site Characterization

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The use of site-specific shallow shear-wave velocity (Vs) to account for earthquake site response is an important consideration in seismic hazard investigations, and in design applications by the earthquake engineering community. The need for rapid, accurate, and inexpensive collection of shallow Vs data over large areas within cities is increasingly important for urban hazard mapping, site amplification estimation, and earthquake-effects studies. As part of a continuing effort to evaluate the strengths and limitations of Vs survey methodologies in various geologic and environmental settings, the U.S. Geological Survey has developed a site acquisition strategy using a co-located multi-method approach. Our multi-method approach requires the acquisition of co-located body- and surface-wave data for each site. A key advantage of this approach is that it captures independent wave-field propagation effects that can yield a more robust estimate of seismic velocity and layer thicknesses.

We present for comparison the results of Vs data acquisitions from a site characterization urban environment study in New Castle, Australia, a data set collocated with portable seismograph stations deployment for an earthquake aftershock study around Mineral, Virginia, and a data set acquired for a regional seismic hazard mapping project of Puerto Rico. Vs-versus-depth profiles from sites underlain by different geologic materials are used to (1) analyze the resulting Vs structure derived from the collocated multi-method data sets, (2) examine how geology influences data quality and reliability, and (3) calculate first order estimates of site natural frequencies.

Our Vs data are also compared to horizontal-vertical spectral ratio (HVSR) data derived from recordings in the Virginia study. Robust linear regression of HVSR to both site frequency and Vs30 demonstrate moderate correlation to both, and thus both appear to be generally representative of site response in this region.

The Role of Non-Invasive Ambient Noise Analysis in Improving Seismic Microzonation Mapping in Vancouver, British Columbia, Canada

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There is renewed interest in improving seismic microzonation mapping in Vancouver, British Columbia (BC), the highest seismic risk city in Canada. To highlight the suitability of emerging non-invasive seismic array techniques to regional seismic hazard assessment, we apply them to key high-risk locations in south-western British Columbia. The motivation of this study is to allow the assessment of amplification potential for applications such as engineering analysis and ground motion modeling. Few shear-wave velocity (v_s) measurements in Greater Vancouver are freely available in published literature; this study is a notable contribution to public earthquake site assessments in the area.

We first investigate seismic amplification due to local geology as the cause of varying peak ground acceleration (PGA) in the region from the 2015 M 4.7 Vancouver Island earthquake. We perform single station techniques to analyse the ground motions at strong-motion stations within ~85 km of the epicenter. We show that the spatial distribution of amplification generally agrees with the current regional seismic microzonation map, but with notable exceptions. High amplification is observed on both thick sediment sites and on the northern edge of the Fraser Delta, where the sediment thickness may be favourable to amplify the dominant frequencies, as observed for previous earthquakes.

We then perform passive array-based seismic measurements at 10 high-priority risk schools of the BC school seismic retrofit program primarily in Metro Vancouver, with the aim of investigating v_s profiles. Preliminary dispersion results from array sites are well constrained across all frequencies and are consistent between processing schemes. Joint inversion of resulting dispersion estimates and horizontal-to-vertical (H/V) spectral ratios provides one-dimensional shear wave velocity (v_s) depth profiles for earthquake site classification.

A Study of Vertical to Horizontal Ratio of Earthquake Components in the Gulf Coast Region

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A new model is developed for the response spectral ratio of vertical-to-horizontal (V/H) components of earthquakes for the Gulf Coast region. The proposed V/H response spectral 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 30 m of the site (V_{S30}) for the Peak Ground Acceleration (PGA), and a wide range of spectral periods (0.01 to 10.0 s). The model evaluation is based on a comprehensive set of regression analyses of the newly compiled Next Generation Attenuation (NGA-East) database of available Central and Eastern North America (CENA) recordings with the moment magnitudes ($\mathbf{M}$) greater or equal to 3.4 and the rupture distances R_{rup} up to 1000 km. The 50th percentile (or median) pseudo-spectral acceleration (PSA) values computed from the orthogonal horizontal components of ground motions rotated through all possible non-redundant rotation angles, known as the RotD50 (Boore, 2010), is used along with the vertical component to perform regression using a nonlinear mixed-effects regression algorithm. The predicted V/H ratios from the proposed model are compared with the recently published V/H spectral ratio models for different regions. The derived V/H ratios can be used to develop the vertical response spectra for the sites located within the Gulf Coast region, which include the Mississippi embayment.

Estimation of the Site Amplification in the New Madrid Seismic Zone Using Regional and Local Earthquake Data

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Measuring site amplification in New Madrid Seismic Zone (NMSZ) using the dual station standard spectral ratio (SSR) method for local and regional earthquakes is the main purpose of this study. Several algorithms have been used to estimate site effects using earthquake data in different regions, among them horizontal to vertical spectral ratio (HVSR) and standard spectral ratio method are the most popular methods. The SSR procedure uses amplification factor ratios of three component records from different earthquakes in various stations. This technique takes into account the ratio between the spectrum at a site of interest and the spectrum at a reference site, which is usually a nearby rock site. If the two sites have similar source and path effects, then the resulting spectral ratio creates an estimate of site amplification. In this method, it is difficult to separate the attenuation factor from the site effect. We have used a joint inversion method to determine the attenuation coefficient and site response from spectral ratios.

In this study, we use direct S and Lg waves recorded in the seismograms of New Madrid seismic zone to determine the site effect and attenuation factors.

Waveforms used in this study are from regional and local earthquakes, and the magnitudes of used events are in the range of 3 to 5.7 with sampling rate of 100 samples per second.

We measure the Lg and direct S wave spectral and pre-event noise Fourier amplitudes for frequencies between 0.2 Hz and 10 Hz. From these Fourier amplitudes, we calculate the signal to noise ratios for individual frequencies, and we omitted those events with their corresponding signal to noise ratios lower than 2. Therefore, we use only the data with high quality for each individual frequency in the inversion to calculate the site response and attenuation factor for both direct S waves and Lg waves.

Results of Six-Degree-of-Freedom Recording at The Geysers, California: True Backazimuth, Phase Velocity, and Site Characterization

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This paper addresses a microearthquake study at a major geothermal area in California, known as The Geysers. This area is volcanic and lies within the Franciscan formation. In particular, we are using a six-degree-of-freedom (6DOF) geophone-based instrument called a Rotaphone. The instrument provides short-period collocated records of three seismic translational and three seismic rotational components. From June to September 2015 we performed field tests of our latest Rotaphone prototype, model D, at this geothermal site. We recorded hundreds of shallow proximal microearthquakes with magnitudes up to 3.8 ML and epicentral distances from 260 m to 14.2 km and depths up to 6 km below sea level. Thanks to relatively low noise, these 6DOF records are suitable for analysis aimed at retrieving the true backazimuth and S-wave phase velocity from a single Rotaphone, which are obtained using rotation-to-translation relationships. For distant earthquakes, we used an assumption that the S wave can be approximated as a plane wave, but that assumption is not adequate for proximal sources. In our study, the rotation-to-translation relations are expressed instead by equations derived for a spherical S wavefront radiated from a shallow point source in a homogeneous medium. Results show that at local distances (up to several km), at lower frequencies (up to a few hertz), and at locations with rapid amplitude changes due to the radiation pattern, the rotational components are a linear combination of terms proportional to translational velocity and acceleration, and none of the terms can be neglected in most cases. Our approach yields not only the true backazimuth and the apparent S-wave phase velocity, but, in certain cases, also the S-wave velocity near the surface. All these quantities are obtained from a single 6DOF instrument. The wave velocity is a weighted average down to a depth not exceeding one wavelength, so may be used to estimate vs30, from a single instrument.

Reducing Uncertainties in the Estimation of Deep VS Profiles at the Location of CERI Stations, Using Joint Inversion of Earthquake Receiver Functions and Site-Specific Geophysical Phase Velocity Dispersion Curves

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Ground motions in the New Madrid Seismic Zone (NMSZ) are significantly affected by the properties of deep sediments in the Mississippi embayment which are not adequately described by the shear-wave velocity structure of the upper 30 meters represented by VS30. The basement of the Mississippi Embayment is formed from Paleozoic rocks at a depth of about 1000 m below Memphis and Shelby County, and sediments consisting of clays, silts, sand, gravel, chalk and aged lignite fill the embayment. A more accurate representation of site amplification is needed for improving earthquake hazard estimates in this region. The entire depth of the soil column should be considered when performing a site response analysis which is important in modeling ground motions in the NMSZ. We show that there is a need for high-resolution shear-wave velocity profiles in the Mississippi embayment, especially at the locations of seismographs operated by the Center for Earthquake Research and Information (CERI). The most reliable non-invasive techniques to estimate subsurface shear-wave velocity profiles are field methods including spectral and multi-channel analysis of surface waves (SASW, MASW), and refraction microtremor (ReMi). Rosenblad and Stokoe (2005) performed a series of surface seismic field tests at multiple CERI stations to develop low frequency phase velocity dispersion curves and deep shear-wave velocity profiles where they used MASW, SASW, and passive techniques. Considering the potential non-uniqueness associated with the inversion of the phase velocity dispersion data, we propose to obtain improved deep VS profiles at the locations of multiple CERI stations using a joint inversion of dispersion curves and receiver functions. We show that using dispersion curves obtained from the geophysical field tests at multiple CERI stations, and constraining the VS profiles using earthquake receiver functions in a joint inversion scheme can improve the shear-wave velocity profile.

Seismic and Liquefaction Hazard Mapping and Early Earthquake Warning in West Tennessee

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The Center for Earthquake Research and Information (CERI) is beginning a five-year earthquake hazard mapping and earthquake early warning study funded under the National Disaster Resilience Competition by the Department of Housing and Urban Development (HUD). The study area of this hazard mapping project comprises four counties adjacent to the Mississippi River in westernmost Tennessee—Dyer, Lauderdale, Lake, and Tipton—and one major population center—Jackson, TN and all of Madison county. This hazard-mapping project will extend the urban hazard mapping already done in Shelby Co. to adjacent parts of the state and use the techniques and approaches developed in Shelby Co. The project will include the gathering of available geological and geotechnical well and boring log information to supplement our existing database of subsurface information in the Mississippi embayment. Field geophysical measurements will help fill data gaps in the 3D geological/geotechnical model for these counties. Geophysical techniques will include surface-wave and ambient noise measurements for the soil profile layering and Vs values (mainly uppermost 100 m). Supplemental techniques and novel approaches of developing 3D geological/geotechnical models with limited data on the subsurface conditions will be evaluated as well. Liquefaction probability curves will also be developed to supplement existing curves in Shelby Co and the embayment. During the first year of the project, earthquake early warning (EEW) research will also be conducted. The focus of the EEW research is to determine the feasibility of EEW in western Tennessee and develop a monitoring improvement plan that will facilitate EEW in the central US (see Ogweno *et al.*, this meeting). The EEW and seismic hazard mapping studies will mainly focus on flood mitigation structures and support facilities, but will also help earthquake planning and mitigation efforts in communities within these counties.

Comparison of Earthquake Damage Patterns and Shallow-Depth vs Structure across the Napa Valley, Inferred From Multichannel Analysis of Surface Waves (MASW) and Multichannel Analysis of Love Waves (MALW) Modeling of Basin-Wide Seismic Profiles

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We conducted an active-source seismic investigation across the Napa Valley (Napa Valley Seismic Investigation-16) in September of 2016 consisting of two basin-wide seismic profiles; one profile was 20 km long and N-S-trending (338°), and the other 15 km long and E-W-trending (80°) (see Catchings *et al.*, 2017). Data from the NVSI-16 seismic investigation were recorded using a total of 666 vertical- and horizontal-component seismographs, spaced ~100 m apart on both seismic profiles. Seismic sources were generated by a total of 36 buried explosions spaced ~ 1 km apart. The two seismic profiles intersected in downtown Napa, where a large number of buildings were red-tagged by the City following the 24 August 2014 M_w 6.0 South Napa earthquake. From the recorded Rayleigh and Love waves, we developed 2-D S-wave velocity models to depths of about 0.5 km using the multichannel analysis of surface waves (MASW) method. Our MASW (Rayleigh) and MALW (Love) models show two prominent low-velocity (Vs = 350 to 1300 m/s) sub-basins that were also previously identified from gravity studies (Langenheim *et al.*, 2010). These basins trend N-W and also coincide with the locations of more than 1500 red- and yellow-tagged buildings within the City of Napa that were tagged after the 2014 South Napa earthquake. The observed correlation between low-Vs, deep basins, and the red-and yellow-tagged buildings in Napa suggests similar large-scale seismic investigations can be performed. These correlations provide insights into the likely locations of significant structural damage resulting from future earthquakes that occur adjacent to or within sedimentary basins.

Geophysical Investigations for Site Characterization at Unstable Sea Cliffs: Case Study of Selmun (Malta)

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The area of Selmun Malta is characterized by a coastal cliff environment having an outcropping layer of hard coralline limestone resting on a thick (up to 70 m) layer of clays and marls (Blue Clay). This configuration gives rise to coastal instability effects, in particular lateral spreading phenomena and rock falls.

Currently at the site, the ruins of a watchtower built in 1658 by the Knight of St. John are threatened by a progressive moving of this landslide process towards the stable area and all area is affected by a constant retreating of the cliff. During 2015 and 2016, engineering-geological surveys were carried out to define the rock mass properties. We also investigate the site dynamic characteristics of this study area by recording ambient noise time-series at 118 points. The H/V graphs illustrate and quantify aspects of site resonance effects due both to underlying geology as well as to mechanical resonance of partly or wholly detached blocks. The polarization diagrams indicate the degree of linearity and predominant directions of vibrational effects. In addition to the single-station noise measurements seismic array antennas were deployed to define the seismic response of the site. The passive seismic array measurements were conducted using geophone array equipped with 4.5 Hz vertical sensors. A total of 42 geophones were used, and placed in an L-shaped configuration with a regular interstation distance of 5 m. We were able to derive a 1D shear-wave velocity profile by jointly inverting both H/V and effective dispersion curves using Genetic Algorithms. Finally, we computed an amplification function for the site. Our results can contribute to management protection strategies, reducing the landslide risk and preserving the historical heritage of the site.

High-Resolution Tomography of Vp, Vs, Vp/Vs, and Poisson's Ratios of Quaternary-Active Chabot Fault of the Hayward Fault Zone

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California State University, East Bay (CSUEB), located in Hayward, California, lies atop the San Leandro block in the Hayward fault zone (HFZ), an active seismic zone composed of the Hayward Fault as well as numerous secondary, subparallel, subsidiary faults, including the Quaternary-active Chabot Fault (CF).

As part of an ongoing collaborative effort by CSUEB and the United States Geological Survey (USGS) to gain a high-resolution understanding of the HFZ, researchers from CSUEB and USGS conducted a seismic survey (SS2) on October 2015 on the CSUEB campus, subparallel to a previous survey (SS1) deployed across and centered on the mapped trace of the CF.

We deployed a 71-channel array, employing 14Hz and 4.5Hz geophones spaced at 5m to record P- and S-wave data, respectively.

S-wave sources were generated by a 3.5kg sledgehammer and shear-wave block; P-waves sources were generated by both 226kg accelerated weight drop as well as sledgehammer and steel plate.

2D tomographic images, including Vp, Vs, Vp/Vs, Poisson's Ration, MASW, and MALW, show a prominent low velocity zone, which we interpret as evidence of a water-saturated trace of the CF. Our results suggest a continuing trace of the CF underlies SS2, supported both by results from SS1 as well as previous geological mapping.

We will also obtain and compare seismic reflection images from both SS1 and SS2 in order to better understand the CF's local behavior across the CSUEB campus as well as a broader high-resolution understanding of the HFZ.

Shallow vs Structure of Subsidiary Faults in the Hayward Fault Zone Inferred from Multichannel Analysis of Surface Waves (MASW)

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The Hayward Fault zone (HFZ) includes the Hayward fault (HF), as well as several named and unnamed subparallel, subsidiary faults to the east, among them the Quaternary-active Chabot fault (CF), the Miller Creek fault (MCF), and a heretofore unnamed fault, the Redwood Thrust fault (RTF). With an ≥M6.0 recurrence interval of ~130y on the HF and the last major earthquake in 1868, the HFZ is a major urban seismic hazard in the San Francisco Bay Area, exacerbated by the many unknown and potentially active secondary faults of the HFZ. In 2016, researchers from California State University, East Bay, working in concert with the United States Geological Survey conducted the East Bay Seismic Investigation (EBSI). We deployed 296 RefTek RT125 (Texan) seismographs along a 15-km linear seismic array across the HF extending from the bay in San Leandro to the hills in Castro Valley. Two-channel seismographs were deployed at 100m intervals to record P- and S-waves, while additional single-channel seismographs were deployed at 20m intervals where the seismic line crossed mapped faults. The active source survey consisted of 16 buried explosive shots located at approximately 1-km intervals along the seismic line. We used Multichannel analysis of surfaces waves (MASW) method to create 2-D shear wave velocity models of the three sections on our seismic line that coincided with CF, MCF, and RTF. Preliminary MASW tomography show areas of anomalously low S-wave velocities coincident with these three mapped faults; additional velocity anomalies in our results suggest other unmapped faults within the HFZ.

Rayleigh-Wave Phase Velocity (VR40) based VS30 Estimates

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Shear-wave velocity profiles have traditionally been used to calculate VS30, the time-averaged shear-wave velocity (VS) in the upper 30 m. We propose the use of the Rayleigh-wave phase velocity at a wavelength of 40 m (VR40) to expedite the estimation of VS30 values. We, however, do not advocate circumventing the development of VS profiles, as site-specific response analyses require VS profiles. While VS profiles can be developed from invasive borehole recordings, they are often cost and environmentally prohibitive. By comparison, noninvasive active or passive surface-wave methods (SWM) cost less and have become popular as many believe that these surface-array based profiles are more representative of the average near-surface site conditions than results from vertical-array borehole methods. Reliable profiles from SWM, however, require considerable time to develop. We evaluate the reliability of directly using the fundamental-mode dispersion curve, the so-called site signature, which is typically derived from the VR spectrum processed from SWM. We follow Brown *et al.* (2000) and compare VS30 estimates from standalone, or combinations of, SWM with VR40 values for 175 sites measured by Yong *et al.* (2013). We find VR40-based VS30 values correlate well with those derived from SWM ($r^2 = 0.99$). Moreover, VR40 values can be readily derived using a single-source two-receiver spacing configuration, thus facilitating rapid data collection. It is also beneficial to use VR40 values as a means to rapidly prescreen the subsurface for lateral velocity variability or to supplement data where there are insufficient records. For microzonation purposes, VR40 values can also be used to densify sparse distributions of profile-based VS30 point values. Nevertheless, direct reliance on VR40 values as the standalone approach is not recommended because a complete dispersion curve is necessary to confirm that the VR40 parameter was indeed derived from the fundamental mode.

Novel Approaches to Understanding Active Volcanoes

Poster Session · Tuesday 18 April ·

Investigating the Relationship Between Deep Long-Period and Deep High Frequency Seismicity at Mammoth Mountain, California, 2012–2014

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Deep long-period (DLP) earthquakes are a relatively common, though poorly understood, type of seismicity observed at volcanoes worldwide. They are thought to be related to the movement of magma and exsolved gases as they work their way to the surface from the mantle, and may be among the first indicators of volcanic unrest and potential eruption. Mammoth Mountain, situated on the southwestern boundary of Long Valley Caldera, California, has been especially prolific in DLP seismicity, with long-lived swarms in 1989, 1997–1998, and 2012–2014 at a depth of 8–20 km. We focus on the most recent swarm, the onset of which was coincident with a nearby high-frequency swarm a few kilometers deeper. Both swarms occurred during a temporary deployment of 11 additional broadband seismometers at Mammoth Mountain, which can provide improved sensitivity and location accuracy. The potential relationship between these swarms based on their spatiotemporal coincidence suggests an opportunity to investigate the underlying physical mechanism(s). We use waveform cross-correlation techniques to improve the catalog's completeness and better isolate individual clusters of repeating sources, then use these additional observations to clarify each swarm's structure in space and time with precise relative relocations.

Monitoring of Oregon and Washington Cascade Volcanoes: In a Time of Quiescence

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Despite the apparent quiescence of the Cascade Range, eight volcanoes in Oregon and Washington have been classified as very high-threat by the 2005 National Volcano Early Warning System (NVEWS) threat assessment and require a commensurate level of monitoring to provide awareness of potential volcanic activity and enhance public safety. The U.S. Geological Survey/Cascade Volcano Observatory (USGS/CVO) is responsible for monitoring the activity of these volcanoes. Over the last 10 years CVO has upgraded and expanded its monitoring capabilities significantly, adding over 50 stations throughout the Cascade Range. Despite these improvements, only Mount St. Helens and Newberry Volcano meet the NVEWS criteria in full. The volcano networks operated by CVO consist of a diverse array of stand-alone and co-located monitoring instrumentation (seismic, deformation, gas, and infrasound). Data from these networks are telemetered in real-time and near-real time to the Observatory, where they are archived, processed, and analyzed to assess levels of volcanic activity and conduct volcanological research. Monitoring in times of quiescence provides evidence of background behavior and an opportunity to build conceptual models of these volcanoes to help recognize and interpret periods of unrest. CVO is continuously working towards developing more reliable and robust monitoring stations, expanding the existing networks, and establishing new networks at under-monitored very high-threat volcanoes. Expanding our monitoring networks promotes accurate and timely forecasts and alerts to maintain public safety and hazard mitigation by allowing us to detect very subtle changes in volcanic behavior prior to an eruption. Our monitoring networks also act as a backbone for more detailed temporary experiments that are necessary to push forward our understanding of volcano structure and process.

Searching for Correlations between Seismicity and Volcanic Eruptions for Improved Eruption Forecasting

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Eruption forecasting commonly relies on comparison between patterns in seismicity and historical activity at analogous volcanoes worldwide. However, such comparisons are often performed in an ad-hoc fashion and assessments are highly dependent on the knowledge and experience of the group of experts involved. Rapid statistical assessment of pattern similarity is not currently feasible. The USGS Volcano Disaster Assistance Program is building an Eruption Forecasting Information System (EFIS) to address common forecasting questions statistically using global data. This effort relies heavily on local monitoring and eruption chronology data for analysis. Unfortunately, detailed local data from many eruptions are not accessible, limiting global analysis. Global earthquake data from the International Seismic Centre and eruption data from the Global Volcanism Program are readily available, but these databases lack important details regularly cataloged by volcano observatories. In this study, we search for patterns between precursory seismicity and volcanic activity using these global datasets. We then illustrate the improvements to forecasting that may be possible by using a more complete local monitoring and eruption chronology dataset from the Alaska Volcano Observatory, now populated in the EFIS database. The former analysis allows us to obtain global statistics for use in forecasting, but the usefulness is reduced by the lack of local seismic and detailed chronology data. In the latter analysis, we can answer more specific forecasting questions, but the results are regionally limited to Alaska and may not be representative of global activity. The inclusion of more local monitoring and chronology data into EFIS will continue to improve our ability to forecast eruptions globally. We plan the addition of more local data into EFIS as we progress toward more complete and rigorous assessments of seismicity preceding volcanic activity worldwide.

Hydroacoustic Observations of Recent Submarine Eruptions at Ahyi and Bogoslof Volcanoes

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Submarine volcanic eruptions are poorly understood, challenging to detect, and difficult to evaluate in real-time. Two recent submarine eruptions at Ahyi Volcano in the Northern Mariana Islands and Bogoslof Volcano in Alaska demonstrate the need for improved monitoring, both by hydrophones in the ocean and seismometers on land. Hydrophones are preferable, since hydroacoustic waves are readily generated by underwater eruptive activity and propagate over a long range. Seismic T-phases measured on land are a secondary option due to variable efficiency of ocean-land coupling.

In late April 2014, Ahyi Volcano ended a 13-year-long period of repose with an explosive eruption lasting over 2 weeks. Quantitative error estimates provided by the CTBTO on the backazimuth of hydroacoustic arrivals at Wake Island (IMS station H11) were critical to quick identification of eruptive activity at Ahyi. T-phases registered across the NMI seismic network at the rate of approximately 10 per hour until May 8 and were observed sporadically until May 17. They were also identified at Guam and Chichijima seismic stations. Comparison of pre- and post-eruption bathymetry at Ahyi revealed a new scoured-out landslide chute extending SSE from the crater downslope to a depth of at least 2300 m

Bogoslof Volcano began erupting in mid-December 2016 and continues as of January 2017. Several episodes of hydroacoustic wave generation have occurred during the eruption. For example, an explosive eruption on January 9, 2017 generated T-phases that registered on a seismometer at Tanaga Volcano over 700 km away. From bathymetry data, we identified a possible T-phase conversion zone north of Tanaga within 10 km of the seismometer. Volcano-tectonic earthquakes at Bogoslof have also been accompanied by T-phases. Compared with Ahyi, hydroacoustic propagation at Bogoslof is more complex due to the presence of a shallow polar half channel in the Bering Sea during winter and the lack of a deep sound duct.

Seismic Observations of a Lava Delta Collapse at Kīlauea Volcano, Hawai'i

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When lava enters the ocean, it quenches into variable-sized fragments that accumulate in metastable layers at the angle of repose on the submarine slope. Over time, an unstable fan-shaped lava delta composed of pāhoehoe is constructed subaerially on top of this rubbly substrate, extending up to hundreds of meters beyond the shoreline. These deltas can collapse in hazardous submarine landslides. Dozens of significant lava delta collapses have occurred during the ongoing Kīlauea East Rift Zone eruption since lava first entered the ocean in 1986.

We report seismic observations from a lava delta collapse that occurred incrementally over an 8-hour period on 1 January 2017 UTC, when an area 25 acres in size fell into the ocean. The event resulted in a temporary closure of the Kamokuna ocean entry area within Hawai'i Volcanoes National Park. USGS Hawaiian Volcano Observatory (HVO) seismic stations provided short period and broadband recordings of at least a dozen discrete collapse events, some of which correlate with eyewitness accounts of explosions, landslides, and abnormal ocean waves. Each event has a composite character that begins with a high frequency (6–20 Hz) onset followed by lower frequency (0.6–2.1 Hz) coda lasting up to a minute in duration. Signals recorded on coastal stations to the west tended to have stronger arrivals and longer codas compared to inland stations to the north, which could be related to source or network geometry. HVO's tremor detection system (Wech and Thelen, 2015) found over 100 possible long-period sources near the delta over several hours leading up to and following the collapse. However, we did not see signals on three infrasound arrays located between 20 km and 40 km away.

Further characterization of these signals and tuning of automated detectors may help provide better understanding of the mechanisms behind lava delta collapses and possibly provide advance notice of impending collapses.

Analysis of the Seismicity Occurred in the Volcano of San Miguel in the Years 2013 and 2014

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San Miguel volcano is a stratovolcano 2130 m.a.s.l, is located east of the Salvadoran volcanic arc, just 11 kilometers from the city of San Miguel, the third most populated city in the country. Its most recent eruption occurred on December 29, 2013.

Earthquakes that occurred in this period were located at the northern and northwestern flank of the volcano with a depth less than 5 km. Their location in agreement with escarpments of ancient lavas flows and faults with northwest-southeast direction crossing the volcano, indicating that the seismicity is probably related to the local fault system.

By analyzing the spectral content and waveform of a sample of earthquakes, four main types of events are found: volcano tectonic (VT), hybrids, long period (LP) and explosions, whose swarms marked both pre and post eruptive stages. These kinds of events are related to the fracturing of rocks, fluid injection and gaseous magma rising through the ducts of the volcano.

The b value of the located earthquakes was calculated using the Gutenberg -Richter relationship, finding b values greater than 1.0 which is typical for volcanic areas. Higher values are for the year 2014, which could indicate a greater flow of heat, which was evidenced by an increment of fumarolic activity after the eruption.

KivuSNet: A Broadband Seismic Network for the Lake Kivu and Virunga Volcanic Region, Democratic Republic of the Congo

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The Kivu Basin is located in the bordering region of the Democratic Republic of Congo and Rwanda, in the Western branch of the East African Rift. Here the active volcanoes Nyamulagira (the most active in Africa) and Nyiragongo (host to the largest persistent lava lake on Earth) threat the city of Goma and neighbouring agglomerations. For many years already, urbanisation in that region undergoes sustained rapid growth, and Goma counts 1 million inhabitants today. In 1977 and 2002, eruptions of Nyiragongo caused major disasters. Destructive earthquakes can also affect the region, as was the case in 2002 in Kalehe (M_w 6.2) along the western shore of Lake Kivu, or in 2008 in Bukavu (M_w 5.9), south of Lake Kivu. At the same time, until recently modern seismic monitoring infrastructure was lacking in the area, leaving many aspects about the volcanic activity and seismicity up to speculations.

In the framework of several Belgo-Luxembourgish collaborative research projects (the most recent one being RESIST: "Remote Sensing and In Situ Tracking of geohazards", funded by the Belgian Science Policy and the Luxembourg National Research Fund), we deployed the first dense real-time telemetered broadband seismic network in the region, with the first two stations in 2012 and 2013. It is now a network of 15 stations and still under continuous development. Many KivuSNet stations are co-located with GNSS KivuGNet stations, and three KivuSNet sites are in addition equipped with infrasound arrays.

We present an introduction to the key features of the network and an overview of the first scientific results, including unprecedented insights into tectonic and volcanic seismicity patterns and initial structural investigations (1D velocity model determination). KivuSNet opens a new window for the state of knowledge on the seismic and volcanic activity in this highly threatened region and represents an indispensable tool for monitoring operations of the Goma Volcano Observatory.

Diverse Long Period Tremors and Their Implication on Degassing and Heating inside Aso Volcano

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Long-Period Tremors (LPTs) are frequently observed and documented in many active volcanoes around the world, Typically, LPTs are in the period range of 2-100 seconds and total duration of 300 seconds or less. In many instances, LPTs in different volcanic settings are repetitive, but time-invariant in their location, frequency content and waveform shape, suggesting a nondestructive source and providing critical insights into the fluid-dynamic processes operating inside a volcanic system. However, the diversities of LPTs in a single volcanic system are not necessarily well understood and they could potentially provide a clue on the interplay between volcanic degassing, magmatic heating and the style of upcoming eruption.

To explore possible diverse LPT behavior in a volcanic system, we investigate LPTs in Aso-san, one of the most well studied and active volcanoes in the southwest Kyushu, Japan. We carry out systematic analysis of continuous seismic data (2011-2016) operated at V-net by NIED and JMA Volcanic Seismic Network, covering the interval where Aso-san experiences diverse behaviours, including long period of quiescence, phreatic eruption, Strombolian-type eruption and phreatomagmatic eruption.

We use LPT waveforms identified in previous studies as templates and cross-correlate them against the entire dataset in the wavelet domain to construct LPTs catalog. However, LPTs with different phase, but similar frequency content and location are also retained to examine possible temporal changes in the characteristics of LPTs. Through waveform cross-correlation and stacking, we identify four types of LPTs that are located in close proximity as those identified in prior studies, but they display diverse waveform polarity and shape. We will present waveform semblance analysis and moment tensor inversion of these LPTs and discuss how their frequency, amplitude and energetics may be indicative of the state of degassing and magmatic heating inside the Aso volcano.

Analysis of Deep Long-Period Seismicity from a Subglacial Volcano in Marie Byrd Land, Antarctica

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We utilize subspace detection methodology to extend the detection and analysis of deep, long-period seismic activity associated with the subglacial and lower crust magmatic complex beneath the Executive Committee Range volcanoes of Marie Byrd Land (Lough *et al.*, 2013). Marie Byrd Land (MBL) volcanic province is a remote continental region that is almost completely covered by the West Antarctic Ice Sheet (WAIS). The southern extent of Marie Byrd Land lies within the West Antarctic Rift System (WARS), which includes the volcanic Executive Committee Range. In 2013, stations in the POLENET/ANET seismic network detected two swarms of seismic activity during 2010 and 2011. These events have been interpreted as deep, long-period (DLP) earthquakes based on their depth (25-40 km), tectonic context, and low frequency spectra. The DLP events in MBL lie beneath an inferred volcanic edifice that is visible in ice penetrating radar, and have been interpreted as a present location of Moho-proximal magmatic activity. The magmatic swarm activity in MBL provides a promising target for advanced subspace detection, and for the temporal, spatial, and event size analysis of an extensive deep long period earthquake swarm using a remote and sparse seismographic network. We utilized a catalog of 1370 traditionally identified DLP events to construct subspace detectors for the nine nearest stations and analyzed two years of data spanning 2010-2011. Via subspace detection we increase the number of observable detections more than 70 times at the highest signal to noise station while decreasing the overall minimum magnitude of completeness. In addition to the two previously identified swarms during early 2010 and early 2011, we find sustained activity throughout the two years of study that includes several previously unidentified periods of heightened activity. These events have a very high Gutenberg-Richter *b*-value (>2.0). We also note evidence of continuing seismicity through 2015.

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

Poster Session · Tuesday 18 April ·

Three-Dimensional High-Performance Computing Simulations of Near-Fault Earthquake Ground Motions for Engineering Applications: Large Generic Events and Scenarios in the San Francisco Bay Area

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We are performing earthquake ground motion simulations for engineering applications with emphasis on near-fault hazard. Applications include steel moment-frame building response using structural mechanics simulations and coupled soil-structure interaction simulations. Consequently, applications require that we compute realistic motions with frequencies up to and above 5 Hz. To compute fully deterministic ground motions in realistic three-dimensional (3D) Earth models with sufficient frequency content we are running simulations on massively parallel computers using ~100,000 cores. Simulations are performed for generic large (MW 6.0-7.5) earthquakes in canonical 3D Earth models (1D hard rock, 3D open basins including stochastic heterogeneity) as well as specific scenario ruptures for the San Francisco Bay Area (*e.g.* Hayward, Rodgers Creek, Calaveras and Greenville Faults) using the United States Geologic Survey 3D model of the region. Earthquake rupture models are created with the Graves and Pitarka (2016) rupture generator. Ground motions in the near-fault region (<30 km) are computed with SW4, LLNL's 3D anelastic finite difference seismic wave propagation code based on the summation-by-parts principle. SW4 has many desirable features for earthquake simulations including attenuation, mesh refinement and surface topography. Simulations of ground motions on a dense grid of points are compared quantitatively with Ground Motion Prediction Equations (GMPEs). Results so far show good agreement with GMPEs. For the 1D hard rock model spectral accelerations are within the bounds of four Next Generation Attenuation (NGA-2 West) project models. For 3D Earth models, we show that the spread of spectral accelerations increases comparable to or greater than that predicted by NGA-2 West GMPEs. We are working on additional ground motion intensity measurements to characterize simulated motions.

Performance of the Source Physics Experiment (SPE) Geological Framework Velocity Model with Stochastic Heterogeneity in Modeling SPE-6 Far-Field Waveforms

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Analysis of recorded waveforms from the Source Physics Experiment (SPE) and high frequency ground motion simulations using a preliminary velocity model have revealed the implication of underground structure in generation and propagation of shear waves during underground chemical explosions at the SPE site.

Here we investigate the performance of the Geological Framework Velocity Model (GFM) and its variants produced with different realizations of stochastic heterogeneity (GFM-S) in high-performance computing of broadband ground motion recorded during the sixth SPE chemical explosion (SPE-6). GFM is constrained by available geological and geophysical data. However, the crude representation of unknown small-scale structural heterogeneity diminishes its performance in high frequency wave propagation modeling. We applied a cross-correlation technique to LargeN dense array data recorded during the SPE-6 shot to infer statistical properties of structural heterogeneity in the upper sedimentary layers of the Yucca Flat basin. The statistical properties were used to constrain small-scale stochastic velocity perturbations that were added to the GFM to create the GFM-S model. Using several realizations of GFM-S with different stochastic velocity perturbations, we performed sensitivity analysis of the far-field motion to strength and correlation length of structural heterogeneity by performing physics-based simulations that combine hydro-regime modeling of the near-field motion from a chemical explosion source with far-field elastic modeling of wave propagation in the frequency range 0.1-15 Hz. Effects of wave scattering and velocity model uncertainty on the quality of SPE-6 simulated waveforms, in particular the amplitudes of P, S and Rg waves, at the largeN and radial linear arrays stations, will also be shown.

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Modeling Earthquakes and Source Physics Experiment Broadband Recordings at Regional Distances: Effects of Multiple Basins

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We use recent Source Physics Experiment (SPE) conventional explosions at the Nevada National Security Site (NNSS) and local earthquakes to investigate the effects of local and regional basin structure on regional broadband waveforms. The SPE series has been conducted in granite in northeast NNSS. We hypothesize that Rg waves in Nevada do not build to the expected amplitudes for explosions because their energy is trapped within deep Tertiary volcanic and sedimentary basins, that tend to convert Rg into regional Love waves. We compare low-frequency synthetics to recordings at regional distances. Lawrence Livermore Lab's SW4 v1.1 code and UNR's Model Assembler v6.0 model the SPE-5 and SPE-6 blasts with simple sources, initially at a central frequency of 0.2 Hz. Model inputs include gravity-derived basin-thickness maps and an average density vs. depth profile for the Basin and Range, NSL database geotechnical measurements, a Nevada-average earthquake-location velocity model, velocity-Q relationships derived for the LA basin, and geotechnical velocities from the Clark County Parcel Map. Basin thickness and geotechnical velocities are the only 3D components of the model. Incorporating local basin structure into our model produces low-frequency synthetics that can fit the SPE and earthquake data at regional distances, including path effects from numerous basin structures. Rg waves in the SPE synthetics are highly variable in their amplitude and duration, depending heavily on station azimuth and proximity to basin edges. There is evidence of additional strong phases such as basin-side reflections of surface waves. SPE synthetic energy can be trapped within the volcanic and sedimentary basins having thicknesses up to 8 km, converting blast energy to Lg waves. Planned tests include comparisons to other velocity models, higher-frequency modeling, full-wave inversion to refine model features, and modeling of small to moderate earthquakes in the region.

Modeling Topographic Effects and Site Response for Strong Ground Motions at Los Alamos National Laboratory, New Mexico.

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The goal of this study is to build physics-based models of topography and site effects for strong ground motions at Los Alamos National Laboratory, New Mexico. This work is part of an ongoing effort to characterize seismic hazard for this area that is controlled by a nearby normal fault system (Pajarito fault system). The area is characterized by a complex subsurface geology consisting of successive basalt, volcanic ash and sedimentary deposits cut by steep canyons as a result of erosion.

Our modeling first uses a 3D finite element method in order to reproduce observed topographic effects. The University of Texas deployed Ten Trillium Compact broadband seismometers and collected passive and active seismic data in the summer of 2014. Sensors were deployed in two crossing profiles that spanned the top and three sides of a ~50 m high and 180 m wide mesa with a east-west elongated shape. Spectral analysis gives evidence of a strong topographic amplification of the passive data, reaching a high-level (factor of 5) at a frequency of about 1.7Hz. We constructed a 3D local model, extending to a depth of about 1.5km around the topographic feature, using a large geological and geophysical database collected to build a 3D structural model for geohydrology modeling. We use the software, SPECFEM3D to model ambient noise propagating in that model. SPECFEM3D is based on the Spectral Element Method (SEM) that is a high-order finite element method with a remarkable low computational load. In this paper, we will present comparison between the modeling results and the data.

We will also present results of modeling surface peak ground motion and spectral response of higher-frequency signals amplified when propagating through tuffs and top soil, characteristic of the local geology. For this, we use Random Vibration Theory (RVT). Comparison of results of the SPECFEM3D and the 1D RVT are used to isolate the effects of plane layer site amplification and 3D topography.

A Vs30-Dependent Sediment Velocity Model for High-Frequency Simulated Ground Motions in the Los Angeles Basin

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The near-surface soil layers of sedimentary basins play a critical role in modifying the amplitude, frequency and duration of earthquake ground shaking. These phenomena, referred to as site effects, play a very important role in ground-motion simulations, in the development of site amplification factors, and more generally in earthquake hazard and risk predictions on a regional scale. In this study, we develop a sediment velocity model (SVM) that translates Vs30, the only proxy available to describe the stiffness of the near surface sediments, into a generic velocity profile suitable for use in wave propagation-based ground motion models. We specifically develop a Vs30-dependent shear wave velocity model (previously referred to as Geotechnical Layer or GTL), based on the statistics of nearly a thousand measured velocity profiles with Vs30 ranging from 150 m/s to 1000 m/s. We validate the model by comparing the site amplification factors of the measured profiles and the SVM. We lastly develop and demonstrate the implementation of a spatially correlated random realization algorithm, intended to populate the near surface of the 3D UCVM domain with our SVM. The next step of this work is to use the profiles to improve high-frequency predictions of 3D physics-based ground motion simulations; and to develop Vs30-dependent amplification factors for implementation in the SCEC broadband platform.

Simulation on Strong Ground Motion of Xiaojiang Fault Zone

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Xiaojiang fault zone is an important active fault zone in the southern segment of the South-North Seismic Belt in China, and the main body is located in the Yunnan Province. It is a lithospheric seismic zone with high risk of large earthquakes and possible concatenation rupture mode. First, Xiaojiang fault zone is divided into four sections in this study: the Dongchuan section of Xiaojiang fault(N1), the west branch of Xiaojiang fault(N2), the north section of east branch of Xiaojiang fault(N3), and the south section of east branch of Xiaojiang fault(N4). Second, Xiaojiang fault characteristic source model is based on the empirical relationship. The parameters of the internal source determined that the asperity was mainly composed of one big and two small, the ratio of the asperity was 0.2. The rupture velocity is 2.8km/s. The initial rupture direction was selected in three ways, from south to north, from north to south, and bilateral rupture. 16 different schemes of different source rupture process are set to analyze the ground motion distribution by 3D the finite difference method(GMS). Last, numerical simulations results indicated that, (1) In N1+N2(N12) case, Qiaojia, Dongchuan, Songming, Xundian, Yiliang and Chengjiang will be affected by large ground motions. The ground motion of Songming, Chengjiang and Kunming in N13 case is less than that of fault N12. In N123 case, the ground motion of area between the east branch and west branch of the Xiaojiang fault zone is obviously increased. In N1234 case, the maximum value and the maximum range of strong motion are generated. (2)each city began to suffer strong earthquake impact time are different, such as Dongchuan 15s, Qiaojia 17s, Songming 35s, Kunming 50s etc. (3)In N1234 case, the magnitude may reach M_w7.8, the duration of ground motion may exceed 100s and the peak ground velocity may reach 642cm/s. Overall, it has a little theoretical and application value on emergency preparedness and disaster mitigation.

Sedimentary Basin Amplification in the Puget Sound and Willamette Valley Regions: Observations from Local Earthquakes and 3D Simulations

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Sedimentary basins in the Puget Sound region, Washington State and Willamette Valley, Oregon can increase ground motion intensity and duration of shaking of local earthquakes. Frankel *et al.* (2009) showed clear evidence of amplification in the Seattle basin due to S-wave focusing, conversion of S-waves to surface waves by the southern basin edge bounded by the Seattle fault zone, and directional dependence of amplification on source location. We calculate spectral ratios from recordings at Pacific Northwest Seismic Network and U.S. Geological Survey stations for local earthquakes with varying magnitudes, depths, and azimuths to compare the amplitudes of seismic waves at basin stations to sites outside the basins. Amplification factors from spectral ratios are plotted on regional maps to study their spatial distribution. We model a set of local earthquakes (M3.7- 6.8) using the 3D finite-difference method and the latest revision of the 3D Cascadia velocity model (Stephenson, 2007), comparing observed and synthetic waveforms up to a frequency of 1 Hz. Preliminary results show peak amplitudes and S-wave and surface wave arrivals are fairly well matched. Synthetics also exhibit complex basin phases we see in observations. The goal of this project is to characterize and model sedimentary basin effects within the Seattle basin in Washington and the Tualatin and Portland basins in Oregon to improve estimates of ground shaking from future large earthquakes in the region, which is critical for mitigating seismic hazard near major metropolitan centers.

Exploring the Implementation of an Equivalent Linear Method in 3D to Approximate Nonlinear Response in Regional Ground Motion Simulation

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Nonlinear soil effects during earthquakes are important because they can change considerably the characteristics of wave propagation through sediments, and thus alter the expected levels of ground motion. While much progress has been made on earthquake simulation, this has been mainly limited to linear anelastic conditions, and the simulation of nonlinear behavior on a regional scale remains a challenging task. The main obstacles in nonlinear modeling are the numerical representation of material behavior and the associated computational demands. Despite recent efforts, three-dimensional (3D) nonlinear effects in sedimentary basins are far from being well understood. In this study we explore the implementation of an equivalent linear method adapted to 3D problems using a finite element approach to modeling ground motion in large basins. While the limitations of the equivalent linear method in both one- (1D) and two-dimensional (2D) are well-known and cannot be ignored in a detailed analysis, this is an approach that lends itself practical in engineering applications. However, to our knowledge, no 3D implementation has been tried before. The main obstacle here is defining the strain level used to set the elastic modulus based on predefined degradation curves and the associated changes in damping, which are the controlling parameters of the equivalent linear method. Unlike in the 1D and 2D implementations in which these parameters can be limited to shear deformation, in 3D further approximations and assumptions are necessary. In this study we explore the implementation of an equivalent linear method in 3D, through application of different combinations of strain level in the strain tensor. We validate our implementation indirectly via comparisons with results from other nonlinear simulation implementations. The potential strain combination could be dependent on different parameters, including the characteristics of earthquake, which we also explore in this study.

3D Dynamic Rupture Simulations along the Wasatch Fault, Utah, Incorporating Rough-Fault Topography

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Studies have found that the Wasatch Fault has experienced successive large magnitude (>M_w 7.2) earthquakes, with an average recurrence interval near 350 years. To date, no large magnitude event has been recorded along the fault, with the last rupture along the Salt Lake City segment occurring ~1300 years ago. Because of this, as well as the lack of strong ground motion records in basins and from normal-faulting earthquakes worldwide, seismic hazard in the region is not well constrained. Previous numerical simulations have modeled deterministic ground motion in the heavily populated regions of Utah, near Salt Lake City, but were primarily restricted to low frequencies (~ 1 Hz). Our goal is to better assess broadband ground motions from the Wasatch Fault Zone. Here, we extend deterministic ground motion prediction to higher frequencies (~ 5 Hz) in this region by using physics-based spontaneous dynamic rupture simulations along a normal fault with characteristics derived from geologic observations. We use a summation by parts finite difference code (Waveqlab3D) with rough-fault topography following a self-similar fractal distribution (over length scales from ~100 m to the size of the fault) and include off-fault plasticity to simulate ruptures > M_w 6.5. Geometric complexity along fault planes has previously been shown to generate broadband sources with spectral energy matching that of observations. We investigate the impact of varying the hypocenter location, as well as the influence that multiple realizations of rough-fault topography have on the rupture process and resulting ground motion. We utilize Waveqlab3's computational efficiency to model wave-propagation to a significant distance from the fault with media heterogeneity at both long and short spatial wavelengths. These simulations generate a synthetic dataset of ground motions to compare with GMPEs, in terms of both the median and inter and intraevent variability.

Ground Motion Variability and the Modeling of the Source of the 2011 Mw 5.2 Lorca Earthquake, SE Spain

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Spatiotemporal details of the rupture process show up mostly on near-field records, while the signature of the overall point-source earthquake mechanism appears on far-field signals. The variability of the ground motion is modulated by near- and far-field recording ranges, which depend on the earthquake size. This work analyzes the ground motion and the source-related near-field variability for the moderate magnitude (M_w=5.2) 2011 Lorca earthquake, in SE Spain, which produced localized significant damage. The wavenumber integration method is used to simulate the low-frequency content (up to 1 Hz), assuming four published source models which were obtained by inversion of geodetic or seismological data, or a combination of both. The variability of the ground motion considering each of the models is first estimated. The scatter in the simulated peak and spectral parameters is larger at the closest station (LOR) to the source, and decreases as the source to site distance increases where the finite-fault effects become negligible (more than about 50 km far from the source). The variability of the simulated PSV at 2s is within the motion predicted by the GMPE ± one sigma, except for the closest station and those affected by forward directivity effects. Similar behavior is observed in the simulated high-frequency seismograms, obtained by the empirical Green's Functions approach.

How to Anticipate Future Earthquake Characteristics on a Multi-Segmented Fault? A Practical Example of Dynamic Rupture Modeling to Evaluate the Maximum Magnitude

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When faced with complex network of faults in a seismic hazard assessment study, the first question raised is to what extent the fault network is connected and what is the probability that an earthquake ruptures simultaneously a series of neighboring segments. Physics-based dynamic rupture models can provide useful insight as to which rupture scenario is most probable, provided that an exhaustive exploration of the variability of the input parameters necessary for the dynamic rupture modeling is accounted for. Given the random nature of some parameters (hypocenter location) and the limitation of our knowledge, we used a logic-tree approach in order to build the different scenarios and to be able to associate them with a probability.

The methodology is applied to the three main faults located along the southern coast of the West Corinth rift. Our logic tree takes into account different hypothesis for: fault geometry, location of hypocenter, seismic cycle position, and fracture energy on the fault plane. The variability of these parameters is discussed, and the different values tested are weighted accordingly. 64 scenarios resulting from 64 parameter combinations were included. Sensitivity studies were done to illustrate which parameters control the variability of the results. Given the weight of the input parameters, we evaluated the probability to obtain a full network break to be 15 %, while single segment rupture represents 50 % of the scenarios.

These rupture scenario probability distribution along the three faults of the West Corinth rift fault network can then be used as input to a seismic hazard calculation.

The SCEC Broadband Platform: Open-Source Software for Strong Ground Motion Simulation and Validation

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The Southern California Earthquake Center (SCEC) Broadband Platform (BBP) is a carefully integrated collection of open-source scientific software programs that can simulate broadband (0-100 Hz) ground motions for earthquakes at regional scales. The BBP can run earthquake rupture and wave propagation modeling software to simulate ground motions for well-observed historical earthquakes and to quantify how well the simulated broadband seismograms match the observed seismograms. The BBP can also run simulations for hypothetical earthquakes, often referred-to as scenario simulations. In this case, users input an earthquake location, fault plane geometry and moment magnitude, a list of station locations, and a 1D velocity model for the region of interest, and the BBP software calculates ground motions for the specified stations.

The BBP scientific software modules implement kinematic rupture generation, low- and high-frequency seismogram synthesis using wave propagation through 1D layered velocity structures, 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 multiple alternative ground motion simulation methods, and software utilities to generate tables, plots, and maps. The BBP has been developed over the last six years in a collaborative project involving geoscientists, earthquake engineers, graduate students, and SCEC scientific software developers.

The SCEC BBP software can be compiled and run on recent Linux systems with GNU compilers. It includes six simulation methods, eight simulation regions covering California, Japan, and Eastern North America, and the ability to compare simulation results against empirical ground motion models (aka GMPEs). The latest version includes updated ground motion simulation methods, a site-effects module, and a suite of new validation metrics.

A Ground-Motion Prediction Equation for California Constructed Using an Artificial Neural Network

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I construct a ground-motion prediction equation in California with an artificial neural network model using data from the PEER NGA-West2 ground-motion database. Artificial neural networks provide an alternative to traditional regression approaches, especially as ground-motion prediction equations attempt to capture more complicated source, path, and site effects and as ground-motion datasets grow. Artificial neural networks offer a general methodology to capture complex relationships among input parameters that may be difficult to describe in traditional regression equations. Additionally, the models are relatively easy to specify and implement in applications because they mainly involve matrix-vector operations. Artificial neural networks have been applied extensively in computer vision, medical diagnosis, search engines, language translation, and spam filtering and are being applied to new disciplines, including ground-motion prediction, as tools become more widely available and accessible to domain scientists. I use the open-source tools Keras (https://keras.io/) and TensorFlow (https://www.tensorflow.org/) to construct an artificial neural network for ground-motion prediction and examine the effectiveness of various parameterizations and normalizations for site location. I also compare the features of the ground-motion prediction equation derived using this technique to previously published ground-motion prediction equations developed for California.

Accurate and Efficient Viscoelastic Finite-Difference Simulations in Realistic Media with Material Discontinuities: The Method and Application to the Mygdonian Basin

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The accuracy and efficiency of numerical simulations of seismic wave propagation and earthquake ground motion in realistic models strongly depend on discrete grid representation of the material heterogeneity and attenuation.

We have developed a new discrete representation of heterogeneous viscoelastic medium with material discontinuities for the FD modeling of seismic wave propagation and earthquake ground motion. An interface is represented by an averaged orthorhombic medium with the Generalized Maxwell body (GMB-EK) rheology. Anelastic coefficients of the averaged medium for a grid position are determined from quality factors for all 9 components of the matrix of the viscoelastic coefficients of the averaged orthorhombic medium. The FD scheme uses a coarse spatial distribution of the anelastic functions (memory variables)—an anelastic function corresponding to one relaxation frequency and stress-tensor component is distributed with a spatial period of 2h, h being a grid spacing. Our definitions of the anelastic functions and their spatial distribution account for all relaxation frequencies at any grid position of the anelastic function.

We analyze and compare accuracy of the viscoelastic modeling with respect to distribution of relaxation frequencies and determination of the anelastic coefficients for different Q(omega) laws. We propose the optimal procedure for a joint determination of the anelastic coefficients and distribution of the relaxation frequencies for an arbitrary Q(omega) law.

We demonstrate accuracy and computational efficiency of our method using numerous numerical tests against the discrete-wavenumber and spectral-element methods for canonical models and for the complex model of the Mygdonian basin near Thessaloniki, Greece.

Kinematic Rupture Generator Based on 3D Rough Fault Dynamic Rupture Simulations

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Spontaneous rupture simulations using geometrically-rough faults have been shown to produce realistic far-field spectra and comparable fits with GMPEs, but they are too computationally demanding for use with physics-based probabilistic seismic hazard analysis efforts such as the Southern California Earthquake Center CyberShake or Broadband Platforms. Here, we present our implementation of a kinematic rupture generator that mimics (at least in a statistical sense) the processes of rough-fault spontaneous rupture models that are responsible for generating realistic broadband sources. To this end, we analyze ~100 dynamic rupture simulations on strike-slip faults ranging from M_w 6.4–7.2. We find that our dynamic simulations follow empirical scaling relationships for inter-plate strike-slip events, and provide source spectra comparable with an ω^{-2} source model. To define our kinematic source model, we use an exponential source-time function parameterized in terms of slip, peak slip velocity, and rupture velocity. These parameters are represented by random fields whose distributional parameters are estimated from the dynamic rupture ensembles. Our method uses sequential Gaussian co-simulation to generate the random spatial fields using two-point statistics defined by a linear model of coregionalization. We incorporate a nested-model of linearly independent variogram basis functions to capture correlations at all scale lengths between all source parameters and the initial friction on the fault. Additionally, we introduce the variability observed in one-point statistics by defining a multivariate Gaussian random variable model. Finally, we show that ground motions calculated by the kinematic model have amplitudes and spectral content comparable with those of the dynamic rupture simulations.

Multicycle Dynamics of a 3D Strike-Slip Fault System with Bends

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A fault bend may serve as a favorable location to initiate or terminate an earthquake rupture. Fault geometrical complexities such as a fault bend are conceptualized as earthquake gates that control earthquake rupture behavior over multicycles. Previous 2D models of faults with bends demonstrate that stresses on faults significantly deviate from the assumption of uniform prestressess around the bend even after one dynamic event. These models show that the bend segment may fully or partially rupture or may not rupture at all, depending on rupture histories of the fault system. In this work, we extend 2D multicycle dynamic models to 3D. We build a fault system consisting of two planar fault segments and a linking bend segment. We explore the effect of the bend as an earthquake gate to control event size and rupture pattern, and the roles of 3D fault geometry and the free surface. The method consists of a viscoelastic solution for fault stresses during the interseimsic period and a spontaneous dynamic rupture for the coseismic process. The slip-weakening law is used in dynamic ruptures. Preliminary results show that normal stresses are reduced on the dilatational sides of the bend and are increased on the compressional sides of the bend, and favorable initiation locations are at the dilatational sides of the bend over multicycles. These results are consistent with previous 2D models. We also find large events in which the entire fault system fails actually consist of two ruptures. The first rupture initiates at the one dilatational side of the bend and propagates bilaterally. The rupture slowly ceases in the middle of the bend, while a second rupture is triggered at the other dilatational side of the bend. This second rupture also propagates bilaterally and stops in the middle of the bend. We work on model parameter spaces to explore possible rupture behaviors on the fault system.

Earthquake Cycle Simulations with Rate-and-State Friction and Nonlinear Viscoelasticity

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We have implemented a parallel code that simultaneously models both rate-and-state friction on a strike-slip fault and off-fault viscoelastic deformation throughout the earthquake cycle in 2D. Because we allow fault slip to evolve with a rate-and-state friction law and do not impose the depth of the brittle-to-ductile transition, we are able to address: the physical processes limiting the depth of large ruptures (with hazard implications); the degree of strain localization with depth; the relative partitioning of fault slip and viscous deformation in the brittle-to-ductile transition zone; and the relative contributions of afterslip and viscous flow to postseismic surface deformation.

The method uses a discretization that accommodates variable off-fault material properties, depth-dependent frictional properties, and linear and nonlinear viscoelastic rheologies. All phases of the earthquake cycle are modeled, allowing the model to spontaneously generate earthquakes, and to capture afterslip and postseismic viscous flow. We use a nonlinear power law rheology, which laboratory data indicates represents the lower crust and upper mantle. The effective viscosity is a function of the temperature profile and stress state, and therefore varies both spatially and temporally. We compare a set of models ranging from one in which the lower crust is dominated by bulk viscous flow to one in which the lower crust is effectively brittle, and discuss the results from each. Surprisingly, though the mechanism by which deeper deformation is accommodated varies, the resulting loading of the upper crust remains approximately identical, resulting in earthquakes with the same recurrence interval, nucleation depth, and surface slip. The postseismic surface deformation, however, can be used to differentiate the models.

Paleoseismology of Subduction Earthquake Cycles

Poster Session · Tuesday 18 April ·

Late Holocene Paleoseismology of Shuyak Island, Surface Deformation and Plate Segmentation within the 1964 Alaska M 9.2 Earthquake Rupture Zone

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Recent paleoseismological studies question whether segment boundaries identified for 20th and 21st century great, >M 8, earthquakes persist through multiple earthquake cycles, or whether smaller segments with different boundaries rupture and cause significant hazards. The smaller segments may include some currently slipping rather than locked. The 1964 Alaska M 9.2 earthquake was the largest of five earthquakes of >M 7.9 between 1938 and 1965 along the Aleutian chain and southcentral Alaskan coast that helped define models of rupture segments along the Alaska-Aleutian megathrust. The 1964 earthquake ruptured ~950 km of the megathrust, involving two main asperities focussed on Kodiak Island and Prince William Sound and crossed the Kenai segment, which is currently creeping.

Paleoseismic studies of coastal sediments currently provide a long record of previous large earthquakes for the Prince William Sound segment, with widespread evidence of seven great earthquakes in the last 4000 years and more restricted evidence for three earlier ones. Shorter and more fragmentary records from the Kenai Peninsula, Yakataga and Kodiak Archipelago raise the hypothesis of different patterns of surface deformation during past great earthquakes.

We present new evidence from Shuyak Island, towards the hypothesised north-eastern boundary of the Kodiak segment, to illustrate different detection limits of paleoseismic indicators and how these influence the identification of segment boundaries in late Holocene earthquakes. We compare predictions of coseismic uplift and subsidence derived from geophysical models of earthquakes with different rupture modes. The spatial patterns of agreement and misfits between model predictions and quantitative reconstructions of coseismic submergence and emergence suggest that no earthquake within the last 4000 years had a pattern of rupture the same as the 1964 earthquake.

Observations on the Distributions of Modern Benthic Diatoms to Improve Estimates of Past Coseismic Land-Level Changes, Humboldt Bay, California

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Previous paleoseismology studies at Humboldt Bay, California, at the southern end of the Cascadia subduction zone (CSZ), have provided stratigraphic evidence for past episodes of coseismic land-level changes attributed to rupture on the CSZ or along local structures. The stratigraphic evidence for coseismic deformation—abrupt contacts between buried marsh soils and overlying deposits—has been corroborated by changes in assemblages of diatoms across contacts of different ages and at several locations along the bay. Attempts to estimate absolute amounts of vertical coseismic land-level change based on diatom have included large errors, however, without accompanying detailed data on distributions of modern taxa with which to develop transfer functions and produce more precise results. A new dataset documenting the distributions of modern diatom species relative to tidal datums in Humboldt Bay provides the basis with which to reevaluate the record of past coseismic land-level changes in the area, reducing the errors for some estimates to less than 0.3 m. In addition to new observations on the distributions of individual taxa, the results show that evaluating modern diatom populations with the goal of specifically reconstructing paleoenvironments necessarily involves practical techniques for achieving the most useful results.

Evidence for Great Earthquakes of Variable Rupture Mode beneath Marshes of the Nehalem Estuary, Central Cascadia Subduction Zone

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After three decades of debate, consensus remains elusive about the rupture lengths, magnitudes, and frequency of past megathrust earthquakes at the Cascadia subduction zone. Along-strike correlation of coastal earthquake evidence has largely relied on the stratigraphic position of evidence within tidal wetland stratigraphic sequences and maximum-limiting 14C ages with errors of decades to hundreds of years. Numbers and times of lesser great earthquakes (~M8-8.8), which may have ruptured only a few hundred kilometers of the megathrust, are especially uncertain. Resolving such issues requires reconstructing megathrust history through comparison of precisely dated evidence at many sites along the subduction zone. Here we report a history of great earthquakes and accompanying tsunamis along the shores of the lower Nehalem River in northern Oregon. Our mapping of wetland stratigraphy in outcrops and cores illustrates difficulties in tracing abrupt contacts over distances sufficient to interpret them as evidence of coseismic subsidence during megathrust earthquakes. Despite the abundant sediment supply in this estuarine lowland, we found evidence of only 5 earthquakes in the past 3000 years. Diatom and foraminiferal analyses yield variable amounts of coseismic subsidence (~0 to ~0.7 m) marked by the three youngest contacts, implying differences in earthquake rupture extent and magnitude. Whereas our 14C ages on plant macrofossils date contacts more precisely than at most sites, correlating earthquake evidence from site to site remains uncertain. Comparison of OxCal-calculated age models for subsidence contacts at Nehalem with age models for other sites suggests three closely spaced earthquakes during 700–1200 cal yr BP, only two of which have been identified at Nehalem (~850 and ~1100 cal yr BP). If accurate, the comparison implies incomplete earthquake histories at many of Cascadia's coastal sites, perhaps due to minimal subsidence during lesser earthquakes.

Possible Structural Evidence for Heterogeneous Plate Coupling and Linkages to Geodesy and Paleoseismology, Cascadia Margin, USA

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The structure of the submarine Cascadia forearc can be divided into a number of distinct domains. The outer wedge in northern Oregon and all of Washington is a landward/mixed vergence wedge with low wedge taper, widely spaced folds, high pore-fluid pressure and mud volcanoes. This domain is separated from an older complex by a significant landward vergent splay fault, truncating older structures and suggesting a prior episode of frontal erosion during the Pliocene. A middle domain consisting of tight folds and intense deformation occupies much of the upper slope and shelf, but is heterogeneous along strike. Inboard of this domain where observed offshore, deformation is weak and in some cases transverse to the margin.

A boundary between the inner forearc and upper slope domains may represent a change in principal horizontal compressive stress from ~N-S (inboard) to ~ E-W (outboard), and may map the long-term downdip limit of significant interplate basal shear traction, consistent with scattered borehole breakouts and focal mechanisms. The updip boundary may be located approximately at the transition to the landward vergent domain.

Interplate coupling in GPS models is similar to the long-term structural evidence for strong coupling. The lack of coupling in several extending and lightly deformed regions is also matched in GPS and structural data. This suggests that locking heterogeneity is related to long-term forearc architecture, similar to observations in Sumatra (2004) and NE Japan (2011). The proposed stress boundary is not particularly well correlated to along-strike variability of co-seismic subsidence, possibly due to poor areal coverage of the coastal data, ambiguity of the subsidence data relative to expected subsidence profiles across-strike, long-term mismatch between strain accumulation and co-seismic slip. The coupling model is otherwise compatible with both onshore and offshore paleoseismic data and proposed segment boundaries.

Possible Sedimentary Evidence for Paleoearthquakes along the Northern Lesser Antilles: Preliminary Results from CASEIS16

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The Lesser Antilles subduction zone in the western equatorial Atlantic has a short historic record of earthquakes and little is known about the prehistoric record of great earthquakes and tsunami. The oblique convergence between the North America and Caribbean plates forms the Barbados Accretionary prism and may be a significant source of earthquake and tsunami hazard. The megathrust may be segmented due to the presence of several fracture zones in the subducting North America plate. In May and June of 2016, an international team of scientists conducted an oceanographic cruise aboard the N/O Pourquoi Pas? with a goal to evaluate the seismogenic potential of the megathrust by using the turbidite paleoseismology method.

We selected core sites using both newly collected and existing high resolution bathymetric and seismic reflection data. Core sites include isolated slope basins, slope canyons, the subduction trench, and turbidite channel and levee systems. Sites were chosen to optimize for (1) isolation from confounding factors like terrigenous storm generated sediment input, (2) site spacing to test for structural segment boundary determination, and (3) locations that have isolated sediment source areas.

Our team collected ~50 piston cores along the northern margin with lengths exceeding 30 m. We collected core geophysical data including gamma density, P-wave velocity, magnetic susceptibility, resistivity, color reflectivity, and color imagery for the cores. U-Channels were collected for rock magnetometer analyses. We interpret that the sedimentary facies include turbidites and homogenites interbedded with hemipelagites and tephra. Preliminary stratigraphic correlation analyses, using the core geophysical data, suggest that these cores may include a sedimentary record of earthquakes in the form of turbidites and homogenites. New seismic reflection data suggest that these earthquake related sedimentary deposits are widespread, spanning 100s of km.

Seismology Software Tools That Improve What We Do and How We Do It

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Seismology and GIS: USGS Near Real-Time Significant Earthquake and Earthquake Scenario GIS Feeds

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Until recently GIS accessibility to many USGS earthquake products has been limited to downloading shapefiles on an event by event basis. However, many consumers have requested the ability to view and analyze data for earthquakes in a more flexible and systematic manner using ArcGIS, Web-based GIS viewers, and Web Mapping Services (WMS). In response, the USGS Earthquake Program now provides GIS feeds that contain event, ShakeMap, and Did You Feel It? (DYFI) data for significant earthquakes that have occurred within the last month. The aforementioned feeds are updated every 15 minutes in near realtime. These services are accompanied by an aggregated map in ArcGIS Online which allows all users (including non GIS) to reference, query, and display feed data in customized formats. The event GIS service displays attributes associated with a given significant earthquake. The ShakeMap GIS service contains station and shaking data layers (intensity, peak acceleration, velocity, and spectral accelerations) as well as ShakeMap event metadata. The DYFI GIS service contains geocoded DYFI responses that are geographically aggregated into 1km and 10km boxes. All of these services promote RESTful data access to the geospatial features they contain. Users can query data in a variety of ways including by spatial extent or by leveraging a keyword search. The ability to download map tiles and extract specific features is also supported. Thus, ArcGIS users can take advantage of the ability to stack layers, for instance, placing ShakeMap contours or grids or reported intensities over their own data layers, such as, users' facilities, population, or infrastructure. The ArcGISOnline web map also gives much of this GIS functionality to any user via the browser. Most recently the USGS has undergone an effort to publish similar data for earthquake scenarios, and thus a GIS service feed is currently in development to support scenario users as well.

Integrated Research, Development, and Operations of USGS Real-Time Earthquake Shaking and Impact Information Systems: An Update

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USGS systems intended for near–real-time earthquake shaking and impact assessment are used widely for planning, response, financial decision-making, and scientific analyses. The diversity of applications and societal import of these systems mandates continual research and development as well as operational and delivery advancements. Recent enhancements include software modernization and uniformity, product development and integration, and building shaking and loss datasets for system testing and calibration. An update on integration of "Did You Feel It?", ShakeMap, ShakeCast, and PAGER systems is provided along with a description of ground failure probability calculations that augment real time shaking and loss estimates. Part of the development strategy is integrating the output of each system as input to the next: ShakeMap's intensity measure grid is the shaking input for the ground failure, PAGER, and ShakeCast computations, for example. Operationally, the product link is through the USGS Product Distribution Layer (PDL). Software Integration of these systems is being accomplished by refactoring the code into a common Python development protocol, which includes code management in GitHub, review by the development team, unit testing and system testing, and continuous integration. One can follow or contribute to the development through GitHub, or submit feature requests. Use of a common language has facilitated shared libraries including ground motion prediction equations (GMPEs) and other tools in GEM's OpenQuake hazard library. These recent developments have facilitated more rapid integration of scientific advancements in our hazard and loss algorithms, such as a switch to multiply-weighted GMPEs, inclusion of source directivity models, spatial variability, and advanced engineering building modules for loss modules. A side benefit of software uniformity is a greater depth of expertise among our team for development and operational proficiency on these systems.

ISC-EHB: Reconstruction of the EHB Earthquake Database

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The EHB database, originally developed with procedures described by Engdahl, Van der Hilst and Buland (1998), currently ends in 2008. The aim is to expand and reconstruct the EHB database, in collaboration with the International Seismological Centre (ISC), to produce the ISC-EHB. We begin with events in the modern period, 2000-2014, and apply new and more rigorous procedures for event selection, data preparation, processing, and relocation.

The ISC-EHB criteria selects events from the ISC Bulletin which have more than 15 teleseismic (> 280) time defining stations, with a secondary teleseismic azimuth gap of < 1800, and a defining prime magnitude > 3.75 (Di Giacomo and Storchak, 2016). These criteria minimize the location bias produced by 3D Earth structure, and select many events that are relatively well located in any given region.

There are several processing steps; (1) EHB software relocates all the events using the ISC location and depth as the seed; (2) Near station and secondary phase arrival residuals are reviewed and a depth is adopted or assigned according to best fit, and in some instances depths may be reassigned based on other sources (*e.g.*, USGS broadband depths); (3) All events are relocated with their new depths and plotted in subduction zone cross sections, along with events from the ISC-GEM catalogue for comparison; and (4) These plots are used to confirm or modify weakly constrained depths.

The new ISC-EHB database will be most useful for global seismicity studies and high-frequency global tomographic inversions. This will be facilitated by online access to the ISC-EHB Catalogue and Bulletin via the ISC, and will include maps and cross sections of the seismicity in subduction zones. Example maps and cross sections for events in the years 2000-2003 will be presented.

ShakeMap 4.0

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In 2017, we expect to release version 4.0 of ShakeMap, the USGS's post-earthquake information tool. Here we discuss several new features anticipated in this upcoming version of ShakeMap. Version 4.0 is being refactored in the Python programming language and is a major redesign of the entire ShakeMap system. Moving the code base to Python allows us to take advantage of the many tools introduced by the large scientific Python development community, as well as extensive libraries for mapping and vectorized math. The use of Python also allows us to seamlessly integrate with the GEM OpenQuake (OQ) HazardLib library of seismology software tools—most notably an expansive set of ground motion prediction equation (GMPE) modules. The use of the OQ modules frees our team from the need to develop and maintain an ever-growing library of these often-complicated models, and leverages the substantial efforts of the OQ team. Using the OQ modules, we have developed a tool for combining multiple, weighted GMPEs in a way that is more consistent with probabilistic seismic hazard maps. ShakeMap 4.0 also employs a new ground-motion interpolation scheme based on conditional multivariate normal distribution, providing a significant improvement in modeling ground motions and uncertainty by fully accounting for the correlation between observations. The well-established conditional mean spectrum approach, with new modifications to allow for multiple conditioning periods, means ShakeMap can produce ground-motion maps at additional spectral periods. Additionally, new, more flexible, fault rupture representations, version 2 of the strike-parallel and strike-normal coordinate system (*i.e.*, GC2 by Spudich and Chiou), and the new directivity models will be supported in ShakeMap 4.0. We are also introducing new median-distance adjustment factors, which are a function of magnitude and tectonic environment, for estimating rupture distances for events without rupture models.

Products and Services Available from the Southern California Earthquake Data Center (SCEDC) and the Southern California Seismic Network (SCSN)

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The Southern California Earthquake Data Center (SCEDC) archives continuous and triggered data from nearly 10578 data channels from 528 Southern California Seismic Network recorded stations. The SCEDC provides public access to these earthquake parametric and waveform data through web services, its website scedc.caltech.edu and through its client application STP. This poster will describe the most recent significant developments at the SCEDC.

The SCEDC now provides web services to access its holdings.

Event Parametric Data (FDSN Compliant): http://service.scedc.caltech.edu/fdsnws/event/1/

Station Metadata (FDSN Compliant): http://service.scedc.caltech.edu/fdsnws/station/1/

Waveforms (FDSN Compliant): http://service.scedc.caltech.edu/fdsnws/dataselect/1/

Event Windowed Waveforms, phases: http://service.scedc.caltech.edu/webstp/

In an effort to assist researchers accessing catalogs from multiple seismic networks, the SCEDC has entered the earthquake parametric catalog into the ANSS Common Catalog (ComCat).

The SCEDC data holdings now include a double difference catalog (Hauksson et. al 2011) spanning 1981 through 2016/09 available via STP, and a corresponding focal mechanism catalog (Yang *et al.* 2011).

As part of a NASA/AIST project in collaboration with JPL and SIO, the SCEDC now archives and distributes real time 1 Hz streams of GPS displacement solutions from the California Real Time Network.

The SCEDC has implemented the Continuous Wave Buffer (CWB) to manage its waveform archive and allow research users to access continuous data available within seconds of real time. This software was developed and currently in use at NEIC.

SCEDC has moved its website (http://scedc.caltech.edu) to the Cloud. The Recent Earthquake Map and static web pages are now hosted by Amazon Web Services. This enables the web site to serve large number of users without competing for resources needed by SCSN/SCEDC mission critical operations.

Earthquake-Detection-Formats and HazDev-Broker: Standards for Formatting and Distributing Seismic Detection Data Using Open Source Software

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A challenging aspect of operations within the National Earthquake Information Center (NEIC) is formatting and distributing small, often unassociated, source parameter data. The NEIC has a need to support and maintain many different formats and methods of exchanging these data between internal systems and external organizations. These detection data, which include waveform phase arrival time picks, back azimuth/slowness observations from seismic arrays, and preliminary seismic event detections from cross-correlation algorithms, associators, and social-media, are relatively small in size and high in frequency compared to earthquake event derived product data distributed by existing NEIC formats and systems (such as QuakeML and the Product Distribution Layer (PDL)). These detection data are also relatively large and low in frequency compared to continuous seismic waveform data acquired and distributed by the NEIC. The NEIC has developed two open-source and platform independent libraries, Earthquake-Detection-Formats and HazDev-Broker, to standardize and streamline formatting and distributing these detection data. Earthquake-Detection-Formats utilizes JavaScript Object Notation (JSON) to create pick, beam, correlation, and detection messages in a single, readable, and easy to produce set of formats. HazDev-Broker employs the open source Apache Kafka message queuing system to distribute data in an ordered, rapid, and decentralized manner. Together Earthquake-Detection-Formats and HazDev-Broker will be used to support the NEIC's near-real-time picking and event detection operations. Additionally, the libraries will be employed to further the NEIC in moving towards service-oriented architectures and/or microservices.

EQcorrscan: Open-Source Python Package for Detection and Analysis of Near-Repeating Seismicity

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Recent developments in earthquake detection have provided computationally efficient routines for the detection of repeating and near-repeating seismicity. Notably, matched-filter detection has been used extensively to study a range of seismological phenomena, including the detection of low-frequency earthquakes and repeating earthquakes, analysis of aftershock sequences and swarms, explosion detection, and tracking of induced seismicity. Despite the popularity of the matched-filter method, few open-source implementations of the methodology exist. *EQcorrscan* provides an open-source implementation of the matched-filter method, and other methods including subspace detection and so-called brightness detection methods, alongside functions for analysis of detected events. The package is distributed via the Python package index, PyPi, and stored and developed on Github. All functions are documented online, with examples for most functions, and more extensive tutorials for major functions. All code is tested via continuous integration software to reduce the number of bugs present and increase reproducibility. The core detection routines in *EQcorrscan* are optimized for massively parallel deployment, allowing large-scale (multi-year, hundreds of possible templates) projects to be run in hours, rather than months previously experienced for similar problems with other implementations. *EQcorrscan* is written in Python, with C routines for time-critical internal loops. Due to the relatively low start-up cost of learning Python, *EQcorrscan* is intended to lower the entry-level for working with these methods. *EQcorrscan* uses ObsPy paradigms, allowing for integration with a multitude of other commonly used seismology software. In this presentation we show some examples of the API, alongside examples of the results obtained using the software.

Advanced Data Selection for Research Ready Data Sets

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As the amount of seismic data available to and used by researchers continues to increase, the challenge of selecting data appropriate for any given study also increases. A very common pattern of data use starts with collection followed by one or more culling steps. For many researchers the culling steps have historically been a manual effort, often including some level of visual inspection. For a study using any significant amount of data the culling step(s) can be tedious and time consuming. The IRIS DMC's Research-Ready Data Sets (RRDS) initiative aims to assist data users with this data culling challenge and ultimately reduce the time researchers spend pre-processing data. In concept, RRDS is simple: provide users with additional criteria related to data quality that may be specified when requesting data from the IRIS DMC. Leveraging the data quality measurements provided by our MUSTANG system, these criteria will include ambient noise, completeness, dead channel identification and more. A data user may mix the quality-based criteria as they wish, effectively specifying custom "filters" that can be tuned as needed. The external interface for RRDS is a web service that accepts a data request along with quality-based criteria and returns a filtered request limited to data that matches the criteria. Additionally, a log of which data were filtered out and the quality measurement values used in the determination are returned. The style of the service interface and data request format are based on the standardized interfaces supported by the DMC. This similarity allows data users to easily add RRDS-based filtering to new and existing data collection systems. Furthermore, we are integrating RRDS capability into DMC-supported data request tools so that users can take advantage of this new capability simply by specifying new options. In the end, we hope this allows researchers to spend less time pre-processing data and more time on science.

The Subduction Zone Observatory

Poster Session · Tuesday 18 April ·

Live Tsunami Warning System

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The Really Big One (earthquake/Tsunami) could occur in the Cascadia Subduction Zone Northwest U.S. at any time, and the potential casualties could be 13,000 or higher, as reported by the New Yorker on July 20, 2015. According to Althea Rizzo's paper "Surviving the Big One", dated May 21, 2013, the last Big One occurred in 1700. The big one periodicity in this region is 240 years, and the big one is now overdue. The article stated that there are no effective tsunami warning systems available in the Northwest U.S. to warn the 15 million people who are in the tsunamis' destruction path.

The solution is to install the Live Tsunami Warning System (LTWS) in the Northwest U.S. region, and this system will significantly mitigate the potential 13,000 casualties. The 1st tsunami wave does not arrive at all the cities concurrently, and the LTWS would exploit this time difference. The System's drone stations/communication hubs would be placed in the key U.S. Northwest Coast cities, and would be linked to cell communication. When an earthquake of a greater than set magnitude is detected, all the drones would be deployed from these key stations/hubs automatically and simultaneously to their cities' predetermined sea locations to search for a 1st tsunami wave. If the 1st tsunami wave is sighted by a city, then in real time, the 1st wave sighted video with text and auditory warning messages, containing the name of the 1st wave sighted city, the wave's expected arrival time, the expected wave height, and the city's evacuation information, would be transmitted to cells, tablets, and TV stations to warn the public in this city, as well as all others in the region and in the nation. Furthermore, when the 1st tsunami wave destroys the initial city, the drone would continue to transmit the initial city's real time DESTRUCTION video and the warning messages to the initial city as well as all the other cities in the region to provide further urgency for the public to evacuate.

Reevaluating the Tsunamigenic Potential of Shallow Subduction Zones from Probabilistic Megathrust Earthquake Source Models

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Shallow subduction zones have repeatedly produced destructive tsunamis during great earthquakes. In Japan, the 2011 M_w 9.0 Tohoku-oki earthquake induced a surprisingly large tsunami, challenging the conventional view that the outer forearc is generally aseismic. We consider this event along with the 2010 M_w 8.8 Maule and 2014 M_w 8.1 Iquique earthquakes in Chile, which represent two recent tsunamigenic events in regions with a reasonably known megaquake history.

We develop a Bayesian approach to image the tsunamigenic process of the Tohoku-oki and Maule events. For Tohoku-oki, we derive posterior ensembles of seafloor displacement models from near-field tsunami records; for Maule, we derive ensembles of fault slip models using both tsunami and geodetic data. In both cases, our method incorporates an estimate of uncertainty in modeling dispersive tsunami waves, as well as the elastic structure when surface deformation is computed. In a multiscale analysis of posterior solutions, we find that the uplift of near-trench seafloor during both events share similar patterns: peak uplift (5±0.6 m and 3.5±1 m, respectively, over ~40 km scales) occurs ~50 km landward from the trench, near the inner-outer forearc transition, and tapers down toward the trench axis (reaching ~2 m and ~1 m, respectively).

For the Tohoku-Oki and Maule earthquakes, these results suggest a coseismic slip deficit near the trench, in agreement with a metastable frictional model for the shallowest megathrust—seismic slip can occur in response to deeper rupture, while also slipping aseismically between major events. In comparison, the smaller Iquique event in northern Chile, with negligible shallow slip, and its larger, more tsunamigenic 1877 predecessor, suggest complexity in shallow slip history. These examples highlight the need of interseismic monitoring of near-trench seafloor deformation along with models of dynamic fault behavior and long-term deformation history to better assess tsunami hazard.

Slab2—Updated Subduction Zone Geometries and Modeling Tools

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The U.S. Geological Survey database of global subduction zone geometries (Slab1.0), is a highly utilized dataset that has been applied to a wide range of geophysical problems. In 2016 we initiated a project to update these models with Slab2. Our objective is to provide improvements to the existing database and modeling approach, and generate a model set that will serve as a more comprehensive, reliable, and reproducible resource of three-dimensional slab geometries for all of the world's convergent margins.

The newly developed framework of Slab2 is guided by: (1) integrating a larger variety of geophysical datasets (earthquake hypocenters, moment tensors, active-source seismic survey images of the shallow slab, tomography models, receiver functions, bathymetry, trench ages, and sediment thickness information) along with their associated uncertainties; (2) implementing a dynamic filtering scheme aimed at constraining modeled geometric parameters by only slab related data; (3) accounting for which datasets represent the slab center or slab surface; (4) providing an inherently 3D data interpolation approach instead of a 2-D to 3D framework; (5) incorporating uncertainty information in both the final slab model and the intermediate calculations used to achieve it; (6) migrating the slab modeling code to a more universally distributable language, Python; and (7) adding further layers to the base geometry dataset, such as historic moment release, earthquake tectonic providence, and interface coupling. Additionally, the modeling code base and input data will be made publicly available such that they can be added to and improved upon by others in the future. This presentation will discuss the current status of Slab2 development, as well as the anticipated availability of the model and modeling tools.

Catalog of Near-Shore Seismicity in the Pacific Northwest from Cascadia Initiative OBS Data

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We have created a catalog of near-shore seismicity for the coasts of Washington, Oregon, and Northern California using data from the 4-year Cascadia Initiative OBS deployment. With amplitude-based filtration methods, we identified and located 270 earthquakes with epicenters located over, on and under the locked portion of the Cascadia megathrust fault, between the trench and shoreline. 74 of the events were already identified in regional land-based seismic catalogs. These earthquakes were found in regions both previously known and unknown to harbor seismicity. Event locations were found using SVD least-squares methods (Locsat and Hypoinverse), with depths updated from previous work. We quantify the completeness of our catalog by plotting the spatial and time distribution of stations used during event detection. We plan on further populating our catalog through the use of cross-correlation-based detection methods. Our long term goals include using the updated catalog to assess regional land-based seismic networks' ability to locate offshore seismicity, assessing the ability of OBS networks to monitor seismicity, and ultimately to better understand earthquakes and tectonics along the Cascadia Subduction Zone.

Using Earthquake Body Wave Travel Times to Explore Upper Plate Structure along the Washington Forearc

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Modern active source datasets have sampled portions of the Cascadia forearc at discrete locations across the Washington margin (*i.e.* the Puget Lowlands, Olympic Peninsula, Grays Harbor, Willapa Bay) to characterize the distribution of and contacts between the primary onshore geologic units. However, until recently, portions of the offshore region have lacked seismic observations to constrain the velocity, and in some locations, first order properties such as the width of the accretionary prism remain loosely constrained. The Cascadia Initiative (CI) array of ocean-bottom seismometers provided the first margin-scale dataset to potentially help constrain broad-scale variations. Here, we investigate the Washington forearc using observations of local earthquakes recorded on CI stations to explore the utility of these recordings for evaluating structural models. We compile previously identified intermediate depth earthquakes sourced primarily within the down-going slab beneath Washington from the Pacific Northwest Seismic Network (PNSN) catalog that are well recorded on CI instruments. We then model body wave travel times and propagation paths of these events using a hybrid velocity model based on existing structural models of the forearc region. We explore how well these models can be used to predict earthquake travel times along the southern, central, and northern portions of Washington. These models incorporate significant changes in margin structure along-strike, such as the extent of shallow accretionary material and the contact with the Siletz terrane, that produce measurable differences in travel times. Through documenting modeled travel time misfits from these sparse but valuable earthquakes recorded offshore, we can begin to identify segments of the Washington margin where existing velocity models do not capture details of the distribution of accreted terranes and sedimentary material that should influence the style of deformation offshore.

Cascadia Seismogenic Zone Seismicity as Detected by the Cascadia Initiative Amphibious Data

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Anticipating the behavior of a megathrust rupture requires knowledge of the location and extent of its seismogenic zone, as well as the distribution of its heterogeneous fault zone conditions. We lack this knowledge for the Cascadia subduction zone (CSZ), where a great earthquake rupture and subsequent tsunami would result in severe consequences for numerous large, nearby population centers. Fault conditions for the CSZ are poorly understood. Although paleoseismic evidence points to prehistoric great earthquakes, no such events have been recorded historically; moreover, our catalogs of small to moderate sized events is sparse. Geodetic and thermal modeling suggest that the locked seismogenic zone resides completely offshore; hence, the land-based seismic networks may be too far to provide adequate detection levels. This issue is addressed through the Cascadia Initiative (CI) amphibious seismic array, which from 2011-2015 augmented coastal, land seismometers with more than 60 ocean-bottom seismometers (OBS) situated directly above the presumed seismogenic zone. We search these data for small interplate earthquakes whose existence has largely gone undetected by existing land networks.

Subspace detection facilitates our search for small events. Our subspace is built from existing earthquake catalogs, using template events that appear to have occurred on the plate interface. Waveforms for nearby CI OBS and land seismometers are extracted for the selected events. Initial efforts focused on a repeating cluster of sources associated with subducting topography, and successfully detected >60 new events in the target area. Here, we expand our analysis to the entire CSZ margin during Year 1 of the CI deployment. Ongoing work includes continued detection throughout the CI deployment, and source parameter analysis of margin earthquakes for fault zone characterization.

High-Resolution 3D Seismic Imaging of Reflectors above the Subducting Slabs and Slab-Mantle Interaction

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In plate tectonics, cold and dense lithospheres sink into the mantle at the subduction zone after their ephemeral residence on the surface of the Earth. As the slab descends in the mantle, fluids released from the downgoing slab can flush the overlying mantle over time and generate seismic reflectivity in the mantle. Seismic imaging of the spatial distribution and reflectivity of these reflectors may provide important clues to understand various processes during subduction such as the corner flow, metasomatism, metamorphic reactions, and phase changes.

We have developed a 3D seismic imaging algorithm using deep earthquakes in the slab to image reflectors above the deep earthquakes. The radiated seismic wave (P, S, or SH) leaves the source and travels upward to a possible reflector at depth 'x' and is then reflected downward (as P, S, or SH) going to the receivers on the Earth surface. We are able to image down to about 500km from the surface. A 3D true-amplitude seismic imaging is developed with illumination correction for the earthquake radiation pattern, geometric spreading, spatial distribution of earthquakes and seismometers. The algorithm produces images whose amplitudes are proportional to the physical reflectivity. We have collected seismic waveform data from the IRIS Data management center (DMC) for earthquakes in 1990-2016. Data from more than 3,900 earthquakes with depths deeper than 200 km and magnitudes larger than 5.0 was collected. To date, we have identified and picked about 29,000 pP, 25,000 sP, and 11,000 sSH high-quality large-amplitude phases.

We have imaged multiple subduction zones. The 410km discontinuities are imaged clearly in all subduction zones with elevated depths inside the cold slabs, consistent with the olivine phase change. We also found that the spatial distribution of the reflector exhibits differences among different subduction zones, which may be related to subduction dynamics.

Refine Fault Geometry with Broadband Waveform Modeling for Earthquake Source Parameters: Case Studies in Nepal and Sumatran Subduction Zones

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Earthquake location and focal mechanism have provided one of the most important evidences for plate tectonics. However, the resolution in the modern global catalogs is usually not good enough to well resolve the geometry of the active faults. Here we take advantage of the global seismic stations and conduct broadband waveform modeling for medium size earthquakes (M>4.5) to refine their source parameters, which include location and fault plane solutions. We propose a novel approach that makes correction to the high frequency waveform using Amplitude Amplification Factor (AAF). This method allows us to model teleseismic waveforms at the frequency range of 0.5-2Hz, resulting in higher resolution in particular to the depth. AAF also helps us to obtain the focal mechanisms of some early aftershocks, which is not possible with other approaches. The earthquake horizontal location is relocated with careful hand picked arrivals. We applied our approaches to refine the fault geometry for the 2015 Nepal earthquake sequence and the Mentawai region. Our results for the Nepal earthquake sequence reveals a ramp-flat-ramp fault geometry, with the flat portion consistent with the coseismic slip of the mainshock. Our result is also in agreement with structure geology profile and receiver functions. In the Mentawai region, we found that the seismicity on the main plate interface deviates from Slab1.0 for up to 8km, with stronger variations along the dip direction. In addition, dip angles of the main plate boundary earthquakes obtained by robust teleseismic waveform inversions are systematically 5 to 10 degrees larger than the fault dip delineated by the seismicity. Such discrepancy could either be explained by the irregular topography of the plate interface (*e.g.* seamount) or the fault zone structure above the plate boundary. Our studies shed some new lights on reconsidering the fault geometry around subduction zone plate interface.

Mantle Serpentinization near the Mariana Trench Constrained by Ocean Bottom Surface Wave Observations

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Although water is essential for many subduction processes, the water cycle at subduction zones remains poorly constrained. Serpentinization within the subducting and overriding plates have been observed at numerous subduction zones, with significant percentage variations. Widespread normal faulting on the incoming plate and serpentinite seamounts on the outer forearc in Mariana makes it an ideal place to study serpentinization of the incoming plate and the forearc mantle, and thus helps us to better understand the water budget of subduction zones. We investigate the shear wave structure of the crust and uppermost mantle across the Northern and Central Mariana trench using data collected by a temporary network involving both ocean bottom seismographs (OBSs) and land stations on the arc islands. Rayleigh wave phase velocities (10s–64s) are obtained with three different methods, including ambient noise tomography for short periods, Helmholtz tomography for the intermediate periods and two-plane-wave tomography for long periods. The dispersion curve obtained at each location is then inverted to SV velocities. Linear inversion results show low velocity anomalies around the trench axis, both within the incoming plate mantle and the forearc mantle wedge. The low velocity anomaly extends to about 30 km deep from the seafloor, well correlated with the 600-degree isotherm. The western and eastern boundaries of the anomalies are sharp, and have good correlation with the forearc serpentinite seamount locations and the incoming plate normal faulting earthquake distributions. The mantle shear velocity is as low as 3.2 km/s, indicating ~60% serpentinite component if the velocity reduction is purely caused by serpentinization. We will further apply a Bayesian Monte-Carlo algorithm to avoid the potential biases due to starting models and to better apply a priori constraints. We will also present some preliminary results from Love wave tomography in the meeting.

A Review of the Complex Geometry of Cocos Slab under North America

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The Cocos plate subducts under North American plate with a complex geometry. In general, upper mantle seismic anisotropy is consistent with the direction of relative plate convergence and corner flow in the mantle wedgewedge, and also with subslab entrained flow. Anisotropy also suggests mantle flow through the tear between the Rivera and Cocos slabs, and is consistent with the ongoing process of slab rollback. Under central Mexico, Cocos is subducting horizontally, underplating the North American plate from ~140 to ~300 km from the trench. The plate then dives into the mantle with an angle of 76° beneath central Mexico reaching a depth of 570 km where it has broken from the remnant Farallon plate. Along the horizontal-subduction region, there is an ultra-slow velocity layer (USL) on top of the slab; and slow slip events (SSE) and tectonic tremors (TT) have been observed. To the northwest, the projection of the Orozco Fracture Zone to depth seems to be the limit of the USL and the for transition of horizontal subduction to steeper subduction (~30°). A tear below 100 km depth has been suggested to fragment the Cocos slab into Cocos North and Cocos South micro-plates. To the south-east, the projection of the Tehuantepec ridge seems to be the southern limit of the USL, and again the transition to steeper subduction (26°). This may be another tear in the plate but it has not been fully mapped. Further studies on anisotropy are underway in this region to determine the significance of this tear.

Prediction of Ground Motion from Megathrust Earthquake Using the Ambient Seismic Field

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Megathrust earthquakes have the potential to generate strong ground motions and their prediction is critical to mitigate seismic risk in coastal areas. The Nankai Trough, Japan, is expected to experience a large earthquake in the near future. The DONET1 network, which is composed of 20 offshore permanent stations, has been deployed above the shallow subduction zone to continuously monitor the seismotectonic activity in this highly seismically active region. The surrounding onshore area is covered by hundreds of seismic stations, which are operated by the National Research Institute for Earth Science and Disaster Resilience (NIED) and the Japan Meteorological Agency (JMA), with a spacing of 15-20 km. We use seismic interferometry with deconvolution to construct the Earth impulse response function between offshore and onshore seismometers. We first demonstrate that after amplitude calibration, the impulse response functions can be used to simulate the ground motions of moderate offshore M_w 5 earthquakes. We extend this point-source-like method to finite rupture modeling to predict the ground motions of potential M_w 7-8 class earthquakes using kinematic source representation. Results show that this technique can provide additional insights to the existing physics-based simulations for a better prediction of the long-period ground motions generated by megathrust earthquakes.

Theoretical and practical advances in ambient noise and coda studies

Poster Session · Tuesday 18 April ·

Special Noise Field Characteristics of a Small Aperture Seismic Array on the Southeast Coast of China

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The noise condition of the seismic array is closely related to its signal-to-noise ratio. Therefore, the research on background noise makes it possible for seismic detection, seismic location, seismic data analysis and other in-depth seismic research. In order to obtain the differences of characteristics of the noise field between the seismic arrays along the coast and the seismic arrays in the mainland, the data recorded by Fuqing array, which is in Fujian Province and the data recorded by LZDM, which is in Gansu Province were chosen randomly to be analyzed in this research. Cross-correlation method was used in this research to tell us the truth that the noise cross-correlation between site pairs along the coast present a linear relation with the increasing of the separation between two sites in 0.1-1 Hz and 0.5-1.5 Hz, while the noise cross-correlation in the mainland show different type. The noise cross-correlation values for the array located along the coast are very high, and dropped to 0.5 in 2000 m?1200m?750m?500m?and 200m for the frequency bands of 0.1-1?0.5-1.5?0.8-2.5?1-2?and 2-4 respectively, while the noise cross-correlation values for the array in the mainland are very low, and dropped to 0.5 in 200m for the frequency bands of 0.5-1.5, which show us the array along the coast was effected by the low frequency sea wave severely. We also find obvious minus cross-correlation values in Fuqing array, the distances where appear the maximum minus cross-correlation values are 1800m,1500m and 600m for 0.8-2.5?1-2?and 2-4 frequency bands respectively. The LZDM array show blurred minus cross-correlation values, they occurred in about 400m for 0.8-2.5?2-4 Hz frequency bands respectively.

Rayleigh Wave Ellipticity and Anisotropy from Ambient Noise Cross-Correlations in Southern California

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We analyze Rayleigh wave ellipticity, or Rayleigh wave H/V (horizontal to vertical) amplitude ratios, computed from multi-component ambient noise cross-correlations using 315 stations throughout Southern California in 2015 for 6-18 second periods. As Rayleigh wave H/V ratios are sensitive to shallow local earth structure, this method enables simple and accurate resolution of near-surface geological features. For every station pair, we first calculate the cross-correlation in 1-day time windows before stacking. Pre-processing includes concurrent three-component temporal normalization and spectral whitening in order to preserve amplitude ratios between each component. We measure amplitude ratios between cross-correlations of different components to determine Rayleigh wave H/V ratios at the two station locations for each noise cross-correlation pair. The ratio between the radial-radial and vertical-radial (or radial-vertical and vertical-vertical) corresponds to the H/V ratio of the first station while the ratio between radial-radial and radial-vertical (or vertical-radial and vertical-vertical) corresponds to the second station. We use the mean and standard deviation of the mean for all available H/V ratio measurements at the station to estimate the H/V ratio and its uncertainty for each station. Period dependent isotropic maps of H/V ratios show strong correspondence with known near-surface structure, including high ratios in the LA Basin, Santa Barbara Basin and Salton Trough; and low ratios in the San Gabriel, San Jacinto and southern Sierra Nevada mountains. In addition to isotropic H/V ratios, we also examine the azimuthal dependence of the H/V ratio to ascertain anisotropy patterns for each station. Clear 2-psi (180 degree periodicity) anisotropy patterns are observed for many stations suggesting strong shallow anisotropy across the study area. We discuss the correlation between observed anisotropy, local stress direction and tectonic features and implications.

A New Method to Determine Coda-Q, Magnitude of Earthquakes and Site Amplification

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Seismic coda waves can be used to measure attenuation, estimate earthquake magnitudes, and determine site amplification factors. We have developed a new multi-station and multi-event method to determine these three important seismic parameters simultaneously. We analyze 89 representative local (≤ 100 km) and shallow (≤ 20 km) earthquakes with magnitudes between 1.95 to 4.39 in southern California at multiple frequency bands centered at 0.75, 1.5, 3, 6, 12 Hz. We find that the length of the moving averaging time window can affect the measurement of coda-Q, but our tests indicate that the optimal window length is about 4 to 5 times the dominant data period. We use linear regression to fit each coda section and use only those portions that agree with the model decay rate with a correlation coefficient larger than 0.9. Our results indicate that the estimated frequency dependent coda-Q ($Q=Q_0{*}f^{a}$) at 1 Hz (Q_0) and the power a-value ranges are 110-305 and 0.69-1.49, respectively. Our coda magnitude estimates are linearly correlated with catalog magnitudes, and our observed lateral variations in coda-Q and our site amplification factors are in general agreement with previous results, although there are notable differences at some locations. Our results suggest that our approach provides a unified, accurate and stable method to measure coda-Q, earthquake magnitude, and site amplification using coda waves of locally recorded earthquakes.

To Tweet or Not To Tweet: Effective Use of Social Media for Citizen Science and Science Communication

Poster Session · Tuesday 18 April ·

Tweet-Based Earthquake Detections and Impact Assessment Integrated with Traditional Seismic Processing

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Since 2009, the USGS has been operating a real-time system with crowd-sourced tweets as the only input to detect and assess the impact of felt earthquakes worldwide. This independent system often finds small earthquakes that are undetected by traditional seismic algorithms in populated, yet sparsely instrumented, regions of the globe. In such regions the tweet-based detections precede seismic detections at a rate of ten to one, with 90% of the tweet detections occurring in less than two minutes and some as fast as 20 seconds. The main drawbacks of the tweet-based system are false detections from tweets that are not due to a felt earthquake, poor locations, and the lack of accurate magnitude estimates. To capitalize on the speed and overcome the limitations of both traditional seismic systems and tweet-based detections, we integrate detections from fast, free, and copious tweets as seeds into our existing real-time seismic processing systems to produce more complete and rapid earthquake detections for awareness, response, and research purposes. To do this, we convert rapid tweet-based detections into an international standard seismic data exchange format and distribute them to existing seismic processing systems. The traditional seismic systems then use these detections to associate seismic instrument data and compute more accurate locations, magnitudes, and other derived earthquake information products. One advantage of this approach is that fewer seismic phase picks are required to derive an event if the general location and origin time of an earthquake is known. Likewise, the accuracy of the tweet-based detections will be improved by using seismic algorithms to reduce or eliminate the false tweet-based detections and significantly refine the location. Additionally, tweets submitted after an earthquake provide short, first-impression narratives from people who experienced the shaking and sometimes include photographs, that can supply rapid indications of impact.

Using Social Networks for Enhancing Outreach at the National Seismological Network of Costa Rica

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Costa Ricans experience 12 earthquakes every month on average. Since 1973, the National Seismological Network of Costa Rica (RSN: UCR-ICE) studies the seismicity and volcanic activity in the country. A couple of decades ago, when an earthquake happened, information was slowly provided from RSN and then was disseminated by television and radio. Nowadays, due to the new trends in information flow, a new approach for transmitting knowledge from scientific research has taken place. In this study, we describe the different channels to report earthquake information that the RSN is currently using: email, Facebook, Twitter, a website, and a smartphone application. Additionally, we describe the social media strategy followed in the RSN since 2015, which includes educational campaigns. This strategy was developed by a team of scientists and journalists to enhance outreach during important geological events, such as large earthquakes, earthquake swarms, and volcanic eruptions. Since the RSN started actively participating in Social Networks, an increase in awareness in the general public has been noticed particularly regarding felt earthquakes. This paper also describes the three objectives of our social media strategy: education, prevention, and crisis management. This strategy also comments on how to balance the immediacy of social media demands and the scientific accuracy and rigorousness. Finally, this paper indicates how social media followers can help to expand and complement scientific research about geological events, with their reports on the reach of volcanic ashes after eruptions and the seismic intensity of an earthquake. The RSN has approached social media as a new era of Science Education and an opportunity to transform the view of earthquake hazards in Costa Rica.

South Napa in 140 Characters or Less: Earthquake Response via Twitter

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Twitter is a versatile platform. Regardless of the 140-character limit per tweet, it is an active venue for discussion of earthquake science, whether between fellow scientists, or between scientists and the public. This becomes particularly true following a significant earthquake, as many members of the public turn to Twitter for a realtime source of developing information, and an increasing number of scientists use it to discuss technical details. Following the 2014 M6.0 South Napa earthquake, I ended up using Twitter in multiple ways: communication of immediate post-earthquake best practices to the general Bay Area public, continued updates on the scientific details to the public and discussion thereof with other scientists, coordination of fieldwork and sharing photos and details from the site, and even discussion with reporters. I will discuss these experiences and uses of Twitter, both in the context of South Napa specifically and in the context of possible ideas and strategies for using Twitter following future earthquakes.

Varied Modes of Fault Slip and their Interactions—Slow Earthquakes, Creep to Mega Quakes

Poster Session · Tuesday 18 April ·

Breaking Down Large Slow Slip into a Cascade of Aseismic Transients

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Slow slip is the transient aseismic release of built-up tectonic stress along the roots of plate boundaries. Capable of reaching similar magnitudes to large megathrust earthquakes ($M_w > 7$), slow slip events play a major role in accommodating tectonic motion. Thought to represent a slow rupture along the plate interface that is smooth in both time and space, we demonstrate here that slow slip is in fact a complex cascade of small transient aseismic slip events. Using a dense catalog of low-frequency earthquakes as a guide, we investigate the large slow slip event that happened along the subduction interface 40 km beneath Guerrero, Mexico. We show that while the long-period surface motion as recorded by GPS suggests a six month duration, motion in the direction of tectonic release only sporadically occurs over <60 days and its surface signature is attenuated by rapid relocking of the plate interface. This intermittent motion reveals a temporally clustered cascade of aseismic transients that follows a steadily migrating rupture front. These results demonstrate that our current conceptual model of slow and continuous rupture is outdated and is an artifact of low-resolution geodetic observations. Our proposed model of slow slip as a cascade of aseismic transients implies that we significantly overestimate the duration and underestimate the moment magnitude of large slow slip events.

Tremor Modulation by Dynamic Stresses from Teleseismic Earthquakes in the Alaska-Aleutian Subduction Zone

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Non-volcanic Tremor is characterized by emergent signal of sustained energy in lower frequency lasting from seconds to days, sometimes for months or longer. Since its first discovery [Obara, 2002], a growing number of observations of dynamically triggered tremors have been reported. Tremor is triggered and/or modulated by tiny tidal stresses and dynamic stresses from passing teleseismic waves in Japan, Cascadia, Parkfield and Taiwan [Ghosh *et al.*, 2009; Kundu *et al.*, 2016; Miyazawa and Brodsky, 2008; Peng and Chao, 2008; Rubinstein *et al.*, 2008; Thomas *et al.*, 2013]. We use Aleutian Array of Arrays (A-cubed) to systematically study triggering and modulation of tremor in the Alaska-Aleutian subduction zone. A-cubed consists of three mini seismic arrays in the Unalaska Island strategically placed to simultaneously image subduction fault and nearby volcanic systems. Using the array of arrays, we detect continuous tremor activities located to the south of the Unalaska Island using the beam back-projection method. We explore tremor activities before, during and after the arrival of seismic waves from distant earthquakes with magnitude larger than 6.5. We observe several instances of modulating tremors, with increased amplitude and clear tremor beating during the passage of telesismic waves, especially during the long-period Love and Rayleigh waves. We systematically explore tremors behavior during the passage of telesismic waves, calculate the dynamic stresses and study the migration of the modulating tremors. It may help better understand the physical processes that influence tremors generation, its triggering potential and the physical properties of the transition zone of the Alaska-Aleutian subduction zone.

Coming up from the Deep? Seismological Evidence of Changing Slip-Regimes with Depth on the Alpine Fault, New Zealand.

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New Zealand's Alpine Fault is the major on-land expression of the Pacific-Australian plate boundary, forming a dextral-reverse transpressional fault. The Alpine Fault is expected to fail in a great ($M \geq 8.0$) earthquake in the coming decades, with a conditional probability of a large ground-rupturing earthquake in the next 50 years of 27%. In this work we highlight the different slip regimes of the deep extent of the Alpine Fault and the shallow, seismogenic portion by comparison of catalogs of shallow microseismicity, and deeper low-frequency earthquakes. Both catalogs are composed of seismicity adjacent to the Alpine Fault and are generated using matched-filter detection techniques.

Our catalog of low-frequency earthquakes indicates a near-constant background rate of LFE generation, punctuated by more active periods associated with both ambient and triggered tremor. In contrast, the catalog of shallow microseismicity is dominated by clustered, non-repeating seismicity that is not directly on the main plane of the Alpine Fault. These observations, alongside geodetic information, suggest that the Alpine Fault at the location studied is currently locked and accumulating stress throughout the seismogenic zone.

Further analysis of repeating low-frequency earthquakes, with a specific focus on understanding how low-frequency earthquake size and inter-event timing relates to slip-rate, may provide a useful tool for understanding varying loading-rates of the Alpine Fault and other faults globally.

Mixed Seismic/Aseismic Slip Transient in a Seismic Gap Region Revealed by Dense Geodetic Measurements: the 2011-2014 Pollino (Southern Italy) Earthquake Swarm

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The expansion of geodetic networks worldwide has significantly contributed to reveal the wide spectrum of fault slip behaviour with significant advances from subduction zones and strike slip tectonic environments. The mode by which crustal extension of the continental crust is accommodated by seismic/aseismic fault slip is less clear. Here, we study the 2011-2014 Pollino, southern Italy, swarm sequence (main shock MW 5.1) occurred within the Apennines extensional belt, analysing the surface deformation derived from Global Positioning System and Synthetic Aperture Radar data. Inversions of geodetic time series show that a transient slip (corresponding to a MW 5.5 event), with the same mechanism of the main shock, started around 3-4 months before the main shock and lasted almost one year, evolving through time with phases of acceleration that correlate with the rate of seismicity. The behaviour observed during the Pollino swarm sequence suggests that seismically-radiating fault patches (velocity-weakening) may be heterogeneously distributed in the upper 10 km of the crust, whereas velocity-strengthening zones (producing the 2011-2014 transient slip event) may be more widely distributed. The paleoseismological evidence of $M > 6.5$ events suggests, on the other hand, that the dimensions of velocity-weakening patches are not limited to $M \approx 5$ events but may reach the values required to generate surface-rupturing events ($M \geq 6.5$). The large aseismically-released moment and paleoseismological evidence suggest that a large fraction of the overall crustal deformation is released aseismically possibly explaining the absence of historical records of "large" macroseismic intensities in the Pollino seismic gap.

Observing Episodic Tremor and Slip and Slow Slip Events in the GAGE Geodetic Networks

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UNAVCO operates the Geodesy Advancing Geosciences and EarthScope (GAGE) Facility, which manages the Plate Boundary Observatory (PBO)—a geodetic network in the western US and Alaska consisting of 1100 GPS stations, 79 borehole seismic stations, 75 borehole strainmeters, 26 tiltmeters, 23 pore pressure sensors, and 6 long-baseline laser strainmeters. UNAVCO also collaborates in the Continuously Operating Caribbean GPS/GNSS Observational Network (COCONet) and the Trans-boundary Land and Atmosphere Long-term Observational and Collaborative Network (TLALOCNet) in the Caribbean region and Mexico, respectively. The GAGE Analysis Centers process ~2000 stations from these and other networks to produce daily position time series, which with the BSM data provide a rich data set for studying episodic tremor and slip (ETS) and slow slip events (SSE) at subduction zones. The ability to observe ETS depends on slab geometry, availability of geodetic+seismic instruments, and timing+magnitude of slip events. Conditions are favorable in the Pacific Northwest, where the depth of occurrence (30-40 km) is below the well-instrumented North American plate, and ETS is observed along the length of the subduction zone. In eastern Alaska SSE has been tentatively identified on Kodiak Island and Kenai Peninsula based on GPS observations. Observing ETS/SSE requires additional processing of GPS time series: tectonic motion must be removed, earthquake offsets and post-seismic deformation must be corrected, and seasonal signals must be filtered. For strainmeter data the earth tide and ocean load signals must be removed and non-tectonic signals (barometric pressure effects) must be identified. The resultant time series are then ready for analysis by researchers. Time series for individual stations can be downloaded from the UNAVCO web site, as can custom event responses for earthquakes recorded in the PBO network that include static offsets, high-rate RINEX files, and compiled borehole data files.

Tremor and Slow Slip in an Antarctic Ice Stream

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The Whillans Ice Plain (WIP), West Antarctica experiences twice-daily tidally modulated stick-slip cycles. We use rate-and-state friction to describe the strength of the ice-bed interface throughout these stick-slip cycles. Slip events on the WIP occur over an area of 10,000 sq. km, have maximum sliding rates ~0.5 mm/s, duration ~30 min, and are accompanied by seismic tremor due to small repeating earthquakes at the ice-bed interface. We create numerical simulations of WIP motion that match these properties. Our cross-stream, depth-averaged simulations treat ice as an elastic solid and parameterize all loading in the streamwise direction. The best fitting part of parameter space is in the slow-slip limit, a regime which inspires comparison to tectonic subduction zone slow-slip events. We estimate subglacial effective pressure to be ~28 kPa and the frictional evolution distance ~10 mm. Slip on the WIP initiates at the southern grounding line and propagates to the north. We find that this unilateral rupture propagation requires heterogeneous frictional properties along the ice-bed interface. By raising pore pressure, we are able to induce a transition to quasi-steady tidally modulated sliding velocities as observed on other Antarctic ice streams. This study provides an empirical validation of rate-and-state friction as an ice stream sliding law. As such, it is a contribution to our general understanding of slow-slip phenomena, and to the strength of the ice-bed interface in particular.

Assessment and Management of Hazards from Seismicity Induced by Hydraulic Fracturing

Oral Session · Wednesday 19 April · 1:30 PM · Plaza E
Session Chairs: Gail Atkinson, David Eaton, Ryan Schultz, and Honn Kao

Poroelastic Stress Change and Fault Slip Induced by Fluid Injection

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Solid matrix stress and pore pressure changes due to fluid injection are key factors for inducing earthquakes on pre-existing faults. In this study, we first present poroelastic stress modeling results for multi-stage hydraulic fracturing (HF), with applications to induced earthquakes near Fox Creek, Alberta. Due to the low permeability of the tight shale formation, shear and normal stress changes resolved on a nearby fault are much greater than the pore pressure increase, and consequently dictate the Coulomb stress distribution, which demonstrates strong spatio-temporal correlation with the December 2013 Fox Creek seismicity sequence.

We further introduce the poroelastic stress changes as perturbations to a nearby, pre-existing fault governed by the rate-state friction to simulate conditions for inducing aseismic and seismic slip. In the application to the Fox Creek sequence, we find that slip on the fault evolves in a manner similar to the onset of seismicity. For a modeled 15-stage HF that lasts for ~ 10 days, fault slip rate starts to accelerate after 3 days of fracking, and rapidly develops into a seismic event ($V_{max} > 5$ mm/s), which temporally coincides with the onset of seismicity. Fault slip rate continues to evolve and remains high (but below the seismic threshold) for several weeks, which may explain the continued seismicity after shut-in. By comparison, fault slip rate quickly decreases to the pre-fracking level when perturbations are instantaneously returned to zero at shut-in. Furthermore, when perturbations are removed just a few hours after the fault slip rate starts to accelerate (that is, fracking is terminated prematurely), only aseismic slip is observed in the model. Our results thus suggest the design of HF stages and flow-back strategy, either allowing stress perturbations to passively dissipate in the medium or actively reducing to the pre-fracking level, is critical for inducing seismic versus aseismic slip on pre-existing faults.

Statistical Modeling of Induced Seismicity

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The unconventional extraction of shale oil or gas is typically accompanied by the subsurface injection/extraction of large volumes of fluids. The fluids are used in the process of hydraulic fracturing and are injected subsequently into high volume disposal wells. These operations usually trigger various levels of seismic activity and in some cases result in the occurrence of moderate to large earthquakes. It is suggested that the increase in seismicity within the central U.S. in the last decade or so is primarily associated with large-scale disposal of wastewater. The Western Canada Sedimentary Basin (WCSB) is an active exploration area for the extraction of oil and gas. The average rate of seismicity is lower than in the central U.S., however, there are several active clusters, where in the last decade or so, there has been an increase in the occurrence of moderate earthquakes. In this study, I analyse the statistical properties of seismicity associated with the WCSB. To model the rate of the occurrence of earthquakes I introduce a modified version of the Epidemic Type Aftershock Sequence model to account for the associated variability in the injection/extraction volumes of fluids and other production data. The earthquake occurrence rate associated with several prominent clusters is characterised by bursts of activity associated with specifics of hydraulic fracturing operations. The proposed model can be used in the probabilistic assessment and mitigation of the risks associated with energy related anthropogenic activities that lead to the changes in the seismicity.

A Seismological Overview of the Induced Earthquakes in the Duvernay Play near Fox Creek, Alberta

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This work summarizes the current state of understanding regarding the induced seismicity in connection with hydraulic fracturing operations targeting the Duvernay Formation in central Alberta, near the town of Fox Creek. We demonstrate that earthquakes in this region cluster into distinct sequences in time, space, and focal mechanism using (i) cross-correlation detection methods to delineate transient temporal relationships; (ii) double-difference relocations to confirm spatial clustering; and (iii) moment tensor solutions to assess fault motion consistency. The spatiotemporal clustering of the earthquake sequences is strongly related to the nearby hydraulic fracturing operations. In addition, we identify a preference for strike-slip motions on subvertical faults with an approximate 45° P-axis orientation, consistent with expectation from the ambient stress-field. The hypocentral geometries for two of the largest magnitude (M ~4) sequences that are robustly constrained by local array data provide compelling evidence for planar features starting at Duvernay Formation depths and extending into the shallow Precambrian basement. We interpret these lineaments as subvertical faults orientated approximately north-south, consistent with the regional moment tensor solutions. Finally, we conclude that the sequences were triggered by pore-pressure increases in response to hydraulic fracturing stimulations along previously existing faults.

Event Origin Depth Uncertainty—Estimation and Mitigation Using Waveform Similarity

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The induced seismicity event localization is still a problem requiring special attention. Often a catalog of events detected and located using limited on-surface instrumentation lacks the precision of origin depth. Such errors can hinder the interpretation of activated zones using seismicity as a proxy.

The location constraints are affected by the inaccuracy of the velocity model, limited acquisition geometry and the assumptions inherited by the location algorithm, among other factors. The issue becomes even more aggravated when only surface arrays are employed, where the geometry strongly favors the accuracy of epicentral location as opposed to depth location. The reported depth errors are sometimes comparable to a formation thickness or even the origin depth itself. The passive seismicity is often located using the P and S first breaks only. Finding additional features of the seismic signal that could be informative of its origin can be a first step towards constraining the depth uncertainty.

Therefore, the purpose of this study was two-fold. First, we characterized the uncertainty in the event origin due to the inaccuracy in the effective velocity model using Monte-Carlo simulations. We show that presence of a low velocity zone (LVZ) can cause the non-uniqueness and a spread of the solution over a depth range.

Subsequently, seismograms from a set of synthetic earthquakes were simulated spanning the depth range of 2-5 km, covering LVZ. By varying the focal mechanism and event origin, we numerically generate a bank of waveforms corresponding to the events with known locations. A set of classifiers is trained on the bank to predict the event location with respect to LVZ based on arrival times and statistical features of the signal waveforms. We demonstrate that adding several features of the signal, descriptive of its origin can improve the location depth constraint, as opposed to using arrival times only as predictor variables.

Potential Seismic Hazards from Induced Earthquakes in Eastern Kentucky

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The Rogersville Shale was identified as an organic-rich hydrocarbon source rock and is being explored for oil and gas in the Rome Trough of eastern Kentucky. For example, a deep well was drilled to a depth of 4,863 m below the ground surface and tested in 2015 in Lawrence County of eastern Kentucky. Earthquakes, including those related to coal mining, have also occurred in eastern Kentucky, though infrequently. The strongest event is the 1980 Sharpsburg earthquake (M 5.3) in Bath County, just north of the Rome Trough. As experienced in Kansas, Oklahoma and Texas, and the neighboring states of Ohio and West Virginia, unconventional oil and gas production and the injection of the co-produced wastewater, have induced earthquakes. Thus, eastern Kentucky could face potential seismic hazards from the induced earthquakes. The Kentucky Geological Survey is conducting a study to characterize the background microseismicity in the Rome Trough prior to major oil and gas development and induced events if they occur. The study features a network of 14 broadband seismic stations within the ~10,000 km2 project area.

Although there are several kinds of seismic hazard that could be generated from an earthquake, strong ground motion is the main concern from induced earthquakes. Because their onset and recurrence are caused by human activities, and because rupture often occurs on unmapped faults and seismically quiescent areas, induced earthquakes are different from natural events. In other words, the methods that are used to assess ground motion hazard from natural earthquakes, such as probabilistic seismic hazard analysis, might not be appropriate for assessing ground motion hazard from induced earthquakes. We propose using a scenario-based seismic hazard analysis to assess and prepare for ground-motion hazard from potential induced earthquakes in eastern Kentucky.

Correlation Algorithms to Better Characterize Seismicity Induced by Hydraulic Fracturing

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Cross-correlation has proven useful for identifying repetitive microearthquake sequences in vast passive seismic datasets. Multi-station waveform template matching has been used to characterize induced seismicity from hydraulic fracturing (HF) and wastewater disposal (WD). A swarm of events with similar waveforms driven by localized fluid injection can help discern induced seismicity from natural occurrences. Cross-correlations from template matching are also ideal for advanced seismic source location and magnitude estimation. In our previous work in Ohio, we used template matching of cataloged earthquakes since 2010 to identify 10 swarms correlated temporally and spatially with either HF or WD, while nearly 30 less repetitive earthquakes were not and appear to be natural. To enhance detection of repetitive seismicity with magnitudes below the catalog detection threshold, we developed an agglomerative clustering algorithm that does not require a pre-existing cataloged template. We identified 14 more sequences correlated with HF in Ohio using this approach. 70% of the additional sequences have small magnitudes and shallower depths consistent with being caused by operational fracturing of the target interval, while 30% have larger magnitudes (M≥2) and deeper depths consistent with reactivation of basement faults. There are now ~3 times more sequences of M≥2 seismicity induced by HF than WD in Ohio, although there are ~10 times more HF wells than WD wells. Still, this result is surprising considering that induced seismicity in the central and eastern US has been far more frequently linked to WD than HF. Using correlation algorithms to improve detection of induced seismicity in other areas of the central and eastern US, we will present evidence for seismicity associated with hydraulic fracturing in Oklahoma, Arkansas, Pennsylvania, West Virginia, and Texas.

Dynamics of Fault Activation by Hydraulic Fracturing in Overpressured Shale Formations

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Hydraulic fracturing is a wellbore stimulation method used in low-permeability reservoirs, wherein fluids are injected under high pressure to induce tensile fracturing of the rockmass. While M < 0 induced microseismicity is normally expected, providing a useful diagnostic tool to monitor tensile fracture growth, M > 2 anomalous induced seismicity (AIS) is undesirable. Localized areas of AIS from hydraulic fracturing are increasingly well documented in western Canada, yet definitive geological risk factors remain largely elusive—possibly due to the evidently subtle seismic expression of potential seismogenic faults. In several AIS-prone areas, however, localized overpressure (defined by suprahydrostatic pore pressure gradient) exhibits a significant correlation with induced seismicity. Detailed studies of HF-induced seismicity in one such area in west-central Alberta reveal a series of en echelon, near-vertical faults with contrasting activation characteristics. Seismicity of a more distal fault strand, located ~ 700m from the closest injection point, was primarily confined to the time window of hydraulic-fracturing operations; in contrast, a more proximal fault strand delineated by a planar event distribution bisecting the two horizontal treatment wells remained active for a period of at least several months after HF operations ceased. These contrasting responses are interpreted to reflect distinct triggering mechanisms arising, respectively, from perturbations in solid matrix stress and pore pressure. Moreover, pre-existing faults in this area may be critically stressed due to overpressure from slow but ongoing hydrocarbon generation within the organic-rich target formation.

Mitigation Strategies to Prevent Damage to Critical Infrastructure Due to Induced Seismicity

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There has been a significant increase in the rate of felt earthquakes in western Alberta and eastern B.C., associated with hydraulic fracturing and, to a lesser extent, wastewater disposal (Atkinson *et al.*, 2016 SRL). The increased seismicity rates, and potential for localized strong ground motions due to very shallow events, poses an increased hazard that may be consequential for critical infrastructure. The likelihood of damaging motions depends on numerous factors including the activation probability of induced-seismicity sequences, the statistical characteristics of the sequences, their ground-motion attributes, and the response characteristics of infrastructure. I overview the factors that affect the likelihood of damaging ground motions and their implications for hazard, and outline a mitigation strategy to meet reliability targets for critical infrastructure. The proposed strategy is two-pronged: (i) targeted exclusion zones around vulnerable high-consequence infrastructure; and (ii) real-time monitoring and analysis that is tied to a response protocol.

An exclusion zone can be used to provide a deterministic safety margin to ensure the integrity of those few facilities whose failure consequences are unacceptable (such as major dams). Real-time monitoring tied to a response protocol can be used to control the rate of significant induced events on a regional basis, and thereby limit the ground-motion hazard. For most applications, the monitoring-and-response approach should provide sufficient hazard mitigation, while for vulnerable high-consequence infrastructure both an exclusion zone and a monitoring-and-response protocol are warranted. In such cases, preliminary analyses suggest an exclusion zone having a radius of ~5 km (at all depths), coupled with a monitoring-and-response protocol to track the rate of events at the M>2 level within 25 km, and make adjustments to operational practices if this rate exceeds an acceptable level.

Geomechanical Modeling of Induced Seismicity from Multi-Stage Hydraulic Fracturing

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Over the last few years, Western Canada as seen an increase in the occurrence of induced seismicity from hydraulic fracturing, including a magnitude M=4.6 event. The mechanism is attributed to increased pore pressure leading to fault activation and release of stored tectonic stress. Here we study the link between fluid injection and induced seismicity through geomechanical modeling of a mutli-phase hydraulic fracturing treatment in the proximity of a fault. Several published examples illustrate how progressive hydraulic fracture stages can repeatedly active a fault. Synthetic seismicity is used to quantify seismic energy released by the slippage on the fault for different injection scenarios. Moment release rate typically drops during the shut-in period, but depending on the distance between the fault and the injection point, a delay can be seen between the start of the injection and the increase of slip on the fault, thus acceleration of moment release rate can be observed during shut-in periods. Stress shadowing also has an influence on the moment release rate. This basic model could be used as a framework to examine the impact of other geomechanical characteristics or other operational factors to help mitigate seismicity when faults begin to be active. For example, to investigate if there are scenarios where flow-back the injection well can lead to further seismicity.

Anisotropic Inhomogeneous Modeling of Hydraulic Fracturing Surveys

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It has been well observed that downhole microseismic surveys of hydraulic fracturing can possess the azimuthal and polar coverage required to estimate effective in-situ seismic anisotropy in homogeneous layers. Solving for inhomogeneity has been attempted through voxel based isotropic tomography, by segmenting velocity models into stage based effective medium models, and by layer deformation tomography. This paper presents a gradient and control point based representation (hereafter referred to a GCP) to solve for effective anisotropy in a heterogeneous medium with arbitrary layer surfaces. This method is attractive as it can solve for velocity as it relates to known geologic formations in the subsurface and that it can result in mathematically well posed inverse problems. The major feature of the GCP method is in its model representation. A layer is defined as a region in which control points have defined velocities and values between control points are described by a invertable function (the least complicated being a linear gradient). For a single control point the result is a homogeneous layer; the other far end member is a fully voxel independent 3D model. For a limited number of control points, perforation shots in the injection well can be used to create a robust model that is still mathematically well posed because the velocity is only updated at the control points. This works shows the feasibility of the GCP method for anisotropic velocity model updating with nonuniform layer boundaries. As such it has the potential to better resolve velocity profiles that are manifested in the subsurface.

Earthquake Impacts on the Natural and Built Environment

Oral Session · Wednesday 19 April · 1:30 PM · Governor's Square 14

Session Chairs: Eric Thompson, Kate Allstadt, Kishor Jaiswal, and Nilesh Shome

HayWired Scenario Mainshock—Liquefaction Probability Mapping and Hazus Loss estimation

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The HayWired scenario is a hypothetical earthquake sequence with an M7 mainshock on the Hayward Fault in the East Bay of California's San Francisco Bay area. We produce 50-meter resolution liquefaction probability maps of northern Santa Clara and western Alameda counties by adapting the approach of Holzer, Noce, and Bennett (HNB) (U.S. Geological Survey), who use the liquefaction potential index to characterize hazard severity. Areas of artificial fill along the bay margin and youthful alluvial deposits along larger streams have the highest likelihood of producing liquefaction-related ground-surface damage. The range and variability of the mapped ground motions (peak ground accelerations) in the HayWired mainshock contribute to a more variable depiction of liquefaction hazard than shown by HNB and existing susceptibility maps.

The liquefaction probabilities are used in the Hazus-MH 2.1 loss estimation tool for each census tract by (1) assuming a uniform distribution of building inventory; (2) constraining loss analysis to developed areas based on the National Land Cover Database; (3) overwriting Hazus census tract liquefaction susceptibility table with the weighted (by probability) susceptibility class and running Hazus to estimate ground failure displacements (4) overwriting the resultant Hazus census tract liquefaction probability table with the average of nonzero probabilities in developed areas and rerunning Hazus to estimate loss; and (5) scaling down the loss in proportion to developed area with non-zero liquefaction probability. Liquefaction loss estimates for Alameda and Santa Clara counties are $3.2 B and $0.3 B (20% and 6% increases over shaking losses), respectively. The loss estimates for Alameda county are similar to those from a default Hazus assessment, but differ in geographical distribution, and lower liquefaction probability estimates in Santa Clara county translate into lower loss estimates there.

Can We Predict the Impact of Seismically Induced Landslides?

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Among the most prominent causes of earthquake-related fatalities are seismically induced landslides. As populations grow, there is increasing pressure to inhabit landslide-prone areas, leading to growth in landslide vulnerability. In this study, we present a new approach to assess the potential impact of seismically induced landslides on affected populations. The analysis makes use of a comprehensive database of 138 historical earthquakes, including 60 events with known landslide fatality counts. Using this database we develop a model that estimates the relationship between exposure of population to expected landslide occurrence and recorded fatalities from landslides. We calculate predicted landslide probabilities in individual pixels surrounding each earthquake using a global statistical landslide model (Jessee *et al.* 2016), then identify predicted population exposure by overlaying the predicted probability grid with a global population database. The expected population exposure to landslides is calculated by summing over all affected pixels for each event to determine a predicted 'landslide impact factor.' We compare these values to the number of actual fatalities for each training event, and use these comparisons to calibrate a scale of relative impact; in principle, this scale can then be used to project the potential impact of future earthquakes. We observe a significant positive correlation between predicted and observed fatalities, but with high variability in fatality rates for similar exposure levels, suggesting that other factors (building type, landslide density, population growth curves) may improve this estimate. These estimates of landslide impacts, in collaboration with use of scenario earthquakes, can be used by vulnerable communities to improve land-use planning, structural design, and emergency response in landslide-prone areas. Ultimately, our goal is to integrate these estimates into the USGS PAGER system for rapid earthquake impact assessment.

The Impact of Rockfalls on Dwellings During the 2011 Christchurch, New Zealand Earthquakes

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Rockfalls and debris avalanches triggered by earthquakes during the 2010-2011 Canterbury earthquake sequence killed five people. In total, about 100 dwellings were directly impacted by some of the ~6,000 field mapped rockfalls and debris avalanches that occurred across the Port Hills of Christchurch. We present results from the analysis of a high-quality, empirical dataset of 61 individual rockfall impacts on 29 dwellings in the Port Hills of Christchurch, New Zealand. Dwellings in the Port Hills are typically simple timber framed structures with wooden or unreinforced masonry cladding and they are comparable to most residential dwellings across New Zealand, North America, Australia, and elsewhere. Rockfall impacts on the dwellings in this study were observed to follow a power-law relationship between kinetic energy and: (1) the runout distance into and through the dwelling; and (2) the impacted area within the dwelling. The results have been quantified and are presented as a "damage proportion", which is defined as the proportion of the area affected by an individual rock-block inside the dwelling divided by the total area of the dwelling. These data provide a fundamental input for rockfall risk analysis and will allow the losses from rockfall impacts to be better constrained.

Rapidly Imaging Earthquake Damage Using Satellite SAR Data: 2016 Central Italy Earthquakes

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The recent sequence of powerful earthquakes in the Central Italy claimed more than 300 people's lives. In response to those earthquakes, we rapidly produced and delivered building damage maps derived from SAR observations. The M6.2 August 24, 2016 Amatrice earthquake has caused significant damage in the historic town of Amatrice, Italy. We produced damage proxy maps (DPMs) using COSMO-SkyMed and ALOS-2 SAR Data. Red pixels represent areas of potential damage due to the earthquakes as well as ground surface change during the time span of interferometric pairs. The color variation from yellow to red indicates increasingly more significant ground surface change. Preliminary validation was carried out by comparing with high-resolution pre- and post-event optical imagery acquired by DigitalGlobe's WorldView satellites, and a damage map produced by the European Commission Copernicus Emergency Management Service based upon visual inspection of high-resolution pre- and post-event optical imagery. The DPM from ALOS-2 (L-band) data covered 65-by-120 km from two consecutive frames (cyan rectangle), and the DPM from COSMO-SkyMed (X-band) data covered 40-by-50 km (red rectangle). Both DPMs cover Amatrice, revealing severe damage on the western side of the town (right panels). The time span of the data for the change is Jan. 27, 2016 to Aug. 24, 2016 for ALOS-2 and Aug. 20, 2016 to Aug. 28, 2016 for COSMO-SkyMed. Each pixel in the damage proxy map is about 30 m across. We also produced a DPM of the M6.6 October 30 Norica earthquake using COSMO-SkyMed Spotlight SAR data with pixel spacing of about 5 m and covering an area of 10-by-10 km, centered at Norcia, Italy. These DPMs provide broad geographic coverage of the earthquake's impact in the region in a consistent manner that may bring more robust detection compared to human visual inspection.

Improving Regional Liquefaction Hazard Maps Using Hydrological Remote Sensing Data: A Proof of Concept Study at Imperial County

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Soil liquefaction and related phenomena, such as ground deformation and lateral spreading, pose significant risk to distributed and critical infrastructure systems. Although liquefaction vulnerability is controlled by geologic and groundwater conditions, its regional assessment is almost exclusively based on geologic material properties or proxies thereof. Dense field testing programs could reduce the uncertainty of empirical models that correlate material properties to proxies such as topographic slope, but they are both expensive and not viable for mapping inaccessible areas. In this work, we are developing a multivariate methodology that introduces hydrological variables (obtained via remote sensing) in regional liquefaction vulnerability maps. More specifically, we use remote sensing data and publically available well-monitoring data to set up an integrated hydrological model that provides estimates of depth to water table. By combining water table depth estimates with geologic properties, we obtain regional maps of liquefaction vulnerability that take into account both the prevailing geology as well as the groundwater conditions. We demonstrate the methodology by presenting a case study from the 2010 El Mayor-Cucapah earthquake in Imperial County. We use supervised classification to train a logistic regression algorithm, which yields probabilistic maps (of liquefaction occurrence) by maximizing a likelihood function. Preliminary results indicate that the proposed approach can improve the accuracy of regional liquefaction vulnerability at no additional site investigation cost or effort. However, a more systematic study is necessary to draw quantitative conclusions on the accuracy improvements of ground failure hazard maps when introducing remote sensing derived hydrological models.

Ground Motion Prediction Equations for Arias Intensity, Cumulative Absolute Velocity, and Peak Incremental Ground Velocity for Rock Sites in Different Tectonic Environments

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In this presentation, we discuss the development of ground motion prediction equations (GMPEs) for the maximum rotated (RotD100) horizontal component of five intensity measures (IMs): Arias intensity (AI), cumulative absolute velocity (CAV), cumulative absolute velocity above the 5 cm/s^2 threshold (CAV_5), standardized cumulative absolute velocity (CAV_{STD}), and peak incremental ground velocity (V_{gi}). These ground motion intensity measures were previously identified by the authors as the most efficient and sufficient predictors of building performance on liquefiable soils during earthquakes. The equations are applicable for predicting the ground motion intensity at outcropping rock sites. This scope reflects the critical importance of outcropping rock motion properties used either directly as the main predictor of structural response or used as input to site response and soil-structure interaction analyses. We present equations for the shallow crustal, intraplate, and subduction tectonic environments, and between- and within-event standard deviations for each. We also provide supplemental logistic models predicting the probability that CAV_5 and CAV_{STD} exceed zero in a given earthquake scenario. These equations are valid for earthquakes with magnitudes between 4.0 and 9.0 and source to site distances up to 400 km, depending on the tectonic environment.

Case Study: How Stochastic Modeling is Driving the Next Generation of Resilience

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Big data analytics and the sharing economy are fueling one of the fastest-growing financial innovations: Micro-insurance—specifically, "on-demand" and "use-based" micro policies that cover specific risks for specific times. Micro policies are being used not just for ride-sharing but also natural disaster risk, in the form of "parametric" insurance, where insureds receive automated payouts upon occurrence of pre-defined parameters—*e.g.*, magnitude and/or shaking intensity as reported by an independent third-party.

Micro-insurance for natural disasters also builds lasting social impact and financial resilience. For example, currently 9 of 10 Californians are uninsured for earthquake risk, which means the amount of money flowing in after a quake will be a fraction of what's needed to rebuild. Micro-insurance can multiply—by up to 10x—the amount of money circulating in a post-event economy, thus speeding-up recovery both for individuals who receive payouts, as well as for the region as a whole.

However, disaster micro-insurance, and the resilience it stands to build, is feasible only with comprehensive understanding of the probabilities and uncertainties of the specified parameter(s). This presentation will provide a case study in which stochastic modeling is used as the basis of developing a parametric earthquake insurance policy for California. It will describe an implementation of the UCERF3 model, a comparison of outcomes among two different earthquake parameters, and the overall process of applying model outputs for practical development of an insurance product.

Broadband Ground Motion Simulation within the City of Duzce (Turkey) and Building Response Simulation

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Recently, simulated ground motions are used frequently in both hazard and engineering analyses, especially in areas with insufficient seismic networks despite significant seismic activity. From an engineering point of view, one important task is to evaluate the efficiency of the simulated records in building response estimation. In this study, a hybrid ground motion simulation framework is presented to obtain broadband ground motion time histories of past and potential events in Duzce (Turkey). The objective is then to evaluate the efficiency of broadband ground motions for structural response simulation. The hybrid ground motion simulation framework presented herein is a combination of a discrete wave-number finite element method for simulating low frequencies and stochastic finite fault method for the higher frequencies. The proposed technique is first validated by simulation of the 12 November 1999 Duzce earthquake (M_w=7.1) which occurred on North Anatolian Fault Zone, Turkey. Comparison of the results demonstrates that there is a good match in between the simulated and real records. In addition, peak ground motion parameters of the simulated records are compared against existing Ground Motion Prediction Equations (GMPE) derived with global and local datasets. Next, simulated time histories at selected locations and spatial distributions of peak ground motion intensities in terms of PGA and PGV values are obtained for the 1999 Duzce earthquake and other potential large events on the same fault. In order to evaluate the proposed simulation methodology in building response estimation, nonlinear time history analyses of typical reinforced-concrete multi-degree-of-freedom structures are performed for real and the corresponding simulated records of the 1999 Duzce earthquake using the OpenSees platform. The results reveal that reasonable predictions can be made regarding the dynamic response of structures using simulated motions presented in this study.

Practical Uses of a Scenario Describing Earthquake and Earthquake-Induced Landslide Impacts on Aizawl, India

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Residents of ridgetop Aizawl, capital of northeast India's Mizoram state, face high risk from seismically vulnerable hillside concrete buildings, coupled with high to very high landslide hazard. To motivate and support action to address these threats, GeoHazards International and partners prepared a scenario describing a M7 earthquake and earthquake-induced landslide impacts on people, buildings, and infrastructure, and providing detailed recommendations to address vulnerabilities. The scenario earthquake is 10 km away and 30km deep, below a thick sedimentary layer with high attenuation. We estimated it would cause more than 14,000 building collapses, over 1100 landslides, and over 25,000 deaths in Aizawl. Because no reliable, publicly available loss estimation software for India existed when we prepared the scenario, we necessarily kept calculations simple, describing topics such as utility interdependence and fire following earthquake qualitatively. USGS provided shaking estimates. We based estimates of landsliding on a study area with representative slopes, for which we used both quantitative statistical methods (using empirical landslide occurrence and density relations) and qualitative methods (based on slope stability calculations and engineering geomorphological mapping) to bound the expected amount of slope failure. We estimated building collapses and casualties using inventory and exposure data from the census, local building department and field reconnaissance; analytical and expert-judgment-adjusted published collapse fragility functions; and published lethality rates adjusted to account for collapsed buildings sliding on steep slopes. Primary scenario uses were risk communication and a process to identify mitigation measures. Because of the scenario process and hard work by local leaders and project team, Aizawl now has a landslide action plan, slope grading regulations, better landslide hazard maps, more capable geologists and officials addressing risk.

Update to FEMA 366: Estimated Annualized Earthquake Losses for the United States

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The annualized earthquake loss (AEL) estimates for the United States, part of the FEMA 366 revision, have been updated using the latest national seismic hazard, census-based population, and revised economic exposure estimates of the general building stock. This comprehensive study highlights that earthquakes continue to pose significant threat to humans and the built environment in the United States and that severe impacts from high earthquake hazard and concentrated exposure are not limited to California. This study makes use of Hazards U.S. (Hazus MH) software version 3.0, a standardized tool that uses a uniform engineering-based approach to estimate damage, casualties, economic losses, and social impacts such as shelter, debris, and displaced households from earthquakes.

The national level AEL based on this investigation is $6.2 billion per year, 16% higher than FEMA 366 2008 study and 28% higher than recent estimates by Jaiswal *et al.* (2015) for the contiguous US. Elevated AEL estimates are primarily due to changes in shaking hazard, improved site soil characterization and increased economic exposure from the recent building inventory update within Hazus. Fifty metropolitan areas, led by the Los Angeles and San Francisco Bay areas, account for 80 percent of the total AEL. The key improvement to the FEMA 366 revision is the inclusion of the 2014 USGS National Seismic Hazard Model, which provides a probabilistic estimate of ground motions on a 5-km grid for a uniform Vs30 =760 m/s site condition. These ground motions were modified using a USGS topo-based Vs30 map and the 2016 NEHRP site amplification model. Similar to the hazard estimates, several important changes were made to exposure datasets to incorporate latest data from the Census, RS Means Cost datasets, and commercial infrastructure inventory. Estimated losses are presented at the state, county, metropolitan, and city levels. FEMA aims to use the new AEL values for future state assistant grant program.

Earthquake Rapid Response

Oral Session · Wednesday 19 April · 8:30 AM · Governor's Square 16

Session Chairs: Anne Meltzer, Jay Pulliam, and Dan McNamara

Some Reflections on Aftershock Deployments in Distant Lands

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When damaging earthquakes occur in poorly instrumented parts of the world, there is a heightened impetus to install portable instrumentation as quickly as possible to collect perishable aftershock data. Such deployments are critical to understand individual earthquakes and local seismotectonics. Given the infrequency of damaging earthquakes around the world, these rapid deployments can also reveal valuable observational results of general importance. For example, the 2010 M_w7.0 Haiti earthquake underscored the potential importance of topographic amplification effects, and the 2015 M_w7.8 Gorkha, Nepal, earthquake has provided important new insights into pervasive nonlinear site response. Aftershock deployments also provide important opportunities for earthquake professionals to provide technical assistance to both U.S. agencies abroad as well as to in-country partner agencies. For this reason, agencies such as the United States Agency for International Development (USAID) can provide financial support for technical assistance projects that stand to contribute directly to risk reduction and capacity development. The mission of such agencies is, of course, different from that of traditional scientific funding agencies; capacity building is not a viewed as a "broader impact," and is moreover often quite different from what research scientists typically view as effective capacity building. For example, providing graduate training for students in outside universities tends to be viewed with suspicion, since students who leave a developing country might never return. A further point is that, whether an outside scientist is an employee of their government or not, they are viewed as a representative of their country in a disaster situation in the developing world. In this talk I share some of my experiences—and suggestions derived from them— leading aftershock deployments and other capacity building projects in Haiti, Nepal, and Myanmar.

Complex Extensional Faulting and Stress Interactions in the Central Apennine Cluster: The 2016 Amatrice, Visso and Norcia, Italy, Earthquakes

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The M_w6.1 Amatrice, M_w6.0 Visso and M_w6.5 Norcia earthquakes ruptured between August and October 2016 in the Central Apennines and are part of an ongoing cluster of events in the region that dates back to the 1979 Norcia earthquakes. Here we show slip models from inversion of Sentinel InSAR and regional GPS offsets from permanent and temporary stations deployed soon after the first event. Based on aftershock relocations from permanent and temporary deployments as well as field mapping we infer a complex multi-fault geometry and use it for the inversion. We show that the sources for the three events include slip on the main Mt. Vettore fault system but also on east-dipping antithetic structures. Our modeling and the aftershock relocations argue for slip on the low angle Altotiberina fault as part of the 2016 Norcia earthquake rupture. We calculated the Coulomb stress contributions of all significant events between 1979 and 2016. We find that while Coulomb stress changes and fluid flow induced by coseismic pressure changes likely play an important role in mediating the stress interactions between the different faults in the system they cannot explain all of the complexity in the timing and location of ruptures. This suggests that other time-dependent mechanisms such as pore pressure transients and postseismic deformation processes likely play an important role in the development of the recent Central Apennine earthquake cluster.

Efficient Characterization of Subduction Zone Segmentation, Rupture Regions, and Seismic Structure: Examples from Large Magnitude Chile Earthquakes since 2010

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Large magnitude and great (M > 7.5) subduction zone earthquakes provide fruitful opportunities to sample subduction zones efficiently. Full exploitation of these opportunities requires seismic equipment available for rapid deployment for > 6 months in the rupture region immediately after the event, to record the prolific aftershocks such events generate. A sufficient number of seismic stations must be deployed in order to record the aftershock series and ambient global seismicity with the necessary fidelity to ensure a good yield of high quality data products. A field team experienced in the deployment, operation and servicing, and demobilization of the temporary seismic network installed is also required; experience with shipping equipment and shepherding it through international Customs agencies is also useful. With a sufficient number of stations to ensure relatively close station spacings, the volume of the subduction zone producing prolific aftershocks can be densely sampled in a relatively short period, 6 months to a year. High frequency spectral content, short travel paths, and sheer numbers yield data—body wave arrival times and waveforms—conducive to relatively high resolution imaging of the deployment region structure. These data, possibly supplemented by recordings of global ambient seismicity, can yield high resolution body wave and ambient noise tomographies, seismic attenuation and anisotropy observations, and crustal structure imaging from stacking of receiver functions. A societally-relevant potential target of such comprehensive imaging includes imaging of lateral heterogeneity in structure of the subducting and/or overriding plate that results in rupture termination, and that may therefore inform seismic hazard estimation and modeling. We will present results from three rapid-response seismic deployments in Chile, those targeting the Maule (M_w 8.8), 2014 Iquique (M_w 8.2), and the 2015 Illapel (M_w 8.3) earthquakes.

Subduction Zone Earthquake Rupture and Aftershock Sequences: Insights from the April 2016 Pedernales Earthquake, Ecuador

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The April 2016, Pedernales Earthquake ruptured a100 km by 40 km segment of the subduction zone along the coast of Ecuador in a M_w 7.8 megathrust event north of the intersection of the Carnegie Ridge with the trench. Immediately after the earthquake, an international response coordinated by the Instituto Geofisico EPN in Quito deployed accelerometers, seismometers, OBS, and GPS receivers above the rupture zone and adjacent fault segments to record aftershocks and post-seismic deformation. This portion of the subduction zone has ruptured on decadal time scales in similar and larger size earthquakes: M_w7.8 (1942), M_w 7.7 (1958), and M_w 8.8 (1906), and exhibits a range of slip behaviors along strike as well as lateral variations in segmentation and degree of plate coupling. The rupture zone of the 2016 Pedernales earthquake overlaps with the previous 1942 event and falls within the estimated rupture area of the 1906 event and appears to be bounded by regions exhibiting slow slip along strike. Data from permanent national seismic and geodetic networks in Ecuador and the 2016 Pedernales earthquake and aftershock sequence recorded by the dense aftershock deployment provide the opportunity to examine the persistence of asperities for large to great earthquakes over multiple seismic cycles, the role of asperities and slow slip in subduction zone megathrust rupture, and the relationship between locked and creeping parts of the subduction interface. While the aftershock deployment was relatively smooth and efficient, improvements in instrumentation and protocols established in advance of destructive events are needed to facilitate rapid coordinated deployments and field studies after large subduction zone earthquakes. These deployments have the potential to uniquely capture a range of subduction zone processes complementing the observations from permanent networks to shed new light on rupture of megathrust earthquakes and transient processes associated with these events.

Structure of the Main Himalayan Thrust in Nepal Derived from Aftershocks of the 2015 M7.8 Gorkha Earthquake Recorded by the NAMASTE Rapid Response Seismic Network

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In response to the April 25, 2015 M7.8 Gorkha earthquake on the Main Himalayan Thrust in Nepal, NSF Geosciences funded our rapid seismological response, project NAMASTE (Nepal Array Measuring Aftershock Seismicity Trailing Earthquake). We deployed an array of 41 broadband and short-period seismometers and 14 strong motion sensors at 46 sites across eastern and central Nepal, spanning the earthquake rupture area with a station spacing of ~20 km. The stations were recording in the field for ~11 months beginning ~7 weeks after the main shock. Using the data from this network combined with data from other available regional seismic stations, we calculate the spatial and temporal locations as well as magnitudes of thousands of aftershocks using Antelope seismic analysis software and the HypoDD double-difference earthquake location algorithm.

Relocations of aftershocks from the NAMASTE network appear to illuminate the geometry of the Main Himalayan Thrust at depth as well as several other possibly related fault structures. We observe significant changes in seismicity across the rupture area including the temporal, spatial, and magnitude variability of the recorded aftershocks. We discuss observed patterns and possible structures down-dip and along-strike that may limit the extent of rupture, or control the nucleation pattern of future earthquakes. We further discuss the implications of the seismicity for regional stress. Finally, we reflect on ways that our seismic dataset can be combined with other rapid response data collection efforts to maximize our understanding of large earthquakes in the Himalaya.

Stranded Slip in the Himalayan Collision Zone and Its Implications for the Seismic Cycle

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Strong evidence for incomplete rupture of the main Himalayan decollement followed by complete locking of the seismogenic fault in the postseismic interval in the Gorkha 2015 earthquake implies that patches of stored elastic strain may occur throughout the fault system, rather than simply accumulating at the base of the locked zone. If true, the capacity of the collision zone to host cascades of triggered events is more complex than previously expected, with implications for hazard assessment and for interpretation of the paleoseismic record for the region. For example, the complete rupture of a Himalayan segment in a megaquake could be expected to obey typical earthquake scaling relations and be recorded clearly at the Himalayan Frontal Thrust, but incomplete ruptures are not recorded at the frontal thrust, and smaller magnitude events that "mine" stored elastic strain might not obey standard scaling. In the latter cases, moment release rate would be either underestimated or overestimated, respectively. There are hints of these behaviors in the historical Himalayan earthquake catalogs, with insufficient moment to close the kinematic budget (*e.g.* Feldl and Bilham, 2006), and evidence for large displacements on relatively short or discontinuous fault segments (*e.g.* Bollinger *et al.*, 2014). Observational data from rapid response deployments after major earthquakes is critical to deciphering episodic and nonlinear aspects of the earthquake cycle and crustal material properties, such as incomplete rupture and absent afterslip, because the response of the Earth to an earthquake typically decays rapidly with time after the mainshock. Capturing these signals, either by luck because instrumentation is already in place, or with a rapid response, allows for both critical scientific advances and quick translation of them to guide response, recovery, and public education.

2015 Mw 7.8 Gorkha Earthquake in Nepal: Imaging of Rupture Complexity and Aftershock Activity Using Global and Local Seismic Network

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Gorkha mainshock ruptures part of the Himalayan fault system believed to be ready to produce large earthquakes. It causes significant damage in Kathmandu—the most densely populated city in Nepal—and numerous towns and villages in and around the rupture area. Better understanding the rupture processes in the of the Himalayan fault system is one of the keys to the better preparedness. Factors controlling the extent of the rupture and its propagation behavior, however, remain poorly understood. We use backprojection technique using four independent global large-aperture seismic arrays at teleseismic distances to image rupture propagation during mainshock. We develop and use an empirical self-consistent calibration method to combine all four arrays to significantly increase the imaging resolution. It allows us to observe rupture complexity not revealed by any individual solo seismic array. In addition, we use the same arrays to track aftershock activity continuously in time immediately following the mainshock. Array techniques are able to detect twice as many earthquakes compared to a standard global catalog. This fast technique rapidly determine rupture complexity and aftershock activity—in some ways better than traditional methods—allowing us to better estimate the hazards and damage immediately after a large devastating earthquake.

Moreover, we deploy a dense seismic network after the mainshock covering the entire rupture area. It captures prolific aftershock activities revealing fault structures that may be responsible for the complexities observed in the rupture processes. We combine results from global and local seismic data to provide new and useful insights into the rupture dynamics of the Himalayan fault system.

Expanding Scales of Rapid Seismic Deployments: New Tools and Techniques to Collect and Explore High-Resolution Datasets

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Rapid seismic deployments that capture ephemeral earthquake sequences provide critical datasets to explore a wide suite of earthquake processes. For many decades, rapid seismic deployments typically took the same form: several-to-tens of high-resolution weak- and/or strong-motion seismic sensors installed at temporary field sites for weeks-to-months following a significant earthquake. These traditional aftershock deployments are generally still in use today and continue to provide important datasets. However, a recent explosion of technology has expanded the options for collecting seismic data in rapid response mode. Here, I survey several types of rapid response deployments and provide a comparison of: (1) required resources (instrumentation and deployment costs), (2) ease of instrument deployment, (3) data volumes collected, and (4) data quality. To aid in the comparison, I present several recent rapid-response deployment efforts and scientific products from these datasets. First, I describe a traditional aftershock deployment at remote sites in the Yuha Desert (California, USA) following the 2010 M7.2 El Mayor Cucapah earthquake that resulted in high-resolution images of structure and crustal stress orientations. Next, I show how a reliance on a team of volunteers and low-cost strong motion stations in urban Christchurch created an extremely dense 180-station array capable of exploring ground motion variability and source properties of the 2010 M7.1 Darfield, New Zealand earthquake sequence. Finally, I demonstrate the potential of short-term, large-scale deployments by describing a recent 1800-node study that targeted a region of transitory induced seismicity in northern Oklahoma. Each of these types of seismic arrays has different strengths and limitations that can be assessed to determine the optimal rapid response deployment.

Aftershock Sequence of the 2011 Virginia Earthquake with High Spatial Resolution and Low Magnitude Threshold Using the Dense AIDA Array and Back-Projection

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The Aftershock Imaging with Dense Arrays (AIDA) deployment shortly after the 2011 M_W 5.7 Virginia earthquake recorded 12 days of aftershocks. AIDA benefited from stand-alone, small, industry seismographs that enable the rapid deployment of a large number of stations, aiming to capture seismic wavefields rather than just isolated waveforms. Following the main shock, short-period, vertical-component recorders were deployed at 200-400 m spacing in the epicentral area. Inter-station correlation of unaliased signal enabled detection of tiny events with signal-to-noise ratio <1 that fall below the threshold of sparser networks. Seismic tomography and event back-projection of unaliased waveforms produced velocity and hypocenter images with improved spatial resolution. Automated back-projection is currently being applied to the AIDA data for simultaneous event detection and location. Back-projection of kurtosis of the waveform proved most robust for detection in the presence of noise. Back-projection of the seismic waveform of the detected events improved spatial resolution and preserved magnitude. Preliminary automated analyses detected and located about an order of magnitude more events than a careful analysis of data from a traditional array, with thresholds as low as magnitude −2. Hypocenters are accurate to ~20 m horizontally and ~75 m in depth without using cross-correlation and double-difference methods. A more complete catalog that includes smaller magnitudes and has improved spatial resolution will expand our knowledge of the spatio-temporal evolution of stress and strain in the aftershock zone. On-going work involves completing the catalog, quantifying the improvement in detection and location, and comparing the space-time patterns of seismicity, the Gutenberg-Richter recurrence relationship and the spatial and temporal decay of aftershocks at smaller magnitudes.

Aftershock Imaging with Dense Arrays (AIDA): Insights from the 2011 Mineral Springs Virginia RAPID Experiment

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Aftershocks from the magnitude M_w 5.8 August 23, 2011, central Virginia (Mineral) earthquake were recorded using an unusually dense array of seismometers in what has been termed an AIDA (Aftershock Imaging with Dense Arrays) deployment. Over 200 PASSCAL Texan recorders were set out at a nominal spacing as close as 200m in the epicentral area of this event to a) more precisely determine hypocentral locations and source properties of the aftershocks down

to ultra-low magnitudes, b) more accurately define velocity structure in the aftershock zone, c) image geologic structures in the hypocentral volume using reflection techniques with the aftershocks serving as illumination sources, d) characterize regional propagation characteristics and e) assess the potential of seismic interferometry for subsurface imaging using both body and surface waves from aftershocks and ambient noise. The waveform data obtained by the dense array has not only allowed detection of extremely small aftershocks (*e.g.* mb less than -2), they have facilitated recovery of rupture mechanisms of events well below the resolution of conventional aftershock arrays. The densely recorded aftershocks also serve as sources for high resolution 3D imaging of key structure in the hypocentral region by application of Vertical Seismic Profiling (VSP) and seismic interferometry. More suitable hardware to collect true 3D imagery is now more easily available than it was at the time of the Mineral, VA, event. The large N, nodal recording systems in routine use by the oil exploration industry are now finding more widespread application to the study of natural and cultural ambient sources. The dense array experience in Virginia clearly demonstrates why true 3D deployments are necessary, but also illustrates how properly designed, strategically staged deployment can be most effective.

Estimating Earthquake Hazard from Geodetic Data

Oral Session · Wednesday 19 April · 1:30 PM · Governor's Square 12

Session Chairs: Jeff Freymueller, Elieen Evans, and Jessica Murray

Estimating Interseismic Surface Strain and Moment Deficit Rates in Southern California Using Geodetic Data

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Using geodetic data to constrain the interseismic moment deficit rates (IMDR) is currently an under-utilized but potentially powerful method for understanding the seismic hazard presented by crustal faults. One class of methods historically used to estimate the IMDR are known as Kostrov-type summation, which integrate surface strain rates (Ward, 1994; Savage and Simpson, 1997). This method gives an approximate estimate of the minimum scalar MDR. Strain-rate can be estimated by triangulating velocities to find line-length changes (*e.g.* Savage and Simpson, 1997), estimating strains analytically using basis functions (*e.g.*, Tape, *et al.*, 2009), or interpolating geodetic velocities onto a regular grid followed by numerical differentiation (*e.g.*, Haines and Holt, 1993; Kato *et al.*, 1998; Shen *et al.*, 2015; Wu *et al.*, 2011). There is an inherent trade-off in these methods between misfit and smoothness.

I adopt a geostatistical approach that estimates the surface velocity field using parameters estimated from the data itself, and generate many random realizations of the velocity field true to the data that that are smooth and fit the data within errors everywhere. Numerically differentiating these gives strain and moment deficit rates with uncertainties. I apply this method to Southern California and compare my results to other strain rate estimates and moment accumulation rates for Southern California. I also briefly introduce a new method for estimating IMDR using traditional finite fault models and compare the results obtained using an elastic block model developed by Johnson (2013) for Southern California to that obtained by integrating surface strain. I use estimate how much of the surface strain can be explained by backslip on faults.

Understanding the MDR with its uncertainty provides valuable information for understanding earthquake hazards in this geologically complex region.

Strain Accumulation on Faults beneath Los Angeles: The Importance of the Sedimentary Basin, the Roles of Thrust and Strike-Slip Faulting, and the Return Period of M>7 Earthquakes

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The Big Bend of the San Andreas leaves a component of ~8 mm/yr of north-south contraction across the Los Angeles region to be accommodated by slip on thrust systems such as the Sierra Madre, Puente Hills and Compton faults. A large earthquake on one of these systems could constitute a worst-case-scenario event for Los Angeles, and so it is essential to use geodetic data to constrain where, and how quickly, tectonic strain is accumulating on these faults. Using the refined GPS velocity field of Argus et al [2005] and accurate models both of 3D fault geometries and of elastic structure (based respectively on the SCEC CFM5 and CVM-H15.1), we show that: 1) The Los Angeles sedimentary basin has a first-order effect on the problem; more coupling at depth is required to fit a given contractional gradient with the basin than without, increasing the inferred buildup rate of seismic moment by over 50%. 2) Deep creep on strike-slip faults at their geologic slip rates can produce an apparent N-S contractional gradient of ~1.5 mm/yr across the LA region. 3) The contractional gradient in GPS is well fit by models featuring slip rates of ~5 mm/yr on the Sierra Madre Fault, ~3.5 mm/yr each on the Puente Hills and Compton faults, and a moment buildup rate of 2.4-3.4 x 1017 Nm/yr. This buildup rate requires a M=7 earthquake every 120-160 years if released in a characteristic M=7 earthquake, but this does not account for seismicity at other magnitudes. Using the SCEDC and relocated Hauksson *et al.* [2011] catalogs, we find that the slip budget can be balanced by a Gutenberg-Richter distribution of earthquakes and the aftershocks of those earthquakes with maximum-magnitude M=7.2-7.4 earthquakes every 900-1300 years. We will augment these findings with two new methods to assess interseismic coupling: 1) a method that finds best-fitting locking depths by penalizing the 1-norm of the coupling gradient and 2) an iterative method that allows for a probabilistic representation of coupling.

Moment Accumulation Rates on Faults in Southern California from GPS Data

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Moment accumulation rate on faults is a fundamental parameter in earthquake hazard assessment. Because moment accumulation rate on faults is related to strain accumulation rates in surrounding rock, geodetic measurements of surface strain rate can be used to place constraints on fault moment accumulation rates. In southern California, we find that geodetically-inferred present-day moment accumulation rates in southern California are 60-300% higher than the 1.06 x 10^19 N-m/yr historical seismic moment release rate since 1857. The large uncertainty in this estimate can be attributed to limits in data quality and uncertainty on models that relate deformation data to moment accumulation rate. To examine the epistemic uncertainties in these calculations, we adopt a variety of methods including Kostrov-summation approaches that integrate strain rates over the crustal volume to fault-based methods that infer slip deficit rates on specified faults. For fault-based methods we adopt a block-model approach as well as a new method that maps observed baseline elongation rates directly to moment accumulation rate on faults. We show that Kostrov-type estimates using the relationship between principal strain rates and scalar moment yield moment accumulation rates of 1.5 – 2.9 x 10^19 N-m/yr and fault-based models considered in this study yield similar moment accumulation rates of 1.7 – 3.3 x 10^19 N-m/yr. For context, adding an additional M_w=8 earthquake to the historical seismic moment release rate yields 2.1 x 10^19 N-m/yr. Our baseline inversions show that a large portion of the geodetic moment accumulation rate cannot be mapped to moment accumulation rate on faults and may represent distribution crustal deformation. The large epistemic uncertainty in the geodetic-based rates largely reflects inherently poor depth resolution in inversions of surface observations and non-uniqueness in methodology for relating geodetic data to fault slip rates.

Model Uncertainties in Geodetic Slip Rates for Seismic Hazard in California

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Inputs into seismic hazard models include 1) fault slip rates, 2) their uncertainties, and 3) off-fault deformation rates. Fault slip rates can be estimated by modeling fault systems, based on space geodetic measurements of active surface ground displacement, such as Global Navigation Satellite Systems (GNSS) and interferometric synthetic aperature radar (InSAR). Geodetic slip rate estimates may vary widely due to measurement and epistemic (model) uncertainties, presenting a challenge for both estimating slip rates and accurately characterizing uncertainties: models may vary in the number of faults represented and the precise location of those faults. Since 2003, 33 published geodetic deformation models have produced slip rate estimates within California. Variability among these models represents variability among valid model choices, and may be considered a proxy for model uncertainties in geodetic slip rate estimates. To enable rigorous comparison between geodetic slip rate estimates, I combine these models on a georeferenced grid and find an average standard deviation on slip rate of ~1.5 mm/yr over 542 grid cells (average area of 1304 km^2 per cell). Furthermore, the average strike-slip and tensile-slip rates over all 33 studies, in each grid cell, may then be projected onto Unified California Earthquake Rupture Forecast (UCERF) 3.1 faults for a single summary model of geodetic slip rates. Slip rates that do not project perfectly onto UCERF 3.1 faults form a summary model of off-modeled-fault (OMF) deformation. Most of this OMF deformation occurs in grid cells that intersect UCERF 3.1 faults, suggesting that 'off-fault' deformation may be in part a product of epistemic uncertainty in geodetic slip rate estimates, and may be physically accommodated on, or very near (within a region of ~1304 km^2), UCERF faults.

A New Geodetically-Derived Seismicity Model for Italy

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The exponential increase of continuously recording GNSS stations allows the accurate mapping of the distribution of tectonic strain rate in the Italian peninsula. A compilation of the available station velocities has been recently submitted as input data in the framework of the planned update of the Italian probabilistic seismic hazard map (MPS16; https://ingvcps.wordpress.com). Starting from the GPS velocity field (919 horizontal velocities, excluding volcanic areas and velocities discrepant with regional velocity field) a geodetically-derived seismicity model for the Italy and neighbouring regions has been submitted for MPS16. The strain rate field has been calculated on a regular 0.1° x 0.1° grid using the VISR software (Shen *et al.*, 2015) taking into account the variable station spacing for the optimal smoothing parameters and finally applying a Gaussian filter of 50 km (6-sigma width) to the scalar strain rate value. The rate of seismic moment accumulation density is converted to earthquake rate density under the assumption that seismic moment distributes into earthquake sizes that follow a tapered Gutenberg-Richter. Due to the limited knowledge on the spatial variation of the relevant parameters entering in the conversion from strain rate to seismicity rates, I assumed spatially invariant values of b, maximum magnitude and seismogenetic thickness. The effect of uncertainties in these parameters have been introduced by considering alternative realizations of the seismicity model and considering the 50th, 5th and 95th percentiles as representative of the median and associated uncertainties of the final seismicity model. Results have been compared with the historical seismic release as documented in the recently released CPTI15 catalogue for various spatial and temporal scales and for different declustering approaches. I also discuss the advantages and limitations of the proposed geodetically-derived seismicity model.

Slow Slip Events and the Earthquake Cycle: Nicoya, Costa Rica

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In February of 2014 a M_w=7.0 slow slip event (SSE) took place beneath the Nicoya Peninsula, Costa Rica. This event occurred 17 months after the 5 September 2012, M_w=7.6, earthquake and along the same subduction zone segment, during a period when significant postseismic deformation was ongoing. A second SSE occurred in the middle of 2015, 21 months after the 2014 SSE. These events allow for analysis of SSE behavior during both the late and early stages of the earthquake cycle. The recurrence interval for Nicoya SSEs was unchanged by the earthquake. However, the spatial distribution of slip for the 2014 event differed significantly from previous events, only having deep (~40 km) slip. Previous events showed both deep and shallow slip. The 2015 SSE marked a return to the combination of deep and shallow slip of pre-earthquake SSEs. However, slip magnitude in 2015 was nearly twice as large (M_w=7.2) as pre-earthquake SSEs. The large amount of shallow slip in the 2015 SSE maybe a result of missing slip during the 2014 SSE. These observations highlight the variability of aseismic strain release rates throughout the earthquake cycle and thus provide considerable uncertainty when considering long term strain accumulation rates.

Geodetically-Constrained Viscoelastic Block Models and Time-Dependent Stress Transfer along the North Anatolian Fault

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Along the North Anatolian fault (NAF), the surface deformation associated with tectonic block motions, elastic strain accumulation, and the viscoelastic response to past earthquakes has been geodetically observed over the last two decades. These observations include campaign-mode GPS velocities from the decade prior to the 1999 M_W=7.4 Izmit earthquake and seven years of continuously recorded postseismic deformation following the seismic event. We develop a three-dimensional viscoelastic block model of the greater NAF region, including the last 2000 years of earthquake history across Anatolia, to simultaneously explain geodetic observations from both before and after the Izmit earthquake. After accounting for viscoelastic effects, the fastest slip deficit rate estimates along the entire fault system (~27-28 mm/yr) occur less than 50 km from Istanbul, along the northern strand of the NAF in the Sea of Marmara. We combine this geodetically-constrained rheological model with the observed sequence of 8 M_W>6.7 earthquakes along the NAF since 1939 to calculate the time evolution of Coulomb failure stress changes (CFS) along the fault due to viscoelastic stress transfer. The mean CFS along the earthquake rupture extents may increase by up to ~177% due to non-coseismic viscoelastic effects. By 2023, we infer that the mean time-dependent stress change along the northern NAF strand in the Marmara Sea near Istanbul, which may have previously ruptured in 1766, may reach the mean apparent time-dependent CFS level of the previous NAF earthquakes.

Strain Invariance over an Earthquake Cycle and Geodetic Assessment of Seismic Hazard

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Earthquakes are caused by the release of tectonic strain accumulated between events. Recent advances in satellite geodesy mean we can now measure this interseismic strain accumulation with a high degree of accuracy and it has been proposed that the data have value in seismic hazard assessment. However, it remains unclear whether short-term (decadal) geodetic observations can be useful when estimating the seismic hazard of faults that accumulate strain over centuries to millenia. Here we show that interseismic strain accumulation rates around a major continental transform fault are nearly constant for the entire interseismic period, except in the few years following an earthquake. We measure strain rates along the entire North Anatolian Fault zone using InSAR and GNSS, allowing us to sample strain rates at times ranging from 1 month to 240 years after the most recent earthquake. The observations require a weak fault zone embedded within a strong lower crust with viscosity in the range ~10^20 to 10^23 Pa s. The results support the notion that short-term geodetic observations can usefully contribute to long-term seismic hazard assessment and suggest that lower-crustal viscosities derived from postseismic studies are not representative of the entire lower crust.

Dark Energy and Earthquakes: Elastic Strain Invisible to Geodesy

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Borehole stress measurements indicate that most of the Earth's surface can retains significant elastic strain over thousands of years. Although its local release in intraplate earthquakes can be readily quantified using geodetic methods, in regions of low strain rate geodesy is unable to assess the contribution of this untapped elastic energy to future earthquakes. Somewhat surprisingly, recent plate boundary earthquakes demonstrate that this impotence also applies to regions of high strain rate. In the 2015 Nepal earthquake, the Himalayan hanging wall slipped 1-6 m southward but failed to rupture the southernmost 30 km of the decollement to the surface, thereby incrementing strain in the mid-décollement locally by more than 100 µstrain. A similar earthquake in 1833 also failed to rupture the frontal thrusts, suggesting that the 2015 Gorkha earthquake either added to or canibalized the relict strain imposed by this former earthquake. Neither geodesy nor microseismicity in the two decades prior to the 2015 Gorkha earthquake provided any indication that the strain imposed by the 1833 or 2015 earthquakes was able to drive creep or seismic-slip on the shallow decollement, except near the interseismically locked region near the Tibet border. Nor has any historical earthquake unequivocally ruptured the decollement to the south of these rupture zones. We conclude that great ruptures in the Himalaya, as in many seismic zones, are fueled in part by numerous invisible pools of latent stored elastic energy. Their presence is partly responsible for the variable slip evident in dynamic rupture models. Since these latent strain reservoirs cumulatively exceed the decadal strain changes at the world's plate boundaries, the field of seismic geodesy faces a similar problem to the astrophysicist confronting Dark Energy. Although we may observe the release of "Dark Strain Energy" by earthquakes, the enormity of its influence on future earthquakes remains invisible to geodesy.

A Robust Estimation of the North American Intra-Continental Strain Rate Field with Implications for Seismic Hazard

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Strain rate fields derived from GPS velocity data have proven powerful indicators of seismic hazard. For example, there is a direct correlation between the geodetic strain/moment rate and earthquake productivity rates for areas of diffuse deformation, which means that all geodetic deformation is released seismically there. It is, however, not known yet if such correlation exists for intraplate areas, where the expected strain rate signal is at the level of the data noise. Fortunately, the amount of data has recently increased tremendously, such that the effect of outliers has diminished and any coherent signal in the data might be revealed. We focus here on the North American plate and use GPS data analyzed by the Nevada Geodetic Laboratory with robust IGS08-fixed rates determined automatically by the MIDAS algorithm (Blewitt, *et al.*, 2016).

We use a three-tier approach. First, we present a new outlier detection algorithm that exploits anomalies in the local dilatational strain rate signal around each station. Secondly, we apply a spatial median filter on the remaining GPS velocities (Hammond *et al.*, 2016), which smooths the data and minimizes the effect of any remaining velocity outliers. Thirdly, we apply a new algorithm (MELD: Median Estimate of Local Deformation) to estimate strain rates. MELD determines the median strain rate tensor and rotation for a grid point based on a set of strain rate tensors and Euler poles determined from all local Delaunay triangles that encompass the grid point.

The dominant strain rate signal is associated with Glacial Isostatic Adjustment: extension in most of Canada, contraction in the far-field, and elevated contraction rates just outboard from the former ice sheet. We find that the residual far-field velocities point towards the former ice sheet. While there is a positive correlation between the strain rate map and seismicity at higher latitudes, we find no such correlation for the conterminous U.S., including New Madrid.

Fine Scale Structure of the Crust and Upper Mantle

Oral Session · Wednesday 19 April · 8:30 AM · Plaza D

Session Chairs: Peter Molnar, Barbara Romanowicz, and Steven Roecker

Imaging the Farallon Slab and Other Upper-Mantle Structure under USArray Using Long-period Reflection Seismology

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Top-side reverberations off mantle discontinuities are commonly observed at long periods following teleseismic arrivals. For example, stacks of USArray transverse-component data from 3250 earthquakes, using direct S as a reference phase, show clear reverberations off the 410- and 660-km discontinuities. However, interpretation of these features is complicated by the fact that they include both near-source and near-receiver reflections. We have developed a method to isolate the station-side reflectors in large data sets with many sources and receivers and applied it to the USArray data, using recent USArray crustal and upper-mantle tomographic models to account for 3D velocity structure. Because our results are sensitive to the impedance contrast (velocity and density), they provide a useful complement to receiver-function studies, which are primarily sensitive to the S velocity jump alone. In addition, reflectors in our images are more spread out in time than in receiver functions, providing good depth resolution, because they are sensitive to the two-way S travel time rather than the S–P time.

Our images show strong discontinuities near 410 and 660 km across the entire USArray footprint, with intriguing reflectors at shallower depths in many regions. Overall, the discontinuities at all depths east of 100°W appear simpler and more monotonous with a uniform transition zone thickness of ~250 km compared to the western United States. In the west, we observe more complex discontinuity topography and small-scale changes below the Great Basin and the Rocky Mountains, and a decrease in transition-zone thickness along the western coast. We also observe a dipping reflector in the west that aligns with the top of the high-velocity Farallon slab anomaly seen in tomography models. The coherence of this reflector can be improved by applying common reflection point stacking methods, and often appears as a multiple reflector rather than a single feature.

GLImER—A New Database of Teleseismic Receiver Functions for Global Imaging of Crustal and Upper Mantle Structure

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Teleseismic receiver functions provide a simple means to image structure in the Earth's subsurface. Despite its ease of use, the method has traditionally required considerable user input to ensure that key processing operations run in a stable manner and yield robust results. As a consequence, large-scale applications to global datasets have been limited. Here we present preliminary results from a global database of receiver function data products (GLImER—Global Lithospheric Imagining using Earthquake Recordings) dedicated to imaging structure in the crust and upper mantle. Earthquake signals recorded at seismic stations worldwide are downloaded, quality controlled and processed using a range of deconvolution approaches to generate robust receiver functions. We describe our automated workflow and apply it to the entire data holding of the Incorporated Research Institutions for Seismology, producing 1,300,424 individual radial and transverse Ps receiver functions computed at 8258 stations. We then present a series of tools that are designed to visualize the results and will be made publicly available on the project's website. These include a map-based interface that allows users to inspect receiver functions at individual stations, and interactive programs that can generate cross-sections through 3D volumes of receiver functions.

Constraining Fine Scale Lithospheric Structures by Full Waveform Inversion of Teleseismic Waves

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During the last decades, receiver functions and more recently CCP stacks have been seismologist's main workhorses to image seismic interfaces such as the crust/mantle boundary worldwide. However, because these approaches have little sensitivity to large scale structures (> 2 km), their results are often insufficient to decipher the causal links between geodynamic or tectonic processes and lithospheric architecture. The recent development of dense deployments at the regional scale opens new opportunities to exploit the complete wave fields by full waveform inversion (FWI). Indeed, FWI of short period teleseismic P waves bridges the gap between regional travel time tomography and receiver functions studies, thereby allowing us to obtain finely resolved tomographic images of the lithosphere, accurate over a broad range of scales. I will illustrate the interests of FWI by showing the first applications to continental orogens. FWI also opens important perspectives for 3D imaging of seismic anisotropy, and I will introduce the basic principles to extend FWI to the problem of imaging the fine scale anisotropy of the lithosphere and asthenosphere.

Tectosphere from Receiver Functions

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Differential motion between tectonic plates and the underlying mantle is usually thought to be accommodated at the lithosphere-asthenosphere boundary (LAB), which, beneath cratons, is found at a depth of about 200 km. However, seismic data suggested long ago that the tectosphere (mantle layer which translates coherently with the crust of the craton) may be up to 400 km or more thick. I discuss indications of the tectosphere in recently obtained P and S receiver functions. In presently active hot-spots the receiver functions often provide evidence of a depressed 410-km seismic discontinuity and a low-S-wave velocity zone at depths of 450-510 km . These anomalies are very likely linked to elevated temperatures in the mantle transition zone. Beneath cratons at the sites of basaltic eruptions 250–50 Ma old, there are indications of similar anomalies in the mantle transition zone, although the subsequent plate motions are on the order of a thousand kilometers. These observations suggest that the anomalies in the transition zone might migrate coherently with the plates, and the differential motion is accommodated not so much at the LAB at a depth of 200–250 km as in the underlying mantle layer a few hundred kilometers thick.

Lithospheric Structure in Central California across the Isabella Anomaly and Tectonic Implications

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The tectonic origin of the Isabella high-velocity anomaly in the upper mantle beneath California's southern Great Valley is unclear. Previous low-resolution seismic imaging studies of the region have been unable to identify the structural connection between this anomaly and the overlying lithosphere. The two competing hypotheses attribute the Isabella anomaly to either a fossil slab or the foundered lithospheric root of the Sierra Nevada batholith. The Central California Seismic Experiment (CCSE) was designed to distinguish between these hypotheses. We present results from the CCSE, which consisted of 44 broadband seismometers deployed in a linear array spanning from the Pacific coast, across the Great Valley, to the Sierra Nevada foothills at an average station spacing of 7 km. Receiver function images reveal a prominent West-dipping crustal discontinuity beginning near the surface beneath the Sierra Nevada foothills (~119.15°W) and reaching ~25 km depth beneath the Great Valley, some ~80 km to the west. We speculate that this feature represents the top of a high-velocity ophiolite body that underlies most of the Great Valley. Teleseismic events recorded by the CCSE reveal scattered waves arriving tens of seconds after the S-wave, which can be mapped to scattering points outlining an East-dipping structure at depth. An East-dipping interface in the upper mantle beneath the Great Valley is also seen in receiver function and surface wave tomography images at ~30-80 km depth. The location and orientation of this structure is consistent with a fossil slab origin for the Isabella anomaly and inconsistent with a foundered lithospheric root. In addition, body wave travel-time measurements indicate that the Isabella anomaly extends west to beneath the coastal range, further supporting the fossil slab hypothesis.

Imaging Lithospheric Drips and Delaminations with Large Seismic Arrays

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Tectonically active orogenic belts and plateaus occupy roughly 10% of the Earth's surface. Most orogenic belts have thin mantle lithosphere compared to surrounding oceans and stable continental interiors, suggesting that their mantle lithosphere has been recycled during the orogenic cycle.

The loss of lithospheric mantle from beneath orogenic belts and plateaus has been ascribed to: 1) initiation of Rayleigh-Taylor instabilities caused by loads applied to otherwise stable, density-stratified fluids, 2) delamination of parts of the lithosphere, 3) ablation or viscous entrainment during subduction, and 4) edge convection. Strictly speaking these mechanisms are not part of classic plate tectonic theory. To initiate a downwelling requires a trigger consisting of a load, (*e.g.*, crustal loading by mountain building, or positive density anomalies resulting from melting or phase changes), that acts with other mediating physical factors such as lithospheric weakening by hydration, heating or melt fluxing, or advantageous geometry of a nearby subduction zone or craton.

The development of large portable broadband seismic arrays has resulted in detailed images of drip and delamination-like features under most orogenic belts: the western Mediterranean, the Alpine system, the Tibetan Plateau, and the North and South American Cordillera. Detailed imaging of these drips suggest that elements of all of the conceptual models are operative somewhere on the globe, often in combination with one or more of the others. In the western U.S. upper mantle, 6 positive velocity anomalies in tomography images are interpreted as downwellings (Schmandt and Humphreys, 2010). These drips occupy 5-10% of the orogenic belt surface area. Descending drips sinking at plate tectonic rates can be identified seismically for 5-10 Myr. This suggests that during a 100 Myr orogenic lifespan, most of the lithospheric mantle incorporated into an orogenic belt can be recycled to the deeper mantle.

Preliminary SKS/SKKS Shear Wave Splitting Results for the GRASP Seismic Array in the Dominican Republic

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Shear wave splitting measurements are a well-established method to detect seismic anisotropy within the Earth. Seismic anisotropy has been observed at numerous depths and environments stemming from Earth's crust to the core-mantle boundary using shear wave splitting techniques. Strong anisotropic structures are common in the upper mantle. Consequently, shear wave splitting measurements are often used as an analogue to infer upper mantle flow patterns and subsequently upper mantle tectonic structures. Here we present preliminary shear wave splitting measurements for the GRASP array in the Dominican Republic for SKS and SKKS phases calculated using the SplitLab MatLab interface developed by Wustefeld et al (2008). Events used in this study are limited to events between 2013-2016 with a minimum magnitude of 6.0 M_w and epicentral distances between 90°-130° to ensure quality SKS and SKKS phases. Preliminary results reveal a general trend in the splitting parameters across the array; the fast axis trends towards an WNW-ESE direction with azimuths of approximately -65° to -80° and a delay times between 1.0-1.5s. However, of particular interest are three stations located in a roughly North-South transect at 70°W; each of these stations are dominated by NULL results. Additionally, this longitude is also near where the edge of the subducted material beneath the Dominican Republic is speculated to be located. One possible interpretation of this preliminary data is the NULL measurements represent a sliver of turbulent flow adjacent to a slab edge. However, significantly more data is required to confirm the observed splitting and NULL pattern as quality splitting measurements are currently quite limited. Future plans include expanding the current data set to explore other splitting phases such as SKiKS, PKS, and pSKS/sSKS.

Lithospheric Foundering and Underthrusting Imaged beneath Tibet

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New tomographic images unveil a large-scale, high wave speed structure beneath South-Central Tibet in the middle to lower portions of the upper mantle. We interpret this structure as a remnant of an earlier lithospheric foundering event. Spatial correlations between foundering lithosphere and ultrapotassic and adakitic magmatism support the hypothesis of convective removal of thickened Tibetan lithosphere causing a major rise of Southern Tibet during the Oligocene. Lithospheric foundering induces an asthenospheric drag force, which drives continued underthrusting of the Indian continental lithosphere and associated shortening of the remaining Tibetan lithosphere. We speculate that more recent asthenospheric upwelling leads to a thermal modification of thickened lithosphere beneath Northern Tibet and subsequent surface uplift, consistent with the correlation of recent potassic volcanism and an imaged narrow low wave speed zone in the uppermost mantle. In contrast, the unusually high seismic wave speeds in the uppermost mantle beneath Southern Tibet, reminiscent of images beneath the North American craton, suggest a possible prototype of modern craton formation due to continued under-accretion of Indian continent.

Plateau Subduction, Intraslab Seismicity and the Denali Volcanic Gap

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Tectonic tremor in Alaska is associated with subduction of the Yakutat plateau, but its origins are unclear due to lack of depth constraint. We have processed tremor recordings to extract constituent low frequency earthquakes (LFEs), and generated a set of 6 high signal-to-noise ratio waveform templates via iterative network matched filtering and stacking. Timing of impulsive P- and S-arrivals on template waveforms places LFEs between 36-53 km depth, 5-10 km above the envelope of intraslab seismicity and immediately updip of increased levels of intraslab seismicity. S-waves at near-epicentral distances display polarities consistent with shear slip on the plate boundary. We compare characteristics of LFEs, seismicity and tectonic structures in central Alaska with those in warm subduction zones, and propose a new model for the region's unusual intraslab seismicity and the enigmatic Denali volcanic gap. We argue that fluids in the Yakutat plate are confined to a (meta)basaltic upper crust, and that protracted shallow-dip subduction leads to conditions at the slab interface in central Alaska akin to those in warm subduction zone where similar LFEs and tremor occur. These conditions lead to fluid release at shallow depths, explaining strike-parallel alignment of tremor occurrence with the Denali volcanic gap. Moreover, the lack of double seismic zone and restriction of deep intraslab seismicity to a persistent low velocity zone are natural consequences of anhydrous conditions prevailing in the metagabbroic lower crust and upper mantle of the Yakutat plate.

Linearization Scheme for 1D Anisotropic Inversion of P Receiver Functions

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The interpretation of seismic receiver functions in terms of isotropic and anisotropic layered structure can be complex. The relationship between structure and body-wave scattering is nonlinear. The anisotropy can involve more parameters than the observations can readily constrain. Finally, reflectivity-predicted layer reverberations are often not prominent in data, so that nonlinear waveform inversion can search in vain to match ghost signals. Park and Levin (2016) linearized the hybridization of P and S body waves in an anisotropic layer to predict first-order Ps conversion amplitudes at crust and mantle interfaces. In an anisotropic layer, the P wave acquires small SV and SH components. To ensure continuity of displacement and traction at the top and bottom boundaries of the layer, shear waves are generated. Assuming hexagonal symmetry with an arbitrary symmetry axis, theory confirms the empirical stacking trick of phase-shifting transverse RFs by 90 degrees in back-azimuth to enhance 2-lobed and 4-lobed harmonic variation. Theory predicts that P-wave anisotropy generates Ps converted waves far more efficiently than does S-wave anisotropy. If the ratio of the two anisotropies is fixed, the 2-lobed and 4-lobed Ps harmonics can constrain the orientation and polarity (fast or slow) of the anisotropic symmetry axis with no formal ambiguity. Ps scattering is generated by sharp interfaces, so that RFs resemble the first derivative of the model. We show that multiple-taper receiver functions in the frequency domain can be manipulated to obtain a first-order reconstruction of the layered anisotropy, under the above modeling constraints and neglecting reverberations. Synthetic examples show promise, even in the case of multiple layers.

Park, J., and V. Levin, 2016. Anisotropic shear zones revealed by back-azimuthal harmonics of teleseismic receiver functions, Geophys. J. Int., v207, 1216-1243, doi:10.1093/gji/ggw323.

Fine Scale Structure of Seismic Anisotropy beneath Western Tibet.

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Deformation of the lithosphere and the underlying asthenosphere results in systematic rock fabric, and is manifest by the directional dependence of seismic wave velocity. Observations sensitive to anisotropy (shear-wave splitting, P-to-S conversions) offer a means to map rock fabrics at depth. However, translation of observable waveform attributes into depth distribution of anisotropic seismic properties is far from straightforward. Vertical and lateral variations in fabric strength, changes in the sense of anisotropy, and differences in symmetry (axis orientation and plunge, symmetry type) are all likely, especially in regions with complex geodynamic conditions.

We present a case study of one such region—the western Tibetan Plateau. The ongoing convergence between India and Asia here is in N20°E direction, radial anisotropy within 75-80 km thick crust implies flattening, and reported measurements of shear wave splitting are highly variable. Most fast axis orientations inferred from split shear waves are at odds with either the direction of relative plate convergence or the strike of surface tectonic features. This mismatch and the significant directional scatter in splitting measurements are likely indicators of vertical changes in anisotropic fabric.

We use teleseismic body wave data to constrain vertical variations of anisotropic properties in three different geodynamic regimes: on the Indian lithosphere of Tethian Himalaya, at the Indus-Yarlung Suture (IYS), and north of the Bangong-Nujiang Suture (BNS). Exploiting complementary constraints on anisotropic properties available from azimuthally variable receiver functions and split shear waves, we show that the incoming Indian lithosphere has very weak mantle anisotropy, that texture in the crust near the IYS is aligned with strike-slip deformation along the Karakoram Fault, and that at least two distinct layers of upper mantle rock fabric are present beneath the BNS in the central Tibetan plateau.

Lithospheric Fabric and Shear Zones in Southern California and the Basin and Range from Anisotropic Receiver Function Conversions and Other Stress and Strain Observables

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We present a method to image contrasts in horizontal azimuthal anisotropy, dipping rock fabric, and dipping isotropic contrasts based on azimuthally varying conversions in receiver functions. Unlike shear wave splitting, azimuthally varying *P* to *S* conversions provide a large-amplitude, robustly observable signal even for small (few percent) contrasts in anisotropy in thin (few km) shear zones, and the depth of anisotropic contrasts is resolved. Results in the Basin and Range favor subhorizontal fabric consistent with extension, while results in Southern California show dominant dipping fabric despite subvertical near-surface dips of the major faults that accommodate transform motion. Strikes of dipping fabric in Southern California remain parallel to surface fault strikes even away from faults and throughout the lithospheric depth range. We infer that deformation is laterally distributed beneath the brittle-ductile transition zone. We show quantitative geographical correlations between strikes from receiver functions to anisotropy from *Pn*, surface waves, and shear wave splitting, as well as to orientations of inferred stress from focal mechanisms, surface faulting, and paleo-subduction orientation to place the geographical and depth distribution of anisotropy from receiver functions in context with other observables related to lithospheric deformation.

Comparative Riftology: Insights from Crustal Structure Into the Evolution of Continental Rifts and Passive Continental Margins

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Continental rifts evolve to seafloor spreading and are preserved in passive margins, or fail and remain as fossil features in continents. Rifts at different stages give insight into their evolutionary paths. Of particular interest is how volcanic passive margins evolve. These are characterized by sequences of volcanic rocks yielding magnetic anomalies landward of and sometimes larger than the oldest spreading anomalies. Seaward-dipping reflectors (SDR) occur in stretched continental crust landward of the oldest oceanic crust and are underplated by high-velocity lower crustal bodies. How and when these features form is unclear. Insights are given by the Midcontinent Rift (MCR), formed by 1.1 Ga rifting of Amazonia from Laurentia, that failed once seafloor spreading was established elsewhere. MCR volcanics are thicker than other continental flood basalts, due to deposition in a narrow rift rather than a broad region, giving a rift geometry but a LIP magma volume. The MCR gives a snapshot of deposition of a thick highly magnetized volcanic section during rifting. Surface exposures and seismic-reflection data near Lake Superior show a rift basin filled by inward-dipping flood basalt layers. Had the rift evolved to seafloor spreading, the basin would have split into two sets of volcanics with opposite-facing SDRs, each with a strong magnetic anomaly. Because the rift formed as a series of alternating half-grabens, structural asymmetries between conjugate margins can naturally occur. Hence the MCR shows that many features form prior to breakup. Because the MCR was massively inverted by regional compression long after it failed and was uplifted, its structure is better known than failed rifts that incurred lesser degrees of inversion. It provides an end member for the evolution of actively extending rifts, characterized by upwelling mantle and negative gravity anomalies, in contrast to failed and inverted rifts without upwelling mantle and positive gravity anomalies.

A New Lithospheric Density Model of the Conterminous United States and Implications for Intraplate Seismicity

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The density of the crust and upper mantle reflects both thermal and compositional variations and therefore provides a window into tectonic history. Furthermore, density variations produce localized sources of stress that can be important in focusing/defocusing strain, especially at great distance from plate boundaries. Here, we pair seismic velocity models derived predominantly from Transportable Array data with gravity and topography data to produce a high-resolution (<20 km laterally) model of lithospheric density across the continental United States from the surface to 150 km depth and use this model to estimate gravity-derived stress in the seismogenic crust. In the mantle, we note anomalously buoyant material beneath the Wyoming and Superior cratons interpreted as melt-depleted Archean lithosphere and anomalously dense mantle beneath the Gulf Coast that we suggest contains abundant eclogite. Sharp boundaries coincide with the Rocky Mountain front and the rifted Atlantic margin, possibly reflecting step-like changes in lithospheric thickness. We recover known sedimentary basins in the shallowest crust, and the middle-lower crust bears the scars of ancient tectonism, with especially dense material beneath extended zones (the Midcontinent and Reelfoot rifts, the Southern Oklahoma Aulacogen, and the Atlantic margin). By contrast, the southern Appalachians, particularly eastern Tennessee, host modestly thickened but exceptionally buoyant lower crust. Inverting earthquake moment tensors, we also find anomalous states of stress in three of the four highest-hazard seismic zones in the central/eastern U.S. Finite-element modeling suggests that the gravity-derived stress associated with our density model is a plausible explanation for these stress anomalies, and in some cases elevated long-term earthquake rates. If so, such prospective stress modeling could be used to complement the existing source-modeling component of the National Seismic Hazard Model.

From Field Site to Data Center: Network Innovations for Earthquake Early Warning

Oral Session · Wednesday 19 April · 8:30 AM · Governor's Square 15

Session Chairs: Christopher Bruton and Rayo Bhadha

Borehole Instrumentation for Strong Ground Motion Monitoring at Swiss Nuclear Power Plant

Sites

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Between 2014 and 2016 a strong ground motion monitoring system has been installed at the nuclear power plant sites of Beznau (KKB), Gösgen (KKG) and Leibstadt (KKL) in Switzerland. The system at each site consists of a triaxial surface accelerometer and one or two triaxial downhole accelerometers installed at different depths that range from 120 m to 670 m. The borehole of 670 m at KKG is the deepest in Europe for seismic monitoring, and the deepest worldwide for selected technology.

The seismic instruments are continuously recording (24 hours per day) with a sampling of 250 sps and thus, allows a spectral resolution up to 100 Hz. Real-time data is streamed to, and stored in hour-long miniseed at the swissnuclear data center. When an event is identified (exceeding an acceleration threshold of 0.01 g), the event data is recorded with 20 s pre- and 30 s post-event and customized automatic strong-motion analyses reports are at present sent via e-mail notifications to swissnuclear, but this notification can be expanded to several stakeholders. The sensor signals are digitized by Kinemetrics multi-channel Rock Digitizers

Beside building a rich ground motion database, obtained from the new instrumentation, the aim is to study in detail site- specific parameters such as, site amplification between bedrock and surface, V/H at surface and depth, kappa (high frequency damping), site specific aleatory variability (single-station sigma).

The primary objective of this work is to replace theoretical models and expert estimates with site-specific data in the framework of an update to the PSHA. Details on the instrumentation layout, customized data processing and reporting, and expected long-term benefits are presented here.

The Southern California Seismic Network, a Multi-Purpose Seismic Observatory

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In operation under various names since 1932, the Southern California Seismic Network (SCSN) has been continuously monitoring earthquakes occurring from central California (just south of San Luis Obispo) to the U.S.-Mexican border. This network is cooperatively operated and maintained by the U.S. Geological Survey and Caltech, with funding from both federal and state sources. The SCSN is a part of the California Integrated Seismic Network (CISN), and also a contributing Regional Seismic Network within the Advanced National Seismic System (ANSS). With a wide scientific and public mission, the network has developed into a multipurpose observatory capable of satisfying multiple operational objectives. With over 400 stations, this mostly real-time digital network now comprises strong motion, weak-motion, and broadband instrumentation.

As part of the Earthquake Early Warning (EWW) System, additional stations are currently being installed across Southern California. The design of these stations incorporates instrumentation and techniques that maximize the signal-to-noise ratios of the seismic wave field as well as reduce the latency of data transmission for EWW. In this presentation we discuss the performance characteristics of this network showing the noise characteristics and data latency.

UC Berkeley Network Operational Improvements and Challenges for Earthquake Early Warning

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For over 100 years UC Berkeley seismic and geophysical networks have contributed to both earthquake monitoring and fundamental research into earthquake sources and properties. Data from these networks are now used in the ShakeAlert Earthquake Early Warning (EEW) system being developed and deployed in the western US. EEW provides some new challenges for network operations and data management. Reduced data latency, systems and network security, real-time GPS data streams, real-time update of station and sensor metadata, and network resilience have become higher priority issues, and compete for both dollar and staff resources with previously established network goals such as data completeness, careful metadata verification, and telemetry efficiency.

This presentation will provide an overview of the Berkeley network operations and how it addresses the many facets of EEW, traditional earthquake monitoring, and reliable data archiving. We will highlight improvements made to support EEW, and discuss the outstanding operational challenges as the network expands and evolves to fully serve the ShakeAlert system. Information on Berkeley networks can be found at /http://seismo.berkeley.edu, with additional information and data distribution at http://www.ncedc.org and http://service.ncedc.org.

Reducing Digitiser Latency for Earthquake Early Warning: New Strategies for Seismic Hardware

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The two main contributors to data delivery delays in Earthquake Early Warning Systems (EEWS) are data packetization (Brown *et al.*, 2011) and digitization. For transmission, many regional seismic networks use the SEEDlink protocol; however, this transmission method can typically cause large data transmission latencies of >0.7 s at regular sample rates. To add to these delays, many seismic data-loggers implement acausal (linear phase FIR) filters. These filters cannot be computed in true real-time and give spurious precursors to seismic wave onsets, contributing >0.3 s to data delivery delays.

Using the new Güralp Minimus data-logger, we implement a twofold strategy of causal filtering combined with a rapid data transmission protocol, providing a cost-effective strategy of dramatically reducing data delivery times. The use of causal filters, which only depend on past samples, can reduce digitization delays to 20¬–60 ms (at sample rates of 100¬–250 sps). However, causal (minimum phase) FIR filters are typically non-standard in seismic data-loggers, yet, the improved latency and sharper onset determination mean that causal filters offer significant advantages for EEWS. For data transmission, we propose a new ultra-low-latency protocol, GDI, which is an efficient and flexible method of exchanging seismic data in large networks. Instead of using fixed-length packets, the main principle of GDI is to dispatch data sample-by-sample as they are acquired by the data-logger. A self-adaptive scheme assesses the bandwidth available and judges the smallest packet size needed for the fastest transmission.

Based on tests carried out on a Güralp Minimus data-logger, we show that GDI protocol combined with causal filters can significantly reduce data delivery latencies to 40–60 ms (at typical sample rates). Our low-latency hardware strategy provides an innovative solution for hybrid on-site/regional warning in next-generation EEWS.

Data Latency, Compression and Encryption

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Because of interest in the capability of digital seismic data systems to provide low-latency data for "Early Warning" applications, we have examined the effect of data compression on the ability of systems to deliver data with low latency, and on the efficiency of data storage and telemetry systems. Quanterra Q330 systems are widely used in telemetered networks, and are considered in particular.

Q330 data acquisition systems transmit data compressed in Steim2-format packets. Some studies have inappropriately associated the use of data compression with necessarily increased system latency. When the amount of time duration represented per packet is fixed and the physical length of the packet is variable (as in the Q330), rather than a fixed physical size of the packet, latency is defined and can be arbitrarily small. Latency is a function of the number of samples represented in a data packet, not whether the data volume used to represent those samples is compressed. A robust method to measure latencies arising in the Q330 family of data loggers, shows a typical mean latency <0.82s over the public internet using cellular connections, and <0.65s on an Ethernet LAN. For a given number of samples in a data packet, compression *reduces* delay because fewer bits are transmitted to represent a fixed time duration. Higher levels of compression produce further improvements in system and communications efficiency. Acknowledging that the devices of an early warning system need to be protected from malicious unauthorized-access, we are discussing the effects of encryption like OpenVPN on the data transmission.

Machine Learning and its Application to Earthquake and Explosion Signal Analysis

Oral Session · Wednesday 19 April · 10:45 AM · Governor's Square 15

Session Chairs: Timothy Draelos and Hunter Knox

On the Use of Machine Learning for Seismic Event Detection

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In recent years two developments have created exciting new opportunities for data-driven discovery in seismology: the ready availability of massive seismic data sets, and the new developments coming out of the computer science community in scalable algorithms and computing hardware and architectures for processing large data sets. In particular, machine learning and data mining algorithms have shown promise for improving seismic event detection and analysis. Seismologists have been using neural networks and hidden Markov models for seismic signal analysis on a limited basis for decades. Now there is growing interest in integrating modern machine learning and data mining into detection and analysis pipelines on a larger scale.

We will review the broad classes of machine learning algorithms, including both unsupervised learning and data mining techniques for processing large quantities of unlabeled data and supervised learning techniques that can take advantage data annotated by domain experts. We will discuss current research and opportunities for further advancing seismic event detection and analysis. In particular how these techniques can enable new data-driven scientific discovery in large seismic data sets. We will also present ongoing development of a seismic event detection pipeline based on Fingerprint and Similarity Thresholding (FAST), an unsupervised approach to detection that does not rely on template waveforms.

Uncertainty Estimation of Onset Arrival Times Using Parametric Bootstrap of Auto-Regressive Time Series

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The time, geolocation, type, and size of a measured seismic event all come from the processing of the raw seismic waveforms that record ground motion at various sensor locations. Many types of measurements are made on the waveforms, but perhaps the most fundamental are the estimated arrival times of the various seismic phases. While considerable effort has been placed into the research of accurately estimating arrival times, relatively little has been done to quantify the uncertainty of these estimates. We extend the state-of-the-art auto-regressive time series methods of phase onset estimation to include a full estimation of the probabilistic uncertainty of the onset estimate. We propose a parametric bootstrap methodology to obtain a full posterior probability distribution to describe the signal onset detection estimates. We demonstrate our approach on both synthetic and real ground motion data, and discuss the substantial implications that a full uncertainty description affords the subsequent stages of downstream analyses.

Applying Machine Learning to Predict Failure

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Forecasting failure is the goal in diverse domains that include earthquake physics, materials science, nondestructive evaluation of materials and other engineering applications. Due to the highly complex physics of material failure, the goal appears out of reach; however, recent advances in instrumentation sensitivity, instrument density and data analysis show promise toward forecasting failure times. In this work we show that we can predict frictional failure times ('labquakes') in laboratory shear experiments. This advance is made possible by applying Random Forest (RF) machine learning to the continuous time series recorded by a single accelerometer listening to the experiment. The RF is trained applying a number of statistical data features over a time interval over which a number of labquakes occur. Remarkably, during testing we find that the RF predicts upcoming failure time immediately following a labquake, based only on a short time window of data—a 'now ' prediction. The predicted time improves as failure is approached, as other data features add to prediction.

Reference: B. Rouet-Leduc, C. Hulbert, N. Lubbers, K. Barros, C. Humphreys and P. A. Johnson, Learning the physics of failure, in review (2017).

Machine and Auditory Clustering of a Large Set of Seismic Events

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Geothermal heat can be extracted from the crust by advection of water through a fractured reservoir and then used to generate electricity. Pumping cold water into a hot reservoir can drive different but interacting fracture mechanisms: hydraulic fracturing, frictional sliding on existing faults, and thermal cracking. Identification of these processes will enable us to maximize heat extraction while minimizing seismicity. We present here initial results from a transdisciplinary project bringing together researchers from the fields of seismology, rock mechanics, machine learning and acoustics, aimed at identifying characteristics of these fracture mechanisms in seismic signals. Our hypothesis is that each (end-member) fracture process will exhibit particular spectro-temporal features that are not picked up by current seismological signal processing methods, but can be identified by the human auditory system and pattern identification by machine learning. We apply state-of-the-art machine learning methods (non-negative matrix factorization, NMF, and hidden markov models, HMM) over a very large set of spectrograms of small seismic events in the Geyser geothermal reservoir, Sonoma, CA. ``Unsupervised learning'' is used to cluster the spectrograms and reduce the dimensionality of the dataset. The interpretation of the clustering and of the criteria of ``blind'' machine categorization is then made through auditory display: human listening tests are performed, in which signals are converted to sound (audified) and evaluated by listeners. ``Auditory seismology'' has indeed proven to be a promising tool for identifying similarities and differences between seismic signals. Initial results demonstrate clear sonic differences among clusters of natural signals, but we do not yet know how to associate these differences with specific fracture processes.

Examples and Analysis of Adaptive Self-Tuning of a Seismic Signal Detector

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An automated sensor tuning (AST) algorithm that adapts STA/LTA detector trigger level settings to the current state of the environment is applied to two seismic monitoring scenarios and results are analyzed. By leveraging cooperation within a neighborhood of similar sensors, the AST algorithm adapts in near real-time to changing conditions and automatically self-tunes a signal detector to identify (detect) only signals from events of interest. The key metric that guides the dynamic tuning is consistency of each sensor with its nearest neighbors: parameters are automatically adjusted on a per station basis to be more or less sensitive to produce consistent agreement of detections in its neighborhood. Improving signal detection quality early in the seismic processing pipeline leads to fewer false and missed events and has a significant impact on reducing analyst time and effort. The algorithm is applicable to both existing sensor performance boosting and new sensor deployment, allowing systems tuned in this way to achieve better performance than is currently possible by manual tuning, and with much less time and effort devoted to the tuning process.

We show improved performance on data from a seismic sensor network monitoring the Mount Erebus Volcano in Antarctica. With ground truth on detections in a 24-hour period of time, we show that AST increases the probability of detection while decreasing false alarms. We also show improved performance on data from Farnsworth Field, an oil field in Northern Texas that hosts an ongoing carbon capture, utilization, and storage project. Performance is characterized on both of these datasets with respect to two core elements of the algorithm: 1) continuous adaptation of trigger level settings, and 2) event-based filtering of signal detections, which eliminates anomalous (assumed to be false) detections.

Observations and Mechanisms of Anthropogenically Induced Seismicity

Oral Session · Wednesday 19 April · 8:30 AM · Plaza E
Session Chairs: Thomas Goebel, Thomas Braun, Ivan Wong, and Justin Rubinstein

Imaging the Pore-Pressure Diffusion and Triggering Front of Induced Seismicity in Guy-Greenbrier, Arkansas, by Mapping the Seismic B-Value

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Spatio-temporal variations of the seismic b-value during the onset of the potentially-induced earthquake sequence in Guy-Greenbrier, Arkansas are investigated. We construct high-resolution maps of the b-value in both cross-sectional view along the Guy-Greenbrier fault and map view of the region and compare them with the evolving fluid pressure changes from modeling. The range of b-values suggests that the seismicity in the Guy-Greenbrier area is mostly a result of the activation of pre-existing faults. The spatial distribution of the b-values correlate with modeled pore-pressure changes. In general, the b-values decrease with increasing distance from the injection point. Our results show that the high-resolution b-value maps can be used to image the propagation of the buildup pressure and associated triggering front caused by the fluid injection. There is a difference in the polarity of the b-value variations with depth between northern and southern segments of the fault. In the northern segment of the fault b-value increases with depth due to higher pore-pressure changes and opening of new fractures in the deeper part and the relaxation in the shallower parts. Whereas, in the southern segment, the shallower part shows higher b-values due to higher pore-pressure fluctuation but deeper part at the basement has low b-value due to higher confining stress level. The correlation between temporal variation of b-values and hypocentral depths explains a previously observed temporal drop of b-value. This suggests the second-order temporal variations should be interpreted along with the first-order spatial variations. However, considering other important factors such as temporal variations of the local stress regimes might help explain the observations and improve our physical understanding. We estimate the seismogenic indices of the Guy-Greenbrier fault after 82, 96, 100, and 106 days of injection as $\Sigma\_82=-2.01\pm0.016$, $\Sigma\_96=-1.72\pm0.004$, $\Sigma\_100=-1.23\pm0.006$, and $\Sigma\_106=-0.98\pm0.01$

Testing the Quantitative Aftershock Productivity Forecast in Mining-Induced Seismicity

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The characteristics of aftershock sequences in natural seismicity can be well explained by various models based on static stress transfer. In this study we wanted to assess the quantitative aftershock productivity potential in mining-induced seismicity applying a forecast model based on natural seismicity properties, namely constant tectonic loading and the Gutenberg-Richter frequency-magnitude distribution. Although previous studies proved that mining-induced seismicity does not obey the simple power law, here we apply it as an approximation of seismicity distribution to resolve the number of aftershocks, not considering their magnitudes. The model used forecasts the aftershock productivity based on the background seismicity level estimated from an average seismic moment released per earthquake and static stress changes caused by a main shock. Thus it accounts only for aftershocks directly triggered by coseismic process. In this study we use data from three different mines, Mponeng (South Africa), Rudna and Bobrek (Poland), representing different geology, exploitation methods and aftershock patterns. To account for mining-induced seismicity specifics we propose the modification of the original model, *i.e.* including the non-uniformity of M0, resulting from spatial correlation of seismicity with exploitation. The results show that, even when simplified seismicity distribution parameters are applied, the modified model predicts the number of aftershocks for each analyzed case well and accounts for variations between these values. Such results are thus another example showing that coseismic processes of mining-induced seismicity reflect features of natural seismicity and that similar models can be applied to study the aftershock rate in both the natural and the mining environment.

The 2016 Mw5.1 Fairview, Oklahoma Earthquakes: Evidence for Long-Range Poroelastic Triggering at >40 km from Fluid Disposal Wells

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Wastewater disposal in the central U.S. is likely responsible for an unprecedented surge in earthquake activity. Much of this activity is thought to be driven by induced pore pressure changes and slip on pre-stressed faults, which requires a direct hydraulic connection between faults and injection wells. However, direct pressure effects and hydraulic connectivity are questionable for earthquakes located at large distances and depths from the injectors.

Here, we examine triggering mechanisms of induced earthquakes, which occurred at more than 40 km from wastewater disposal wells in the greater Fairview region, northwest Oklahoma, employing numerical and analytical poroelastic models. The region exhibited few earthquakes before 2013, when background seismicity started to accelerate rapidly culminating in the M_w5.1 Fairview earthquake in February 2016. Injection rates in the ~2-2.5 km deep Arbuckle formation started to increase rapidly in 2012, about two years before the start of seismicity increase. Most of this injection was concentrated toward the northeast of the study region, generating a relatively cohesive zone with pressure changes between 0.1 and 1~MPa. Although the near-injection seismicity could have been triggered by pressure effects and fault-assisted pressure diffusion to seismogenic depth, outside of the high-pressure zone, we observed two remarkably detached, linear seismicity clusters. These clusters occurred at 20 to 50 km distance from the initial seismicity and 10 to 40 km from the nearest, high-rate injector. Semi-analytical models reveal that poro-elastically-induced Coulomb stress changes surpass pressure changes at these distances, providing a plausible triggering mechanism in the far-field of injection wells.

Our results indicate that poroelastic stresses in the solid matrix can play a significant role in triggering earthquakes by fluid injection and should be considered for seismic hazard assessment beyond the targeted reservoir.

The Role of Pre-Injection Pore Fluid Pressure in Susceptibility to Induced Seismicity

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Geomechanical and hydrogeological modeling can be a proactive way to manage induced seismic hazard while optimizing underground wastewater disposal. Because sub-hydrostatic formations are economical and efficient disposal volumes, detailed understanding of the ways in which pre-injection pore fluid pressure influences the critical pressure required to induce slip on a given fault is of great societal and economic importance. Here we show that the threshold pressure for inducing slip on an arbitrary fault plane decreases monotonically with decreasing pre-injection pressure, regardless of the tectonic setting or fault frictional properties, for all fault orientations. Using a set of geomechanical parameters representative of northern Oklahoma, our calculations suggest that near the top of crystalline basement—3 km depth—approximately 22% of all possible faults would fail under merely hydrostatic pressure. An even greater proportion of mapped faults, up to 45%, may slip at hydrostatic pressure. Because wellhead pressure in any active injection site is essentially hydrostatic (or greater), maximizing vertical or horizontal separation between the point of subsurface injection and underpressured basement faults may mitigate hazard. This strategy may be additionally effective because of the rapid timescale and short length-scale over which pressures decay with distance from wellheads in high-permeability and underpressured regions such as Oklahoma, Kansas, and the Raton basin. Our findings show that the very underpressured regions in which wastewater disposal is most favorable are geomechanically predisposed to induced seismicity. Careful modeling that includes site-specific geologic structure and hydrogeology, however, may be a powerful tool to optimize injection practices while managing hazard.

Observations of Fault Zone Hydrogeologic Architecture

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Understanding and quantifying fault zone hydrogeological architecture is a critical component of the mechanics of induced seismicity. Fluid pressure is thought to migrate along fault zone channels, however, it is very difficult to measure fault zone hydrogeologic architecture in situ and structures are conceptually described. As a result, hydraulic diffusivity is often inferred from seismicity migration rather than hydrological measurements. The inferred quantities therefore cannot be used to constrain models of earthquake generation for fear of circularity. Water level tidal response inside conventional water wells can measure the hydrogeologic properties of the formation surrounding wells. Utilization of wells at diffident distances to faults therefore allows us to map fault zone hydrogeologic architecture. The San Andreas Fault near Logan Quarry has a surprising uniform diffusivity structure, while with higher specific storage and larger permeability in a localized zone near the fault (within 40 m of the fault). The competition between permeability and storage structure results a uniform diffusivity over ~ 400 m. The faults in the southern Simi Valley also have a uniform diffusivity structure but no significant fault-guided permeability or compliance structures. Such homogenous by fault zone damage is possible in a region of multiple strands and copious secondary faulting. The observed uniform diffusivity structure may suggest that the permeability contrast of fault zones might not efficiently form pore pressure channels in response to water injection. Both of these two sites have a diffusivity of 10^{-2} m^2/s which is also comparable to the post-earthquake hydraulic diffusivity measured on the Wenchuan Earthquake Fault. These studies hint that hydraulic diffusivity of fault zones may evolve to a narrow range of values which are significantly below the hydraulic diffusivities of ~1 m^2/s normally inferred from seismicity migration.

Insight into Subdecimeter Fracturing Processes During Hydraulic Fracture Experiment in Äspö Hard Rock Laboratory, Sweden

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We analyze the nano- and picoseismicity recorded during a hydraulic fracturing in-situ experiment performed in Äspö Hard Rock Laboratory, Sweden. The fracturing experiment included six fracture stages driven by three different water injection schemes (continuous, progressive and pulse pressurization) and was performed inside a 28 m long, horizontal borehole located at 410 m depth. The fracturing process was monitored with two different seismic networks covering a wide frequency band between 0.01 Hz and 100000 Hz and included broadband seismometers, geophones, high-frequency accelerometers and acoustic emission sensors.

The combined seismic network allowed for detection and detailed analysis of seismicity with moment magnitudes M_W<-4 (source sizes approx. on cm scale) that occurred solely during the hydraulic fracturing and refracturing stages. We relocated the seismicity catalog using the double-difference technique and calculated the source parameters (seismic moment, source size, stress drop, focal mechanism and seismic moment tensors). The physical characteristics of induced seismicity are compared to the stimulation parameters and to the formation parameters of the site. The seismic activity varies significantly depending on stimulation strategy with conventional, continuous stimulation being the most seismogenic. We find a systematic spatio-temporal migration of microseismic events (propagation away and towards wellbore injection interval) and temporal transitions in source mechanisms (opening–shearing–collapse) both being controlled by changes in fluid injection pressure. The derived focal mechanism parameters are in accordance with the local stress field orientation, and signify the fracture propagation and reactivation of pre-existing rock flaws. The seismicity follows statistical and source scaling relations observed at different scales elsewhere, however, at an extremely low level of seismic efficiency.

A Macroscopic Study of the Spatio-Temporal Evolution of Induced Seismicity on Single Faults in Oklahoma and Southern Kansas

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For much of Oklahoma, augmentation of the seismic network with new stations in the activated areas has followed rather than preceded the spread of seismicity across the state, and consequently the network geometry is often unfavorable for resolving the underlying fault structures. With this study we augment the existing ANSS catalog with data from two industry operated networks for the period May 2013 to March 2016. These networks include 40 seismic stations and cover seismically active north-central Oklahoma with a station spacing on the order of 25 km. Relative locations obtained from waveform cross-correlation re-veal a striking pattern of seismicity illuminating many previously unmapped faults. Depths are usually well constrained to within 1 km. Relocated epicenters tend to cluster in linear trends of less than 1 km to more than 10 km in length. In areas with stations closer than 10 km, we are able to resolve fault planes by strike and dip. These are generally in agreement with surface wave-derived moment tensors.

Using this data set, we test our understanding of the mechanical conditions for reactivation of dormant faults in the region by elevated pore pressure. Several faults are found to be oriented non-optimally with respect to a homogeneous stress field model for the region. Since pore pressure perturbations by wastewater disposal are generally small, we conclude that local heterogeneities of the stress field in magnitude and orientation play an important role on whether a fault will be reactivated by elevated pore pressure or not.

We further study the spatio-temporal evolution of earthquakes along these faults and find a variety of migration behaviors. For most awakened faults, seismicity tends to initiate at shallower depth and migrates deeper along the faults as the sequence proceeds. However, there are faults where seismicity gets shallower as the sequences progress. Other faults show a radial migration of seismicity or a mixture.

Evaluating Mitigation Strategies for Induced Earthquakes in Light of Recent Moderate Oklahoma Earthquakes

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Until recently, moderate (M5-6) earthquakes in Oklahoma were infrequent with only two documented events, in 1882 and 1952. Since 2011, Oklahoma has experienced four such earthquakes, three of which occurred in 2016. These recent moderate earthquakes all occurred in a region of seismicity largely considered anthropogenic. Under the assumption that these earthquakes were induced by injection, we now have a dataset to evaluate similarities and differences between these damaging events and similarly evaluate the effectiveness of mitigation strategies in this region. The source characteristics for these events are similar: each occurred on a near-vertical strike-slip fault in the shallow Precambrian basement and the existence or extent of the host fault was unknown prior to the earthquake's rupture. The foreshock sequences (M>3) associated with these earthquakes differ dramatically, ranging from seven M4+ earthquakes in the case of the Fairview sequence to minimal foreshock activity in the case of the Pawnee event. These earthquakes have also demonstrated that moderate events can occur at large distances (>10 km) from regions of high-rate injection. The combination of inconsistent foreshock activity, the occurrence of earthquakes on unmapped faults, and the fact that these earthquakes can occur at large distances from primary injectors demonstrates the difficulties in mitigating associated earthquake hazards. This does not imply that current mitigation efforts are ineffective in reducing the rate of moderate earthquakes, as it is unknown if any potential relatively large events have been avoided. In 2015, Oklahoma began regional mitigation strategies aimed at reducing the volume of injected fluid. The rate of earthquakes decreased in 2016 compared to 2015, which suggests that reducing volumes can reduce the earthquake rate. We note 2016 hosted three moderate events and therefore had a substantially larger cumulative moment release as compared to 2015.

Probing Injection-Induced Seismicity in Northern Oklahoma with a Dense Array

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In response to the increase in seismicity in Oklahoma that is likely related to anthropogenic activities, we deployed a temporary large-N array of more than 1,800 vertical-component nodal seismometers over a 25-km-by-32-km region (nominal spacing of ~400 m) in northern Oklahoma during spring 2016. This dense array will allow us to view sequences of likely-induced seismicity in a region of active wastewater injection with unprecedented clarity. We will use data from this LArge-n Seismic Survey in Oklahoma (LASSO) array to assess the locations, frequency, magnitudes, source properties, and spatiotemporal evolution of micro- to minor earthquakes. Improved understanding of the relationship(s) between injection parameters and induced seismicity may lead to more accurate seismic hazard assessment and improved hazard mitigation. We will also identify the locations and orientations of active subsurface faults that may provide insights into where future injection-induced seismicity may occur. Finally, we will perform tomographic imaging of the shallow crust to image the geologic structure and determine if seismicity preferentially locates along particular faults or within specific geologic units. We apply standard event identification methods including short-term average/long-term average (STA/LTA) and waveform-correlation-based detection techniques to find local earthquakes recorded by the array. Detections employing a classic STA/LTA technique identifies more than 3,000 events during the ~30-day deployment, with preliminary hypocentral locations indicating several dense clusters of seismicity that are active throughout the deployment. A database of template waveforms will be constructed from these events and used in a correlation-based detection technique to search for additional smaller magnitude ($M<2$) earthquakes. We will present preliminary results showing the spatiotemporal evolution of seismicity as recorded by the LASSO array.

Geothermal Induced Seismicity: What Links Source Mechanics and Event Magnitudes to Faulting Regime and Injection Rates?

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Improving estimates of seismic hazard associated to reservoir stimulation requires advanced understanding of the physical processes governing induced seismicity, which can be better achieved by carefully processing large datasets. To this end, we investigate source-type processes (shear/tensile/compaction) and rupture geometries with respect to the local stress field using seismicity from The Geysers (TG) and Salton Sea geothermal reservoirs, California. Analysis of 869 well-constrained full moment tensors (MW 0.8-3.5) at TG reveals significant non-double-couple (NDC) components (>25%) for ~65% of the events and remarkably diversity in the faulting mechanisms. Volumetric deformation is clearly governed by injection rates with larger NDC components observed near injection wells and during high injection periods. The overall volumetric deformation from the moment tensors increases with time, possibly reflecting a reservoir pore pressure increase after several years of fluid injection with no significant production nearby. The obtained source mechanisms and fault orientations are magnitude-dependent and vary significantly between faulting regimes. Normal faulting events ($MW < 2$) reveal substantial NDC components indicating dilatancy, and they occur on varying fault orientations. In contrast, strike-slip events dominantly reveal a double-couple source, larger magnitudes ($MW > 2$) and mostly occur on optimally oriented faults with respect to the local stress field. NDC components indicating closure of cracks and pore spaces in the source region are found for reverse faulting events with $MW > 2.5$. Our findings from TG are generally consistent with preliminary source-type results from a reduced subset of well-recorded seismicity at the Salton Sea geothermal reservoir. Combined results imply that source processes and magnitudes of geothermal-induced seismicity are strongly affected by and systematically related to the hydraulic operations and the local stress state.

Overcoming Challenges in Seismic Risk Communication

Oral Session · Wednesday 19 April · 8:30 AM · Governor's Square 12

Session Chairs: Sean McGowan and Taojun Liu

The Public Can Understand Risk and Cares about Building-Code Requirements for New Buildings

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Don't let experts tell you that the public cannot understand risk, cannot express preferences for the performance of new buildings, or does not care about the building code. We offer four counterarguments to such assertions. First, a committee of self-selected volunteers directed much of the San Francisco Community Action Plan for Seismic Safety, which led to several mandatory resilience ordinances. Second, community volunteers advised a city manager on enhancing the wind design requirements for residential buildings in Moore, Oklahoma, after a third fatal tornado in 15 years struck that town. Third, in responding to a web survey, 800 members of the public expressed clear preferences for the building code's seismic performance objectives and its cost-benefit tradeoffs. They said that the issue was important or very important to them. Fourth, the Los Angeles Resilience by Design program garnered broad community support thanks in part to public interest and participation in ShakeOut exercises. These four risk dialogs with the public succeeded where others failed. We think that at least three critical factors separate successes from failures: (1) using plain English rather than technical terminology (*e.g.*, "severe coastal flooding" versus "storm surge"); (2) discussing likely outcomes in detail rather than discussing probabilities and uncertainties (that is, discussing what we know rather than what we don't know); and (3) limiting the ability of scientific rivals or of financially interested builders to misinform the public or to otherwise impugn the credibility of the experts attempting to communicate risk. One can think of these three factors as the words we use, the measures we express, and whom we invite to the dialog.

Human and Economic Losses for Earthquake Scenarios along the Himalayan Arc

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The M7.8 2015 Gorkha, Nepal, earthquake killed nearly 9,000 people and caused approximately $10B in losses from which the country has only partially recovered. Yet, the rest of the Himalayan megathrust system (primarily the Main Frontal Thrust, or MFT) could produce much greater losses based on the extremely high hazards, exposures, and vulnerabilities in the entire region. In 2011, the USGS PAGER team provided a scenario for a hypothesized M8.1 Nepal event to USAID, which proved to be representative of what was faced in the aftermath of the 2015 event. Building on related efforts, such as the work of Bilham and others (2001), scenario efforts of Wyss (2005), and USGS scenario work in the region, we generated ShakeMap scenarios for historical (1200-present) events along the Himalayan arc based on recent studies of seismology and tectonics. Rupture geometries and extents were then constructed to fill in the arc from Pakistan eastward to Burma. The suite of ShakeMaps was used as input for PAGER to estimate fatalities and economic losses, accounting for dramatic increases in exposure. Although our loss calculations consider the effects of damage due to strong shaking, we also estimate landslide and liquefaction hazards; these induced hazards could contribute profoundly to additional impacts. The main project goals were to develop a working model of the geometry of the Himalayan MTF, to calibrate shaking and loss models against historic events, and to produce a suite of scenarios for the entire region useful for planning.

Seismology Meets Theology: Advancing Earthquake Hazard Mitigation by Engaging Pakistan's Religious Community

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With high population density, potential for large-magnitude earthquakes with severe secondary effects, and fragile infrastructure, Pakistan is one of the world's most earthquake-vulnerable countries. In spite of a prominent history of devastating earthquakes, the country remains largely unprepared for future earthquakes, particularly in rural areas closest to Pakistan's seismogenic zones. One major challenge facing earthquake risk reduction lies in "theodicy", or religious explanation of natural disasters, which is frequently at odds with scientific interpretation and modern mitigation methods. We seek to address this challenge by directly engaging Pakistan's religious leaders in a new earthquake education program that promises to bring earthquake hazard mitigation to communities far outside the reach of the central government. Focusing on the impacts of earthquake disasters and the religious mandate to save lives and reduce human suffering, we believe that Pakistan's religious leaders and teachers have the potential to promote the ideas of seismic safety broadly and effectively. The project aims to: 1) improve understanding of earthquake risk in Pakistan's religious institutions, 2) build capacity for managing earthquake risk among religious leaders, and 3) contribute a new element of community engagement to Pakistan's disaster risk reduction efforts. An initial 3-day workshop, planned for February 2017, builds on existing civic education training programs for religious leaders. The workshop will include 20 religious leaders from various earthquake-vulnerable communities in Pakistan. Participants will return to their communities and teach the newly acquired seismic safety principles in religious schools and community forums. Contingent on the success of this pilot workshop, a scaled-up program will be designed to include a broader array of religious leaders and more extensive post-workshop activities in the local communities.

School Seismic Safety Projects in Washington State, USA: A Critical Effort for Earthquake Resilient Washington

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The Resilient Washington State (RWS) strongly recommends making schools structurally, socially and educationally resilient. We, WADNR Division of Geology and Earth Resources (DGER), have been performing projects to develop and improve a methodology that is easy to perform consistently, cost-effective, and comprehensive, and does addresses seismic hazard, liquefaction, and structural and non-structural deficiencies of school buildings to prioritize the seismic risk of the state's schools. Our approach consists of four steps; 1) soil geophysical tests, 2) structural inventory using ASCE41 or FEMA-154, 3) damage assessment, and 4) outreach; hands on activities to support the K-12 Science, Technology, Engineering, Art and Mathematics (STEAM) education. We have been conducting active and passive seismic surveys, and estimating Shear-wave velocity (Vs) profiles, then determining the NEHRP soil classifications based on Vs30m values at school sites in Washington. The surveys methods we have used: 1D and 2D MASW and MAM, P- and S-wave refraction, horizontal-to-vertical spectral ratio (H/V), and 2ST-SPAC to measure Vs and Vp at shallow (0-70m) and greater depths at the sites. We have additionally run Ground Penetrating Radar (GPR) surveys at each site to check possible horizontal subsurface variations between the seismic survey line and the actual location of the school buildings. These seismic site characterization results associated with structural engineering evaluations based on ASCE41 or FEMA 154 (Rapid Visual Screening) were then used as inputs in FEMA Hazus-Advanced Engineering Building Module (AEBM) analysis providing estimated casualties, nonstructural, and structural losses caused by the potential earthquakes in the region. The AEBM analysis results can then be used to prioritize earthquake mitigation actions of the schools. Our efforts have provided unique science and engineering educational opportunities for the K-12 STEAM programs at the schools.

Making Sense of Uncertainty: Risk Communication in the Context of Induced Seismicity

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The relationship between seismic activity and deep wastewater injection extending from oil and gas development has increasingly become the subject of public scrutiny in recent years. Key among the challenges posed by induced seismicity are a dearth of expert consensus about the mechanisms behind such events, escalating property damage and associated economic impacts, and the general state of uncertainty that these events create. This expansive list of unknowns makes communicating with the public a difficult task for researchers and practitioners alike.

At present, there is little systematic research examining how members of the public assess the various risks extending from induced seismicity. Further, even less is known about the social impacts of these risks, whether real or perceived. However, a growing body of literature on community responses to unconventional energy development more broadly demonstrates that the controversies and uncertainties surrounding these issues can foster individual and collective stress that manifest in various forms of social disruption. Developing an understanding of these dynamics is critical for efforts to develop effective public education, policy, and outreach messaging. In this presentation, our team will discuss preliminary findings from data collected via in-depth interviews conducted with community stakeholders regarding induced seismicity in Colorado and Oklahoma. Our discussion will highlight central challenges in risk communication and propose potential strategies for addressing them.

Getting Ready for Earthquakes and Tsunamis in Puerto Rico: ShakeOut vs Caribe Wave Exercises

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Puerto Rico has been hit by 4 destructive earthquakes, two with accompanying tsunamis, over the past 500 years. The most recent deadly event occurred almost 100 years ago on October 11, 1918. The official death toll was 116 persons and the cost of damage probably exceeded 4 million USD. Today, 3.5 million residents (250,000 of which are also at risk from tsunamis) and a Gross Domestic Product of 103 billion USD are at risk from earthquakes and tsunamis. In addition, there are close to 4 million annual visitors that come by air and sea. Puerto Rico is well aware of the potential loss of life and livelihoods from such events and actions have been taken over the years to reduce its vulnerability. Among such activities are the annual tsunami (CARIBE WAVE) and earthquake (ShakeOut) exercises. While they are used to test communications, encourage practice of self-protective actions and response and evaluate preparedness, by raising awareness, they also help offset the disarming effect that the relative infrequency of earthquakes and tsunamis can have on people in the region.

CARIBE WAVE (previously also part of LANTEX-the Gulf of Mexico and US/Canada East Coast Exercise) has been held every March since 2009. It is conducted under the framework of the UNESCO Tsunami and other Coastal Hazards Warning System for the Caribbean and Adjacent Regions and the US National Tsunami Hazard Mitigation Program. In 2016, 140,875 people participated in Puerto Rico. ShakeOut exercises have been held every October since 2012. In Puerto Rico it is coordinated mainly by the Puerto Rico Seismic Network. In the most recent exercise in 2016, 597,000 people registered.

Data and observations from past exercises will be presented and compared. The analysis is important for future enhancements, including CARIBE WAVE 18 and ShakeOut 18 which will also be part of the activities in commemoration of the 1918 Puerto Rico earthquake and tsunami Centennial Anniversary.

People Listen to Seismologists and Still Don't Prepare for Earthquakes… Why?

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In many areas, seismic hazard maps are clear: the probability of a damaging earthquake exists and still most people don't prepare to face that threat. Is there something wrong with the way seismologists communicate? As earth scientists, we may naively believe that communicating the local earthquake potential directly translates into preparedness actions by the public. Unfortunately, basic information on earthquakes is only one preliminary variable that could lead to motivation to prepare, a long way from forming intentions to prepare and the final preparation. research has shown that communicating hazard information is just one element of a much larger picture. Direct earthquake experiences, attitudes and beliefs, and the perception of personal risks are all important factors in message receptivity with respect to earthquakes. Research has also shown that only when people feel a hazard is becoming salient in their lives will they consider taking protective measures. We propose that the role of seismologists is to communicate the possibility of damaging earthquakes and preparedness actions when an educational moment occurs. Examples of these moments are earthquake swarms and aftershock periods. For "non crisis" time periods, seismologists should actively get involved with emergency organisations and promote preparedness.

Bhutan Earthquake Desks: An Affordable, Interim Method of Improving School Earthquake Safety in Countries with High Seismic Risk and Few Resources

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Deaths and injuries from earthquakes would be significantly reduced by replacing or retrofitting seismically vulnerable school buildings, but many countries lack the finances and technical skills to do this. Furthermore, progress would take decades. In some countries, schoolchildren are taught to take shelter under their desks during earthquakes. This makes sense in California, where schools are earthquake resistant and debris that would fall is relatively lightweight. But in other parts of the world, where even moderate shaking would cause roofs or walls to collapse, typical school desks provide poor protection.

In 2016, GeoHazards International initiated a program to provide Bhutan with an affordable, technologically feasible, and rapid means to improve its school earthquake safety. An Israeli-designed "Earthquake Desk" can withstand vertical loads up to one ton dropped from a height of 3.5 meters, which is significantly stronger than a common school desk. We trained Bhutanese carpenters and welders how to manufacture these desks, with the intent to create a low cost, local supply. By involving the nation's Ministry of Education, we also created a sustainable demand for the locally made Earthquake Desks and a means to provide quality control.

Using our building inventory and earthquake modeling framework, we estimate that a repeat of the M8 1714 Bhutan earthquake today, when schools are in session, would cause about 1,000 student fatalities and that replacing existing school desks with Earthquake Desks could reduce these fatalities by about 400. We assume that Earthquake Desks would reduce morbidity by half in severely damaged buildings.

Replacing desks in Bhutan's most at-risk schools is an interim solution now being considered by the Ministry of Education. Lessons learned in Bhutan will help apply this approach in other countries with seismically vulnerable schools, potentially offering increased protection to millions of schoolchildren.

How Science Impacts Decision Making: UCERF 3 Case Study for Loss Estimation in California

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Recent changes in earthquake hazard science in California are transforming the way we think about managing earthquake risk. Loss modeling based on the Uniform California Earthquake Rupture Forecast, version 3 (UCERF3) demonstrates that the footprint of damage from the largest earthquakes in California has changed dramatically. Scientists and risk managers have always viewed Northern California and Southern California earthquake risk being uncorrelated because of the perceived independence of the faults in Northern and Southern California. But, based on UCERF3, the new modeled view of earthquake risk in California illustrates that there is a higher conditional probability of losses impacting both regions simultaneously. Analysis of magnitude 8.0 or higher scenario earthquakes along the San Andreas fault indicates that between 2 and 3.5 million single-family homes could be damaged. This increase ranges from 32 to 126 percent, based on the location and rupture area of the earthquake scenario compared to previous estimates, and could result in total reconstruction cost value of more than $290 billion for the largest event. This dramatic increase is due to the fact that two major urban centers could now be damaged in one single event, not just one. California has always been a high earthquake risk state, but this new view of risk based on UCERF3 may have a greater impact than previously anticipated, which needs to be accommodated accordingly in earthquake preparedness and planning.

Recent Advances in Earthquake Triggering and Aftershock Forecasting

Oral Session · Wednesday 19 April · 3:45 PM · Plaza D
Session Chairs: Margarita Segou and Andrea Llenos

Triggering of Major Earthquakes near the Southernmost Terminus of the San Andreas Fault: Implications of Recent Earthquake Clusters for Earthquake Risk in Southern California

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The southern San Andreas fault (SAF) has not ruptured in more than 320 years. Three earthquake clusters have occurred in direct vicinity of the southern terminus of the SAF in 2001, 2009, and 2016, and raised significant concern regarding possible triggering of a major earthquake on the southern SAF. These clusters of small and moderate earthquakes with $M \leq 4.8$ added to an increase in seismicity rate in the Brawley seismic zone that began after the 1979 M_w6.5 Imperial Valley earthquake, in contrast to the quiet from 1932 to 1979. The swarms so far triggered neither small nor large events on the SAF. The mostly negative Coulomb stress changes they imparted on the SAF may have reduced the likelihood that the events would initiate rupture on the SAF, although large magnitude earthquake triggering is poorly understood. The relatively rapid spatial and temporal migration rates within the clusters imply aseismic creep as a possible driver rather than fluid migration.

Foreshocks to Aftershocks: Insights into the M7.1 Te Araroa Earthquake (NZ), from Matched-Filter Detection

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The September 2, 2016 M7.1 Te Araroa earthquake, was preceded by a M5.7 foreshock 18.5 hours prior. However, understanding the processes linking these events and mapping the spatio-temporal evolution of the sequence is hampered predominantly by the limitations of the onshore network relative to the offshore events. Specifically, the ~100 km epicentral distance from the nearest onshore station limits the ability to detect many small magnitude events, and the small ~20° aperture restricts the ability to accurately determine absolute hypocentres. As an added complication, the effectiveness of routine algorithms based on detecting short and long-term amplitude variations is limited due to the emergent nature of many of the waveforms.

Here we present the results of a template matching method to generate an improved microseismic catalog and examine the sequence evolution. Using 582 aftershock templates we detect a 5.5 fold increase in catalog events (n=8366) between August 6 and September 19, and reduce the catalog completeness of the sequence by a magnitude unit to MLv2.2. We observe a steady background seismicity rate of ~30 events per day prior to the sequence; these events poorly correlate with aftershock templates, and no pre-cursory accelerating moment release is recorded. We further observe increases in seismicity rates immediately following the M5.7 and M7.1 events which exhibit individual exponential decay sequences (*i.e.* detection rates of templates characteristic of the M5.7 sequence are not affected by the M7.1 sequence). Templates characteristic of the M7.1 sequence (including the mainshock template) detect several events in the few hours after the M5.7 foreshock, suggesting triggering of pre-cursory slip on the M7.1 fault patch prior to mainshock failure.

Assessing WCEDS as an Alternative Pipeline Processing System

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We assess the Waveform Correlation Event Detection System (WCEDS) as an alternative pipeline processing system for both broad-area monitoring, and for detecting aftershocks. We report on the application of WCEDS to large quantities of local and regional network data from Utah and Oklahoma, comparing the result with existing seismic catalogs. We also apply the technique to data from an aftershock sequence following the 2011 Circleville, Utah earthquake. We further compare both empirical and synthetic approaches to WCEDS.

Aftershock Duration and the Prevalence of Orphaned Aftershocks in the Apparent Background Rate

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Aftershocks often occur within cascades of triggered seismicity, in which each generation of aftershocks triggers an additional generation, and so on. The rate of earthquakes in any particular generation follows Omori's law, going approximately as 1/t. This function decays rapidly, but is heavy-tailed, and aftershock sequences may persist for long times at a rate that is difficult to discriminate from background. It is likely that some apparently spontaneous earthquakes in the observational catalog are orphaned aftershocks of long-past mainshocks. To assess the relative proportion of orphaned aftershocks in the apparent background rate, I develop an extension of the ETAS model that explicitly includes the expected contribution of orphaned aftershocks to the apparent background rate. Applying this model to California, I find that the apparent background rates can be almost entirely attributed to orphaned aftershocks, depending on the assumed duration of an aftershock sequence. This implies an earthquake cascade with a branching ratio (the average number of directly triggered aftershocks per mainshock) of nearly unity. In physical terms, this implies that very few earthquakes are completely isolated from the perturbing effects of other earthquakes within the fault system. Accounting for orphaned aftershocks in the ETAS model gives more accurate estimates of the true background rate, and more realistic expectations for long-term seismicity patterns.

Constraining the Magnitude of Extreme Aftershocks

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The occurrence of extreme earthquakes is a manifestation of self-similar nature of the frequency-magnitude statistics of seismicity. Among extreme earthquakes large aftershocks constitute significant hazard and can inflict additional damage to the already weakened by the main shock infrastructure. Therefore, constraining the magnitude of the largest event in an earthquake sequence is an important problem in statistical seismology. In this work, we combine the extreme value statistics with Bayesian analysis to derive the Bayesian predictive distribution for the magnitude of the largest events in a sequence of earthquakes. To accomplish this, we use the information of the early events in the sequence to constrain the variability of the model parameters describing the frequency-magnitude statistics and the occurrence rates. We assume that the occurrence of earthquakes in the sequence can be described by a non-homogeneous Poisson point process driven by the Omori-Utsu law. One typical example of such a sequence of events is ubiquitous aftershock sequences. Another example is associated with large foreshocks that can generate their own aftershock sequences and trigger a subsequent main shock. We analyse both types of sequences associated with prominent past main shocks to estimate the probabilities of having a large aftershock above a certain magnitude following the main shock and also of the main shock following the preceding foreshocks. As a main result of this work, we provide a robust scheme in estimating the above probabilities, where we incorporate all the uncertainties associated with the model parameters.

Recent Innovations in Geophone Array Seismology

Oral Session · Wednesday 19 April · 1:30 PM · Governor's Square 15

Session Chairs: Fan-Chi Lin and Marianne Karplus

Structural Properties and Detection of Small Events in the San Jacinto Fault Zone and Other Southern California Regions Based on Seismic Array Data

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I review results on imaging structural properties and detection/location of small earthquakes using data of dense linear and rectangular arrays in the San Jacinto fault zone region, and data of the regional broadband stations in southern CA. High resolution local structural imaging is done with surface and body waves extracted from the ambient noise, fault zone head and trapped waves generated by local earthquakes, and variations of local and teleseismic waveforms across the arrays. The results based on the dense arrays document very low seismic velocities and attenuation coefficients in the shallow crust, strong lateral and vertical property variations, seismic trapping structures, and overall lithology contrast across sections of the San Jacinto fault zone. The detection/location techniques include stacking, beamforming, matched field processing and analysis of spectrograms. The results uncover >4 times as many earthquakes detected with standard techniques and seismic data. These detections provide a basis for creating new templates that can lead to detection of additional events. Analyses of the ambient seismic noise recorded by the broadband stations in southern CA reveal several general changes in the noise field associated with the major fault zones, basins and mountains.

Characterizing Fault Damage Zone Structure Using Low-Cost Large-N Temporary Deployments of Fairfield Nodal Three-Component Instruments: Case Studies from the San Jacinto and Denali Faults

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We present earthquake data, ambient seismic noise, and related statistical characterization of fault damage zone structures from month-long deployments of hundreds of three-component seismometers on the San Jacinto and Denali faults. The Zland 3C instruments have a nominal corner frequency of 5Hz, though we observe clear signals from both local and teleseismic events down to 0.1Hz even in non-ideal substrates such as unconsolidated sediment, packed snow, or in the boles of large trees. Lightweight, low-cost, and portable, these instruments can be deployed in large numbers in terrain that would be inaccessible or prohibitively expensive for traditional seismometers or accelerometers. Applied to fault structure, linear and 2D arrays of instruments with dense spacing can be used to image internal damage zone structure. We perform a bevy of analyses including local event and phase detection, polarization, teleseismic arrival time and receiver functions, multi-component noise cross-correlation, and others; this presentation will focus on a few select results. For two separate arrays with ~15m spacing along San Jacinto fault zone, detections of fault zone head and trapped waves from hundreds of local earthquakes and ambient noise tomography allow us to pinpoint the location of the principal fault surface, damage zone asymmetry, and sub-zones with different damage characteristics. We also observe fault zone normal mode oscillations, identified from amplitude and polarization characteristics which persist from event to event. For an array with ~75m spacing along the Denali fault, we use ambient-noise-derived Rayleigh waves to image velocity structure in the rupture zone of the 2002 M7.9 earthquake. These results, which would be impossible without low-cost dense arrays, motivate future three-component deployments in fault zones with even larger numbers of seismometers.

Data Mining of IRIS Wavefield Experiment in Oklahoma

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The IRIS Oklahoma wavefield experiment provided one of the first three-component geophone-array datasets in our community and the unique opportunity for structural imaging and seismicity studies at local scales. Here, I discuss and demonstrate applications of the geophone arrays using the data of the experiment. The array in this experiment has a variety of different aspects, including linear and 2D arrays, and broadband sensors. The 2D array is useful to characterize the background seismic noise and its wave type. Linear arrays, with local (and global) earthquake records, are used for receiver-function analyses. The shape of sensors is not ideal for ambient-noise tomography, but I can still extract reliable correlation functions to represent a part of Green's functions. Coherent signals are extracted, not only between receivers in this array but also with receivers in Oklahoma regional networks. With the density of the sensors, the locations of microearthquakes around the array are well estimated, and I also use this array as an "antenna" to detect remote seismicity that occurred in the Fairview, Pawnee, and Cushing areas.

Shallow Crustal Structure Revealed by the Yangtze River Large Volume Airgun Shot Experiment in Eastern China

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Imaging high-resolution crustal structures with active source experiments is essential for our understanding of regional tectonics, earthquake hazards, and distribution of energy and mineral deposits. During October 10th-20th, 2014, a large volume airgun shot experiment was carried out in the Yangtze River in Anhui province of eastern China. The airgun shot system was towed by the "Yanping-2" ship that was designed by the Earthquake Administration of Fujian Province, China. There were total 4 airguns (1500LL BOLT airgun) equipped each with the working pressure of 2000 psi (pound per square inch) or 13.79 MPa. These airguns were put 8 meters underwater. There were total 2973 shots excited at 20 fixed sites along the river (~310 km long) and 1872 shots excited during navigation. About 2000 short-period seismometers or geophones were deployed in the field within about 100 km to the shot sites along the Yangtze River. The dominant frequency range of the shots is about 2-8 Hz and the stacked signals (*e.g.*, body waves) of ~100 airgun shots at these fixed sites can be clearly observed at stations several hundred kilometers away from the shot site. Our group is focusing on imaging the shallow crustal structure along the Yangtze River using the surface wave data generated by these active sources, while other groups are focusing on body wave imaging part. We have extracted the high frequency Rayleigh wave group velocity dispersion data within 1-10 Hz from about 150 stations along or close to the Yangtze River. Then these data were used to invert for the shallow crustal structure (from surface to about 1.5 km depth) using the direct surface wave inversion method based on period-dependent raytracing (Fang, Yao *et al.*, 2015). The obtained 3D shear velocity model in the shallow crust is well consistent with surface geology, with high velocities associated with mountain ranges and metallic deposit sites while low velocities in basin areas.

Imaging Seismic Structure of Geothermal Reservoir with Large N Array at Brady Hot Springs, Nevada

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In March 2016, we deployed a dense seismic array to image the structure of the Brady Hot Springs geothermal reservoir in Nevada, where a 4 km * 1.5 km elliptical subsidence area was observed with InSAR (Ali *et al.*, 2016). The array was composed of 244 short-period, three-component geophones and 9,000 m of distributed acoustic sensing (DAS) fiber-optic cable installed in surface trenches plus 400 m installed in a borehole. The geophone array provided about 60 m spatial sampling while sampling of the surface DAS was about 1 m. The acquisition system provided 15 days of continuous records including active source and ambient noise signals.

A large vibroseis truck (T-Rex) was operated at 191 locations to excite a swept-frequency signal from 5 to 80 Hz over 20 seconds using three vibration modes. The cross-correlation method was utilized to retrieve waveforms from the geophone records. The first arrivals (P-wave) were automatically picked from the cross-correlation functions and the travel times were used to invert the P-wave velocity structure. Multichannel analysis of surface waves was used on the DAS records to measure phase velocity of Rayleigh waves between 5 and 20 Hz, providing S-wave velocity structure information.

The ambient noise tomography method was also applied to the continuous geophone and DAS records. The geophone array provided more than twenty thousand noise cross-correlation functions. The group velocity dispersion curves of Rayleigh and Love waves were measured between 2 and 4 Hz using the frequency-time analysis method. The average group velocity is about 400 m/s, which is consistent with preliminary active source results. A low velocity zone is also observed in the area of greatest subsidence.

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Seismicity Detection and Signal Analysis with the Mount St Helens Nodal Array

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The Mount St Helens nodal array recorded continuous data for two weeks in 2014 and consisted of 904 vertical-component geophones. The array overlapped with the active-source component of the iMUSH experiment and recorded a remarkable diversity of seismic signals. This dataset provides an opportunity to test the capabilities and scientific gains that are achievable using dense passive recordings. One of the primary aspects of our ongoing research is the automated identification and location of seismicity that occurred beneath the array. Reverse-time source imaging is applied to the 10 km3 region directly beneath the volcanic edifice where most of the cataloged seismicity occurred during the experiment. These efforts resulted in a five-fold increase in earthquake detections relative to the Pacific Northwest Seismic Network. Additional gains have been made using a new template correlation approach. Earthquake locations resolve a narrow, ≤1 km wide, vertical lineament of seismicity which extends from the surface to 4 km depth beneath the summit crater. This feature is interpreted as a fracture network/conduit that connects the underlying magma chamber to the surface. This analysis has also revealed a distinct type of previously unrecognized long-period seismicity that is lower frequency (<~10 Hz) and longer duration than the typical volcano-tectonic (VT) events. Beamforming and back-projection analysis indicates that these events are not surface features, *e.g.* rockfall, but appear to be occurring in the subsurface (1-6 km depth), often near hypocenters of normal VT earthquakes. Finally, the back-projection method is modified to locate two deep long-period events that were recorded by the array. These events pose a challenge to the array due to their low-frequency content (<5Hz), deep hypocenters (>20 km) and low signal-to-noise ratio. Results are improved by including energy from the S-wave coda and by spatial denoising using the curvelet transform.

Nodal Seismic Recording of Aftershocks of the Mw5.8 Pawnee Earthquake

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We deployed 650 single-component and three-component 10-Hz seismic nodes over the hypocenter of the M_w5.8 Pawnee earthquake, to record aftershock processes and to probe fault zone structure. Deployment of the nodes began 5 days after the mainshock. Instruments were primarily deployed within a ~1-square-km, two-dimensional grid with ~70-meter spacing, crossing over the main fault rupture. A second group of nodes was sparsely deployed over a broader region to provide seismic wavespeed and earthquake location control, supplementing a 13-station network with station spacing of ~3 km, deployed in the three days following the M_w5.8. Nodal instruments recorded for up to 30 days. The largest magnitude earthquake during the time frame of the nodal deployment was an M3.8 earthquake, within the footprint of the nodal array, though waveforms from this earthquake are clipped across the array. Numerous earthquakes with amplitudes below the detection threshold of the 13-station network are recorded on the nodes, and a primary challenge we face is separation of discrete earthquake signals. Our primary goals for the nodal data analysis include evaluation of the minimum detected magnitude of earthquakes within the aftershock series, detailed mapping of fault zone structure using the combined seismic station deployment, and evaluation of seismicity rate changes leading up to and following larger aftershocks within the earthquake sequence. Here we present initial results from the acquired data, including earthquake locations and examples of "nodal" recordings of micro-earthquakes at locations ranging from directly over the source, to over 15 km distant.

Calibrating Dense Spatial Arrays for Amplitude Statics and Orientation Errors

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An iterative procedure is designed to calibrate dense arrays of three-component seismic instruments for station amplitude statics and small (<10 degrees) horizontal component orientation errors. Station amplitude statics refers to differences in sensor calibration and amplification effects due to local site and installation conditions. Amplitude statics and orientation errors can seriously affect computation of the wavefield gradient tensor that is the basis of seismic strain and rotation computations as well as analysis of wave field attributes through wave gradiometry. The technique is based on the assumption of a common wave field observed over a small array using teleseismic earthquake observations. A fast, iterative procedure is set up to first estimate unbiased amplitude corrections for all components and then use the residual wave field to estimate orientation differences between sensors. Calibration of the broad band, 800m-aperture Pinyon Flat (PY) array achieves relative amplitude precision as good as 0.2%. Results will be presented for the gradiometer deployed during the 2016 IRIS Wavefield Community Experiment as well as a 180x300m, 380-element nodal array deployed near Utica, Ohio, during an industrial 3D seismic experiment.

Using Graph Clustering to Locate Sources within a Dense Sensor Array

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We develop a model-free technique to identify weak sources within dense sensor arrays using graph clustering. No knowledge about the propagation medium is needed except that signal strengths decay to insignificant levels within a scale that is shorter than the aperture. We then reinterpret the spatial coherence matrix of a wave field as a matrix whose support is a connectivity matrix of a graph with sensors as vertices. In a dense network, well-separated sources induce clusters in this graph. The geographic spread of these clusters can serve to localize the sources. The support of the covariance matrix is estimated from limited-time data using a hypothesis test with a robust phase-only coherence test statistic combined with a physical distance criterion. The latter criterion ensures graph sparsity and thus prevents clusters from forming by chance. We verify the approach and quantify its reliability on a simulated dataset. The method is then applied to data from a dense 5200 element geophone array that blanketed of the city of Long Beach (CA). The analysis exposes a helicopter traversing the array and oil production facilities.

Weighted Random Sampling in Seismic Event Detection/Location (WRASED): Applications to Local, Regional, and Global Seismic Networks

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Traditional seismology primarily focuses on seismic events with a relatively high signal-to-noise ratio (SNR). This is mainly because reliable picks cannot be made for events with low SNR, so a relatively high threshold is set to avoid false picks. A recent study in the 5200-station Long Beach array shows that random sampling [Zhu *et al.*, 2016] is able to rapidly distinguish the true picks from false ones, which makes reliable detection/location of bad SNR events possible [Li *et al.*, 2016]. However, that study did not consider different confidence levels of the picks, which can be quantified by short-term-average/long-term-average ratio (STA/LTA). In this study, we incorporate this information into our event detection and location method, which leads to a weighted random sampling algorithm. We plan to apply this algorithm to the Long Beach dense array to examine the improvement in event detection/location. In addition, this algorithm can be customized into a new global seismic detection and location framework. In this new framework, the picking threshold can be lowered significantly to include more picks, both true and false, and weighted random sampling is applied to select those weak true picks that were previously below noise threshold and use them for event location. We plan to apply this algorithm to both regional and global seismic networks, and systematically evaluate event detection results compared to those from standard processing procedure. Updated results will be presented at the meeting.

Regional Variations in Seismological Characteristics: Implications for Seismic Hazard Analysis

Oral Session · Wednesday 19 April · 8:30 AM · Governor's Square 14

Session Chairs: Sanjay Bora, Adrian Rodriguez-Marek, and Marco Pagani

Regional Path and Site Effects in Ground Motion Models

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Traditional ground motion models (GMMs) often represent geographically averaged source, path, and site effects for a particular tectonic regime. For example, the NGA-West1 project GMMs characterize active crustal regions using data from California, Japan, Taiwan, and other regions, so the resulting models represent to some degree averaged characteristics of those regions. The approximations associated with this averaging was a necessary compromise to produce a data set sufficiently large to constrain the models over the magnitude and distance range of interest. This remains an important consideration to the present.

Due to regional variations in crustal structure and tectonic stress regimes, global models would be expected to produce misfit when applied to data from a particular region, and indeed this was encountered in the interpretation of the NGA-West2 project data. As a result, several NGA-West2 GMMs include regional terms for path and site effects. Regional effects for source effects were not identified. This presentation will describe how these effects were identified and the regional models were developed. We will also present interpretations of additional data (not used in NGA-West2) demonstrating regional path and site effects from Japan, Italy, and central and eastern North America.

The presentation will be concluded with discussion of the significance of these effects on hazard calculations and quantification of epistemic uncertainty in hazard.

Recommended Central and Eastern North America Seismic Site Amplification Models for USGS Map Applications

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The Next Generation Attenuation East (NGA-East) project resulted in 17 ground motion models (GMMs) for central and eastern North America (CENA). These models provide ground motion intensity measure predictions for sites with a hard rock reference velocity condition of $V_s = 3000$ m/s (Hashash *et al.* 2014), or for sites with the NEHRP B/C boundary condition of 760 m/s. In order to apply the GMMs to weathered rock or soil sites, an additional site amplification model is needed. There have been a number of approaches when developing site amplification models for CENA. These include: (1) adopting models for active tectonic regions (*e.g.* Seyhan and Stewart 2014); (2) regression of NGA-East data to develop a V_{S30}-scaling model (Al Noman and Cramer 2015; Hollenbeck *et al.* 2015; Parker *et al.* 2016); (3) model fitting to data conditioned on peak site frequency calculated from the ratio of horizontal-to-vertical spectra (Braganza *et al.* 2016); (4) and simulation-based approaches (Harmon *et al.* 2016; Darragh *et al.* 2015; Aboye *et al.* 2015; Hwang *et al.* 1996).

We seek to provide guidance to the USGS National Seismic Hazard Map program regarding ergodic site amplification in CENA. We evaluate existing models with respect to several attributes: (1) linear amplification with respect to V_{S30}, (2) amplification of ground motion from 3000 to 760 m/s and (3) nonlinear site effects as a function of PSA period and V_{S30}.

We conclude that the site amplification observed in CENA differs from the current recommended NEHRP factors that were developed based on data from NGA-W2, and recommend a CENA-specific site amplification model and provide associated levels of epistemic uncertainty. The linear amplification is constrained by NGA-East data. The nonlinear model and the 3000 to 760 m/s amplification factors are based on simulations. We note that epistemic uncertainty is reduced if both V_{S30} and site period are included in CENA models.

Investigating Physical Explanations for Path Effects to Reduce Uncertainty in Ground Motion Prediction Equations

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Reducing uncertainty in ground-motion prediction equations (GMPEs) is important for constructing reliable seismic hazard maps, as well as for the safe and cost-efficient design of critical structures. One way to reduce uncertainty is to move from a "global," average GMPE to a region-specific GMPE. Including information regarding physical or seismological processes into GMPEs may allow a model to be tailored to a particular region, thereby reclassifying some of the aleatory uncertainty as knowable features of the region. We present work on our approach to include path-specific information into GMPEs, and demonstrate the feasibility of this method for future application in GMPEs.

To do this, we employ a database of ~100,000 recordings of earthquakes recorded on four seismic networks including the ANZA network. The ANZA network has been in operation since 1981, resulting in redundancy in source-to-station paths. To obtain a regional GMPE for the Anza region, we inverted the recordings with both simple and mixed effects regressions, and used this GMPE to decompose the residuals between observed and predicted ground motions into source, site and path terms. For each recording, we computed raypaths with the regional tomographic model of Fang *et al.* (2016). We sampled regional seismic velocity and attenuation models along these raypaths and formed indices representative of the variation in material properties along each recording's raypath. We then compared these indices with the path terms from our residual decomposition, and find a correlation between the path integral of the gradient of velocity and the path term. We present analyses that may be used to further investigate the effects of material properties on the path effect, and how these relationships may be incorporated into GMPEs. Finally, we demonstrate the resulting reduction in uncertainty from incorporation of this path-specific knowledge, which can result in reduced estimated hazard in certain cases.

Regional Fourier Amplitude Spectra Ground Motion Models Quantifying Source, Path and Site Contributions to Ground Motion in Canterbury and Central New Zealand

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New Zealand comprises several tectonically diverse regions, including Canterbury which shows characteristics typical of an 'intraplate' setting and the tectonically active central region which lies astride the plate boundary. We present newly developed Fourier Amplitude Spectra (FAS) models for the Canterbury and Wellington regions based on spectral inversion of strong motion data from recent aftershock sequences.

We use the generalized linear inversion method of Oth *et al.* (2011) to separate frequency-dependent source, path and site amplification functions for each of the strong motion datasets. Attenuation functions derived from the spectral inversion are non-parametric and not constrained by any a priori functional form. Simple FAS models are constructed based on these results and can be applied to any earthquake scenario and site location using average regional parameters (*i.e.* stress drop, New Zealand site class) with certain limitations in the near-field and under very strong nonlinear ground shaking.

We compare and constrast models from the two regions and discuss regional characteristics of ground motion. We also test our FAS models using more recent earthquake data from Canterbury and central New Zealand that were not included in the model development (*i.e.* M_w 5.7 earthquake in Canterbury and aftershocks of the M_w 7.8 Kaikoura earthquake).

Site-Effects Model for Central and Eastern North America Based on Peak Frequency and Average Shear Wave Velocity

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We develop an empirical site amplification model for sites in central and eastern North America (CENA) using the peak frequency of the site response transfer function (fpeak) and the time-averaged shear-wave velocity in the upper 30 m (VS30). The database for the study includes peak ground-motion amplitudes and 5%-damped pseudo spectral acceleration extracted from the Next-Generation-Attenuation-East database. The site terms are derived by analyzing the residuals calculated from the empirical data with respect to a selected regional GMPE model developed for hard-rock reference site conditions (Atkinson *et al.*, 2015). We develop two alternative site effects models for CENA, each of which assumes that either fpeak or VS30 is the main site variable, then models any remaining residual trends with respect to the other parameter. For the first alternative, assuming that VS30 is the main model parameter, we obtain a frequency-dependent VS30 scaling term that is similar in form to that obtained in previous studies for sites in Western North America (WNA). However, the scaling term is less significant in amplitude for CENA in comparison to that for WNA, suggesting that VS30 is not as indicative of site response in CENA. For the second alternative, assuming that fpeak is the main site-effects parameter, a frequency-independent VS30 scaling term is obtained for CENA, which is much smaller in amplitude compared to the VS30 scaling effect derived in the first approach. This shows that by using fpeak as the primary site-effects modeling parameter, we remove most of the VS30 scaling effects that are implied by the data. Finally, we provide recommendations on the effective use of fpeak and VS30 to model site effects in CENA, differentiating between glaciated and non-glaciated sites. Glaciated sites show larger amplifications compared to non-glaciated sites, especially at intermediate-to-high frequencies, presumably due to the high impedance contrast at the base of the soil profile.

Notes on Strong Ground Motions in the 2011 Fukushima-Hamadori Normal-Faulting Earthquakes

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A sequence of normal-faulting events in Japan following the 2011 Tohoku earthquake have greatly increased the number of strong-motion records for normal earthquakes. Horizontal accelerations (PGA) and velocities (PGV) during the M_w6.7 mainshock were higher than the 2008 NGA ground motion prediction equation. This paper compares 14 normal events with M_w>5 to the 2014 NGA2 West GMPEs. Let the residual for an individual station, s, in earthquake e be defined as the log of the ratio of the data to model. Residuals are estimated by two alternative approaches. In the first, the "NGA method", site-specific estimates of Vs30 are used in the NGA relations to directly estimate an expected model value. In the second, the "KM method", the site-specific station corrections of Kawase and Matsuo (2004) have been applied, as was done by Anderson *et al.* (2013), to convert the observations to a common site condition with Vs30=760m/s, and these values are compared to the NGA models for that site condition. By either method, for an individual earthquake, the residuals for PGA and PGV increase rapidly with distance for the first 100 km, beyond which the distance dependence is weaker and depends on the model. The average residual for a single earthquake therefore depends on the distance range used for the average. We are investigating if this can be explained by crustal and Q structure. This study uses distances 0 to 100 km to estimate the average "event terms", since this is the most significant range of distances for seismic hazards. The event terms by the NGA and KM methods differ, but by either method they show a fairly systematic dependence on depth, consistent with the idea that deeper earthquakes tend to have a higher stress drop. Also, the event terms are greater than zero for 10 of the 14 events, indicating that more research is needed to understand the regional differences in normal faulting ground motions.

NGA-West2 Empirical Fourier and Duration Models for Active Crustal Regions to Generate Regionally Adjustable Response Spectra

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Adjustment of median ground motion prediction equations (GMPEs) from one region (*e.g.*, a data-rich) to another region (*e.g.*, data-poor) is one of the major challenges that remains with the current practice of engineering seismology and seismic hazard analysis. Fourier spectral representation of ground motion provides a solution to address the problem of adjustment that is physically transparent and consistent with the concepts of linear system theory. Also, it provides a direct interface to appreciate the physically expected behaviour of seismological parameters on ground motion. In the presentation, we derive an empirical Fourier model for computing regionally adjustable response spectral ordinates based on random vibration theory (RVT) from shallow crustal earthquakes in active tectonic regions, following the approach of Bora *et al.* (2014, 2015). For this purpose, we use an expanded NGA-West2 database with M 3.2—7.9 earthquakes at distances ranging from 0 to 300 km. A mixed-effects regression technique is employed to further explore various components of variability. The NGA-West2 database expanded over a wide magnitude and distance range provides a better understanding (and constraint) of source and distance scaling of ground motion. Additionally, a frequency-dependent duration model is derived to obtain the easily adjustable response spectral ordinates. A very good comparison of the response spectral ordinates obtained from our approach with those from existing NGA West2 models implies that, this approach can be used as a stand-alone model with an additional advantage of adjustability. Finally, application of the derived models in generating adjustable response spectra for some selected scenarios is shown.

Implications from Comparison of the Ground Motion Prediction Equation and Global Ground Motion Dataset

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Based on the strong motion data observed on the ground surface and those on the bedrock, which were estimated using the amplification factors calculated from the identified soil profiles at the vertical arrays of KiK-net, Si *et al.* (2016) developed an evaluation equation for spectral amplification factors as a function of average shear-wave velocity of top 30 m of soil (V_{S30}) and sediment thickness. Using this model, we eliminated the site effects from strong motion data recorded on free surface to obtain the corrected records on the bedrock where shear-wave velocity is equal to 1.5 km/s. Subsequently, we used the corrected records to develop a ground motion prediction equation (GMPE) for acceleration response spectra (GMRotI50, Si *et al.*, manuscript in preparation). The distance measure used in the GMPE is MED refer to the closest distance from an observation station to the median line of a seismic fault. The earthquake data used for the development of GMPE is derived from Japanese earthquakes with magnitudes ranging from 5.6 to 9.1. Using these two models, one can evaluate response spectra on free surface from a scenario earthquake.

In order to investigate the regional variation in strong ground motion, GMPEs are compared with the ground motion data from the well recorded earthquakes in the database of the PEER NGA-West2 project. In comparison, only observation data at stations with available information of V_{S30} and the thickness of sediment are used. Firstly, all the data are corrected to bedrock with Vs of 1.5 km/s and then the data on bedrock are compared with the predictions by GMPEs. The results show that, in many cases the observation data are almost consistent with the predictions by GMPEs. However, there are differences for some earthquakes. The results imply the possible regional variation in strong ground motion.

Reveal the Difference between Ground Motion Models under Correlated Observations

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The ground motion model is an important component of a seismic hazard model. Assessing the relative performance of ground motion models and choosing the suitable ones to be included in a hazard model is a common task for hazard modelers. Efforts spent in creating advanced ground motion models need to be verified by prospective testing. This study is about testing the performance of ground motion models under realistic environment.

Modern ground motion models include increasingly complicated correlation structures. The simplest form includes an event-to-event correlation. Recent models include situation-dependent event-to-event dispersion and probably additional correlation such as station-by-station. The correlation structure affects its performance. We show examples of the consequence of ignoring this factor. This is especially important when the test data are unbalanced, which is usually the case. We show that the widely used LLH score can be easily extend to incorporate an arbitrarily complicated correlation structure.

Ground motions are modeled as random variables. The evaluation result, therefore, also contains randomness. We demonstrate the use of bootstrap to assess the variability of evaluation. The correlation structure of the data should be preserved in the bootstrap.

Using the presented method, we show that NGA-West2 ground motion models work well for Japanese earthquakes, even better than widely used regional models specifically developed for Japan.

Scaling and Empirical Relationships of Moderate to Large Earthquakes: Re-scaling or Re-thinking?

Oral Session · Wednesday 19 April · 3:45 PM · Governor's Square 16

Session Chairs: Laura Peruzza, P. Martin Mai, and Lucilla Benedetti

Fault Slip Rate and Constant Stress Drop as Improvements to Magnitude-Length Scaling

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We examine the role of slip rate (*s*) in scaling magnitude (*M*) from rupture length (*L*) with a set of 80 earthquakes, principally with surface rupture. Results highlight difficulties working with moderate magnitude events and potential paths to improve *M-L* scaling. The data included 57 strike-slip, 12 reverse, and 11 normal faulting earthquakes. We fit these data with three models, a linear relation between *M* and *log(L)*, a bilinear model *M* vs. *log(L)* where stress drop is constant on each branch, but not constrained to be the same constant, and a bilinear model with the same stress drop for all lengths based on a rectangular dislocation model with surface rupture (Chinnery, BSSA, 1963).

Knowing the fault slip rate improves strike-slip magnitude estimates for all three scaling models. Thus slip rate offers perhaps the most direct path for improving scaling relationships for moderate earthquakes. Dip-slip ruptures show no similar slip rate dependence, perhaps because sample size is smaller and perhaps because slip rate has a smaller range and larger uncertainties. The linear and bi-linear models fit *M-L-s* data similarly well, suggesting that other factors must guide the form of the scaling relation. A linear relationship of $M = a + b\ log(L)$ is not favored because in it stress drop then depends on magnitude, which is not observed. The two bilinear scalings differ in how they model the moderate magnitude range. The first and more commonly used model assumes fracture in an elastic whole space, which does not really fit most of our moderate earthquake data. The Chinnery model is also requires approximations, but at least it explicitly includes the free-surface effect. This and the ability to model constant stress drop across all magnitudes commend the Chinnery dislocation model, or an update of it, as a potential conceptual advance for scaling magnitude from fault length.

Earthquake Scaling Relationships Estimated from 25 Years of Source Models Derived from InSAR Data

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The question of how moment release in earthquakes scales to other source parameters, such as fault length and average slip, is a long-standing controversy in earthquake science. Here we use a catalog of earthquake source parameters derived from published InSAR earthquake studies to address this question. InSAR data are highly suitable for this purpose, as several key source parameters—in particular, the fault length—can in many cases be measured directly from the data.

We have compiled fault length, width, average slip and seismic moment estimates from published studies of over 100 individual earthquakes, with $5 < M_w \leq 9.0$. Using grid searches, we find the best-fitting one- and two-trend scaling relationships between length and moment, treating all events together and also separately by mechanism type (strike-slip, thrust and normal). We also consider the relationship between fault average slip and fault length.

We find that the best-fitting single scaling relationship between moment and length has a slope of 1.81 in log-log space (*i.e.* M_0 is proportional to $L^{1.81}$). This is more consistent with 'L model' scaling (*e.g.* Scholz, 1982) which predicts a slope of 2. Indeed, thrust events, considered separately, show a slope approximately equal to 2; strike-slip events show a slope of ~1.6; there are insufficient normal faulting events at high magnitudes. The data do not require a change of scaling regime around M7.2 as suggested previously (from a slope of 3 to a slope of 1; Romanowicz, 1992). Ratios of average slip to length fall broadly into two fields, high slip-to-length events (1–3 x 10^{-4}) and low slip-to-length events (0.4–4 x 10^{-5}). The low slip-to-length category includes subduction earthquakes and events occurring on strike-slip faults with fast slip rates (> 2 mm/yr); the high slip-to-length category includes several blind faulting earthquakes, typically occurring on faults with low slip rates (< 2 mm/yr).

Examination of Source Scaling Relations for Crustal Earthquakes in Japan

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A three-stage scaling relationship of source parameters for crustal earthquakes in Japan has been developed (Irikura and Miyake, 2001, 2011; Murotani *et al.*, 2015), in which source parameters obtained from the waveform inversion results of strong motion data are combined with those from geological and geomorphological surveys. The first bending point is caused to saturation of the fault width at the seismogenic zone. The second bending is related to saturation of surface rupture displacements becoming apparent from analysis of mega crustal earthquakes (> M_w 7.4) over the world. The 2016 Kumamoto earthquake with M_w 7.0 was one of the largest crustal earthquakes since dense and accurate strong motion networks, such as K-NET and KiK-net, were deployed after the 1995 Hyogo-ken Nanbu earthquake. The scaling relationships of the source parameters of crustal earthquakes in Japan are examined whether they are applicable to the 2016 Kumamoto earthquake (Irikura *et al.*, 2017). The rupture area (A = 46.9 km x 19.8 km) were determined from an average of several slip inversion models from the strong motion data and the seismic moment (Mo = 4.4E+19 Nm) was adopted from F-net solution. We found that A vs M_w for this earthquake follows the second-stage scaling within a standard deviation. The scaling relationship in this study coincides approximately with that of Hanks and Bakun (2002, 2008) in the first and second stages, where most earthquakes they examined occurred in California. This suggests that source parameters extracted from the waveform inversion results of crustal earthquakes in Japan have a good accordance with regressions in California. Then, we simulated the broadband ground motions of the 2016 Kumamoto earthquake using the empirical Green's function method based on a characterized source model from the recipe (Irikura and Miyake, 2011). The synthetic ground motions agree well with the observed motions within the frequency range of 0.2 to 10 Hz.

Surface Rupture Effects on Earthquake Moment-Area Scaling Relations

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Empirical earthquake scaling relations play a central role in fundamental studies of earthquake physics and in current practice of earthquake hazard assessment, and are being refined by advances in earthquake source analysis. A scaling relation between seismic moment (M_0) and rupture area (A) currently in use for ground motion prediction in Japan features a transition regime of the form M_0~A^2, between the well-recognized small (self-similar) and very large (W-model) earthquake regimes, which has counter-intuitive attributes and uncertain theoretical underpinnings. Here, we investigate the mechanical origin of this transition regime via earthquake cycle simulations, analytical dislocation models and numerical crack models on strike-slip faults. We find that, even if stress drop is assumed constant, the properties of the transition regime are controlled by surface rupture effects, comprising an effective rupture elongation along-dip due to a mirror effect and systematic changes of the shape factor relating slip to stress drop. Based on this physical insight, we propose a simplified formula to account for these effects in M_0 – A scaling relations for strike-slip earthquakes.

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Italian Surface Faulting Earthquakes vs Empirical Scaling Laws

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Since early '900 Italy experienced M≥6.0 earthquakes for which surface faulting was clearly documented. The level of completeness and accuracy of the surveyed coseismic ruptures is different between these events and improved with time due to the survey techniques advances and to the increased awareness of the earthquake geologists. At this stage we have a significant dataset of normal fault ruptures to test the compilation of global relationships between earthquake magnitude and surface fault parameters, *i.e.* to verify the agreement of the empirical laws in the Apennines seismic environment and get ready for ad hoc compilation. The compared analysis of these cases with the variability depicted by the laws provides indication on the factors controlling the ruptures parameters both directly connected to the earthquake source and to the dynamic of the rupture (*e.g.* dip, slip distribution, directivity, segment boundary) and subsurface conditions (*e.g.* lithology).

A key case is the 2016 central Italy sequence, that is a unique opportunity to analyze the surface rupture produced by 3 different magnitude mainshocks close in time and space and under the same tectonic setting. In fact, following a M_w6.0 earthquake, a M_w5.9 occurred two months later ~25 km to the north, and after four days a M_w6.5 event located in between the previous two. The 3 events ruptured different portions of the same fault system. The tectonically homogeneous conditions and the high quality survey allow to point at peculiarities of the rupture traces and to attribute the differences and the variabilities mainly to the earthquake source. Although of comparable M_w, the first and second mainshocks were differently expressed at surface in terms of rupture continuity and length. The third event was about 10 times more energetic than the previous two and produced surface displacement values 4 times larger and more. How do these features fit with the empirical laws, do they fall within the data variability?

Source Discovery Using Differential Methods: Applications to Explosion Monitoring

Oral Session · Wednesday 19 April · 8:30 AM · Plaza F
Session Chairs: William Walter, Joshua Carmichael, Steven Gibbons

Absolute Locations of the North Korean Nuclear Tests Based on Differential Seismic Travel Times and InSAR

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We use constraints on the location of the January 6, 2016 DPRK announced nuclear test (2016_01) and differential travel times for Pn, Pg, and teleseismic P-waves to estimate the absolute locations of the 5 announced DPRK nuclear tests. Absolute location constraints are based on the fit of commercial, InSAR-derived ground displacement and predictions of elastic displacement from an isotropic source including topographic effects. The announced tests in January and September of 2016 are under the crest of highest local topography (Mt. Mantap), while the 2009 and 2013 events are south of the topographic crest at a similar contour in local topography. The first announced test in 2006 was located near the crest of a separate topographic high approximately 2.75 km east of the 2016_01 test. Seismic constraints put the events within 1 km of the surface and depths may be inferred, with caution, by differencing the elevation of tunnel entrances and the topographic surface at each event and accounting for tunnel slope needed for drainage. Depths for the 2006_10, 2009_05, 2013_02, 2016_01, and 2016_09 tests are estimated to be 500 m, 530 m, 530 m, 740 m, and 750 m, respectively.

We find that differential P-wave arrival times are self-consistent and can be used in concert to estimate relative locations when slowness values for each phase are adjusted within expected ranges. The Lg phase is observed, but the correlation coefficients are low and differential travel times are inconsistent with relative locations derived from P-waves. Perhaps surprisingly, differential surface waves arrival times are also inconsistent with differential locations determined using P waves, despite clear surface-wave signals and the highest correlation coefficient of any phase. Small phase shifts in the surface-waves may be attributed to source effects, such as tectonic release, and these source effects can complicate the use of differential surface waves for determining precise relative location.

Seismo-Acoustic Analyses of the DPRK Underground Nuclear Tests for the Estimation of Source Depth

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The nuclear tests by the Democratic People's Republic of Korea (DPRK) have generated both seismic and infrasonic signals. This presentation will address seismo-acoustic analyses of these tests.

Special focus will be given to the 2013 and January 2016 tests, that were estimated to have a similar yield. Clear detections were made in the Russian Federation (I45RU) and Japan (I30JP) in 2013 at stations from the International Monitoring System. Both tropospheric and stratospheric refractions arrived at the stations. In 2016, only a weak return was potentially observed at I45RU. Data analysis and propagation modeling show that the noise level at the stations and the stratospheric circumpolar vortex were different in 2016 compared to 2013.

A relative analysis of the 2013 and 2016 DPRK tests, in combination with atmospheric infrasound propagation modeling, motivates the hypothesis that the 2016 test was at a greater depth than the 2013 test. In such a case, less seismic energy would couple through the lithosphere-atmosphere interface, leading to less observable infrasound. A preliminary analysis suggests that the 2016 test occurred at least 1.5 times deeper.

Since explosion depth is difficult to estimate from seismic data alone, this motivates a synergy between seismics and infrasonics.

Discrimination, Relocation, Magnitude Calculation and Yield Estimation of the North Korean Nuclear Tests

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Since 2006, North Korea conducted five successive underground nuclear tests in the China-North Korea border area with the latest one occurred on September 9, 2016. Abundant seismic signals generated by these events were recorded by stations from regional seismic networks located in China, South Korea and Japan. They provided data of ever increasing quality to examine the current techniques in explosion event discrimination, relocation and yield estimation. We collected seismograms from the China National Digital Seismic Network (CNDSN), the Global Seismic Network (GSN), and the Japan F-NET to form a broadband waveform data set which is composed of information from 133 stations through continental path and 64 stations with their paths across the Japan Sea. With this data set, we investigated regional seismic characteristics of the North Korean underground nuclear tests. Using the P/S spectral ratios Pg/Lg, Pn/Lg and Pn/Sn as discriminants, the nuclear explosions and nearby earthquakes can be fully separated at frequencies above 2.0 Hz, indicating an explosion within this magnitude range detonated in China-North Korea border area can be fully discriminated by a regional network. By adopting a relative location method and using the 2006 test as the master event, we calculated the relative locations and origin times by fitting the regional Pn wave travel times for the 2009, 2013 and 2016 explosions. For all 5 North Korean nuclear tests, the Lg-wave body wave magnitudes are 3.93, 4.53, 4.91 4.67 and 4.82, respectively, and Rayleigh-wave magnitudes are 2.92, 3.65, 3.95, 4.05 and 4.23, respectively. Adopting an empirical magnitude-yield relation for body wave magnitude, and assuming that the explosion was fully coupled and detonated at a normally scaled depth, we estimated the seismic yield is approximately 0.5, 2.4, 7.5, 3.7, and 5.9 kt, respectively. However, these yields may be underestimated if the source is greatly overburied.

Mb-Ms for the DPRK Announced Nuclear Tests

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The difference between body wave magnitude and surface wave magnitude, mb-Ms, has historically been one of the most commonly used criteria to distinguish between earthquakes and explosions. The first DPRK announced nuclear test produced an unusually low mb-Ms value, and the subsequent four DPRK explosions have produced similarly low values.

The experimental provisional mb:Ms event screening criterion used at the International Data Centre in Vienna, part of the International Monitoring System of the Comprehensive Nuclear-Test-Ban Treaty Organization, was revised in 2012. This change was made on an empirical basis and there are currently competing physical explanations of the DPRK mb-Ms values, for example damage around the explosion cavity.

It is currently unclear whether there is some genuine systematic difference in mb-Ms between DPRK and other test sites, or whether this difference is simply part of a wider global variation that has only been sampled at a few sites.

Here we discuss the impact on mb-Ms of two factors: 1) the depths of burial of the explosions, bounded by topography at the test site and differential locations, and 2) teleseismic P wave attenuation (t^*) for the DPRK site, estimated using the observed spectra and measurements from earthquakes in the DPRK region.

We find that while variations in depth of burial and t^* can produce variations in mb-Ms of the same size as those observed at the DPRK test site, further work needs to be done to establish accurate values for depth of burial and t^* for the DPRK explosions.

Estimating and Exploiting the Outgoing Seismic Wavefield at the North Korean Nuclear Test Site

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Between October 2006 and September 2016, 5 declared underground nuclear explosions were carried out at the Punggye-ri test-site in North Korea. All events were detected clearly both at regional and teleseismic distances. Waveform similarity allows us to estimate relative locations of all 5 events using classical double-difference techniques. However, using a simple 1D velocity model, these estimates are quite sensitive to the set of stations used with inter-event distances estimated using regional Pn phases consistently longer than those estimated using teleseismic P-phases; the seismic wavefield leaving the test-site is more complicated than the 1D velocity model description. We seek perturbations to the horizontal slownesses of each of the rays leaving the source region which ultimately reach the sensors at which the correlations are performed. We find spatially consistent perturbations which reduce the double-difference time residuals and provide relative location estimates which are consistent on both regional and teleseismic measurements. The perturbations are almost sinusoidal with azimuth, as is frequently observed with the observation of incoming wavefronts at seismic arrays. The spatial form of the outgoing wavefield can also be estimated using classical array processing methods on a virtual source array. The source-array analysis supports independently the perturbations to the outgoing wavefield obtained previously and, given the number of events now recorded at this site, may allow accurate relative location estimates for subsequent events which are recorded by a less favorable set of stations. One such scenario is a lower magnitude event recorded only at regional distances, with the associated limitations in azimuthal coverage. Another scenario is of a test in a different part of the test site for which the waveform similarity at some stations, a particularly acute problem for regional phases, may be significantly diminished.

Surface Wave Relative Amplitude and Travel-Time Anomalies from the 2009, 2013 and 2016 DPRK Declared Nuclear Explosions

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The 9/9/2016, 1/6/2016, 2/12/2013 and 5/25/2009 declared nuclear explosions in the Democratic People's Republic of Korea (DPRK) provided an opportunity to perform differential amplitude and travel-time analysis on surface waves. Relative measurements provided precise estimates of the relative source parameters without the need for propagation and site corrections. We measured peak-to-peak amplitudes using the NIED F-NET dense seismic array across Japan and regional or global IC, JP, KG and IU network stations. Amplitude ratios and lag times, measured from cross correlations, were formed for 6 different DPRK event pairs. Only the ratios formed using the 2013 event showed significant differences in Rayleigh and Love wave radiation. The Rayleigh wave amplitude ratios were fit with predicted ratios derived from moment tensor inversions. The relative differences in the isotropic (ISO) component were ±10% therefore the difference in surface wave radiation were not due to differing amounts of ISO and deviatoric (DEV) moment release but in the rotation of the DEV component. Others have suggested that the regional DEV stress field can influence the formation of the explosion cavity. The azimuth of maximum Rayleigh wave amplitudes was closely aligned with the estimated regional mean tensile principle stress direction of 323°.

There are 2 probable explanations for the differences between DPRK surface and body wave relative locations. One is that there is a lack of resolution from long period surfaces waves. The DPRK events were only several 100 m apart and their relative lag times between event pairs were on the order few tenths of a sec. An alternative is that there is a source phase anomaly of 0.3 sec in the direction to the west. Surface wave relative time residuals to the west are about 1 to 1.5 times the standard deviation relative to the body wave solution. This work was performed under the auspices of the U.S. DOE by LLNL under contract DE-AC52-07NA27344.

The Influence of Topography on Regional P-Wave Observations from the North Korean Underground Nuclear Tests

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In this study we modeled the early P-wave arrivals observed from the North Korean nuclear tests in order to examine the imprint of topography on farfield seismic observations. While recent studies have demonstrated the influence that nonlinear source behavior and strongly varying topography can have on high-frequency *nearfield* seismic recordings, additional work is needed to accurately model and interpret the wavefields recorded at more realistic observation distances—*e.g.*, 50 to 500 km. For example, it is likely that the nonlinear source effects observed in the near field will attenuate out of the high-frequency spectrum observed at regional distances. However, it is not well known whether topography near an explosion site imprints a distinctive signature that is observable in regional recordings. A better understanding of the local-to-regional wavefields generated by shallow explosions in strong topography could help significantly improve depth-of-burial and yield estimates.

To address these issues we simulated the early P-wave arrivals from the five known North Korean nuclear tests using the 3D spectral-element modeling code SPECFEM3D and Sandia National Laboratory's CUBIT mesh-generation software. Our results show that the topography of the North Korean Punggye-ri test site has a significant effect on the amplitudes and relative phase behavior as a function of azimuth from the test site. Observations at stations MDJ (Mudanjiang, China; 370 km) and KSA (Ganseong, South Korea; 307 km) match our simulations for the various assumed lateral positions of the nuclear tests. In our presentation we will demonstrate how the simulation results can be used to derive relative depth and yield estimates for the various tests.

Constraints on Crustal Heterogeneity and Q(f) from Regional (<4 Hz) Wave Propagation for the 2009 North Korea Nuclear Test

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We have run 3D finite difference simulations (<4 Hz) of regional wave propagation for the 2009 North Korea nuclear test and compared to instrument-corrected records at stations INCN and TJN in South Korea. The source is an isotropic explosion with a moment magnitude of 4.1. Synthetics computed in the relatively smooth Sandia/Los Alamos National Laboratory SALSA3D velocity model significantly overpredict Rayleigh wave amplitudes by more than an order of magnitude while underpredicting coda amplitudes. The addition of a von Karman distribution of small-scale heterogeneities to SALSA3D with correlation lengths of ~1000 m, Hurst number of 0.1, and horizontal-to-vertical anisotropy of ~5 improves the fit considerably. The best fits are obtained from scattering due to velocity and density perturbations of 10% relative to the background model, limited to the top 7.5-10 km of the crust. Deeper scattering tends to decrease the initial P wave amplitudes, a critical component of methods used to discriminate between explosive and earthquake sources, to levels much below those for the data. In particular, the onset of Pn is considerably weakened by as little as 2% small-scale heterogeneity in the lower crust and upper mantle. Simulations including constant Q of 200-300 below 1 Hz and Q(f) formulated as a power law at higher frequencies with an exponent of 0.3-0.5 for both P and S-waves generates synthetics in best agreement with the data. Our results demonstrate that state-of-the-art high-frequency 3D wave propagation simulations using high-performance computing can reproduce the general character of records for stations 500 km+ from the source, including the surface waves and coda on the transverse component, generated by P-S wave scattering primarily in the upper crust. We find very limited scattering contribution from the near-source area accumulated over the regional path, and surface topography was not needed to obtain the fits between data and synthetics.

Physical Relations that Quantify the Significance of the Waveform Correlation: Application to the North Korean Explosions

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Distinct seismic sources with hypocenters separated by more than a wavelength of their dominant radiation can produce partially correlated waveforms. Such seismicity confounds multichannel correlation detectors used in treaty verification, which operate with template waveforms recording underground explosions. These confounding "non-target" signals triggered by background seismicity exhibit partial template-correlation because they have template-similar shapes and can therefore give moderate detection statistics that mimic those of noisy "target" waveforms. Multichannel correlation detectors cannot accommodate for such background seismicity. Rather, these detectors operate over a binary hypothesis test that assumes data contain either amplitude scaled copies of the detector waveform template, or only noise. To address this research gap, we discard the conventional assumption that data absent of a target signal includes only noise and derive a general expression that relates partially correlated background seismicity with correlation detector performance. Our expression quantifies the discrimination power of such detectors using physical parameters that depend on the radiation coherency and relative magnitude of the template and target sources. Using these relations, we design a new waveform detector that screens partially correlated background signals from deterministically correlated, amplitude-scaled template copies. We then use seismic records of the announced North Korean explosions to quantify the capability of this detector to screen non-target sources spatially separated 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.

Surface Disturbances at the Punggye-ri Nuclear Test Site: Another Indicator of Nuclear Testing?

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A review of available very high-resolution commercial satellite imagery (bracketing the time of North Korea's most recent underground nuclear test on September 9, 2016 at the Punggye-ri nuclear test site) has led to the detection and identification of several minor surface disturbances on the southern flank of Mt. Mantap. These surface disturbances occur in the form of small landslides, either alone or together with small zones of disturbed bare rock that appear to have been vertically lofted ("spalled") as a result of the most recent underground explosion. Typically, spall can be uniquely attributed to underground nuclear testing and is not a result of natural processes. However, given the time gap of up to three months between images (pre- and post-event), which was coincident with a period of heavy typhoon flooding in the area,[1] it is not possible to determine whether the small landslides were exclusively explosion induced, the consequence of heavy rainfall erosion or some combination of the two. In addition to the apparent temporal correlation, these surface disturbances are also geospatially consistent with the event location determinations by other researchers using both seismic relative re-locationing and Synthetic Aperture Radar (SAR) Interferometry.

SSA-ESC Joint Session on Advances in Geotechnical Borehole Arrays, Data and Analyses

Oral Session · Wednesday 19 April · 1:30 PM · Governor's Square 16

Session Chairs: Jamison Steidl, Ramin Motamed, Umit Dikmen, and Stefano Parolai

Body Wave Interference at Borehole Receivers Helps to Define the Local Velocity Model

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The interference between the body-wave up- and down-going wavefields generates pronounced peaks and throats in the spectral ratio of seismograms recorded at surface and depth of a borehole station. This ratio is called interferometric function: its peaks correspond to the destructive interference of body waves at depth, the well known ghost effect in exploration seismics. The peak positions depend only on the receiver depth and the seismic waves velocity above it.

We propose an innovative method to assess the local geophysical model by comparing the experimental interferometric function to a set of synthetic functions computed for a number of trial velocity models. The effectiveness of the method is demonstrated at the site of Mirandola (Italy). This site is located on the Po river alluvial plane, in an area that suffered heavy damage during the Emilia 2012 seismic sequence. In this study, we use surface and borehole records acquired at the borehole station deployed in 2014 in Mirandola and equipped with three accelerometric sensors deployed at surface, 31 m and 126 m of depth, respectively, to assess the local 1D velocity structure down to the deeper receiver. In order to find the best velocity model, we compare the empirical interferometric function obtained from several earthquakes simultaneously recorded at surface and depth to the synthetic interferometric functions obtained for a set of trial velocity models defined on the basis of the available geophysical studies. The comparison is evaluated by a misfit function defined as the mean square difference between the experimental and synthetic interferometric functions. Being the interferometric function very sensitive to any variation of the shallow portion of the model, this approach proves to be very effective and reliable for assessing the velocity model at borehole instrumented sites whenever simultaneous earthquake recordings at surface and depth are available.

Variation of High Frequency Spectral Attenuation Kappa in Vertical Arrays: A Case Study from Istanbul

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The increased use of vertical seismic networks has contributed greatly to the body of knowledge in wave propagation and the dynamic behavior of soils. Subsequently, achieving further insight on high frequency spectral attenuation (kappa) has been made possible. Kappa has site two parts, namely the parts reflecting attenuation from source to bedrock level and bedrock level to surface at a given site. The vertical arrays provide an opportunity to differentiate between these two parts of kappa.

Three seismic downhole arrays are in operation at the west side of Istanbul. Each of them has different subsoil and topographical conditions as well as the urban fabric around them. In the present work kappa factors are calculated from earthquake recordings of surface and base sensors. The data set used in the study consists of 30+ earthquakes with ML≥3.5 occurred within 200km radius from the arrays. All components of the recordings are treated separately to portray the possible variation of kappa. High frequency portion of S-wave acceleration spectra from each recording is visually detected and kappa is computed. Path dependent and independent kappa values are calculated from epicentral distance-kappa correlations. Correlation of kappa to source-station dependent variables as well as strong motion parameters is discussed and consistency of these results with other studies available in literature is investigated. In addition to these findings, surface recordings were deconvolved to the outcrop level. Kappa calculation is repeated using deconvolved recordings to examine the possible difference between the kappa values calculated from downhole and deconvolved surface recordings. This paper presents and discusses the results of this study.

Investigation of Bi-Directional Shaking Effects in One-Dimensional Site Response Analysis Utilizing Geotechnical Downhole Array Data

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The effect of multi-directional shaking is generally disregarded in typical site response analyses in engineering practice. However, the physical process of seismic wave propagation to the ground surface could be more realistically represented by dissipation of wave energy in all directions (*i.e.* a tri-directional analysis). Previous studies, such as Stewart *et al.* (2008), Carter *et al.* (2014) and Bolisetti *et al.* (2014), reported that wave energy can be diverted from one direction to another when shaking occurs in two directions. Besides, Motamed *et al.* (2015) conducted a case study of the 2007 Niigata-ken Chuetsu-oki Earthquake recorded at the Service Hall downhole array in Japan to explore the significance of bi-directional (2D) shaking. The results suggested that a 2D analysis potentially predicts site response more accurately than uni-directional (1D) analysis, especially for stronger ground motions. In an effort to further investigate the effects of 2D shaking in site response analysis, an extensive study was conducted using soil column models built in the finite element program LS-DYNA and presented herein. Four instrumented downhole arrays in California and Japan were studied using multiple recorded ground motions that cover a broad range of intensities. The soil stress-strain behavior is characterized by MAT_HYSTERETIC_SOIL soil model in LS-DYNA. Due to the soil nonlinearity, shear stresses in the principal directions are typically correlated (Hadjian, 1981). The utilized soil model accounts for the relationship between mobilized stresses in different directions by defining the yield surface of each layer in terms of the stress invariant J2, which is determined internally based on the prescribed maximum shear stress associated with a uniaxial stress state. This allows for a correlated response in orthogonal directions. Finally, the analysis results are compared to that of 1D counterparts to evaluate the significance of including 2D shaking on site response.

Seismic Non-Linear Behavoir of Soil Inferred by the Analysis of the Kik-Net Borehole Data

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Seismic ground motion is strongly dependent on the site geotechnical characteristics. This phenomenon must be taking into account in risk mitigation through the evaluation of soil response. The soil response to a cyclic solicitation is not only depending on the soil parameters but also on the level of the shaking. This non-linear behavior is especially important to consider when modeling strong ground motion. We analyzed this effect through the use of seismological data recorded in Kiban Kyoshin Network (Kik-net) localized in Japan. 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 ground motion amplifications by computing experimental transfer functions using a spectral ratio scheme.

The main effect of the non-linear behavior of the soil on its transfer function is a shift of the amplification towards lower frequencies. This shift is related to the decay of the shear modulus with the deformation. We propose thus to characterize this non-linear behavior by quantifying the frequency shift. This work results in a site-dependent relationship between the frequency shift and the intensity of the ground motion expressed in terms of downhole PGA that can be used to extrapolate the site response from weak input motion to stronger one. We are presenting here our procedure and the precautions to be taking in dealing with borehole data to compute site transfer functions. The results obtained on several cases are showing that this procedure could help to better predict strong motion and thus the seismic hazard, exhibiting by the way the usefulness of borehole seismological data to better understand and take into account the non-linear behavior of the soil.

Investigation of Soil-Structure Interaction Effects through Wave Propagation Analysis in Building-Soil-Layers

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The study of soil-structure and city-soil interaction is currently one of the main challenges for the seismological and engineering communities. Until now, most investigations of these effects have been carried out based on 2D and 3D numerical simulations. Studies based on real data sets were usually performed separately in order to investigate either the dynamic properties of a building or the soil.

In this study, soil-structure interaction is investigated empirically by analyzing a real data set composed of earthquake recordings from a borehole-building strong motion installation at three test locations (Bishkek, Kyrgyzstan, Istanbul, Turkey, and Mexico City, Mexico). The buildings equipped with sensors are located close to borehole installations. Each test case involves different soil

conditions and building construction types, where for each of the analyzed cases, the impedance contrasts between the building and the soil are different, as a well as the wave propagation speeds in the subsurface and building.

The soil-structure interaction effects are investigated by the joint deconvolution which has been shown to appropriately identify wave propagation through the building-soil layers. Both the real seismic input (the ground motion at various depths without the effect of down going waves) and the wavefield being radiated back from the building to the soil are separated through the adopted constrained deconvolution approach. Finally, the energy being radiated back from the building to the soil is estimated.

The values obtained show that even at great depths (and therefore distances), the amount of wavefield being radiated back by the building to the ground is significant (*e.g.*, for the Bishkek case, at 145 m depth, 10-15% of the estimated real input energy is expected to be from the building; for Istanbul at 50 m depth, the value is also 10-15% of the estimated real input energy while for Mexico City at 45 m depth, it is 10-25% of estimated real input energy).

The Mw7.8 Kaikoura Earthquake

Oral Session · Wednesday 19 April · 1:30 PM · Plaza F
Session Chairs: Bill Fry and Matt Gerstenberger

An Overview of the Seismic Source and Ground Motions during the Mw 7.8 Kaikoura Earthquake, New Zealand.

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We present an overview of the seismic source and strong ground motion data during the November 2016 M_w 7.8 Kaikoura earthquake, including a discussion of the role of source and site effects. Our analysis draws together preliminary seismic and geodetic source models, ground motion simulations, observed ground motion analyses and site amplification mapping efforts.

The earthquake was exceeding complex, rupturing at least nine fault segments across the northeastern South Island and offshore towards Cook Strait. Horizontal and vertical accelerations exceeding 1 g were recorded at both Waiau in the epicentral region and the town of Ward, ~125 km to the north, near the rupture termination. Building damage was concentrated in these locations, as well as the town of Kaikoura, but was also observed in town centres further afield, including the central business district of the capital city of Wellington.

Although recorded peak ground accelerations were modest (up to ~0.28g) in Wellington, the duration of shaking was over two minutes and spectral accelerations in the 1-2 s period range exceeded the current 1 in 500 year design level spectra (ultimate limit state) at some recording stations. Serviceability limit state levels were also exceeded throughout the central city, resulting in closure of ~10% of office space as at 7th December. Large spectral displacements of around 0.5 m at ~1.5s period were also observed in the port area. This period range corresponds approximately to both the fundamental site period of soils in the deeper part of the city basin and the resonant period of mid-rise structures in the 8-15 story range, where much of the damage was observed. The south-to-north directed rupture terminated approximately 50-60 km from Wellington. Hence, in this location both site and directivity effects, were important factors influencing ground motions.

Multiple Fault Ground Surface Ruptures in the 14 November 2016 Kaikoura Earthquake, New Zealand

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The M7.8 14 November 2016 Kaikoura Earthquake, South Island New Zealand, was remarkable for the large number of ground-surface fault ruptures. At the time of writing, the fault response teams have documented m-scale displacement on at least 12 faults, and cm-scale displacement on at least 3 others. InSAR data indicate that additional faults ruptured at depth and further surface ruptures will likely be identified from analysis of satellite, LiDAR, and submarine survey data. The length of surface rupture, as generalised by two straight-line segments, is approximately 180 km, although this is a minimum for collective ruptures length due to the complex, multiple-orientation, overlapping fault geometries. About half of the faults that ruptured the ground surface were previously identified as active and included in the 2010 New Zealand National Seismic Hazard Model (NZ NSHM). The 2010 model included only a few segment options, but notably included one for the faults with the largest displacements in the Kaikoura Earthquake—the Jordan Thrust (3-4 m dextral), Kekerengu Fault (10-12 m dextral), and the Needles Fault (submarine). Previously unrecognised faults included a number of N-NNW-striking faults with mainly sinistral reverse displacements (*e.g.*, as much as 5-6 m sinistral and 6-7 m vertical on the Papatea Fault), which may accommodate displacement transfer between the major NE-striking faults. Paleoseismic data suggest that faults which ruptured in the Kaikoura event have slip rates of ~0.5-25 mm/yr and recurrence intervals of 300-400 years to many thousands of years with lowest rates south of the Hope Fault. This shows that the Kaikoura Earthquake is a relatively rare event and can occur no more frequently than the longest recurrence interval on the constituent faults (*i.e.* many thousands of years). Multi-fault ruptures may however be common and should be incorporated in future updates of the NZ NSHM.

The M7.8 2016 Kaikoura Earthquake in the Context of the National Seismic Hazard Model

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The M7.8 Kaikoura earthquake ruptured multiple fault sources defined in the 2010 version of the national seismic hazard model (NSHM), as well as formerly unmapped fault sources. Some of the faults ruptured their full lengths (*e.g.* Kekerengu Fault), and some ruptured parts of their lengths (*e.g.* Hundalee Fault). Overall the ruptures formed a combined length of about 180 km, and produced a magnitude greater than would have been expected from the 2010 fault source model in that area. The 2010 model did consider multi-fault ruptures with an estimated M7.6 in the area, but M7.8 would have required a much longer multi-segment rupture than those defined.

Probabilistic seismic hazard estimates in the Kaikoura area were some of the highest in the country prior to the earthquake, showing that the density, recurrence estimates and predicted ground motions of earthquake sources in the area were not inconsistent with the ground motions of the earthquake. One of many foci of ongoing work on the NSHM is the provision of more complex multi-segment and multi-fault rupture models, the importance of which has been well-reinforced by the 2016 event.

Widespread Triggering of Slow-Slip Earthquakes during the Mw7.8 Kaikoura Earthquake: Implications for Earthquake Forecasting

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The M_w 7.8, Kaikoura, New Zealand earthquake created many new challenges to earthquake forecasting efforts. A difficult task was faced when the main shock triggered widespread slow slip events (SSE) on the Hikurangi subduction zone which underlies much of the North Island. Several characteristics of the SSEs were unprecedented. Three SSEs began to rupture simultaneously with portions undergoing higher rates of slip than previously observed. The SSEs ruptured a shallow patch east coast of the North Island, and two down-dip segments, one to the west of Wellington, and another to the north of Wellington. All three North Island SSE patches have ruptured in the past, but not simultaneously. There also appears to be large slow slip (or possibly afterslip) on the far southern Hikurangi interface beneath the northern South Island. We have not previously observed slow slip events in this region. A section of the megathrust beneath the southern North Island is inferred to be geodetically coupled and is within a potential source area of approximately M8+.

Understanding of the impact of SSE on future seismicity is limited, yet government officials required guidance about the potential for future large earthquakes. This need was further strengthened by an interface M_w 6.1 synchronous with the SSEs. Analysis of past SSE in NZ indicates that there is about a 5-fold increase in seismicity during SSE; however, significant questions remain about the magnitude-frequency distribution and the potential for larger events. Triggering potential is spatially dependent. We coupled this information with analysis of a synthetic seismicity catalog for the region (Robinson *et al.*, 2011) and the results of the EEPAS model (Evison and Rhoades, 2004, 2005) which indicate a significant increase in the next decade for the lower North Island. Based on this information, including the occurrence of tthe M_w 7.8, there is an increased likelihood for large earthquakes in the region in the coming years.

Communicating Science at Speed: Lessons from Responding to the M7.8 Kaikoura Earthquake

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At 12.02 a.m. on the 14 November 2016, the ground began to shake near Culverden, on the South Island of New Zealand. At the end of 2 minutes and twenty seconds, numerous faults were implicated, and deformation of the sea floor off the coast of Kaikoura created a localised tsunami. The earthquake uplifted coastlines, cut off communities in North Canterbury and Marlborough and rattled the capital of New Zealand.

The human impact and interest raised international and national interest in earthquake, tsunami, landslide, and engineering issues, creating a number of challenges including communication about the earthquake. GNS Science and associated science agencies were inundated with public and stakeholder awareness; the GeoNet website alone sustained 250 million hits in less than 24 hours after the earthquake.

Major challenges included communicating information about the earthquake forecasts, slow-slip events triggered by the M7.8, evolving scientific results, as well as a variety of other issues. Communication research and practice were combined to develop the communication response; this integration is also explored.

Back-Projection of Regional Data Yields a Detailed Picture of Complex Multi-Fault Rupture During the Mw7.8 Kaikoura Earthquake

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The M_w7.8 Kaikoura earthquake was the largest earthquake recorded on land in New Zealand since the digital age. It is globally significant in both its complexity and linking of disparate crustal faults and possibly the southern remnants of the Hikurangi subduction megathrust. The availability of GeoNet strong-motion observations at local and regional distances provides a unique opportunity to explore the rupture process in both space and time. We utilize this opportunity to understand the evolution of the radiation of high-frequency energy (> 200mHz) during the event. We back project the recorded ground motions to calculate a 'brightness' funciton in each cell of a 3D volume surrounding the earthquake. Our results clearly image three distinct rupture phases, with northeastward to eastward propagation of rupture on shallow faults in some cases separated by more than 20km. We also develop a relative source time function. The failure on the southern two segments is continuous in time. However, there is an ~20s gap between the southern two ruptures and failure of the northernmost segment. During this gap, there is diffuse energy radiation from the northern region of our model, corresponding to the high energy patch seen on global, long-period models. We interpret this as potential rupture of the southern vestige of the subduction interface. Our results are compatible with geologic mapping of surface rupture and inversion of geodetic data. However, we note that our inversions based on high-frequency regionally recorded ground motions image different aspects of the earthquake than globally recorded low-frequency ground motions. This difference has been noticed in previous large events globally over the past decade. Our results have fundamental bearing on our understanding of fault interaction in large and shallow earthquakes and consequently on seismic hazard assessment.

Reconciling the Dilemma of a Megathrust Earthquake or a Crustal Strike-Slip Faulting Event: the 2016 Kaikoura, NZ Earthquake

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The M_w 7.8 Kaikoura, NZ earthquake presents two distinct characteristics to geophysical observers. Seismologically the earthquake is dominantly a megathrust event, apparently on part of the southernmost segment of the Hikurangi subduction zone. Field observations show surface rupturing fault segments, many of which show substantial surface offset. This presents the earthquake science community with a dilemma—is the earthquake a megathrust event and the surface faulting a byproduct or is the event primarily restricted to upper plate strike-slip (+ some thrust) faulting? Although seismological analyses indicate some strike-slip-like behavior in the initial and latter stages of the rupture (perhaps as much as 1/3 of the moment), most teleseismic analyses require significant thrust faulting consistent with rupture of the subduction megathrust. These observations must be satisfied by a mechanically consistent deformational model; in particular we must address the following:

1. Teleseismic results support models of thrust faulting at depths compatible with the inferred subduction interface;

2. Crustal faulting, with significant offsets, occurred in the same region;

3. Much of this crustal faulting cannot be linked to specific large aftershocks, implying significant co-seismic displacements.

Our model reconciles these two concurrent deformational events includes an inter-seismic period of strain/slip-deficit accumulation along the megathrust plate interface and by the right-lateral shearing of the Marlborough Fault System. Co-seismically, crustal deformation conditions are changed by: (a) reduction of fault-normal stresses acting on the crustal faults, and (b) the decoupling of the upper-plate faults from their base. These effects combine to decouple the faults from their underlying foundation and significantly change the Coulomb stress conditions acting on the faults, allowing appropriately oriented crustal faults to slip concurrent with the megathrust rupture.

Preliminary Broadband Ground Motion Simulations of the 14 November 2016 Mw7.8 Kaikoura, New Zealand Earthquake

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We present insights into the ground motion observations and preliminary broadband simulations of the 14 November 2016 M_w7.8 Kaikoura earthquake.

Over 160 strong motion records were obtained, with several ground motions exceeding 1.0g horizontal recorded, as well as up to 2.7g in the vertical direction at one location. The complexity associated with multi-fault rupture is clearly evident in several strong motion stations in the near-source region, which is represented using a multi-fault implementation of the pseudo-dynamic rupture generator of Graves and Pitarka (2015), with segment rupture delays based on both observed ground motions as well as moment rate functions from teleseismic source inversions. Predictions from several broadband ground motion simulation realizations are compared with observations in the form of intensity measure (spectral acceleration, significant duration, etc.) scaling with rupture distance, as well as spatial bias analysis. Specific attention is given to examining simulations and observations in the near-source and those in the urban Wellington / Lower Hutt regions, where valuable site effect case histories from sedimentary and reclaimed soil deposits and topographic effects are present.

Kinematic Source Modeling and 3D Wavefield Simulations of the 2016 M7.8 Kaikoura Earthquake

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The 2016 M7.8 Kaikoura (New Zealand) earthquake struck the East coast of the northern South Island on November 13th 11:02 (UTM). The damaging earthquake generated extreme surface displacements, land deformations and surface ground motions, a regional tsunami and triggered major slow slip events on the Hikurangi interface. The earthquake was well recorded by GeoNet strong motion and broadband networks. It produced extreme ground motions in the epicentral regions with over 1g measured in the Seddon and Kekerengu areas (Kaiser *et al.*, in prep). It also generated ground motions exceeding design levels for particular building periods in the Wellington region (Kaiser *et al.*, in prep). We invert kinematic rupture parameters for 5 fixed and independent fault planes. The fault planes are imposed by best-fit solutions from geodetic data inversions from GPS and InSAR (Hamling *et al.*, submitted), geological surface rupture observations, and geophysical marine data acquired soon after the earthquake (Barnes *et al.*, in prep). We use 3 component data from 13 regional strong motion stations. Synthetic seismograms are computed using the discrete wavenumber approach of Bouchon (1981). Preliminary results suggest the earthquake ruptured continuously along multiple segments from south to north. Finally, we perform 3D wavefield simulations using the above multiple-fault kinematic source model combined with New Zealand's 3D velocity and attenuation models (Eberharts-Philips *et al.*, 2010). We quantify misfits between simulated and observed waveforms at ~100 strong motion stations that were not used in the source inversion process.

Improving Coseismic Landslide Models: Lessons Learned from the 2016 Kaikoura, New Zealand Earthquake

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The U.S. Geological Survey (USGS), along with academic collaborators, is in the process of developing coseismic landslide hazard models for integration with existing USGS real-time products (*e.g.*, ShakeMap, PAGER, ShakeCast). A USGS reconnaissance team recently traveled to New Zealand to help with the response to the 2016 M7.8 Kaikoura earthquake. The earthquake triggered about 80,000 landslides over an area of about 9,000 km^2, causing 196 landslide dams. While there, we compared the predictions of our existing ground-failure hazard models against field observations and preliminary inventories. Our analyses revealed both strengths and weaknesses in the current model predictions and provided ideas for how to improve future iterations of these models. In particular, field observations suggest that disparities between the model predictions and field observations may have been due to inaccurate ground-motion estimates, particularly on the edges of the affected area. The ground motion estimates provided by ShakeMap, constrained in many areas by seismic station data, did not fully account for all observed spatial variability, topographic amplification, and finite fault effects (*e.g.*, along-strike variations in shaking intensity due to variability in slip magnitude). We also observed strong interactions between surface-fault rupture and deep-seated landslides, and relations between stream channel characteristics and landslide dam formation that could be incorporated into derivative hazard products. We anticipate that analysis of these observations and relations will lead to improved future iterations of USGS ground-failure models.

Rapid Aftershock Detection and Analysis Following the M7.8 Kaikoura Earthquake Using Matched-Filter Techniques

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Based on catalog events detected using classical energy-based methods as part of routine analysis, the aftershock sequence generated by the Kaikoura M7.8 earthquake of 14 November 2016 appears to be relatively low-productivity. Specifically, the catalog seems deficient in both small and moderate magnitude aftershocks. To generate a more complete catalog as an input to aftershock forecasting calculations, we attempted to rapidly re-generate the aftershock catalog using matched-filter detection techniques. Such techniques are effective at detecting signals below the noise levels associated with classical detection techniques, thus allowing the detection of many lower-magnitude and potentially overlapping events.

Our initial response work addressed the first four days of the aftershock sequence. We used 1727 aftershocks as templates and the *EQcorrscan* open-source package. After removing any events detected by more than one template), we find that we detect more than twice as many earthquakes as GeoNet's routine analysis provided in the same time period. The increase in detections is made at magnitudes smaller than M4.5: in other words, we did not detect uncataloged events above M4.5, but did detect markedly more events below this magnitude level.

The Kaikoura aftershock sequence propagated into the region of the 2013 Cook Strait earthquakes but earthquake waveforms from that sequence correlate poorly with those from Kaikoura aftershocks. This suggests that, despite occurring in similar locations, the source characteristics of the two aftershock sequences are different or that paths have changed during the intervening three years.

Following the immediate response phase of this work, we intend to run the matched-filter routine on data recorded throughout the month following the mainshock and to generate cross-correlation-derived picks for each detected event ahead of precise aftershock relocation and further characterisation of this complex earthquake.

Assessment and Management of Hazards from Seismicity Induced by Hydraulic Fracturing

Poster Session · Wednesday 19 April ·

Induced Seismicity Above Crystalline Basement: An Example from Alberta, Canada

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An earthquake sequence starting in the summer of 2015 is associated with hydraulic fracturing in the Marsh Creek area, located ~30 km south of the town of Fox Creek in central Alberta. The maximum magnitude of MW 4.1 during the sequence occurred on 13 June 2015. To further our understanding of the evolution of HF-induced seismicity, we have implemented a matched filtering algorithm (MFA) to obtain a much more complete catalog of events. Using 39 template events, we detected 1971 small earthquakes from continuous data recorded by a temporary local seismic array. Earthquakes of our new catalog range in moment magnitude from -1.36 to 4.1 and are characterized by a Gutenberg-Richter b-value of ~0.9 and a magnitude of completeness of MW ~0.2. The seismicity distribution delineates two distinct seismicity clusters with focal depths ~3 km, trending N-S and NE-SW, respectively. The N-S trending cluster is interpreted as a pre-existing fault located ~400 m to the east of the N-S oriented wellbore. The NE-SW oriented cluster is oriented approximately parallel to SHmax and may reflect activation of fractures or fault segments during growth of the hydraulic fracture. The base of the seismicity appears to be in direct contact with the top of the injection zone (~3.2 km TVD). The M_w 4.1 event occurred ~ 8 days after completion of hydraulic fracturing. This time delay is interpreted as the time required for pore-pressure accumulation on the N-S trending fault due to the diffusion along a permeable pathway, possibility accompanied by aseismic (or weakly seismic) slip. The activities of the NE-SW oriented fault were temporally confined to the time period of HF operations, indicative of triggering by poroelastic stress change, whereas the persistent seismicity (up to 2 months) of the N-S trending fault may be best explained by nucleation, arrest and re-nucleation of dynamic rupture on a pressurized fault.

Improving Earthquake Catalog Locations in the Western Canada Sedimentary Basin Using the Double-Difference Method

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When earthquakes are located with standard catalog practices their associated hypocenters may have large associated errors, depending on the station distribution. By implementing a double-difference method on classic earthquake catalogs, hypocenter error can be reduced by more than an order of magnitude (Waldhauser and Ellsworth, 2000; Schultz et. al., 2016). We use this approach to refine the locations of events in the Western Canada Sedimentary Basin (WCSB). The refined locations are useful for induced-seismicity studies, to facilitate spatial correlation of events with specific oil and gas operations. We begin by compiling a composite catalog of phase arrival times for the WCSB, using information from three seismological sources—the Geological Survey of Canada, the Alberta Geological Survey, and Nanometrics Inc. (TransAlta catalog for western Alberta). We also use multiple information sources to define a simple 3D velocity model for the WCSB region. Using the double difference program HypoDD (Waldhauser, 2001), the regional velocity model, and the catalog of arrival times, a double-difference catalog of relocated earthquakes for the WCSB was generated. This refined catalog should allow for improved statistical spatial analyses such as those performed to identify natural earthquakes, blasts and induced seismicity.

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An Overview of Ground Motion Characteristics from Potentially Induced Seismic Events in Alberta, Canada

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Several clusters of increased seismic activity in Alberta over the last decade have been identified as potentially-induced seismicity, triggered by hydraulic fracturing, oil and gas production, and wastewater disposal (Atkinson *et al.* 2016 SRL). Understanding ground motions from these earthquakes is essential to the evaluation of induced-seismicity hazards to nearby infrastructure. We characterize ground motions from events of moment magnitude **M** >3, recorded within 100 km, in the response spectral domain. In particular, focus is placed on the empirical definition of spectral shapes and amplitudes of the events in Alberta. These are compared statistically to binned-average response spectra (for the same magnitude-distance) from induced events in Oklahoma, as well as to natural events from the Next Generation Attenuation (NGA)-East and NGA-West2 databases. Additionally, motions are compared to parametric expectations based on existing ground-motion prediction equations (GMPEs) (Atkinson 2015 BSSA, Yenier and Atkinson 2015 BSSA). These GMPEs are useful in interpreting the respective influences of stress drop, anelastic attenuation, site amplification and geometric spreading on the high-frequency ground motions. Ultimately, an understanding of induced event characteristics will allow for updated and improved analysis of seismic hazard from these events.

Decision Analysis in Microseismic Surveys Using the Value of Information Technique: A Case Study from the Salton Sea Geothermal Field

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We use a decision analysis metric known as the value of information to determine the configuration of geophones that give the best resolution of seismic events. Value of information (VOI) utilizes the quantitative reliability measurements of a data source to resolve subsurface parameters, and then determines the utility of the data given future decisions that rely on knowing these subsurface parameters.

We present a case study to demonstrate the method. The Salton Sea Geothermal Field is an active geothermal energy harvesting site located in Southern California near the San Andreas Fault. It is essential to monitor induced seismicity to make sure the geothermal field is not triggering larger scale events that can affect local towns. Posterior distributions for location of each microseismic event are determined using a Bayesian algorithm (Myers et. al., 2007). Some geophone configurations lead to wider posterior distributions (*e.g.* poorly constrained event location).

A 1D model was analyzed consisting of cap rock, reservoir, and base rock. The depth of the event is the subsurface parameter of interest, and the posterior distribution from the Bayesian locator is interpreted as the reliability of the geophone data to determine in which of the three layers the event occurred. Any events occurring in the cap or base rock are taken to have a negative value effect because this could represent greater system instability. Events that occur in the reservoir region have a positive value as they represent isolation of activity within the geothermal reservoir.

The results of this study show how VOI can help design an optimal network to monitor microseismicity given limited resources.

Delineation of Basement Faults in Oklahoma and the Relation to Induced Earthquake Sequences

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North-central Oklahoma has been a site of increased seismicity since about 2009, mostly attributable to wastewater fluid injection in disposal wells. As injection activity continues, it is critical to know the locations of major faults within the crystalline basement, where most M>2.0 earthquakes are occurring, especially if they are optimally oriented within the regional stress regime. However, while relocated earthquake sequences often form linear sequences that suggest faults, these are not typically aligned with faults on published maps. This may be because the fault maps are mostly based on data describing sedimentary cover.

We combine magnetic, gravity data and well data to better estimate locations of contacts and faults in the crystalline basement and examine their relationships to earthquake sequences. New and existing gravity station data (5-15 km spacing) have been reduced and modeled to provide a geologic context, including basement topography and major geologic variations. While relatively few wells penetrate the basement, derivative maps showing depth to sedimentary units exhibit linear offsets, interpreted as faults, at higher resolution than current maps. Some of these faults are aligned with earthquake sequences while in other earthquakes appear to occur near offsets between the faults that are not optimally oriented. Reprocessed legacy aeromagnetic data show gradients that highlight contacts between rocks with contrasting magnetic properties. The flight line spacing is typically too wide (5-10 km) to intersect earthquake sequences along more than one survey line, but in some areas gradients show linear features that are aligned with mapped faults and/or earthquake sequences. Some contacts which are not optimally oriented are the site of numerous smaller earthquakes, suggesting that earthquakes may occur along smaller associated faults or perhaps cracks. New aeromagnetic surveys planned for 2017 may help to better resolve these features.

Actions and Regulatory Guidelines for Oklahoma Earthquakes Outside the "Normal" Areas of Seismic Activity

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In anticipation of the boom in oil and gas field development in two recently announced plays, the Oklahoma Geological Survey (OGS) deployed eight temporary (ZP network) Sercel L-22 sensors in southern Oklahoma and four permanent (OK network) Güralp CMG-6T sensors in west-central Oklahoma to supplement our permanent and temporary arrays in the state. Having denser station arrays allows us to detect lower event magnitudes, down to ~M1, or even lower in some instances.

The two plays, South Central Oklahoma Oil Province (SCOOP) and Sooner Trend oil field Anadarko basin Canadian and Kingfisher counties (STACK), are not expected to yield high volumes of produced water—unlike the Mississippi Lime and Cherokee Platform of northcentral and central Oklahoma, where most of the state's anomalously prolific seismic activity normally occur. Hence, if felt seismicity is induced during the development of SCOOP and STACK oil fields, it will most-likely be from hydrofrack stimulations.

We will outline the regulatory protocols implemented by the Oklahoma Corporation Commission Oil and Gas Conservation Division (OCC) to quickly mitigate possible fracking-induced seismicity. We will also review case studies of possible anthropogenically modulated seismicity in Oklahoma.

A Systematic Seismogenic Pattern of Injection-Induced Earthquakes in Northeast British Columbia and Western Alberta, Canada

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We have systematically examined seismic records from stations in northeast BC and western AB for the years of 2014–2016. Various seismic phases were identified and picked to determine the hypocentral locations of regional and local earthquakes. In total, we were able to locate >4000 events in our study area. The updated earthquake catalogue is ~3.5 times larger than the one obtained from routine processing of the Canadian National Seismograph Network. The vast majority of events we located have ML less than 3. A comprehensive database of regional injection operations was compiled for the same time window from data originating from industry and collected by regulatory agencies. To better delineate the possible link between injection operations and the occurrence of local earthquakes, we subdivided the study area into a grid consisting of 10 km by 10 km cells. For each cell, we counted the number of earthquakes and the corresponding seismic moment. Key injection parameters were also indexed for comparison. Our results indicate that the distributions of local earthquakes and injection sites are both very extensive over the study area, but there are some fundamental differences. Most local earthquakes appear to scatter to the southwestern side of a line trending NW–SE across our study area. In contrast, most injection sites are located to the northeastern side. The majority of induced earthquakes occurred along a linear band where the distribution of local earthquakes and the distribution of injection sites overlaps. This preferred band of induced seismicity seems to follow the topography of the eastern flank of the Canadian Cordillera. Our observations suggest that, at least for western Canada, the occurrence of induced seismicity is strongly controlled by the overall seismogenic conditions associated with regional tectonic settings. Injection operations can induce earthquakes only in places where the intrinsic tectonic deformation is in favor of seismogenesis.

Improved Seismological and Geological Characterization of Seismicity Induced by Wastewater Disposal Near Marietta, Ohio

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The area around Marietta, Ohio had no record of seismicity prior to 2010, but a series of small earthquakes since then was suggested to be related to wastewater disposal wells. The closest well (Long Run-1) has one of the largest injection rates in Ohio (~60,000 bbl/mo). This well injects into the Clinton/Medina formations, ~2 km below the surface and ~1.5 km above the Precambrian basement. A few of the earthquakes were felt, reaching a magnitude of 3.1, which has led to the possibility that disposal operations would be shut down. We obtained all digital recordings between 2012 and 2015, including both public data and those via FOIA request to the ODNR. We processed the data and generated initial locations with Antelope, and then used waveform template matching to enhance our detection of seismicity. Template matching found over 26,500 microearthquakes that demonstrate a swarm-like pattern, similar to previous studies of induced seismicity. We performed double-difference relocation of the seismicity utilizing waveform correlation which characterized a cluster of hypocenters ~2 km from the Long Run-1 well at depths of ~3-4 km. The earthquakes are oriented in clusters defining an overall NE-SW (~040°) trend, which is optimally oriented for fault reactivation given the SHmax in the SE Ohio (~064°). Subsurface mapping using geophysical well logs and proprietary 2D seismic reflection data indicate seismicity occurred within Lower Paleozoic strata and the Precambrian basement. The seismicity also follows the trend of small-amplitude folds associated with basement-involved fault systems that extend through the Silurian injection interval, providing a possible pathway for fluid pressure increases that could initiate slip. However, we have also identified a second seismicity cluster that began in 2014 ~7 km from the well. While the cause is less clear, the larger distance from the well suggests this seismicity could be induced via poroelastic stresses.

Monitoring the Background Earthquake Activity on Anticosti Island, Quebec, Canada, Prior to Potential Hydraulic Fracturing Work

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The 55 km wide X 220 km long Anticosti Island is located in the Gulf of St. Lawrence of the Province of Quebec, Canada. The Island rock succession belongs to a sedimentary basin of Early Paleozoic age that unconformably overlies the Precambrian basement. The shale of the Macasty Formation (has been identified as a significant hydrocarbon source rock. It still retains major unexpelled oil- and gas resources, comparable to that of the Ohio Utica shales. In 2014 and 2015, a total of 12 stratigraphic holes were drilled. The operators on the Island are planning the drilling and hydraulic fracturing (HF) of three horizontal wells during the summer of 2017, subject to obtaining the necessary authorizations. Prior to any HF work, it was decided to install a network of seismographs to monitor the level of natural seismicity of the Island. The Island is only weakly active: since 1985, the Canadian Seismograph Network has only detected a handful of earthquakes under the Island and the largest earthquake was a magnitude MN 2.9. In October 2015, three temporary seismograph stations were installed on the northwestern half of the Island. Each site comprises a post-hole broadband seismometer, a digitizer, power supplies (either AC or solar panels with batteries), and cell phone telecommunications. Once received in Ottawa, the data are monitored via an algorithm that plots the triggers. These triggers are examined daily to recognize any local or regional earthquake. Our preliminary estimates indicate that any earthquake above magnitude MN 1.5 within the three station network would be detected and located. At the time of writing (January 2017), no earthquake has been detected or located under the Island. Some earthquakes were detected to the east of the Island in what is known as the Lower St. Lawrence Seismic Zone and to the north, where the Precambrian Shield is either outcropping or found beneath a thin veneer of Paleozoic rocks.

Monitoring Microseismicity in the Rome Trough, Eastern Kentucky: Year One Observations and Network Performance

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The Cambrian Rogersville Shale is a part of a petroleum system in the fault-bounded Rome Trough of eastern Kentucky and West Virginia. In Kentucky, the Rogersville Shale ranges in depth from ~1,800 m to ~3,700 m below the surface with the crystalline basement being ~1,000 m from the base of the formation. Oil and gas from this system can be produced only with high-volume fracking. Baseline microseismicity data in the Rome Trough, focusing on recently completed and planned oil and gas test wells in the Rogersville Shale and clusters of wastewater injection wells, are being collected. Thirteen broadband seismic stations were deployed between June, 2015 and June, 2016 to yield an average station spacing of 25 km in the project area. Existing University of Kentucky and CEUSN seismic stations are also contributing to the monitoring.

Thirty local and regional events for the first year of the project (June, 2015 through July, 2016) have been located and used to calibrate a local magnitude scale for the network. None of these events was proximal to any operating disposal or oil and gas wells in the project area, nor did any occur in the Rome Trough of eastern Kentucky.

Though no seismicity was observed in the Rome Trough, the minimum detectable magnitude was estimated for the project area to confirm that microseismicity is detectable using this network. Seismic station noise models were constructed and theoretical source spectra were calculated for locations within the project area, with a focus on areas of active fluid injection. Noise models were constructed using the probability density functions of multiple power spectral densities calculated by PQLX and theoretical event spectra were based on the Brune (1970) model. The minimum detection threshold is defined as the magnitude at which the theoretical signal exceeds the noise by a factor of 3 at frequencies between 1 Hz and 20 Hz for at least 4 stations.

QuakeMonitorTM: Utilizing a Surface-Based Automated Sensor Network to Monitor and Detect Induced Seismic Events in a Highly-Active Industrial Environment

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Weir-Jones Engineering's QuakeMonitorTM Induced Seismicity Monitoring (ISM) System was deployed in Northern Alberta to monitor hydraulic fracturing operations. The scope of the project was to monitor and detect potential induced seismic events related to multiple hydraulic fracturing operations. The QuakeMonitorTM system consisted of five tri-axial geophones placed at the surface in a circular array surrounding the frac well. Conventional deployments of induced seismic monitoring networks are typically buried in the near surface in boreholes or vaults in order to reduce anthropogenic noise and create a quieter environment for the sensors. Field results from the QuakeMonitorTM system have found that for sensors installed in a high noise operational environment such as an oilfield, the benefits of the sensor burial in a borehole or vault do not necessarily provide an improvement in detection capability. We found that an optimally placed, surface-based QuakeMonitorTM system was able to detect and locate several times more induced seismic events than a buried geophone and seismometer network nearby. The QuakeMonitorTM system was able to achieve a magnitude of completeness of 0.7ML for this surface-based sensor network in a high noise industrial environment. These observations demonstrate that in a highly-active oilfield, the sensor placement locations have a larger influence on the detection capability of the sensor network than the sensitivity and installation method of the sensors alone, contributing to the cost-effectiveness of the induced seismicity monitoring solution.

Earthquake Impacts on the Natural and Built Environment

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Probabilistic Seismic and Liquefaction Hazard Analysis of the Mississippi Embayment Incorporating Nonlinear Site Effects

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The influence of deep sediment deposits of the Mississippi Embayment (ME) on the propagation of seismic waves is poorly understood and remains a major source of uncertainty for site response analysis. Many researchers have studied the effects of these deposits on seismic hazard of the area using available resources at the time. Cramer (2006) showed the effects of these sediments using reference Vs profiles for Quaternary (lowland) and Tertiary (upland) from Romero and Rix (2001) and using SHAKE91, an equivalent linear code, for site response analyses. Holzer *et al.* (2013) prepared liquefaction maps using scenarios to estimate strong ground motion caused by 1811-1812 New Madrid earthquakes. In this study, we have used updated and newly available resources for seismic and liquefaction hazard analyses of the ME. We have developed an improved 3D geological model. Additionally, we used surface geological maps from Van Arsdale and Cupples (2013) to prepare liquefaction hazard maps.

Both equivalent linear (SHAKE91) and nonlinear (NOAH_IWAN) site response codes were used to develop site amplification distributions for use in generating hazard maps. The site amplification distributions are created using the Monte Carlo approach of Cramer *et al.* (2004, 2006) on a 0.1-degree grid. The 2014 National Seismic Hazard model and attenuation relations (Petersen *et al.*, 2014) are used to prepare seismic hazard maps. Then liquefaction hazard maps are generated using liquefaction potential curves from Holzer (2011). The results show at short periods (PGA) seismic hazard is higher on the upland loess and lower in the lowland alluvial deposits. The NOAH_IWAN site response code amplifies hazards on lowland soils in comparison to those obtained from SHAKE91. At long periods, lowland deposits amplify hazards more in comparison to upland loess. The liquefaction hazard tends to be high in Holocene and late Pleistocene lowland sediments and low in Pleistocene loess of the uplands.

An Update on the Integration of Ground Failure Hazard and Loss Estimates with USGS Real-Time Earthquake Products

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After any significant earthquake worldwide, USGS real-time products rapidly estimate both shaking ("Did You Feel It?"; ShakeMap), and shaking-related losses (PAGER, ShakeCast). Currently missing is the quantitative estimation of hazard and losses from earthquake-triggered landslides and liquefaction, but efforts are underway to develop this capability. We have developed parallel global statistical models for both landslides and liquefaction based 1) on ground failure inventories from past earthquakes, and 2) ground motions estimated using ShakeMap procedures. The candidate models are being tested and refined and will serve as a foundation for hazard estimation. However, much work remains to achieve a robust and defensible suite of openly-available models that will meet the needs of various end users. Necessary efforts include: 1) adapting, developing, and testing higher resolution physically-based models for application when necessary input data exist; 2) developing a methodology for combining models of different types in a unified framework and decision tree logic; 3) making use of higher quality and higher resolution input data (*e.g.*, rock strength, surficial geology, soil moisture) where available, yet exploring and developing proxies where unavailable; 4) expanding the number of ground failure inventories accessible for model development and testing; 5) using old and new inventories to develop models for deep-seated landslides and travel distance; 6) developing statistical techniques for combining inventories of inconsistent quality together in testing and development; 7) improving ShakeMap shaking estimates to account for spatial variability and topographic amplification and 8) compiling loss data to facilitate the development of vulnerability functions. We will describe progress on these fronts and the anticipated products.

Estimating and Communicating the Impact of Earthquake-Induced Ground Failures

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In recent years, earthquake-induced ground failure (EQGF; specifically landslides and liquefaction) models have been developed that we intend to integrate into the U.S. Geological Survey's (USGS) near–real-time (NRT) earthquake shaking and impact assessment systems. We are evaluating algorithms that include both statistical and mechanistic models that can be applied at the global scale, as well as models that make use of more detailed inputs but cover smaller geographical footprints. Although we are still in the process of operationalizing the NRT estimation of EQGF occurrence, current efforts seek to simultaneously consider how the output products of these models can best be communicated as well as how they will be employed for loss-modeling. The USGS PAGER (Prompt Assessment of Global Earthquakes for Response) system currently provides a warning if prior events within 400 km are known to have had additional losses caused by EQGF. As an initial step toward improving the NRT communication of EQGF hazards, we focus on the aggregated output of existing global EQGF models in order to characterize the overall extent of EQGF. We use a handful of case histories to optimize an algorithm for classifying the aggregate EQGF hazard as "low," "moderate," or "high." Though ideally we would provide loss estimates due to EQGF at a global scale, it is difficult to do so given the lack of detailed infrastructure inventory. To overcome this deficiency, we superimpose lifeline datasets and EQGF hazard maps where available for awareness of potential impacts and use the estimated population exposed to EQGF hazards as a proxy for aggregate societal impact. In the U.S., ground deformation-based losses can, however, be estimated with FEMA's Hazus (Hazards U.S.) platform. Thus, for domestic uses, we develop susceptibility classifications that are consistent with use in the Hazus approach and calibrate against losses from U.S. earthquakes and scenarios.

Rapid Estimates of Earthquake-Induced Ground-Failure Likelihood in Switzerland

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In Switzerland, nearly all historical M ~> 6 earthquakes are associated to damaging landslides and rockslides, resulting in some cases into destruction of settlements and loss of lives. Liquefaction is known to have occurred historically due moderate earthquakes in southwestern Switzerland where the floor of the alluvium-filled Rhone valley is presently highly built and industrialized. We describe in this contribution the customization to Swiss conditions of globally calibrated empirical (statistical) approaches originally developed to assess earthquake-induced landslide and liquefaction likelihoods in near-real-time. In this approach the probability of occurrence of induced phenomena is described through a set of geo-referenced susceptibility proxies (*e.g.*, geomorphology, surface geology, ground types, soil wetness) and intensity measures (*e.g.* peak ground acceleration, PGA). The coefficients of the predictive models are calibrated against the shaking constraints from past events and optimized for near-real-time estimates based on USGS-style ShakeMaps used at the Swiss Seismological Service since 2007. Emphasis is on the use of high-resolution (30m or 90m) geo-referenced datasets along with additional local information on ground failure susceptibility. This study facilitates future investigations on earthquake induced lake tsunamis triggered by underwater landslides and has a high practical relevance to Swiss ShakeMap end-users and stakeholders managing lifeline systems.

Expansion of the USGS ShakeCast System for Rapid Post-Earthquake Assessments of Critical Facilities

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ShakeCast is employed by public and private emergency responders, lifeline operators, and facility engineers to automatically receive and process ShakeMap products for situational awareness, inspection priority, or damage assessment. As part of ongoing ShakeCast research and development and an extensive rewrite of the ShakeCast application, we have enhanced functionality, updated the code base (from Perl to Python), and improved the user interface. The engineering-based approaches for determining damage state (or inspection priorities) have been improved, implementing the interactive HAZUS capacity spectrum method and HAZUS Advanced Engineering Building Module (AEBM). An enhanced ShakeCast Workbook (an Excel spreadsheet) exports users' data into ShakeCast and allows for more intuitive management of facilities, fragilities, users, and notifications, as well as ShakeCast configurations. Users can select structure fragilities based on a minimum set of user-specified facility features (building location, size, height, use, construction age, etc.) and "expert" users can import user-modified structural response properties into facility inventory associated with the HAZUS Advanced Engineering Building Modules (AEBM). In addition to accessing real-time ShakeMaps, ShakeCast now accesses a new collection of scenario and atlas ShakeMaps via the USGS real-time earthquake information GeoJSON feeds for both pre-event planning and loss calibration. Lastly, we describe further expansion of the ShakeCast user base, notably for state Departments of Transportation (DoTs) facilitated by a USDOT Transportation Pooled Fund, connecting the DoTs in 10 states. Though ShakeCast is supported by the USGS, important financial and technical contributions come from critical users including the California Department of Transportation (Caltrans), the U.S. Nuclear Regulatory Commission (USNRC), the International Atomic Energy Agency (IAEA), and the U.S. Department of Veterans Affairs (VA).

Re-Evaluation of Seismic Hazards at the Central and Eastern United States Nuclear Power Plant Sites

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Following the March 11, 2011 Tohoku earthquake, the US Nuclear Regulatory Commission (NRC) and the nuclear energy industry undertook a comprehensive reanalysis of natural hazards at nuclear power plant sites in the United States. In particular, the NRC requested that nuclear power plant licensees re-analyze seismic hazards at their sites using current NRC regulations and guidance, to determine if the plants could cope with the re-evaluated seismic hazards and submit their assessment results to the NRC. In parallel, the NRC undertook a series of confirmatory analysis for seismic hazards at the currently operating NPP sites. The purpose of NRC's effort was to develop an efficient and effective review process of the licensees' seismic hazard submittals. The licensees submitted all Central and Eastern United States (CEUS) seismic hazard re-assessment results by March 2014. Using risk insights from the confirmatory analyses, the NRC staff reviewed these hazard submittals and documented the reviews in Staff Assessment reports, which were completed by February 2016.

In this presentation, we outline the process, including guidance documents, licensees used to conduct the re-analyses and will summarize the resulting seismic hazards at CEUS nuclear power plants. We will present an overview of the seismic source and ground motion models used for NRC staff's confirmatory analyses. In addition, we will describe the approach used to develop NRC staff's site-response analysis for sites in the CEUS. Specifically, we will describe the approaches used for two types of sites: one with limited information about the subsurface structure and one with well-constrained information. We will discuss how differences in subsurface model uncertainty affected the approach NRC staff used to calculate the site responses and the resulting effects this uncertainty had on the overall seismic hazard results.

Validation of Simulated Ground Motions via Measuring the Sensitivity of Structural Demands to Different Characteristics of Ground Motions

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This article provides the analyst with an understanding regarding the degree to which different aspects of ground motions records are important for ground motion selection as well as ground motion simulation and validation. In other words, the current study presents a list of ground motion parameters identified as important in predicting the response of structural systems to be considered in the ground motion selection and on the validation of simulated ground motion records. Therefore, the results of the present paper enable seismologists to measure the similarity between the simulated and the as-recorded ground motion records using the proposed intensity measures and other parameters of ground motion records can be easily neglected due to their negligible impact on the response of engineered systems. To this end, cloud analysis which requires nonlinear dynamic analysis of the structure subjected to a set of un-scaled ground motions has been carried out to establish probabilistic seismic demand models between engineering demand parameters of several different structural systems (from low- to high rise-buildings) and intensity measures of ground motions. A large number of as-recorded shallow crustal earthquakes GMs that a structure may experience are considered to make the results independent of the set of applied GMs. The efficiency and the importance of various ground motion parameters in predicting the structural response of interest have been evaluated. Finally, a basis through prediction equations of the structural response for the engineering validation of simulated ground motion records is developed.

Linking Sample Structural Responses to Seismological Parameters Inferred from Population through Hierarchical Modeling

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Contemporary seismic structural demand analysis links structural demand (EDP) and scalar earthquake Intensity Measures (IM) using ordinary least squares regression. An implicit assumption in such a linkage of EDP and IM is that the latter variable accounts for all the aleatory variability associated with earthquake occurrence at a site. This assumption is true if and only if Ground Motion Prediction Models (GMPM) were exact. However, depending upon the choice of IM there can be considerable variability in GMPM, which is assessed by the standard deviation in predicted ground motion, indicating that a scalar IM does not propagate all the uncertainty in earthquake occurrence to structural response. In this study, we propose a novel methodology for linking EDP and IM while accounting for the aleatory variability in seismological parameters. We first generate sample structural responses by conducting seismic analysis on a structural model utilizing earthquake records. Then, we link these sample structural simulations to seismological parameters that describe earthquake occurrence at a site, such as Magnitude (M) and distance (R), through a Hierarchical Model. The model is constructed via a variant of Gibbs sampling wherein M and R are randomly drawn from a population distribution within each iteration of the algorithm. The hierarchical model is constructed at six IM levels using different distributions for the seismological parameters at different IM levels. The distributions for seismological parameters are inferred from a ground motion database (*e.g.* PEER database). Through this hierarchical model, the EDP-IM linkage can account for the aleatory variability associated with earthquake occurrence at a site, which can potentially improve structural demand hazard predictions due to better uncertainty propagation.

Correlation of Building Damage with Spectral Aspects of Near-Source Motions—Cushing, OK Induced M5.0 Earthquake of November 7, 2016

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The M_w5.0 Cushing, Oklahoma earthquake of 7 Nov 2016 (depth 5km) occurred at 35.984N. 96.798W, ~2 km west of Cushing (population 8000, the site of the a major hub of the U.S. oil and gas pipeline transportation and storage system [https://www.npms.phmsa.dot.gov] . The earthquake was the largest of six M>4 earthquakes since the 7 October 2014 M_w4.3 and M_w4.0 events that occurred south of Cushing. An increase in seismicity in Oklahoma and other Central US regions began in 2009 with deep injection of wastewater (855 M≥3 earthquakes were recorded between 1973-2008 while 2845 were recorded between 2009-November 2016).

Within a 10 km distance from the epicenter, peak accelerations were between 0.35-0.58g as recorded by four stations (www.strongmotioncenter.org, last visited November 30, 2016). The strong shaking duration of the near source stations was approximately 2 s. McNamara *et al*., (pers. comm., 2016) compared peak accelerations recorded during the event with the GMPE equations of Atkinson (2014, 2015) for induced western Canada earthquakes at 5 and 15 km depth. The recorded near source peak accelerations fall between the two Atkinson GMPEs.

Three different spectra are discussed: (1) 5% damped response spectra of accelerations of five near-source stations reveal consistent spectral amplification at ~0.1 s period (.07-1.3s)—within the fundamental periods of the1-2 story buildings typically found in Cushing. (2) There are significant differences between the recorded response spectra and the ASCE 7-10-based design response spectrum (5 % damped) for Cushing. (3) Comparison of the recorded response spectra to induced-seismicity-based hazard response spectra with peak and 0.2 and 1 s spectral accelerations for two forecasts (A:1/100 and B:1/2500) probabilities of exceedance during the year of 2016; http://earthquake.usgs.gov/hazards/induced/data.php) clearly shows that the response spectra of recorded motions significantly exceed spectrum A but fall short of B.

Location, Amount and Width of The 1906 San Andreas Fault Surface Rupture at the Upper and Lower Crystal Springs Reservoir Embankment, San Francisco Peninsula

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Surface faulting on the embankment between the Upper and Lower Crystal Springs reservoirs on the San Francisco Peninsula was well documented following the 1906 San Andreas fault (SAF) rupture and earthquake. A single fault strand with 2.3 m of right-lateral offset was reported in 1906 from the northeast end of the embankment that now supports transportation, water supply and gas lifeline infrastructure. Geologic mapping and reconstructions of the 1906 fault rupture in the 1980s revised the 1906 SAF rupture location to suggest that there were at least two 1906 coseismic surface ruptures to the northeast and southwest of the rupture mapped in 1906. As part of an assessment of the SAF location at the Upper and Lower Crystal Springs embankment for PG&E, we reassessed the 1906 rupture location and width based on the 1906 post-earthquake observations, review of 1906 historical photographs, measurements of a fault-offset tunnel from the 1920s, and interpretation of Crystal Springs Lakes' swath bathymetry published in 2010. We interpret these data to confirm that the 1906 SAF surface rupture was a single, northwest-striking (N36°W) fault located at the northeastern end of Upper and Lower Crystal Springs embankment, and without significant secondary displacement. Rupture occurred within the Franciscan Complex rocks, and not at the contact between the Franciscan Complex and the Plio-Pleistocene Santa Rosa Formation sediments as suggested by earlier workers. The 1906 right-lateral displacement is estimated at 2.68 ±0.18 m including uncertainties associated with fault strike and tunnel offset measurements. The 1906 SAF rupture width was about 6.1 to 10 m in the Franciscan rock, and increased to 11 to 14.6 m at the embankment surface as it ruptured through the engineered earthfill materials. The analysis shows that the location and width of surface fault rupture can often be well quantified to support analysis and mitigation of major lifelines.

Earthquake Rapid Response

Poster Session · Wednesday 19 April ·

Fault Structures Illuminated by the Aftershocks of the 2015 Mw 7.8 Gorkha Earthquake in Nepal as Captured by a Local Dense Seismic Network

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In April 2015, the M_w 7.8 Gorkha earthquake produced 4 m of peak co-seismic slip as the Main Himalayan Thrust (MHT) fault ruptured 130 km east, under dense population centers, such as Kathmandu. As a result of the Gorkha earthquake and its several large aftershocks, more than 9,000 people were killed due to a combination of infrastructure failure and triggered landslides. Since the MHT did not fully release much of its strain by rupturing to the surface, another large damaging earthquake in this area may be likely. To rapidly assess the evolving state of stress in this region, we developed and deployed a dense, 45-station, seismic network ("NAMASTE"), which operated from June 2015 to May 2016. Composed of a mix of broadband, short-period, and strong motion sensors, with an average spacing of ~20 km, NAMASTE captured the dynamic sequence of aftershock behavior by blanketing the 27,650 km2 rupture area. With 10 months of data starting just one and a half months after the Gorkha event, we generate a high-resolution earthquake catalog using double difference algorithm based on relative relocation. It contains over 7,000 precisely located earthquakes that range in local magnitude between 0.3 and 6.5. This earthquake catalog illuminates the complex Himalayan fault system with unprecedented resolution. In addition, we computed focal mechanism of strategically located earthquakes to decipher the geometry of this fault system. We observe the MHT lies between a depth of 10 and 20 km in the rupture area, extending down-dip towards the north. Moreover, we observe steeply dipping splay faults above the MHT, some of which may have previously remained undetected due to seismic inactivity. Seismicity patterns imaged in this study is possibly reflecting structural and frictional heterogeneities along the Indian-Eurasian plate boundary, providing an improved understanding of the fault structures and physical processes controlling the earthquake cycle in this part of the Himalayas.

Local Seismic Amplification Measurements and Strong Motion Simulations in Port-au-Prince (Haiti)

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In order to help estimating the seismic ground motion expected in the Port-au-Prince area (Haiti), we characterize local site effects, pointing out the seismic waves trapped in the loose layer of Cul-de-Sac basin, and provide realistic synthetic accelerograms for an hypothetical future earthquake.

To this end, we analyze signals from 78 earthquakes (M_w<5) that occurred between March 2010 and February 2013, by applying two well-known methods of spectral ratios: The H/V earthquake and the classical spectral ratio (SSR). A strong spatial variability was observed in the measured amplifications, which is quite consistent with the heterogeneous surface geology of the area. We notice in particular strong amplification on marine sediments close to the coast and the top of the hills (BSSA April 2016). Following this work, we implement two approaches to simulate strong seismic motion in Port-au-Prince. We first use an Empirical Green Function (EGF) methodology simulating earthquakes of different magnitudes starting from several aftershocks in Haiti in 2010. The results for these simulations show that the strongest acceleration is expected in Quaternary sediments near the coast and on the ridge of south hills of Port-au-Prince. A hybrid simulation method combining complex transfer functions and the EGF simulation on bedrock has also been established and validated by comparison with the results obtained directly with the EGF approach. This hybrid simulation technique work on a reconstruction in the time domain of site-specific signals using reference to site transfer function obtained by the SSR method including not only the module but also phase changes. This approach leads in results almost identical to those obtained by the EGF simulation method. In addition, it allows to reproduce the increase of the duration of the signal likely to be generated by surface waves on some stations in the city of Port-au-Prince.

Assessment of the Pacific Tsunami Warning Center's Readiness to Assume Local Tsunami Warning Center Responsibilities for Puerto Rico and the Virgin Islands Based on Performance Statistics between 2004 and 2016

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The Pacific Tsunami Warning Center (PTWC) has routinely processed earthquakes occurring within the Caribbean region since at least 2004. In mid-2013 the PTWC set up a local processing system for the Caribbean relying exclusively on the official Earthworm real time monitoring software, with a particular focus on Puerto Rico, the Virgin Islands, and the Lesser Antilles. To evaluate PTWC's performance for this region we relied on the compilation and cross-validation of 221 observatory messages and tsunami bulletins retrieved from the communication circuits' logs. We calculated core statistics such as message delay times, epicenter offsets, and magnitude residuals by comparing the message parameters with later source parametrizations reported in seismic catalogs compiled by the International Seismological Center (ISCGEM), the Global Centroid Moment Tensor (GCMT) Project, and the National Earthquake Information Center (NEIC). Statistical analysis reveals that the PTWC has processed an increasingly larger number of earthquakes for this region, from no more than 5 in the mid-2000s, to as many as 49 in 2016. Along the way, the PTWC has also succeeded in gradually reducing the time needed to send these messages from a median of 15 minutes in 2004 to just 3 minutes in 2016. Likewise, the PTWC has also succeeded in gradually reducing the time needed to send these messages from a median of 15 minutes in 2004 to just 3 minutes in 2016, as well as decreasing the median epicentral offset from over 30 km in 2004 to 10 km in 2016. Relative to their catalog counterparts, the PTWC magnitude estimations for the Caribbean have a median residual value of 0.2 magnitude unit. Results of improved station coverage, enhanced automatic event processing, and improved post-processing tools demonstrate readiness for PTWC to assume the scheduled official responsibilities as local tsunami warning center for Puerto Rico and the Virgin Islands in 2017.

Geodetic Infrastructure, Data, Education and Community Engagement for Earthquake Rapid Response: An Overview of UNAVCO Support Resources and Earthquake Response Examples

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UNAVCO responds to community requests for rapid support during and following earthquakes and other significant geophysical events such as volcanic activity, landslides, glacial and ice-sheet movements, unusual uplift or subsidence, extreme meteorological events, or other hazards. UNAVCO event response resources include geodetic infrastructure, data, and education and community engagement.

Specific support resources include: field engineering personnel; continuous and campaign GNSS/GPS station deployment; real-time and/or high rate field GNSS/GPS station upgrades or deployment; data communications and power systems deployment; tiltmeter, strainmeter, and borehole seismometer deployments; terrestrial laser scanning (TLS a.k.a. ground-based LiDAR); InSAR data support; education and community engagement assistance or products; data processing services; generation of custom GNSS/GPS or borehole data sets and products; equipment shipping and logistics coordination; and assistance with RAPID proposal preparation, budgeting, and submission.

The most critical aspect of a successful event response is effective and efficient communication. To facilitate such communication, UNAVCO creates event response web pages describing the event and the support being provided, and in the case of major events also provides an online event response forum. These resources are shared broadly with the geophysical community through multiple dissemination strategies including social media of UNAVCO and partner organizations.

We provide here an overview of resources available to the community from UNAVCO for earthquake rapid response. We also highlight examples of the infrastructure, data and data products, and education and community engagement support provided by UNAVCO for major recent earthquakes.

Early Results from Testing and Deployments of a Cascadia, an Instrument with over 200dB of Dynamic Range, Specifically Built for Aftershock Studies

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Integration of mature instrument systems such as broadband sensors and accelerometers used in strong motion studies has to be done with care to preserve the low noise and low frequency performance while providing over 200dB of dynamic range. The new Cascadia is a stainless steel sonde with both a broadband seismometer and class A accelerometer that can be quickly buried for deployment without compromising the performance or reliability of the device. We will present results from the testing and verification of the integrated sensors along with data quality reviews of recent deployments. This instrument provides high fidelity recording of both weak motion and strong motion up to ± 4g in an environmentally rugged enclosure and easy to install form factor that suits both long term and short term deployments.

Estimating Earthquake Hazard from Geodetic Data

Poster Session ·Wednesday 19 April ·

Mitigating Postseismic Bias in Global Positioning System Secular Velocity Estimates for the Central California Coast Region

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Postseismic motion produces long-period signals that are difficult to separate from secular motion and can bias Global Positioning System (GPS)-derived velocity estimates. For GPS sites installed post-earthquake it is challenging to uniquely estimate constant velocities and postseismic signals and to determine when the postseismic transient has decayed sufficiently to allow using subsequent data to estimate secular rates.

Within 60 km of the 2003 M6.5 San Simeon and 2004 M6 Parkfield earthquakes in California, 16 continuous GPS sites were established before mid-2001, providing data to test strategies for mitigating velocity bias for sites installed after the events. While position time series could be corrected for postseismic effects using afterslip and viscoelastic models, this propagates those models' uncertainties into secular rate estimates. Instead we fit time series with combinations of constant rate, seasonal terms, offsets, and postseismic decay while optimizing a temporally correlated noise model consisting of white, flicker, random walk, and, if needed, band-pass filtered noise.

Solving for a constant rate and logarithmic decay when fitting the full time series gives secular velocity estimates that match pre-San Simeon rates better than do those obtained by fitting only a constant rate to the post-Parkfield data, even when the first several (*e.g.*, >5) years of postseismic data are left out. While velocities estimated from only recent years' data match the pre-San Simeon rates within errors for most sites, spatially coherent west-oriented velocity differences remain. This may reflect interaction of afterslip, viscoelastic relaxation, and spatially-variable interseismic locking of the San Andreas Fault. We will compare our results to the spatiotemporal extent of secular velocity bias implied by published postseismic deformation models and assess if using a combination of logarithmic and exponential decay in the time series analysis can further reduce bias.

Geodetic Evidence for a Blind Segment of the San Jacinto Fault

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The San Jacinto Fault (SJF) splits into several active branches south of Anza, including the Clark fault and the Coyote Creek fault. The Clark fault is believed to terminate at the southern tip of the Santa Rosa mountains, and the Coyote Creek fault (CCF) is currently considered to be the main strand at the southern end of the SJF (Jennings, 1994). Space geodetic observations using ERS-1/2 InSAR data have revealed high gradients in the line-of-sight (LOS) velocity to the east of the CCF, possibly indicating a "blind" continuation of the Clark fault further to the south (*e.g.*, Fialko 2006, Lindsey *et al.* 2013a). We present new InSAR data from Envisat and Sentinel-1 missions that confirm high deformation rates along the southern extent of the Clark fault. We derive high-resolution maps of horizontal and vertical surface velocities by combining LOS velocities from two different satellite look directions, and local azimuths of the horizontal components of the velocity vector obtained from interpolated GPS data. We differentiate the fault-parallel component of the horizontal InSAR velocities to compute strain rates across the southern San Jacinto and San Andreas fault systems. InSAR-derived strain rates reveal a peak to the East of the CCF, aligned with the southern continuation of the Clark fault. We complement InSAR data with campaign GPS measurements of secular velocity of an array of monuments with 1-2 km spacing along Highway 78, surveyed between 2010-2016. Velocities derived from campaign GPS measurements are in good agreement with InSAR data. We perform joint inversions of InSAR and GPS measurements of fault-parallel deformation rates to resolve the slip partitioning on the CCF, the blind segment of the Clark fault, and the southern San Andreas fault. We show that the blind southern segment of the Clark fault accommodates a significant fraction of relative motion between the North America and Pacific plates, and poses a currently unrecognized seismic hazard.

Can Interseismic Geodetic Observations and Microseismicity Shed Light on Large Earthquake Behavior? Insights from Models of Long-Term Fault Slip

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Modern observations of tectonic faults are often limited to the interseismic periods between major earthquakes. Geodetic observations and microseismicity provide independent estimates of the fault locking depth, which serves as an approximate metric for assessing seismic potential and hazard.

To connect interseismic observations to large earthquake behavior, we study seismic and geodetic observables in models of faults governed by laboratory-based friction laws. Assuming layered distributions of quasi-static and dynamic friction properties, our models suggest that the geodetically-estimated locking depth is close to or even deeper than the depth of concentrated microseismicity. This prediction is generally consistent with observations from major segments on the San Andreas Fault and San Jacinto Fault (SJF) in Southern California, most notably the Carrizo and Coachella segments, where deeper coseismic slip and/or significant afterslip is inferred from our modeling results. In these models with quasi-periodic seismic cycles, the geodetic estimates can be used to constrain the potency release during large events.

A few notable exceptions include the Anza segment of the SJF and the Imperial Fault. In particular, on the Anza segment, the geodetic locking (~10 km) is shallower than the depth extent of microseismicity (15–18 km). We suggest that the discrepancy may point to a broad, heterogeneous lower transition zone of the seismogenic layer. Models of faults with stochastic heterogeneity in rate-and-state friction successfully reproduce the observations. They further demonstrate that such faults can produce pervasive aseismic transients and large earthquakes penetrating below the geodetic locking depth, with increased complexity of rupture downdip.

As highlighted in these cases, the combined use of high-resolution geodetic and seismic observations and state-of-the-art fault models provides new insights into the deep fault zone properties and large earthquake behavior.

Incorporating Geodetic Data into Seismic Hazard Assessment: Impact on Local Earthquake Risk

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Incorporating geodetic data into a probabilistic seismic hazard assessment (PSHA) is especially important when the deformation signal in the these observations is different from that in the earthquake or fault slip data.

Power-Law Rheology Controls Aftershock Triggering and Decay

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Aftershocks are ubiquitous in nature. They are the manifestation of relaxation phenomena observed in various physical systems. In one prominent example, they typically occur after large earthquakes. The occurrence of aftershocks displays a prominent temporal behavior due to time-dependent mechanisms of stress transfer. There are compelling evidences that the lower continental crust and upper mantle are governed by various solid state creep mechanisms. Among those mechanisms a power-law viscous flow was suggested to explain the post-seismic surface deformation after large earthquakes. In this work, we consider a slider-block model to mimic the behavior of a seismogenic fault. In the model, we introduce a nonlinear viscoelastic coupling mechanism to capture the essential characteristics of crustal rheology. For this purpose, we employ nonlinear Kelvin-Voigt elements consisting of an elastic spring and a dashpot assembled in parallel to introduce viscoelastic coupling between the blocks and the driving plate. We show that the nonlinear viscoelasticity plays a critical role in triggering of aftershocks (Zhang and Shcherbakov, Sci. Rep., 6, 2016, 36668). It explains the functional form of the Omori-Utsu law and gives the physical interpretation of its parameters. The proposed model also suggests that the power-law rheology of the fault gauge and underlying lower crust and upper mantle control the decay rate of aftershocks. To verify this, we analyze several prominent aftershock sequences (generated by the 1992 Landers, 1999 Hector Mine and 2002 Denali mainshocks) in order to estimate their decay rates and to correlate with the rheological properties of the underlying lower crust and mantle, which were estimated from the postseismic surface deformation. Our modeling suggests that the power-law rheology exponent n controls the decay rate of aftershocks and is related to the parameter p of the Omori-Utsu law.

The 2016 Earthquake Sequence and Associated Coseismic Deformation in Central Apennines in Italy

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The Central Apennines in Italy were struck by multiple moderate-size but damaging shallow earthquakes in 2016. We optimize the fault geometry and invert for fault slip based on GPS and Interferometric Synthetic Aperture Radar (InSAR) analysis of Copernicus Sentinel-1A and -1B, JAXA ALOS-2 data, and ASI COSMO-SkyMed for the 2016 M_w 6.2 Amatrice, M_w 6.1 Visso, and M_w 6.4 Norcia earthquakes in Italy. For the Amatrice event, there was less than 4 cm static surface displacement at the town Amatrice where the most devastating damage occurred. We find evidence of coseismically triggered deep-seated landslides NW and NE of the epicenter where coseismic peak ground acceleration was estimated > 0.5 g. We estimate the landslide thickness as at least 100 and 80 m near Mt. Vettore and west of Castelluccio, respectively. The landslide near Mt. Vettore terminates on the pre-existing fault Mt. Vettore Fault (MVEF) scarp. Two months after the Amatrice earthquake, the M_w 6.1 Visso and M_w 6.4 Norcia earthquakes stroke Central Apennines in late October. Both events occurred ~30 km north of the Amatrice earthquake. We combine ascending/descending InSAR and GPS measurements to constrain the fault geometry as well as the slip distribution. The geodetic data infer that the majority of slip is on a west-dipping moderately dipping normal fault. However, the InSAR result suggests antithetic normal faults above a shallow detachment with normal sense of motion also slipped. The antithetic faults and the detachment all slipped during or right after the Norcia earthquake. Although the complicated slip on multiple faults cannot be well constrained by strong motion seismic data, the aftershocks recorded three months following the earthquake illuminate the antithetic fault as well as the detachment. Our results demonstrate how earthquakes can illuminate geological structures and the significant advantage of using space geodesy to obtain detail of surface deformation during earthquakes.

Integrating Sentinel-1 InSAR and GNSS Data for Deformation Monitoring across the Alpine-Himalayan Belt

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Geodetic data are becoming an increasingly important component of efforts to assess earthquake hazard across tectonically active regions. The ongoing densification of GNSS networks and rapidly advancing InSAR data and processing techniques have improved our ability to confidently measure crustal motions and map regions of localized strain. For example, the recently launched Sentinel-1 (S1) radar satellites are now able to measure deformation at the tectonic-plate scale and ultimately across slowly straining regions where earthquake hazard is likely underestimated. We have used the first 1.5 years of S1 mission data to measure crustal velocity for most of the Anatolian microplate, including the North and East Anatolian Faults, and uncertainty on S1-derived line-of-sight velocities will reach 2 mm/yr within the next year for the ~100-km length scales important for measuring interseismic deformation. Further, we are systematically processing interferograms for the entire Alpine-Himalayan belt (AHB) and these products are freely available to the geoscience community. We can use this information to map the accumulation of strain around faults and to place constraints on how often earthquakes can occur in a given region. However, before strain rates can be calculated by taking the spatial derivative of the velocity field, a continuous or dense representation of that field is required. Here we present our progress to date on using S1 to map tectonic strain and seismic hazard across the AHB while focusing on obstacles associated with combining InSAR- and GNSS-derived surface displacements to produce large-scale crustal velocity and strain fields. We evaluate methods commonly used to combine the complementary geodetic datasets including "non-physical" approaches that use mathematical functions to interpolate the surface velocities on to regular grids and "physical" methods that ensure elastic coupling between components of the interpolation. We highlight some of the challeng

National Seismic Hazard Maps for Ecuador

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Probabilistic seismic hazard assessment (PSHA) consists in developing earthquake recurrence models, selecting ground-motion prediction equations, and determining probabilities of exceedance of ground-motion levels over future time windows. PSHA results, hazard maps for given spectral periods and return periods, are used to derive countrywide seismic zonings. Ecuador is a country facing a high seismic hazard, both from megathrust subduction earthquakes (such as the 2016/04/16 M_w7.8 event) and shallow crustal moderate to large earthquakes.

Building on the knowledge produced in the last years in tectonics, geodynamics, geodesy, historical seismicity and earthquake catalogs, an earthquake recurrence model is developed. As active faults are only partially characterized, an area source model is first proposed, deriving frequency-magnitude distributions for the seismogenic sources defined in Yepes *et al.* (2016). Maximum magnitudes are estimated considering the maximum length of fault segments and applying scaling laws. The hazard maps obtained highlight a major issue: several source zones enclosing fault systems exhibit low seismic activity, not representative of the geological and/or geodetical slip rates on the faults. These slip rates are then used to develop alternative earthquake recurrence models including the best-characterized faults, taking into account the uncertainty on the geologic and/or geodetic rates, and making assumptions on the aseismic component of the deformation.

Combining these alternative earthquake models in a logic tree, and using a set of selected ground-motion prediction equations best adapted to Ecuador's different tectonic contexts, a mean hazard map is obtained. Uncertainties related to the earthquake model and to the ground-motion prediction model are quantified. Results show that their respective contribution to the overall uncertainty on hazard varies strongly depending on the geographical location of the site.

New Velocity Field for Northern Colombia and Western Venezuela and Implications for a Great Earthquake in the Southwest Caribbean

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The motion of the Caribbean plate is approximately due east relative to the South American Plate. In NE Venezula, plate motion is largely taken up by pure strike slip motion along the El Pilar fault, but in northern Colombia motion is partitioned between the strike-slip Bocono fault system and normal convergence along the northern coast of Colombia. Recent densification of GPS networks through the NSF funded COLOVEN and COCONet projects, seismic reflection profiles, gravimetric and seismic inversions and revised earthquake locations suggest the existence of incipient oblique subduction zone at ~10 mm/yr beneath

the coast of NE Colombia. Although there is no history of major subduction zone earthquakes since the arrival of Europeans in the region, and no volcanism indicative of well-established deep subduction, there is evidence for incremental coastal uplift and local subsidence in the past several thousand years, and both local and distant tsunami, which may owe their origin to pre-European arrival events. At Chengue, NE of Santa Marta, a well dated shell and gravel tsunami horizon within a salt marsh sequence, appears to have been emplaced ~1200 years ago, and this may correspond to a tsunami deposit of similar age on the southeast Yucatan peninsula, and near Cartagena. The probable rupture area and slip deficit since that time suggests the potential for a great earthquake in the region, with a possible magnitude of $8.0<M_w<8.5$, which could result in a tsunami directed to the NNW. This is by far the largest seismic hazard in the Caribbean. We present a new GPS derived velocity field, used to constrain a revised simple regional block model, it's relation to recent seismic and gravimetric inversions and discuss the earthquake and tsunami hazards implied by this model.

Fine Scale Structure of the Crust and Upper Mantle

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Lithospheric Structure of Canadian Lithosphere from Joint Interpretation of Receiver Functions and Regional Travel Time Tomography

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We present preliminary results of an integrated study of the crust and the lithospheric mantle of the North American craton using regional travel time tomography and receiver functions. Teleseismic events recorded by the POLARIS array and the Yellowknife station are used to calculate a sufficient number of receiver functions for P (PRF) and S (SRF) waves within Slave craton. Velocity (Vp and Vs) and Vp/Vs profiles from the Earth's surface down to 300 km are obtained through the simultaneous inversion of PRF and SRF with travel time residuals for 410 and 660 km discontinuities.

Seismic tomography of North American craton from a joint inversion of surface and body waves can significantly increase the vertical resolution of resulting velocity models.

From the receiver function analysis we observe highly a heterogeneous structure of the cratonic upper mantle. The Lehman discontinuity is found in the western Slave carton, whereas it is not observed in the eastern part of the Slave carton. At the stations located in the northern part of the craton we do not observe an increase of S-wave velocities (as compared to the Earth reference model) in upper mantle, which is typical for depleted cratonic lithosphere.

Developing and Validating Path-Dependent Travel Time Uncertainty Estimates for All Phases of the Regional Seismic Travel Time (RSTT) Model

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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) has been released (http://www.sandia.gov/rstt). Travel time uncertainty estimates for RSTT are determined using one-dimensional (1D), distance-dependent error models, that have the benefit of being very fast to use in standard location algorithms, but do not account for path-dependent variations in error, and structural inadequacy of the RSTTT model (*e.g.*, model error). Although global in extent, the RSTT tomography model is only defined in areas where data exist. A simple 1D error model does not accurately model areas where RSTT has not been calibrated. We are developing and validating a new error model for RSTT phase arrivals by mathematically deriving this multivariate model directly from a unified model of RSTT embedded into a statistical random effects model that captures distance, path and model error effects. An initial method developed is a two-dimensional path-distributed method using residuals. The goals for any RSTT uncertainty method are for it to be both readily useful for the standard RSTT user as well as improve travel time uncertainty estimates for location. We have successfully tested using the new error model for Pn phases and will demonstrate the method and validation of the error model for Sn, Pg, and Lg phases.

The 3D Crustal Velocity Structure Under the Changbaishan Volcanic Area in Northeast China Inferred from Ambient Noise Tomography

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Previous studies show the prevalence of low velocities beneath the Changbaishan volcano, but debate continues about the details of the structure. We try to obtain the refined velocity structure under the Changbaishan volcanic area in Northeast China with our dense temporary NECsaids array (NorthEast China Seismic Array to Investigate Deep Subduction). The vertical component of continuous data recorded by our NECsaids array and regional permanent (CSN) broadband seismic stations from July 2010 to December 2014 in northeast China are used to obtain the Rayleigh wave phase velocity maps at periods between 6-40s in study area (124°E-131°E—41°N-48°N), then the Rayleigh wave phase velocity dispersions are inverted to determine 1D shear wave velocity and assembled into 3D model at depth between 0~50km. The results show the S wave velocity structure of the crust has lateral and vertical heterogeneity, the velocity structure of shallow crust is well related with the geology units on the surface, and the deep structure reveals the volcanism and regional thermal erosion. The low velocity anomaly bodies are found at depth of 9-30 km beneath the Changbaishan volcano and have a tendency to extend to deeper, which may be the magma chamber in crust of the Changbaishan volcano. There is also a weak low velocity anomaly body at depth of 12-30km beneath the Longgang volcano, which may be the remains after eruption, and no distinct low velocity anomaly body found under the Jingpohu volcano, which means that there is no partial melting magma in the crust beneath it.

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Active Magmatic Underplating in an Intraplate Setting: Crust/Mantle Moho Transition in the Western Eger Rift, Central Europe

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The Eger Rift is an active element of the European Cenozoic Rift System. It is associated with the intense Cenozoic intraplate alkaline volcanism and system of sedimentary basins. The intracontinental Cheb Basin at its western part displays concurrent geodynamic activity with fluid emanations, persistent seismicity, Cenozoic volcanism, and neotectonic crustal movements at the intersections of major intraplate faults. The CO2-rich gases have increased helium isotope ratios evidencing their lithospheric mantle origin. Active and passive seismic data show increased lower-crustal velocities, which points to the magmatic addition at the base of the crust and to a concept of magmatic underplating. However, character of the seismic image differs laterally, which enables to differentiate two types of the magmatic underplating related to its different timing and tectonic setting. High-velocity lower crust with increase seismic reflectivity evidences the first type of magmatic underplating related to Variscan or pre-Variscan age westward of the Eger Rift. High-velocity reflection-free lower crust together with a strong reflector at its top at depths ~28-30 km forms a lower-crustal magma body. Lateral extent of this body correlates with the distribution of mantle-derived fluid emanations at the surface. Thus, seismic and seismological evidence of the crust/mantle Moho transition supplemented by gas-geochemical investigation and xenolith studies from corresponding depths indicate the second type of magmatic underplating of the Late Cenozoic to recent. Finally, different behavior of fluids in the Cheb Basin with the highest isotope mantle fractions together with Quaternary volcanism points to the ongoing magmatic activity within the broader Late Cenozoic magmatic body and its re-activation in the last 0.3 Ma during Mid Pleistocene to Holocene.

The Effects of the Iceland Plume Track on the Greenland's Lithosphere

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The effects of the Iceland mantle plume on the overpassing Greenland's craton are still poorly understood. To better understand these effects, we image Greenland's lithosphere using ambient noise tomography. Seismic records used in this study were collected from the Greenland Ice Sheet Monitoring Network (GLISN) between December 2011 and July 2016. Our phase velocity maps reveal profound and prolonged impact of the mantle plume on Greenland's lithosphere. In east Greenland the detected velocity reduction at longer periods (30, 33, 35 and 40 s) illuminates substantially thinned lithosphere. This lithospheric thinning may relate to thermal ablation by the Iceland plume, which passed under this area ~40 Ma [*e.g.* Lawyler and Muller, 1994]. From the east, the reduced velocities shift NW at shorter periods, indicating shoaling of the plume-related slow anomaly towards the northwest. In north-central Greenland we detect a pronounced slow anomaly at intermediate and short periods (8-20 s). The anomaly appears in the proximity of the plume ~60 Ma along the track estimated by Forsyth *et al.* [1986]. Since this area is associated with elevated heat flow (>70 mW/m2, Fox-Maule *et al.*, 2009] and high ice sheet basal melting [Petrunin *et al.*, 2013; Stevens *et al.*, 2016], the velocity reduction can be explained as the plume-related residual heat that persists within the lithosphere. The detection of velocity reduction at intermediate and short, but not at long periods, indicates that the heat is transferred from sub-lithospheric depths towards the surface, where it possibly affects the stability of Greenland's ice sheet. Our results illuminate the connection between deep and surface processes in this critical tectonic region.

Velocity Model beneath the Reykjanet Array Derived from Rayleigh Wave Dispersion

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The main aim of this study is to obtain a site-specific structural model beneath the Reykjanes peninsula, southern Iceland, that would be suitable for location of proximal earthquakes recorded in the Reykjanet network. The network of fifteen stations was installed in summer 2013 in order to monitor seismic swarms in this geodynamically active region.

Eight broadband stations of the network are used to find Rayleigh phase velocity dispersion in a relatively wide range of periods (from 3 to 40 s). The records analyzed in this study come from the years 2013 to 2015 and are from fourteen selected earthquakes whose epicentral distances range from tens kilometers to almost ten thousand kilometers.

Our approach to retrieving Rayleigh phase velocity dispersion involves two partly independent methods: 1) the so-called zero-crossing point method utilizing time shifts of given zero-crossing points across the array, and 2) the so called rotation-to-translation relation method utilizing amplitude ratios between relevant rotational and translational components. Rotational components (namely tilt rates) are derived from the array records utilizing a novel approach allowing for array apertures larger than a wavelength. In both methods, propagation of a single plane wave is implicitly assumed. This assumption is carefully checked during the data analysis. A good match between the dispersion curves obtained with the two methods is an indicator that the assumption of a single plane wave was reasonably fulfilled.

The Rayleigh wave phase velocity obtained is inverted to derive a one-dimensional isotropic model that we will use to locate swarm events in the Reyjkjanes peninsula.

3D Local Earthquake Tomography of the Cocos Ridge Subduction at the Southeastern End of the Middle American Trench

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Southeastern Costa Rica remains as one of the less understood regions along the Middle America Subduction Zone. This highly complicated region includes the presence of the submarine Cocos Ridge, an exposed forearc, a ~190-km gap in the Quaternary volcanic arc, a lack of deep seismicity, and the outcrop of Pliocene-Pleistocene adakites. Using the VELEST and SIMULPS packages, we inverted travel times from ~500 selected local earthquakes recorded by Red Sismológica Nacional (RSN) since 1998, simultaneously determining hypocenters and the 3D tomographic P-wave velocity structure of the shallow part of the subduction zone. The new tomographic data show a well-defined, thick steep slab (~55° at depths > 30 km), reaching depths of 65 km, 70 km landwards from the trench. The subducting slab is imaged as a high-velocity perturbation with a band of low velocities on top encompassing the intraslab seismicity deeper than ~20 km. The Wadati Benioff Zone is displayed from 40 to 65 km beneath the Fila Costeña Range. In the upper plate, we observe three main velocity anomalies: a high velocity anomaly beneath the Talamanca Cordillera and two low velocity anomalies beneath the Fila Costeña Range and the Limon Basin. An anomalously deep intracrustal seismicity (down to 40 km) in the Panama Block was detected below the thrust belt of Fila Costeña and the Talamanca Cordillera. These new results favor the presence of a steeply dipping subducted slab beneath Southeastern Costa Rica and a Wadati Benioff Zone seismicity extending to at least ~70 km depth. The velocity anomalies observed within the upper plate suggest a very heterogeneous crust. The geometry determined by our seismic tomography provides a new frame to interpret the driving mechanisms for the upper plate deformation and the presence of the volcanic arc gap.

The Lower Crust and Upper Mantle beneath the Tien Shan from Full Waveform Tomography

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The Tien Shan is the best example of contemporary intracontinental orogeny, but the roles that the various geologic features have played in the evolution of this mountain range remains a subject of debate. Much has been learned over the past several years from analysis of broad band data recorded from seismic arrays deployed in Kyrgyzstan and China. In an effort to improve the resolution of elastic wavespeed images of the crust and upper mantle beneath the Tien Shan and the bounding lithospheres beneath the Kazakh Shield and Tarim Basin, we applied a 2.5D full waveform tomography algorithm to data recorded by the dense MANAS linear array that was deployed across the Tien Shan in 2006. In particular, we examine the extent to which the crust of the Tarim Basin has been consumed, rather than simply shortened, as a contribution to the building of the Tien Shan. Our preliminary results suggest that a significant fraction of the Tarim crust has been subducted into the mantle beneath the Kokshal range at the southern boundary of the Tien Shan.

Upper Mantle Layering in the North American Craton Using Short and Long Period Seismic Constraints

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The lithospheric thickness under the north American craton is well constrained from seismic tomography and in particular from the change in fast axis direction obtained by joint inversion of seismic waveforms and SKS splitting data (eg Yuan and Romanowicz, 2010). This type of approach also reveals the presence of at least one mid-lithospheric discontinuity (MLD) with strong topography.

On the other hand, receiver function (RF) studies detect at least one, and sometimes several sharp MLD's, while the lithosphere-asthenosphere boundary (LAB) is not clearly detected everywhere.

Here we consider the relationship between the MLDs found by RFs and that found from anisotropic tomography as well as various constraints on the LAB. In particular, we apply Monte Carlo Markov Chain trans-dimensional modeling to a combination of converted phase waveform data, Love and Rayleigh wave dispersion data (including azimuthal variations) at a representative set of seismic stations in North America. We confirm the presence of several MLDs (corresponding to sharp drops or increases in shear velocity) in at least some parts of the craton, and show that some MLDs are also discontinuities in azimuthal anisotropy.

We present preliminary results of the construction of a shear wave, radially anisotropic model of the lithosphere, in which we combine constraints on discontinuities from the MCMC modeling, and 3D time-domain inversion of long period (T>40s) three-component waveforms using numerical (Spectral Element) wavefield computations.

A Global Radial Anisotropic Model of the Upper Mantle from Surface Wave Observations

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We present a new radial anisotropic (xi) tomographic model (HPD2017xi) for the upper mantle and discuss the significance of the observed lateral variations in the radial anisotropy. HPD2017xi is based on large (4.0 million paths) Vsv and (0.5 million paths) Vsh data sets. This model confirms large-scale upper mantle features seen in previously published xi(z) models, but a number of these features are better resolved because of the increased data density of the fundamental and higher modes. The average xi(z) is similar to PREM in the upper 100 km but shows a stronger value of xi deeper than 100 km. At shallower upper mantle depths (<200 km) there is a strong correlation between continental areas of fast wavespeed, the cratonic roots, with xi, much more so than in most of the regional and global xi models. At 150 km depth all of the cratons show xi < 1. This switches to xi > 1 in the 200-250 km depth range. In the Pacific the depth of maximum xi increases with seafloor age to about 75 m.y. then remains at a near constant depth beneath the older part of the Pacific. The depth of maximum xi tracks the upper part of the LVZ. Below about 275 km xi is close to 1, however there is a small positive increase in xi at transition zone depths. The pattern of radial anisotropic we observe, when compared with the pattern of azimuthal anisotropy determined from Rayleigh waves, suggests that the shearing at the bottom of the plates is only sufficiently strong to preferentially align the crystals when the plate motion exceeds some critical value which Debayle and Richard (2013) suggests is about 4 cm/yr.

Composite Stochastic Models for Fine-Scale Structure of the Crust and Upper Mantle

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Fine-scale structure of the crust and upper mantle involves 3D elastic heterogeneities that are both locally anisotropic, owing to mineral alignment during formation and deformation, and geometrically anisotropic, owing to layering and other compositional correlations. We describe a class of spatially stationary stochastic models with orthotropic statistics that can represent both local and geometric anisotropy. We assume the medium is stochastically separable to second-order; *i.e.*, the 8th-order covariance tensor of its elastic properties can be factored into a one-point, tensor-valued variance $V_{ijklpqrs}(\mathbf{x})$ and a two-point, scalar-valued correlation function $\rho(r)$. We also assume the geometric anisotropy is ellipsoidal; *i.e.*, the spatial correlation depends on relative position $\mathbf{r} = \mathbf{x} - \mathbf{x'}$ only through a length $r = \mathbf{r}^{\mathrm{T}}\, \mathbf{Q}\, \mathbf{r}$, defined by a constant metric tensor $\mathbf{Q}$. Although this model can represent heterogeneity with orthotropic stochastic symmetry, we restrict the instantiations presented here to media with transversely isotropic (TI) statistics. The local anisotropy is given by a rotational model in which the axis of a hexagonally symmetric stiffness tensor is locally rotated to align it with a 3D stochastic Gaussian vector field that has TI statistics. The geometric anisotropy is specified by a self-affine spatial correlation function $\rho(r)$, which we select from the Matérn class. We represent chemical and mineralogical variations by introducing stochastic mixing distributions. We illustrate the application of these models to the representation of crustal and mantle anisotropy. In particular, we apply Jordan's (*GJI*, 2015) second-order effective medium theory to show that the seismic anisotropy of the upper mantle is dominated by local rather than geometric anisotropy.

Seismic Structure of the Crust and Upper Mantle of Madagascar

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A recent deployment of broadband seismometers across Madagascar has allowed for the first island-wide study of its lithosphere and asthenosphere. Data are from the 2011-2013 NSF-funded MACOMO broadband seismic array from the PASSCAL program of IRIS. Additional data come from the RHUM-RUM and SELASOMA projects. Studies included seismicity, body-wave receiver functions, Pn tomography, body-wave tomography, and ambient-noise and two-plane-wave surface waves tomography. Madagascar's crustal thickness varies greatly, from 20 km beneath the western rift basins and northern Neoproterozoic lithosphere (0.8-0.7 Ga), to 45 km beneath the central Neoarchean craton (2.5 Ga), but is also relatively thick along the east coast, where Mesoarchean lithosphere (3.2 Ga) was severed from the Indian plate. The west coast also has thick sedimentary basins up to 8 km thick. Madagascar has relatively high intraplate seismicity, with 918 earthquakes located during the 2-year deployment. Most seismicity is located within the central Neoarchean craton, associated with normal faulting along graben structures, compatible with the presence of a diffuse Somalia-Lwandle plate boundary. Separate tomographic studies using Pn, teleseismic body waves, and surface waves all show three regions within Madagascar (north, central, and southwest) that display strong seismic low-velocity zones (LVZs) that underlie regions of Cenozoic alkaline volcanic activity. Surface waves show that these LVZs extend down into the asthenosphere and body-wave tomography shows them extending even deeper. Pn tomography shows the width of the central LVZ to be ~100-200 km in diameter at the top of the mantle, and body wave tomography indicates that the three LVZs might be connected at depth within the mantle, perhaps due to lithospheric delamination. Complex anisotropy patterns, from Pn tomography and SKS splitting, are in agreement with asthenospheric flow from the Comores to the northern volcanic regions, but not southern.

Assessing the Robustness of Seismic Imaging Methods: A Study toward Quantifying Resolution in Seismic Tomography

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To test the robustness of seismic imaging methods, one should employ various resolution assessments to quantify smearing effects in an integrated statistical manner, and to evaluate the optimum regularization weights such as damping and smoothness operators. These tests may include applying different (ir)regular parameterizations, classical checkerboard and simulated anomalies-driven tests. For some datasets, one may perform different weighting schemes for the traveltime data; these schemes serve to balance the uneven ray coverage due to uneven distribution of seismic sources.

Furthermore, squeezing tests that vary the model box volume or progressively change the free inversion parameters during a given run provide novel insights into the imaged anomalies. Such tests are important to define the optimum inversion parameters. Additionally, as a requirement for mantle seismic studies, assessment procedure must involve a detailed investigation of the effects of crustal correction on the final velocity model that strongly influence the image fidelity for the deep structures.

For applying the afore-mentioned tests, we present a resolution study of the velocity structure beneath the Arabian plate as constrained by teleseismic traveltime tomography using data from Saudi Geological Survey and the Egyptian National Seismic Network. This study may clarify the resolving power of the regional seismic experiments. The suite of different tests is used to constrain the range of models that satisfy the traveltime observations.

From Field Site to Data Center: Network Innovations for Earthquake Early Warning

Poster Session · Wednesday 19 April ·

ANZA Seismic Network: Real-Time Continuous Response Spectra Exceedance Calculation

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An approach is presented that that can be used for near real-time earthquake alarms for structures at distributed locations and large facilities using real-time estimation of response spectra obtained from near free-field motions. Influential

studies dating back to the 1980s identified spectral response acceleration as a key ground motion characteristic that correlates well with observed damage in structures. Thus, monitoring and reporting on exceedance of spectra-based thresholds are useful tools for assessing the potential for damage to facilities based on input ground motions only. With as little as one strong-motion station per site, this scalable approach can provide rapid alarms on the damage status of remote towns, critical infrastructure (*e.g.*, hospitals, schools) and points of interests (*e.g.*, bridges) for a very large number of locations enabling better rapid decision making during critical and difficult immediate post-earthquake response actions. Real-time calculation of PSA exceedance and alarm dissemination are enabled with Bighorn, a component of the Antelope software package. Examples will be shown using several recent M~5 event recorded in the near field by the ANZA seismic network.

Cybersecurity for Seismic Networks

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In August 2016, the seismology community was alarmed by a presentation at DEF CON 24, an annual hacking conference: “Exploiting and attacking seismological networks remotely”. The Southern California Seismic Network, a cooperative project of Caltech and USGS, went into crisis mode, first to identify key vulnerabilities, then to quickly implement security measures. We determined that the greatest threat was to Internet-connected devices using default or stale passwords. We rolled out password changes across our network, as well as disabling unused accounts, services, and ports where possible.

Though we improved our first line of defense, many security threats remain. For example, one of the protocols commonly used to communicate with digitizers is inherently insecure. Even if strong passwords are used, the protocol itself is unencrypted and unauthenticated, potentially allowing a hacker to inject harmful commands into a data stream. The best long-term solution is to eliminate all unencrypted traffic across the public Internet by using technology such as IPsec and Virtual Private Networks. If implemented correctly, this will prevent all unauthorized access to equipment, even if the higher-level protocols and passwords are insecure.

Seismological networks are now in hackers’ sights. With the advent of Earthquake Early Warning systems, it is even more critical to protect our networks. In this presentation, we will discuss vulnerabilities and simple common-sense measures that networks can take to protect their infrastructure. We will also discuss long-term security strategies. Cybersecurity needs to be a fundamental part of seismic network design, rather than an afterthought or a reaction to publicized threats. Caltech/USGS intends to keep this discussion at the forefront and continue to be a leader in the field of earthquake monitoring.

Machine Learning and its Application to Earthquake and Explosion Signal Analysis

Poster Session · Wednesday 19 April ·

Supervised Machine Learning on a Network Scale: Application to Seismic Event Classification and Detection

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A new method using a machine learning technique is applied to event classification and detection at seismic networks. This method is applicable to a variety of network sizes and settings. The algorithm makes use of a small catalog of known observations across the entire network. Two attributes, the polarization and frequency content, are used as input to regression. These attributes are extracted at predicted arrival times for P and S waves using only an approximate velocity model, as attributes are calculated over large time spans. This method of waveform characterization is shown to be able to distinguish between blasts and earthquakes with 99% accuracy using a network of 13 stations located in Southern California. The combination of machine learning with generalized waveform features is further applied to event detection in Oklahoma, United States. The event detection algorithm makes use of a pair of unique seismic phases to locate events, with a precision directly related to the sampling rate of the generalized waveform features. Over a week of data from 30 stations in Oklahoma, United States are used to automatically detect 25 times more events than the catalogue of the local geological survey, with a false detection rate of less than 2%. This method provides a highly confident way of detecting and locating events. Furthermore, a large number of seismic events can be automatically detected with low false alarm, allowing for a larger automatic event catalog with a high degree of trust.

Single-Channel Based Earthquake Detection by Matching Spectrogram Images

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Recognition of events of interest using waveforms from seismic stations remains challenging. Currently many approaches to detect seismic events use short-term average to long-term average ratios, and cross-correlation. However, these approaches are not robust enough towards variation in the signals, in particular for low signal-to-noise ratios and novel events. There is a growing interest in investigation of machine learning techniques to address the challenges related to seismic event recognition.

We pose earthquake recognition as a spectrogram image classification problem. We present support vector machine (SVM) based approach for earthquake recognition using waveforms recorded from a single channel. First, the spectrogram image is computed from waveform time series. Second, characterization of the spectrogram image is based on the spatial pyramid matching (SPM) approach. The idea is to capture the distribution of energy in the spectrogram image that corresponds to occurrence of earthquakes. SPM constructs the image representation by iteratively partitioning the image into increasingly fine rectangular sub-blocks and then concatenates histograms of SIFT (scale invariant feature transform) descriptors found inside each sub-block. For a compact image representation, a visual vocabulary is built by clustering SIFT descriptors using the k-means algorithm. Finally, to classify spectrogram images, we use SVM to work with this bag of visual words representation.

For validation, we used labeled single-channel seismic waveforms recorded over a nine-month period. Evaluation was done using 20-fold cross-validation on 2,614 positive (containing the earthquake) and 5,228 negative spectrogram images spread over the nine-month period. The classification approach is characterized by True Positive Rate of 0.99, and False Positive Rate of 0.01. The method can serve as a baseline for further development. The logical extension is to process three-component seismic waveforms.

Evaluation of Adaptive Sensor Tuning for Microseismic Event Detection Across Multiple Arrays and in Varying Noise Conditions at a Carbon Capture, Utilization, and Storage Site, Farnsworth Unit, Ochiltree County, Texas

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We present seismic detections and STA/LTA detection parameters from multiple datasets from Farnsworth Field, an oil field in Northern Texas that hosts an ongoing carbon capture, utilization, and storage project. Datasets include those recorded from a continuous passive vertical downhole seismic array (16 levels of 3-component 15Hz geophones) from January 2014 to present, a VSP survey conducted at the site in January 2015 and recorded on the passive array and a vertical array in a nearby well, and continuous surface broadband seismometers recording since summer 2016. Unfortunately, microseismic events that can provide tremendous insight into the dynamic behavior of the pressurized subsurface are inherently difficult to detect. To improve the performance of event detection, an adaptive sensor tuning (AST) algorithm developed by Sandia National Laboratories is utilized. The key metric that guides the AST algorithm is consistency of each sensor with its nearest neighbors: parameters are automatically adjusted on a per station basis to be more or less sensitive to produce consistent agreement of detections in its neighborhood. Furthermore, we explore the effects that changes in neighborhood configuration have on signal detection, as we have shown that neighborhood based detections significantly reduce the number of both missed and false detections in ground truthed data. Finally, we quantitatively evaluate the algorithm’s performance during a variety of noise conditions. This work was supported by the U.S. Department of Energy’s (DOE) National Energy Technology Laboratory (NETL) through the Southwest Regional Partnership on Carbon Sequestration (SWP) under Award No. DE-FC26-05NT42591, Chaparral Energy, L.L.C., Schlumberger Carbon Services, and the Laboratory Directed Research and Development program at Sandia National Laboratories.

Analysis and Characterization of Hydroacoustic Data Collected by Autonomous MERMAID Floats

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The Mobile Earthquake Recorder in Marine Areas by Independent Divers (MERMAID) project is on a mission to close the seismic data gap in the world's oceans. The platform has matured into a suite of dedicated floating hydrophones that sink to a cruising depth (down to 1750 m), collect hydroacoustic data, and then resurface to transmit data when onboard event detection algorithms determine that a signal suitable for global seismic tomography was received.

More than twenty MERMAIDs have been deployed over the past four years, first into the Mediterranean Sea and later into the Pacific and Indian Oceans. Tens of newer instruments are projected to enter the fleet in the next three years under the umbrella of an international project baptised "EarthScope-Oceans".

Already, deployments have ranged in length from months to years and have returned more than one thousand seismograms of positively identified earthquakes. Many more seismograms have been returned with unique earthquake identifications, unmatched to any earthquake recorded elsewhere. Hence, MERMAID is living up to its potential of recording earthquake data useful for a range of regional and global seismological studies in previously unsampled regions.

Given these data, what can we expect in terms of signal-to-noise ratios for the MERMAID experiments of the future? Can we construct a robust distance-magnitude relationship for positively identified events? How will this inform our analysis of the thousands of unidentified phases in the MERMAID catalog? How coherent is the noise environment sampled by MERMAIDs drifting in the same region? Will network-based methods alter or amplify the utility of these data?

We report on automated wavelet-based statistical analysis methods to answer the questions above and investigate the potential of these and other methods to improve the timing accuracy of automatic picking algorithms.

Observations and Mechanisms of Anthropogenically Induced Seismicity

Poster Session · Wednesday 19 April ·

Tilt Trivia: A Multiplayer App Teaching Induced Seismicity Concepts

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Today's technology is opening up new ways to learn. Here, we introduce TILT TRIVIA, a suite of Jeopardy! quiz-style multiple player games for use on mobile devices and tablets (Android or Apple) to help students learn simple definitions and facts. The game was built using the Unity engine and runs on a server, allowing the multiplayer functionality to run seamlessly, all day, every day. Although the game is configurable to any topic, here we focus on our game that teaches players about induced earthquakes. From a suite of 15-20 questions, 6 questions are chosen at random for gameplay. A single TILT TRIVIA game takes 3-5 minutes to complete and allows up to 5 players to play simultaneously in the same gamespace. To begin, each player selects a zany avatar to represent them in the game. While in the competitive playing field, players are presented with a question and then they simply "tilt" their tablets until their avatar rests on the correct answer marker (*i.e.*, true or false). Because the playing field is constantly tilting, keeping your avatar on the correct answer requires a continual counter-tilting motion of the tablet to maintain your position within the game. A countdown timer is incorporated, requiring players to answer the questions as quickly as possible. At the end of a game a leaderboard displays the players' scores and rankings, a metric that motivates repeat play. Players have the option of jostling other players off of the correct answer in the hopes to net the highest score. Join us and play today (http://siogames.ucsd.edu/TiltTrivia/index.html)!

Identifying New Earthquake Templates Adds Valuable Information to Induced Seismicity Sequences

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By reprocessing seismic data from sedimentary basins in the Central United States during the occupation of EarthScope's Transportable Array we added a significant number of new sources to existing earthquake catalogs. Subsequently, using subspace detection to increase the resolution of time-histories for sources near active injection wells revealed prolific seismic sequences in areas where other catalogs show no seismicity, such as sections of the the Denver Basin. In other cases, under the same scrutiny, seismic gaps persisted despite decades of injection (*e.g.*, Williston Basin, North Dakota). In areas where robust levels of seismicity are well documented in existing catalogs, new events either echo event families from relatively stable and consistent sources (*e.g.* Dagger Draw Field, New Mexico) or greatly diversify known families (*e.g.* more than double in Cogdell, Permian Basin). For both cases, catalog enhancement through subspace detection alters event time-histories when new templates contain non-redundant information. We observed that cataloged events are not necessarily the largest events in a sequence based on waveform amplitude and duration. We further observed that the character and complexity in a sequences is not necessarily tracked through the largest magnitude events. The implication of these observations is that additional templates can significantly change interpretations based on correlations between event locations or time-histories and pumping records or fluid migration models.

Persistent Multiplets in EGS Reservoir: The Case Study of Soultz-sous-Forêts, France

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Abundant seismicity is generally observed during the exploitation of geothermal reservoirs, especially during phases of hydraulic stimulations. At the Enhanced Geothermal System of Soultz-Sous-Forêts in France, the induced seismicity has been thoroughly studied over the years of exploitation and the mechanism at its origin has been related to both fluid pressure increase during stimulation and aseismic creeping movements. The fluid-induced seismic events often exhibit a high degree of similarity and the mechanism at the origin of these repeated events is thought to be associated with slow slip process where asperities on the rupture zone act several times.

In order to improve our knowledge on the mechanisms associated with such events and on the damaged zones involved during the hydraulic stimulations, we investigate the behavior of the multiplets and their persistent nature, if it prevails, over several water injection intervals.

For this purpose, we analyzed large datasets recorded from a downhole seismic network for several water injection periods (1993, 2000, ...). For each stimulation interval, thousands of events are recorded at depth. We detected the events using the continuous kurtosis-based migration method and classified them into families of comparable waveforms using an approach based on cross-correlation analysis. We obtain precise relative locations of the multiplets using differential arrival times obtained through cross-correlation of similar waveforms. Finally, the properties of the similar fluid-induced seismic events are derived (magnitude, spectral content) and examined over the several hydraulic tests.

Hopefully these steps will lead to a better understanding of the repetitive nature of these events and the investigation of their persistence will outline the heterogeneities of the structures (temperatures anomalies, regional stress perturbations, fluid flow channeling) regularly involved during the different stimulations.

Spectrogram-Based Detection of Small Earthquakes in Continuous Waveform Data

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Earthquake detection is a fundamental operation in observational seismology, but discriminating small earthquake signals from other sources of radiation remains highly challenging. To better understand earthquake features and detect events robustly, we describe a method based on spectrograms (representation of the spectrum variation with time). The method is illustrated with data recorded in Julian day 146, 2014, by borehole station B946 in the San Jacinto Fault zone. We first transform continuous waveform into spectrogram using Fourier transform with 1.28s short time window and 80% overlap. This transforms the problem from detecting events in a 1D signal to detecting objects in a 2D image. In a pre-detection step, we improve the images by subtracting the background spectrogram from the original one. Based on improved spectrograms of known earthquakes, we find that events with similar travel time have some common features in frequency range, time duration and amplitude decay rate. We separate known event spectrograms into 5 group based on P wave travel time (2.2-2.8s, 2.8-3.4s, 3.4-4.0s, 4.0s-4.6s, 4.6s-5.2s) and get stacked spectrogram of each group. Using the stacked spectrograms we perform 2D template matching method to detect additional events in continuous data. Initial analysis indicates potential for detecting ~3 times more events than exist in the standard catalog from station B946. One important advantage of this method is that spectrogram-based templates generated by data of one station can be used with comparable efficiency at other stations. Updated results will be presented in the meeting.

Reservoir Delineation from Microseismic Events at the Blue Mountain Geothermal Site

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Most commonly used earthquake detection and location algorithms (*e.g.*, STA/LTA algorithms) may miss events if the seismic signal of an earthquake is small relative to the background noise level or if a microearthquake occurs within the coda of a larger event. Advanced correlation-type earthquake detection techniques can be applied in these regions to identify these missed events. For this application, known larger events are used as templates to identify nearby smaller events.

We investigate one year of seismic activity within the Blue Mountain Geothermal Power Plant located in Humboldt County, Nevada between December 2015 to December 2016. We compare the effectiveness of direct spatial-temporal cross-correlation templates with Matched Field Processing (MFP) derived templates and compare these results with earthquake detection results from a traditional STA/LTA algorithm. Preliminary results show significant clustering of microearthquakes, most probably influenced by plant operations. For the events with the highest signal-to-noise ratio, we apply a local Bayesian multiple-event seismic location algorithm that estimated the 95% ellipsoids of the posterior mean locations.

The significant increase in data availability that advanced earthquake detection methods can provide improves the statistical analyses of induced seismicity sequences, reveal critical information about the ongoing evolution of the subsurface reservoir, and better informs the construction of models for hazard assessments.

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2016 Observations and Mitigation Strategies for Hydraulic Fracture Induced Seismicity in Ohio

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Hydraulic Fracture (HF) induced seismicity is now a widely recognized phenomena in many locations around the world. As a result, regulatory authorities in the USA (in particular, in Oklahoma and Ohio) are starting to mandate HF monitoring for traffic light systems in areas of concern. In the state of Ohio over 10 sequences of HF induced seismicity have been observed and documented and in each case a previously unknown basement fault was implicated in the seismicity. In each sequence there was a ramp up in the number and size of earthquakes as the hydraulic fracture completions progressed. There were also significant differences in the fault activation in each case and in some instances mitigation strategies such as halting of zipper fracking, lowering stage volumes, and skipping stages were performed. For some of the sequences well operators deployed seismic stations in addition to the local NSF CEUS network and OhioNet stations, which provided them with more rapid information about earthquakes so that mitigation strategies could be employed. In our presentation we focus on the details of a specific case where mitigation strategies may have been effective in limiting potentially larger earthquakes.

Microseismicity Recorded in the Geothermal Areas of the Central Apennines (Italy)

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Apart from Iceland, the main high-temperature geothermal areas of Europe are all situated in Italy. Located westwards of the high-angle normal faults of the central Apennines—site of the recent seismic sequence with maximum magnitude of M_w6.5—the geothermal areas of Larderello, Mt. Amiata, Latera, Torre Alfina and Cesano are characterized by almost moderate seismicity. However, damaging earthquakes struck those areas already long before starting geothermal exploitation in the 1950's. For the last century, the Parametric Catalog of Italian Earthquakes reports as strongest earthquakes a M_e5.32 (1919) near Mt. Amiata and M_e4.93 (1957) for Castel Giorgio. Recently observed seismic events, as the M_w4.1 seismic event of May 2016—occurring near the actually dismissed geothermal production field of Torre Alfina/Castel Giorgio—give testimony of continuous natural stress relaxation by earthquakes.

After the recent decision by a multinational energy provider for an upcoming reopening of the geothermal production, INGV was commissioned to realize a multi-parametric monitoring system including the observation of gas emissions, microseismicity and ground deformation. Since 2014, we installed a short-period seismic network near the future geothermal production site of Torre Alfina. The observed microseismicity is unexpectedly high (nearly 300 events in 18 months), with hypocenters concentrated between 4-8 km. Already the M_w4.1 earthquake of May 30, 2016 was followed by almost 1,700 aftershocks. The spatial distribution of the hypocenters shows the reactivation of already known synthetic and antithetic structure of predominantly normal fault character within splitting distance to the future geothermal production site. Considering that the future production level will reach a depth of 2,300 m, the discrimination between natural earthquakes and seismicity triggered by anthropic activity will be an important challenge.

Evaluating the Efficacy of Oklahoma Corporation Commission Wastewater Disposal Reductions in Oklahoma

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In response to an unprecedented increase in seismicity throughout north-central Oklahoma, the Oklahoma Corporation Commission (OCC) has instituted voluntary reductions in saltwater disposal (SWD) volumes around north-central Oklahoma. After the September 2016 M_w 5.8 Pawnee and November 2016 M_w 5.0 Cushing earthquakes, the OCC announced their intention for broader mitigation throughout north-central Oklahoma, with specifics to be released in early 2017. The Oklahoma Geological Survey (OGS) monitors seismicity throughout the state utilizing permanent and temporary seismometers installed by OGS and other agencies, while maintaining an earthquake catalog. The catalog is complete down to M2.4 since mid-2014, despite the significant workload for a solely state-funded regional network; for example, there were 3,309 events with M2.5 or greater in 2015. We test what effects these reductions have had on mitigating seismicity. We will present a detailed spatio-temporal analysis of seismicity and SWD over the last few years and evaluate the effects regulatory actions have had on seismicity. We will analyze the earthquake catalogs for any rate changes associated with the past targeted SWD reductions and report on progress towards understanding the effect of the early 2017 reductions. The results of this study highlight the continued need for expansion and densification of seismic monitoring throughout Oklahoma.

Performance of the Colombian Regional Seismic Network and of a Sparse Local Network for Detection and Characterization of the Seismic Activity in the Oil Zone of Puerto Gaitán, Llanos Orientales Basin (Colombia)

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The Colombian National Seismic Network (RSNC) noticed a sudden appearance of high seismic activity in the oil production zone of Puerto Gaitán (midcontinental Colombian Llanos Basin) in April 2013. This zone was known as almost aseismic (0.25 events/yr between 1996 and 2012) and it changed to an active zone with near 900 events with $M_L \geq 2.0$ since 2013, including 41 events with $M_L \geq 3.5$ and three with M_W 4.7. With the main goal of evaluating the RSNC detection and characterization capabilities for the seismic activity in a region about 200 km away from most of the stations, we compare the location, magnitude and event distribution of the sequence recorded by the RSNC (regional network) with those of a two months sequence (April-June 2014) recorded by a small sparse local network installed in the epicentral region. To locate the events in the regional network sequence we calculated preliminary locations using a simple two layers velocity model and then we refined them using HYPODD method. To estimate M_W we first calculated the S-wave spectra of far field records of the RSNC and then inverted the low frequency range of the spectra with a linear regression to recover an average geometric attenuation parameter and the seismic moment. Our calculated M_W magnitudes range was between 3.0 and 4.5; this is comparable to that estimated by the RSNC and higher by 0.1 on average.

The regional network sequence shows two cluster epicentral distribution roughly coincident with the location of some injection facilities at the oil field. Similar distribution but better resolved is shown by events recorded by the local network. Our results suggest that for preliminary observation stages detailed analysis of seismicity recorded by the regional network is a reliable source of information for possible induced activity.

The Milan Kansas Earthquake Fault: Narrow, Hydraulically Conductive and Critically-Stressed

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We have developed a suite of MODFLOW groundwater flow models to explore hydrogeological conditions consistent with triggering the 2012 Milan, Kansas earthquake given injection schedules at nearby saltwater disposal wells. Hydraulic properties of the lower, middle and upper Arbuckle Formation and the fault damage zone were systematically varied, as well as the depth to the hypocenter, dip of the Milan earthquake fault and whether it cuts the Arbuckle formation. Hydraulic properties we infer for the lower Arbuckle and the fault damage zone are consistent with the range of hydraulic diffusivities inferred by Choy *et al.* (2016) from seismicity migration rates (0.3 to 2 m/d).

A minimum Coulomb stress triggering threshold of 0.01 MPa (Stein, 1999) is exceeded at the time of the Milan earthquake for several models. An increase of 0.07 to 0.1 MPa, which is characteristic of other induced seismicity studies (Yeck *et al.*, 2016; Keranen *et al.*, 2014) requires a fault damage zone with a low transmissivity. This could arise from a narrow damage zone (tens of m wide), or from very low hydraulic conductivity (k) and specific storage (Ss) values (preserving the hydraulic diffusivity c = k/Ss). The former hypothesis is more likely, given that damage zones hundreds of meters wide are not likely around low slip-rate faults, and that the second hypothesis requires unrealistically low k and Ss values.

The moderate pore pressure perturbations suggest that the Milan fault patch was critically stressed prior to the earthquake, consistent with orientation of the fault in the local stress field (Alt and Zoback, 2016) and the increased hydraulic conductivity of critically-stressed faults (Barton *et al.*, 1995). Like others before, we conclude that low-slip rate faults in crystalline basement rocks strongly influence pore pressure evolution at seismogenic depths. Hydrogeologic characterization of such features is important for improving models of of injection-induced seismicity.

Interpretation of Microseismicity Observed from Surface and Borehole Seismic Arrays During Hydraulic Fracturing in Shale-Bedding Plane Slip

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We present a geomechanical model explaining seismicity induced by hydraulic fracturing in shales developed from many datasets acquired with two most common types of seismic monitoring arrays, surface and borehole arrays. The new geomechanical model explains the observed source mechanisms and locations of induced events from two stimulated shale reservoirs. We observe shear dip-slip source mechanisms with nodal planes aligned with location trends. We show that such seismicity can be explained as a shearing along bedding planes caused by an aseismic opening of vertical hydraulic fractures.

The source mechanism inversion was applied only to high-quality events with sufficient signal-to-noise ratio. We inverted amplitudes to full-moment tensor and decomposed it to shear, volumetric and compensated linear vector dipole components. We also tested an effect of noise presented in the data to evaluate a reliability of non-shear components.

Observed seismicity from both surface and downhole monitoring of shale stimulations is very similar. Locations of induced microseismic events are limited to narrow depth intervals and propagate along distinct trend(s) showing fracture propagation in direction of maximum horizontal stress from the injection well(s). The source mechanisms have only a small non-shear component which can be explained as an effect of noise in the data, *i.e.* events represent shearing on faults.

We observe predominantly dip-slip events with strike of steeper (almost vertical) nodal plane parallel to fracture propagation. The other possible nodal plane is horizontal. Rakes of the observed mechanisms divide these dip-slips into two groups with opposite polarity. That means we observe opposite movements on the nearly identical fault.

Realizing a typical structural weakness of shale in horizontal planes, we interpret observed microseismicity as a result of shearing along bedding planes caused by seismically silent vertical fracture opening.

The Dallas-Fort Worth Airport Earthquake Sequence: Seismicity Beyond Injection Period

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The Dallas-Fort Worth (DFW) airport experienced the first recorded earthquake sequence on 31 October 2008. The earthquakes were considered triggered based their close proximity and timing to a waste-fluid injection well leading to the well's shut-in. Since the initial studies, several additional earthquakes have been reported within 8km radius of the first earthquake swarm location. We develop a more complete catalog by using located DFW earthquakes as detection templates for cross-correlation with continuous waveform from regional stations that record the sequence for the full period of analysis. We consider the time period from January 2008 to June 2016 in order to document the full spatiotemporal evolution of the earthquake sequence and understand the probable driving force behind the continued seismicity. Using differential travel-time and hierarchical clustering, we locate at least 473 earthquakes that generally migrate from SW to NE over time covering 80% of a 6km long active fault. Seismicity rate peaks at the beginning of the sequence and decays over time with earthquakes occurring in discrete time and space clusters rather than continuously. Using MODFLOW, we model pore-pressure diffusion due to the injection activity around the earthquakes for the period of analysis; wells are located 1km and 10km from the initial 2008 earthquakes. Results indicate that the nearest injection well, though injecting for only 12 months at high volume but close to the mapped fault, contributes most to pressure diffusion into the crystalline basement. In the basement, pressure change around the well peaks during the injection period while 5km from the injection well pressure buildup lags the injection and thereby peaking past the injection period. High injection rate over short duration near a critically stress fault leads to earthquakes over nearly ten years while the low to moderate rate injector has less effect on basement pressures and no spatially associated earthquakes.

A Half-Century of Induced Earthquakes in the Los Angeles Basin?

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A detailed reconsideration of macroseismic and instrumental earthquake data and oil industry records reveals evidence for a possible association between many of the damaging earthquakes in the Los Angeles (LA) Basin between 1900 and 1950 and oil and/or gas production. Potentially induced events include the 1920 Inglewood ($ML \approx 5$), 1929 Whittier ($ML \approx 5$), 1930 Santa Monica ($ML \approx 5.1$), 1933 Long Beach (M_w6.4), 1941 Dominguez Hills (ML4.7), and 1941 Torrance (ML5.1) earthquakes. Notable industry activities in nearby oil fields, (*e.g.*, deepening of wells, expansions of existing fields, increases in production, surface subsidence) at distances of no more than a few km, preceded each of these earthquakes by 6-12 months. We present results from Hough and Page (2016), who considered earthquakes between 1900–1933, as well as new analysis of the 4 $ML \geq 4.5$ events in the LA Basin between 1933-1950 including two earthquakes in 1941 that caused damage to nearby communities: a ML4.7 event on 22 Oct. and an ML5.1 event on 14 Nov.. Macroseismic and instrumental data support the modern catalog magnitudes for both events, and can be used to revisit epicentral

locations. The location of the 14 Nov. earthquake cannot be constrained to better than a few km. The dimensions of a documented zone of damage to oil wells in the Dominguez Hills field caused by the 22 Oct. earthquake are, however, commensurate with the instrumentally constrained magnitude. We conclude that this zone constrains the location and extent of mainshock rupture, with a shallow focal depth, a rupture area of approximately 1-2 sq km, and total slip of ≈0.4 m on two south-dipping reverse faults striking nearly parallel to the axial trend of an anticlinal fold along the Newport-Inglewood fault zone. The isostatic adjustment mechanism proposed by McGarr (1991) can plausibly account for the magnitude, mechanism, and location of the 22 Oct. earthquake.

Comparison of Elastic Wavefield Simulations, Ray Tracing and Surface Array Data at the Groningen Gas Field: Implications for Induced Seismic Event Location and Characterization

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Seismic energy produced by induced seismic events from gas production at Groningen gas field in the Netherlands propagates to the surface through a complex vertical and lateral velocity structure due to anhydrites, salt, chalk and siliciclastics. The combination of a dense surface seismic monitoring array and detailed 3D velocity model from well control and 3D seismic data provides a rich dataset for location and characterization of induced seismicity associated with depletion of the field. However, comparisons of ray-trace modeling to elastic wave-field simulations demonstrate ray theory limitations and the need to understand the impact of uncertainties from both the data and the algorithms used for analysis.

We will present the results of 3D elastic wavefield modeling and compare to ray tracing predictions and observed Groningen seismic event data. These comparisons have helped us to mitigate ray tracing biases that can result in significant event depth error and misleading measures of location uncertainty. We will show conditions under which the source of first seismic arrivals will switch from the upper hemisphere (direct arrival) to the lower hemisphere (turning ray) within the offset range of the dense surface array. Valid focal mechanisms will only be obtained if the abrupt change in take-off angle is identified and accounted for.

Experience with local seismicity monitoring in other locations suggests that the sensitivities observed at Groningen may be commonplace. Hence, when investigating induced seismicity, the introduction of detailed local velocity models and increasingly dense monitoring arrays will require careful application of ray based methods for seismic event location and characterization. More advanced methods are likely needed to utilize the increased information. Expectations should be framed in the context of irreducible uncertainties as well as the sampling of the total wavefield that can be captured and identified in a monitoring array.

Overcoming Challenges in Seismic Risk Communication

Poster Session · Wednesday 19 April ·

SAFRR Tsunami Scenarios and the Importance of Choosing the Right Source

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Hazard scenarios provide emergency managers and others with information to help them prepare for future disasters. One complicated and important aspect of any hazard scenario is defining the source event. Different uses can benefit from different source events, and user involvement in defining the source events increases the utility of the results.

The SAFRR Tsunami Scenario modeled a hypothetical but plausible tsunami, created by an M_w9.1 earthquake occurring offshore from the Alaskan peninsula, and its impacts on the California coast. We presented a comprehensive view of the impact of this one source including the modeled inundation areas, current velocities in key ports and harbors, physical damage and repair costs, economic consequences, environmental impacts, social vulnerability, emergency management, and policy implications for California associated with the scenario tsunami. It provided the basis for many exercises involving, among others, NOAA, the National Institutes of Health, several counties in California, and the State of Washington (where we modeled wave heights but not other impacts).

Building on the lessons learned in the SAFRR Tsunami Scenario, we are now investigating tsunami impacts to Hawaii and to the source region in Alaska, focusing on the evacuation issues of remote communities with primarily shore parallel roads, and also on the effects of port closures. We began with pedestrian evacuation modeling for Oahu and tsunami current modeling in three Alaskan ports based on M_w9.3 and M_w9.6 earthquakes in Alaska, sources the State of Hawaii had chosen for their tsunami evacuation maps. The Port of Honolulu was interested in investigating more frequent events, so smaller source events (an M_w9.1 Aleutian earthquake and an M_w9.3 Kamchatka earthquake) were used to model currents there. The modeled currents from the M_w9.1 Aleutian earthquake exceed 16 knots in the Port of Honolulu, where a damage assessment is underway.

565 Earthquake Hazards Questions

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Email inquiries to the USGS Earthquake Hazards Program (via the website) contain a wealth of information about what the inquirer is looking for regarding earthquakes and the hazards they pose. With that in mind, I reviewed all the emails during the most recent three years (2014-2016), focusing on the hazard/risk-related questions (565 of them) to determine what website visitors were asking and how they were asking it. The content tells me what people do not understand or what information they cannot find. The terminology used in the questions informs me about their thought process. The emails are mainly from the general public but also from educators, students, scientists, media, first responders, engineers, and others. The review of hazard/risk-related emails revealed different types of questions that I separated into 13 categories based on key words and phrases: aftershocks/foreshocks, building/structural safety, faults, hazard maps, increasing seismic activity, induced earthquakes, insurance, prediction, preparedness, probabilities, scenarios, seismic zones, and traveling/moving to place X. Some of the typical words or phrases used are: predict, chances of, possible, normal, can it?, will it?, seismicity increasing? Almost no one used the word "risk", and only a few people asked about preparedness, response, or safety of structures. Most questions fit one of these three scenarios: 1) They are confused when an earthquake occurs where there are "no faults"; 2) They want to know if what happened or is happening is "normal" or not; and 3) They want to know what is going to happen in the future and how it will affect them or their family or friends. Some people still think scientists can predict earthquakes, but many people question the veracity of predictions they hear through social media. Science communicators can use the information gleaned from these emails to craft messages that will improve the public's understanding of the science of earthquakes.

Recent Advances in Earthquake Triggering and Aftershock Forecasting

Poster Session · Wednesday 19 April ·

Improving Iquique: How Detection Techniques Can be Used to Enhance Our Understanding of the 2014 Sequence

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On April 1, 2014, a M8.2 earthquake ruptured a subduction zone in northern Chile that had not been active since a M8.8 event in 1877. Since its occurrence, the 2014 Iquique sequence has been the subject of numerous studies with the goal of better understanding both the progression of the sequence and the effect of this sequence on the seismic gap in which it occurred. In this study, we apply an iterative kurtosis detector on seismic data between March 1, 2014 to May 31, 2014 in order to construct an improved earthquake catalog of the foreshock and aftershock sequences. We first use kurtosis detection to obtain thousands of P-picks. We then associate the P-picks and perform a second kurtosis run tuned to select S-picks. This iterative picking process results in thousands of new events that were not previously documented in the U.S. Geological Survey's Preliminary Determination of Epicenters (PDE) catalog. We apply Bayesian multiple event relocation to the new events and obtain precise locations (to within ~2km) for over 5,000 events. The thousands of additional events detected provide us with the opportunity to conduct a more thorough analysis of repeating earthquakes throughout the progression of the sequence. The relocated catalog along with the analysis of repeating events heightens our understanding of the spatiotemporal evolution of the sequence, and allows us to better analyze the relationship between the initial foreshocks and the mainshock-aftershock sequence.

Visibility Graph Analysis of Southern California

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The large amount of available data from seismic catalogues, which continue to grow with time, is becoming a valuable source for investigating possible patterns useful in earthquake prediction through statistical techniques. One of these techniques, which recently found its way from other areas into seismic studies, is visibility graph analysis. It is basically a mathematical method to convert a time series into a graph keeping its properties, which makes it possible to use network theory for characterizing the original data. In this study, we are going to investigate by means of visibility graph method the seismicity of southern California region using the Southern California Earthquake Center (SCEC) catalogue from 1981 to 2016. There is a connectivity degree (K) defined in the method, which has a correlation with earthquake magnitude. Past studies have suggested the presence of a universal relationship between K-M slope and b-value of a Gutenberg Richter law. We are going to study visibility graph properties of the study area like K-M slope and add it to the data from previous worldwide studies to verify and improve this relationship. We will also try to distinguish noticeable earthquakes of the catalogue by means of K-M slope graphs. Being able to do that might be helpful to further earthquake prediction studies.

Seismic Activity Analysis of Recent 15 Years Nearby Puerto Rico and Caribbean Region

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An earthquake catalog of the earthquakes activity occurred during the last 15 years in the Caribbean region, nearby of Puerto Rico Island (PRI), was compiled in order to capture the big picture of the regional seismicity ratio. In particular, at epicentral regions of several historical and instrumentally recorded (during 2008-20015) large to moderate magnitude earthquakes occurred nearby PRI in onshore and offshore, which include the M6.4 earthquake of 01/13/2014, the largest earthquake recorded instrumentally nearby PRI. From the point of view of joint temporal-spatial distribution of epicenters, episodic temporal-spatial seismic activity is clearly seen as temporal-spatial concentrations during certain time intervals in different regions.

These localized concentrations of epicenters that occur during time intervals in well localized/concentrated regions, may suggest "seismic gaps" that shows no regular time interval, neither spatial pattern. In the epicentral region of the M6.4 01/13/2014 earthquake and the historical Mona Passage M7.5 earthquake of 10/11/1918, episodic concentrations in time and space of small magnitude earthquakes epicenters is evident, however do not show temporal pattern. Preliminary results of statistical analysis of an ongoing research in terms of the parameter b (Gutenberg-Richter relationship), and the Omori's law with the aim to relate the tectonic framework of the region (or sub-regions) such as structural heterogeneity stress are here presented/discussed.

Recent Innovations in Geophone Array Seismology

Poster Session · Wednesday 19 April ·

IRIS Wavefields Community Experiment Using Nodal Arrays

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In June 2016, a field crew of 50 students, faculty, industry personnel, and IRIS staff deployed a total of 390 stations as part of a community seismic experiment above an active seismic lineament in north-central Oklahoma. The goals of the experiment were to test new instrumentation and deployment strategies that record the full seismic wavefield, and to advance understanding of earthquake source processes and regional lithospheric structure.

The crew deployed 363 3-component, 5Hz Generation 2 Fairfield Z-Land nodes along three seismic lines and in a seven-layer nested gradiometer array. The seismic lines spanned a region ~13 km long by ~5 km wide. A broadband, 18 station "Golay 3x6" array was deployed around the gradiometer and seismic lines with an aperture of approximately 5 km to collect waveform data from local and regional events. In addition, 9 infrasound stations were deployed in order to capture and identify acoustic events that might be recorded by the seismic array, and to quantify the wind acoustic noise effect on co-located broadband stations. The variety of instrumentation used in this deployment was chosen to capture the full seismic wavefield generated by the local and regional seismicity beneath the array and the surrounding region.

We present our quality analyses of this open community dataset—including data completeness and noise levels—for the various types of instrumentation. We also examine the performance of co-located surface and buried nodes to determine the benefits of each installation type. In addition, we present performance comparisons between co-located nodes and broadband stations and compare these results to prior wavefields/large-N deployments in Long Beach, CA and Sweetwater, TX. Lastly, we hope to share a few wavefield animations from local events recorded by our nodal and broadband arrays.

PH5 for Archiving and Translating Node and Other Geophysical Data: Examples from the IRIS Community Wavefield Demonstration Experiment

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PH5 is IRIS PASSCAL's file organization of HDF5 used for seismic data. The extensibility and portability of HDF5 allows the PH5 format to evolve and operate on a variety of platforms and interfaces. To make PH5 even more efficient, the seismic metadata is separated from the time series data in order to achieve gains in performance, ease of use, streamline meta-data updates, and simplify user interaction. The flexibility of HDF5 enabled us to extend PH5 to integrate data from the various types of geophysical data (seismic and infrasound) recorded during the IRIS Wavefield Community Demonstration Experiment.

Prior to the Wavefield Experiment, PH5 was used for integrating and archiving active source, passive source, and onshore-offshore seismic data sets with the IRIS Data Management Center (DMC). The Wavefield Experiment provided impetus to extend PH5 by adding mseed, StationXML and FDSN webservices compatibility. With these recent additions, PH5 can now import various data formats (RefTek format, SEG-Y, SEG-D) and export SEG-Y, SAC, mseed, QuakeML and StationXML. With the implementation of FDSN webservices, these PH5 data volumes are poised to be fully integrated with existing DMC tools for data discovery and requests.

The Wavefield Experiment stations consisted of Fairfield Zland Nodes, RefTek RT130 data loggers with Guralp 3T broadband sensors, and RefTek RT130 data loggers with Hyperion microbarometers. With the aforementioned changes to PH5, we are able to store the differing Wavefield stations into a single PH5 data volume affording researchers access to all of the geophysical data recorded by the Wavefield Experiment in a variety of output formats.

Huddle Tests of Fairfield Nodes and Texans on a UTEP Seismic Pier

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Because of their large memories and month-long battery life, the 3-C Fairfield node recorders are becoming one of the more popular instruments for not only active source recording, but also for short-term earthquake recording. Yet little is known about their low frequency response and sensitivity compared to broadband instruments typically used for earthquake recording. We have installed five Fairfield nodes and five Texans on one of the UTEP seismic piers and are recording continuous records. Also, on this pier is a CMG-3T, which will be used for comparison.

We analyze the data collected and calculate self-noise spectra using the methods outlined by Evans *et al.* (2010). In industry type instruments, a 250 sps rate is more common than a 200 sps rate, therefore longest non-zero period in the power density spectra is 131s for a 32,768 samples event length. We use the three-sensor method of Sleeman *et al.* (2006) because it gives better results at higher frequencies, but we calculate every unique three-sensor permutation (a total of 10 each) for the five nodes and five Texans on the pier. This yields insight into differences between mass produced instruments, which we assume to be identical.

The Source Physics Experiment Large N Array

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The Source Physics Experiment (SPE) is a series of instrumented chemical explosions at the Nevada National Security Site (NNSS) designed to improve understanding of seismic wave generation and propagation from explosions. A temporary deployment of 1000 geophones was installed from April 18 to May 23, 2016 at the NNSS. Array node spacing varied from 25 to 100 m and consisted of 500 Z and 500 3C 5 Hz geophones. Data was recorded continuously during the deployment at low-gain from April 18 to April 28 and high-gain (36 db) from April 29 to May 23. A buried (76.5 m) 5000 kg TNT equivalent chemical explosion (SPE5) was recorded on April 26. The array was at a distance of 400 to 3000 m from the shot, which was situated in a weathered granite body surrounded by volcanic tuffs, Paleozoic carbonates, and alluvium. A set of large weight-drops at 53 locations both inside and outside the geophone array were also recorded, as were local, regional, and teleseismic earthquakes. Data recovery was good, with 95% of data recovered from the shot and up to 99% in the following weeks. The dataset will be openly available (via IRIS DMC) in the future.

Results show substantial differences in waveforms and associated particle motions over small spatial distances with considerable coda consisting of apparent basin reverberation. Waveforms generated by the weight drop also displayed considerable variation over short distances and azimuths. Teleseismic P waveforms appear relatively simple on stations located in the granite but show more complexity in the alluvium. Primary focus is on regions with transitional geology (granite to alluvium) and topographic variations as imaged by both active, passive, and receiver functions and by comparison with 3D finite difference synthetics. The overall goal is to understand and model the role of subsurface heterogeneities with respect to other mechanisms such as topography and near-source effects in generating the observed S wave and surface wave energy.

Geophysical Structure at the SPE Site Using Surface Waves Recorded by the Large-N Seismic Array

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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. A Large-N seismic array was deployed at the SPE site to image the full 3D wavefield from the most recent SPE-5 explosion on April 26, 2016. The Large-N seismic array consists of 996 geophones (half three-component and half vertical-component sensors), and operated for one month, recording the SPE-5 shot, ambient noise, and additional controlled-sources (a large hammer). This study uses Large-N array recordings to develop local geophysical models based on surface wave analysis. The results of this study will be incorporated into the large modeling and simulation efforts as ground-truth further validating the models.

Internal Structure of the San Jacinto Fault Zone at Blackburn Saddle from a Dense Linear Deployment across the Fault

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We image the internal structure of the Clark section of the San Jacinto fault zone (SJFZ) at Blackburn Saddle using teleseismic and local earthquake waveforms recorded during a 34-day deployment of a linear array consisting of 134 three-component 5 Hz geophones with an aperture of ~2 km. Geophones are spaced 10 m in a zone 400 m wide centered on the Clark fault surface trace, and spaced ~30 m to the NE and SW of that zone. Analysis of data generated by 3 teleseismic events indicates an abrupt change in early P waveform polarization and amplitude around the central station BS55. In addition, variations in P arrival times suggest slowest structure exists beneath station BS43 (~130 m NE of BS55) and fastest structure at the NE end of the array. Visual inspection of local events located within 10 km of the SJFZ leads to detection of candidate fault zone head waves (FZHW) at most stations SW of BS30 for 16 M>1 events near the Clark fault SE of the array. Similar phases are not observed for events NW of the array. Fault zone trapped waves (FZTW) following S arrivals are detected for 36 M>1 events located in a broader region that includes the San Andreas and Elsinore faults using an automatic algorithm. When considering only stations in the central 400 m zone, 76% of the FZTW detections are for stations NE of BS55 (BS35-BS54). Of these stations, B40 to B50 have the largest amplitude and lowest frequency for waveforms with FZTW, and most likely overlie the core fault damage zone. Based on these findings and geological constraints, the main Clark fault is proposed to be closest to station BS55, rock damage is asymmetric to the NE, with most damage confined to a ~100 m zone bounded by a bimaterial interface close to BS30.

Detection of Small Earthquakes with Dense Array Data on the San Jacinto Fault Zone

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We present a technique to detect small earthquakes not included in standard catalogs using data of dense seismic arrays. The technique is illustrated with data recorded in Julian day 146, 2014, by 1108 vertical geophones in a 600 m x 600 m configuration on the San Jacinto fault zone. We first divide the 1108 array into 9 non-overlapping (200 m x 200 m) blocks. Waveforms are stacked within each block without time-shift to increase the signal to noise ratio. We then calculate the product of the 9 envelope functions of the stacked waveforms to reduce the amplitudes of surface and other sources not coherent across the entire array. About 900 STA/LTA triggers of the product are detected in the test day. Using a local velocity model for the shallow crust layer, and assuming a plane P wavefront incident at the bottom of the layer, we perform beam-forming for each STA/LTA trigger with a 5-second time window. This is used to align, stack and time-integrate the waveforms to calculate the power for all directions of a half-space below the surface layer. Of the ~900 detections, 262 are found to have highly concentrated power distribution, and 124 are confirmed as seismic events by verifying that they are observed in data of 5 or more nearby seismic stations. This provides validation for the events and allows to locate them and calculate magnitudes with standard techniques. The technique allows detection of > 4 times as many events detected with standard techniques and seismic data. Using these events as new earthquake templates can lead to additional detections of many more events.

Signal and Noise Coherence Lengths from 1Hz to 100Hz Using Large-N Deployments in

Nevada and Oklahoma

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Large arrays of sensors deployed over a small area are effective at exploiting signal coherency to provide improved signal fidelity and additional signal propagation information such as signal speed and backazimuth that can be used in seismic monitoring. Currently the seismic signal and noise coherency lengths at the frequencies applicable to monitoring of seismic events at local distances are poorly known and developing this knowledge is the focus of this study. Large-N deployments in particular provide a unique and detailed dataset for exploring the coherency length scales of seismic waves. We examine existing data from the Large-N deployment of the Source Physics Experiment (SPE) in Nevada and the IRIS Community Wavefield Experiment in Oklahoma to guide array design for seismic monitoring at local distances. The Large-N style array of SPE consisted of 1000 geophones (500 vertical and 500 three-component) with spacing from 25-100m was deployed at the Nevada National Security Site (NNSS) in April 2016 for 30 days surrounding the detonation of the SPE-5 chemical explosion. For the IRIS Community Wavefield Experiment in Oklahoma, we focus on the square array consisting of 7 concentric square rings of 16 three-component geophones with spacings from 3-200m deployed in June and July 2016. This research provides an empirical foundation to assess the advantage of a multi-ringed spiral array design over individual sensors and other array designs for seismic signals between 1-100Hz.

Detecting Seismicity in a Prospective Geothermal Play, Using a 48 Geophone Array

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In the summer of 2016 a dense array of 48 geophones was deployed near Milford, Utah on the eastern flank of the Mineral Mountains. The array aperture was approximately 20 kilometers and recorded continuous seismic data for 30 days. Geophones were centered on a previously known shallow (5km depth) MT low-resistivity body. This region of low resistivity was interpreted to possibly contain hydrothermal/geothermal fluids and was targeted for further seismic investigation. Micro-seismicity can be linked to small-scale deformation caused by fluid migration and upwelling in the shallow subsurface. If small earthquake swarms are present, this is further evidence of a hydrothermal/geothermal system. The purpose of this experiment is to identify previously undetected seismic events and categorize them into swarm and non-swarm clusters that will provide insight about fluid migration in the shallow subsurface. A frequency domain detector was applied to these data to detect and locate earthquakes occurring under the array footprint. Detections are identified through spatial and spectral coherence of seismic energy. Preliminary results show that 16 new earthquakes were detected using this approach. None of these events were previously identified by the University of Utah Seismograph Stations permanent network. These new detections have high spatial correlation with the previously imaged Crater Knoll low-resistivity body.

Preliminary Results from the Sevilleta Array in the Central Rio Grande Rift, NM: Virtual Source Reflection Imaging of the Socorro Magma Body

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The Socorro Magma Body (SMB) is one of the largest, actively inflating subsurface magma bodies globally. Previous studies relied on sparse instrument coverage to determine its spatial extent, depth and seismic signature, characterizing the body as a thin sill situated 19 km below the Earth's surface. Here, we use data from the Sevilleta Array, a 12-day deployment of approximately 800 10 Hz vertical component Fairfield Nodal sensors. The array was deployed north of Socorro, New Mexico, over top of and around estimated locations of the SMB with an average station spacing of 30 m in February of 2015. Teleseismic virtual source reflection profiling employs the free surface reflection off of the Earth's surface as a virtual source in dense arrays and has been used successfully to illuminate basin and shallow crustal structure in multiple tectonic environments. Twenty-seven teleseismic events greater than magnitude 5.5 occurred while the Sevilleta Array was deployed. We present a refined catalog of well-recorded teleseismic events as well as preliminary virtual source reflection stacks that will help illuminate the top of the SMB and basin structure.

Applying Cross-Correlation Methods to Broadband and Nodal Data to Detect and Locate Earthquakes Associated with the Socorro Magma Body

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The Socorro Magma Body (SMB), a thin, tabular shaped body of magma located at a depth of 19 km within the Rio Grande Rift in central New Mexico, is the second largest continental mid-crustal magma body in the world. This feature leads to slow regional uplift on the order of a few mm/yr and has been linked to concentrated seismicity at shallower depth. These small earthquakes have been monitored with a variety of long- and short-term local seismic networks over the past several decades, although with large station spacing. For two weeks during February 2015, seven broadband and 804 vertical component short period node seismographs (station spacing of approximately 300 m) were deployed in the northern region of the SMB, making it the largest temporary installation of instruments over the region of maximum SMB uplift. Initial review of the broadband data produced a catalog of 33 small magnitude earthquakes located within the region. Here we use this initial earthquake catalog as templates in a cross-correlation scanner to detect additional events recorded on both the broadband and more numerous node seismographs. We will also compare the newly detected events with detections produced by a back-projection technique using the node data. Our newly detected events will be located using a regionally appropriate velocity model for comparison to longer term earthquake catalogs and regional structure of the SMB.

Seismic Interferometry of the Bighorn Mountains: Using Virtual Source Gathers to Increase Fold in Sparse-Source, Dense-Receiver Active-Source Data

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The Bighorn Arch Seismic Experiment (BASE) was a combined active- and passive-source seismic experiment designed to image deep structures including the Moho beneath a basement-involved foreland arch in Wyoming. In summer 2010, over 1800 single channel RefTek RT125 'Texan' receivers, with 4.5 Hz vertical component geophones, were deployed at spacings of 100-m to 1-km in a region spanning the Bighorn Arch and the adjacent Bighorn and Powder River Basins. Twenty explosive sources were used to create seismic energy during a two-week acquisition period. We utilize both virtual source interferometry and traditional reflection processing to better understand the deep crustal features of the region and the Moho. The large number of receivers, compared to the limited, widely spaced (10–30 km) active-source shots, makes the data an ideal candidate for virtual source seismic interferometry to increase fold. A virtual source gather is produced by the cross correlation of one receiver's recording, the reference trace, with the recordings of all other receivers in a given shot gather. The cross correlation is repeated for all shot gathers and the resulting traces are stacked. The virtual source gather is then cut in half as the gather contains both real and imaginary components. Visual inspection is the primary method for determining which component is real. This process is repeated for every real receiver location. Preprocessing is critical when it comes to reflection strength in a virtual source gather. We applied an amplitude balance across all receivers and a 4-20 Hz band-pass filter designed to remove the shear waves from the data in order to strengthen later arriving P-wave reflections. This allowed us to produce virtual source gathers with a distinct Moho arrival where we previously had no data. Additionally, advanced technology from the seismic industry is applied to the active-source gathers for enhanced image quality compared to previous processing.

3D Basement Structure of Granite-Rhyolite Province in Midcontinent U.S. Using "Surplus" Data from Oil and Gas Explorations

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The capability for continuous recording of very large numbers of nodal seismographs on land is having a major impact far beyond its primary industrial mission. This is because such recordings may contain a wide variety of information that can be used for diverse studies including a) vibrations due to natural ambient noise, b) vibrations due to cultural noise, c) seismic arrivals from local earthquakes, and d) teleseismic arrivals. Here we report another use of such exploration data that include deep reflections from structure at depth below those of exploration interest. As the result, we produced the first industry scale 3D reflection image of deep intrabasement features in the Delaware Basin, New Mexico. This imagery reveals the presence of an extensive layered complex within the crystalline basement which may be correlative to the layering mapped by the COCORP surveys carried out in 1975-1981 in the midcontinent U.S. Stratigraphic ambiguity notwithstanding, the imagery is truly 3D, allowing recognition of features that are unrecognizable in 2D profiles. Spatial correlation of rock samples from boreholes and the new clues from 3D imagery, we postulate the origin of the enigmatic basement layering is relevant to an extensive, continental scale network of tabular mafic intrusions genetically linked to the widespread granite-rhyolite igneous activity that defines Mesoproterozoic terrain of much of the east-central U.S. To the extent that the new generation of continuously recorded 3D exploration datasets achieves penetration below the sedimentary cover rocks, they represent an invaluable source of fresh information on basement structure and evolution.

Reflection Imaging with Earthquake Sources and Dense Arrays

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The M_w 5.8 earthquake that occurred in Louisa County, Virginia, on 23 August 2011 resulted not only in the deployment of traditional temporary seismic networks to monitor aftershocks, but it provided an opportunity to record with several "high" density seismic arrays. Traditional aftershock networks consist of a few dozen stations spread over tens of kilometers. As a result, the recorded seismic waveforms suffer from spatial aliasing that is so severe that many types of waveform processing are not applicable. Here we report the results of recording with a large number of oil industry-type instruments deployed at a spacing that is an order of magnitude closer than traditional deployments. The objective was to record seismic wavefields at sufficiently dense spacing to allow the use of array methods to image structure using the aftershocks as sources. The array recorded continuously for 12 days and consisted of 172 vertical component seismometers that were placed at 200–400 m and a 60 km long 3-component regional profile with stations every 2 km. We demonstrate how processing techniques from Vertical Seismic Profiling (VSP) can produce high resolution 3D reflection images of structure beneath the array. These images display reflectivity that correlates with that observed on a nearby deep reflection survey collected by the USGS. Of particular interest is a strong reflector imaged across multiple profiles. Our analysis demonstrates how a densely spaced surface array of seismometers can provide 3D images of structure using microearthquake sources at a fraction of the cost of conventional surveys.

Regional Variations in Seismological Characteristics: Implications for Seismic Hazard Analysis

Poster Session · Wednesday 19 April ·

On the Regional Characteristics of the Components of Sigma Based on a Global Digital Strong-Motion Dataset

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The misfit of an empirical ground-motion model (GMM) to the data used to derive it (sigma) is considered as total uncertainty. sigma is typically split into at least a between-event (also called inter-event), tau, and a within-event (or intra-event) uncertainty component, phi, in order to isolate event-specific and path-site specific aleatory variability (randomness). Removing the ergodic assumption used to develop GMMs yields to replacing phi with the so-called single site within-event phi, that can significantly reduce the predicted ground-motion variability and the resultant hazard at long return periods. In this contribution we present investigations on the regional characteristics of the components of GMM uncertainty based on a large dataset of worldwide digital records. We use a reference dataset comprising ~ 1900 x 2 orthogonal horizontal accelerometer records with rupture distances < 150km from ~ 100 global earthquakes with moment magnitude in the range 4.5 to 7.9. Emphasis is on understanding the regional variation of sigma and its components as a function of the vibration period and the predictors given the choices adopted in terms of dataset composition, explanatory variables and functional forms.

USGS National Crustal Model for the Western United States, v1.0

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Seismic hazard assessments depend on an accurate prediction of ground motion, which in turn depends heavily on a base knowledge of three-dimensional variations in density and seismic velocity and attenuation. We have compiled and integrated results from a range of previous studies to provide a crustal model for the western United States from which density and seismic velocities as a function of location and depth to 100 km can be extracted. Quantities presently constraining the model include: surface and subsurface lithology and depths to bedrock and crystalline basement or seismic equivalent interpolated on a 1-km horizontal grid; established theory describing how rock properties change with depth; and deep seismic tomography. Future work will involve more direct incorporation of local to regional 3D seismic velocity models. Surface and subsurface lithology, derived from geologic maps and soil studies, is used to help calibrate calculated velocity profiles in order to match observations of near surface seismic velocity. The depths to bedrock and basement are estimated using well, seismic, and gravity data; in many cases these data are compiled by combining previous studies. Uncertainties of parameters derived from the model increase with depth and are dependent on the quantity and quality of input data sets. An interface to the model provides parameters needed for ground motion prediction equations, including, for example, the shear wave velocity in the upper 30 meters (*VS*30) and the depths to 1.0 and 2.5 km/s shear-wave speeds ($Z_{1.0}$ and $Z_{2.5}$), as well as interpolated 3D models for use with various Urban Hazard Mapping strategies. We calibrate near surface model parameters using published *VS*30 datasets, find acceptable agreement, and present sensitivity studies of the effect of our model on earthquake ground motions and hazard.

Ground-Motion Attenuation in the Sacramento-San Joaquin Delta, California from Seven Bay Area Earthquakes, Including the 2014 M6.0 South Napa Earthquake

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The 2014 M6.0 South Napa earthquake was recorded by an extensive accelerograph network. Baltay and Boatwright (2015) analyzed strong motion records from 292 stations within 100 km of the epicenter and found that peak ground acceleration (PGA) and velocity (PGV) fall off significantly faster with distance than the NGA-West2 ground motion prediction equations (GMPEs) would predict. Erdem *et al.* (2016) showed that this variant attenuation was pronounced within the Sacramento-San Joaquin Delta, approx. 50-75km ESE of the earthquake. This observation motivates the current study, in which we evaluate the attenuation for multiple paths into the Delta from seven significant Bay Area earthquakes with magnitudes 4< M <7 (including South Napa). We select stations within azimuthal ranges of 60° to 120° into the Delta and fit the natural log of PGA and PGV residuals to the Boore and Atkinson (2008) GMPEs for each earthquake to the function $a - kr^g$. Here, a is the event term (the ratio of observed to predicted ground motion for a specific event), k is the differential attenuation (the difference between observed and predicted attenuation), and r is distance. The exponent g modifies the falloff of attenuation with distance: for the seven-earthquake dataset g=0.49 and g=0.26 fit PGV and PGA, respectively, reflecting the sharper falloff seen in the acceleration data, likely due to the higher-frequency nature of PGA. The differential attenuations range from 0.3 to 1.26 for PGA and -0.026 to 0.29 for PGV, with no clear dependence on magnitude or location. While there is a large variation in differential attenuation values, the ground motions from all of these events attenuate faster than predicted by the Boore-Atkinson GMPEs (excluding PGV from Loma Prieta, for which k = -0.026 is poorly constrained due to the lack of recordings past 70 km). Overall, these results suggest that attenuation models can be improved by regionalization, but with significant epistemic uncertainty.

The Relationship Between Site Conditions and Kappa: Some Recent Observation

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An important issue in ground-motion modeling and seismic hazard analysis is the high-frequency decay parameter, kappa (Anderson and Hough, 1984) and its relationship to site conditions. Determination of kappa is complicated by its interaction with source and path characteristics. The path effects on kappa can be minimized by limiting analyses to recordings at distances less than ~50 km; however, the trade-offs between kappa and source remain. We use a subset of data from the NGA-West2 catalog to illustrate the interaction between kappa and the corner frequency of the Brune spectrum (*i.e.* the stress drop) in the context of the point-source simulation model (SMSIM) of Boore (2003). Within this context, we then examine what conclusions can be reached regarding kappa for selected seismographic sites in eastern Canada. We determine to what extent these attributes can be correlated with the site conditions at the seismographic sites. This analysis is a preliminary stage in a project aimed at determining kappa for seismographic sites in eastern Canada based on data gathered over the last decade, and correlating these values with site characteristics, including soil/rock types and shear-wave velocity profile.

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Seismic Wave Propagation in Shallow Layers at the GONAF-Tuzla Site, Istanbul, Turkey

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We investigated near-surface seismic wave propagation on the Tuzla Peninsula in Istanbul, Turkey. The dataset consists of 26 mircoseismicity seismograms recorded with the GONAF-Tuzla downhole seismometer array of the Geophysical Observatory of the North Anatolian Fault (GONAF) network. Sensors are at 0, 71, 144, 215, and 288 m depth. To determine near-surface velocities and attenuation structure the waveforms from all sensors were pairwise deconvolved and stacked. This produced low-noise empirical Green's functions for each borehole depth interval. From the Green's functions we identified reflections from the free surface and a low-velocity layer between ~90 and ~140 m depth. The presence of a low-velocity zone was also confirmed by a sonic log run in the borehole. This structure plus high near-surface P- and S-wave velocities of ~3600–4100 m/s and ~1800 m/s lead to complex interference effects between up- and down-going waves. As a result, the determination of quality factors (Q) with standard spectral ratio techniques was not possible. Instead we forward modeled the Green's functions in time domain to determine effective Q values and to refine our velocity estimates. The effective Qp values for the depth intervals of 0–71, 0–144, 0–215 and 0–288 m were found to be 19, 35, 39 and 42. For the S-waves we obtained an effective Qs of 20 in the depth interval of 0–288 m. Considering the assumptions made in our modeling approach, it is evident that these effective quality factors are biased by impedance contrasts in between the observation points. The results show that even after correcting for a free-surface factor of 2, the motion at the surface was found to be 1.7 times greater than that at 71 m depth. Our efforts also illustrate some of the difficulties of dealing with site effects in a strongly heterogeneous subsurface.

The Effect of a Sedimentary Wedge on Earthquake Ground Motions: The Influence of Eastern U.S. Atlantic Coastal Plain Strata

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Coastal regions of the eastern U.S. are underlain by a wedge of partially consolidated Atlantic Coastal Plain (ACP) marine sedimentary strata overlying a bedrock of crystalline or indurated sedimentary rocks. The ACP strata extend more than 200 km inland, tapering landward from as much as 1 km near the coast. Unconsolidated, shallow sedimentary strata strongly influence earthquake ground motions due to low seismic impedance and strong reflections from the bedrock contact. Site response estimates primarily determine high-frequency amplifications from shear-wave velocities in the upper 30 m (Vs30), but thicker sedimentary sequences can increase longer-period ground motions important to large structures. Here we use data from continental-scale seismic experiments that span the ACP (*e.g.* Eastern North America Margin [ENAM], Earthscope Transportable Array) to examine the influence of ACP strata on earthquake ground motions. We use teleseismic and regional earthquake recordings to compute spectral ratios relative to bedrock sites. Thin ACP strata produce fundamental resonance peaks at high frequencies (>5 Hz), but the fundamental peaks decrease to about 0.45 Hz as the sediments thicken to about 500 m. Amplitudes of the fundamental resonance peaks decrease as the strata thicken, but even coastal sites show amplification factors as great as 5. In addition, we use the frequency of the resonance peaks to invert for an average velocity function within the ACP strata. A smaller array within the city of Washington, DC, which is underlain by a wedge 0- to 270-m-thick ACP strata, shows large amplifications at frequencies of 0.7 to 5 Hz. These amplifications likely contributed to the widespread damage to the city during the relatively modest, M5.8 Virginia earthquake in 2011. This work confirms amplification of short-period ground motions by thin ACP strata, and documents longer-period amplifications caused by thick sedimentary sequences beneath coastal regions of the eastern U.S.

Toward Estimating Site Effect in the Central United States from HVSR and Deep Borehole Recordings

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Horizontal-to-vertical spectral ratios (HVSR) of ambient noise and S-waves from earthquakes and blasts were calculated at broadband stations in the central U.S. HVSRs from each energy source revealed dominant peaks at the fundamental frequency, consistent with base-mode resonance due to constructive S-wave interference. However, ambient-noise HVSRs are less sensitive to higher modes, which are observed in S-wave HVSRs. The peak-frequencies of ambient noise HVSRs near basin edges also appear to be shifted to higher frequencies compared with S-wave HVSRs, encouraging a cautious interpretation of peak frequencies in these settings. In addition, the HVSRs of local mine and quarry blasts and earthquakes are very similar, indicating that blasts may provide a viable S-wave source for HVSR analyses in regions with low seismicity rates.

HVSRs were compared with spectral ratios (SR) of surface-to-bedrock S-wave spectra from weak-motion recordings at two vertical seismic arrays in the Mississippi Embayment. Both arrays penetrate the thick sediment overburden and contain sensors in bedrock—depths of 100 m at VSAP and 587 m at CUSSO. The S-wave SRs are generally consistent with the HVSRs in terms of implied amplification and resonance frequencies (up to at least the sixth mode at both sites), suggesting that HVSRs estimate the S-wave transfer functions at these sites. However, HVSR implies almost twice the amplification of the base mode at both locations compared to SR, and vertical-motion amplification suppresses the HVSR at CUSSO between 13 and 20 Hz. Resonant frequencies in HVSRs and SRs are also consistent with those predicted by the theoretical transfer functions determined by 1D site-response analyses (using DEEPSOIL and STRATA software), though predicted amplifications are uniformly subdued at CUSSO. We also confirmed that horizontal-motion SRs are recoverable from the HVSRs when they are corrected for the vertical-motion transfer function and bedrock HVSR.

Simulation of Hazard Consistent Site-Specific Time Histories Using Empirical Fourier Amplitude Spectrum Prediction Equations

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In the framework of both, site-specific seismic hazard computations and nonlinear structural analysis for seismic risk assessment, realistic time histories are needed. Either, simulation or selection of time histories fitting a given scenario, are commonly performed in such applications. In the case of simulated time histories, these should reproduce major features of natural ground motion, as well as respect the site-specific (target) attributes to which the ground motion is adjusted during the hazard assessment phase. These attributes are described by site proxies such as the bedrock shear wave velocity and kappa.

Major features of natural ground motion are generally reproduced in terms of median and ±sigma values of major ground motion intensity measures such as PGA, PGV, CAV and pseudo-spectral acceleration PSA. In many cases, a close fit to the scenario response spectrum is required. The so-called random vibration theory approach is generally applied in order to identify a stochastic model that allows to fulfill this requirement. This procedure is however based on a number of simplifying assumptions, in particular due to the inverse problem to be solved. Recently, Bora et al (2015) have developed a new GMPE for both Fourier Amplitude Spectra (FAS) and ground motion duration, based on the European database RESORCE. In the framework of site-specific seismic hazard assessment, the results of the Probabilistic Seismic Hazard Assessment performed at the target bedrock level are used to select/simulate acceleration time-histories and to run site-response analysis. The FAS models allow to directly predict spectral acceleration for target attributes.

This contribution proposes a new ground motion simulation procedure based on the FAS models allowing to simulate spectrum-compatible and site-specific hazard consistent accelerograms without having to resort to the inverse RVT approach.

Applicability of Peak Frequency as a Site-Effects Indicator in California

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Time-averaged shear-wave velocity in the upper 30 m (VS30) is the most prevalent single site parameter for development of ground-motion prediction equations (GMPEs), especially in California. However, the use of only a single parameter to describe a range of geological conditions results in significant variability in GMPEs (*i.e.* large sigma). In this study, we explore the applicability of fpeak (the peak frequency of the site response transfer function) as an additional site effects variable for sites in California. The database for the study includes peak ground-motion amplitudes and 5%-damped pseudo spectral acceleration (PSA) extracted from the Next-Generation-Attenuation-West2 database. Fpeak values are measured from the horizontal-to-vertical (H/V) spectral ratios of the recorded ground motions for 554 stations in California. We calculate residual site terms from the empirical data adjusted to B/C reference site condition (VS30 =760 m/s) with respect to a selected regional GMPE model developed for the same reference site condition (Boore *et al.*, 2014; BSSA14). Plotting the residual site terms versus their corresponding fpeak values reveals fpeak-dependent trends at all frequencies. Average residual site terms for California sites can be as large as 0.26 in log10 units (factor of 1.8) at frequencies near fpeak. We develop an fpeak-dependent site term function by fitting the residual site term trends at various frequencies. This can be used to adjust the median prediction of the GMPE model, for sites for which both VS30 and fpeak values are available. By incorporating fpeak as an additional site parameter, we are able to slightly reduce the site to site variability component of the GMPE model (by 5% on average). The results of this study show the importance of fpeak as an additional site response variable for GMPE models.

Rupture Direction, Basin, and Distance Effects on Ground Motions from M7 Earthquakes on the Salt Lake City Segment of the Wasatch Fault, Utah

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We have analyzed numerical simulations of six M7 earthquakes on the Salt Lake City segment of the Wasatch fault, Utah, to better understand the long-period ground motions that these simulations predict in the adjacent Salt Lake Valley (SLV). The peak spectral accelerations at 2s (SA-2s) and 3s (SA-3s) were calculated in the Wasatch Front Community Velocity Model (v3d) as well as in a 1D rock model using the same source descriptions. The SAs from the 1D model are generally smoother and smaller in amplitude due to the lack of underlying 3D basin structure. 3D/1D ratios of the SA values depict the 3D basin effects in the SLV, such as focusing, defocusing, and wave entrapment. We developed regression models for the 6-scenario ensemble ground motions as a function of depth to the isosurfaces of Vs=1.0 and 1.5 km/s in the SLV. These models show amplification factors of up to ~3.1 and ~3.7 above the deepest part of the basin for SA-2s and SA-3s, respectively. NGA-West2 GMPEs overpredict the amplification of SA-2s and SA-3s in the SLV by a factor of ~2 on average, suggesting that our results can be used to generate improved SLV-specific GMPEs. The individual scenario SAs show correlations with the underlying rupture parameters, in particular, the slip distribution. The directivity factors for the Bayless and Somerville (2013) model, computed using a 10-section rupture surface approximation, increase the SAs by less than 20% for the scenarios and do little to increase the similarity between the SAs from the NGA-West2 GMPEs and the simulations. As compared to 4 NGA-West2 GMPEs, the long-period scenario ground motions for soil sites increase from Rrup (rupture distance) of 0 to 1-1.5 km and decrease from Rrup ~4 to 10 km. The maximum in simulated ground motions for Rrup ~1-4 km appears at least in part to be caused by basin-edge effects and entrapment of waves in the deeper basin, combined with scenario specific conditions not captured by the GMPEs.

An Equivalent Point-Source Stochastic Simulation of the NGA-West2 Ground Motion Prediction Equations

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It is common in engineering seismology to use point-source stochastic models to simulate ground motions in regions where recorded strong motions are sparse either directly, using the stochastic method, or indirectly, using the hybrid empirical method (HEM). Use of HEM also requires a well-calibrated stochastic model for the host region of the adopted empirical ground-motion prediction equations (GMPEs). In this study, we use a genetic algorithm (GA) to invert estimates of horizontal response-spectral acceleration from the empirical NGA-West2 GMPEs to estimate a consistent and correlated set of seismological parameters that can be used, along with an equivalent point-source stochastic model, to mimic the general scaling characteristics of these GMPEs. The inversion is performed for moment magnitudes (M) of 3.0–8.0, rupture distances (RRUP) of 1–300 km, spectral periods (T) of 0.01–10 sec (f = 0.01–100 Hz), and NEHRP B/C site conditions. The response-spectral values from the stochastic simulations are calculated using random vibration theory (RVT). Seismological parameters are obtained as a function of earthquake magnitude. A trilinear functional form for the geometrical attenuation was used. The near-source geometric spreading was modeled as both magnitude- and frequency-dependent in order to fit the empirical predictions. The inverted equivalent point-source stochastic model fits the median GMPEs within 25% with the best agreement (<10%) for M > 5.5). We believe that calibrating an equivalent point-source model to empirical model predictions rather than from the recordings themselves provides a seismological model that builds upon the expertise of the GMPE modelers. This is especially important in HEM applications that use stochastic models to adjust empirical models in the host region to develop GMPEs in the target region.

Examination of Ground Motion Simulation Modeling Uncertainty for the 2010 Mw 7.1 Darfield, New Zealand Earthquake

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This study aims to assess earthquake source modeling uncertainties on physics-based ground motion simulations via a case study of the 2010 M_w7.1 Darfield earthquake. The parameters varied in the uncertainty analysis are those related to the fault dimension and geometry. Monte Carlo simulations, in which all parameters (slip distribution, fault dimension, fault geometry, etc.) are varied simultaneously accounting for correlations, are performed to obtain the overall uncertainty in ground motion. In addition, each of the parameters were varied separately while the others were held fixed to determine the sensitivity derivatives of each parameter on this uncertainty, allowing identification of the main factors affecting near-source ground-motion complexity. Our results reveal that fault width is as significant as the spatial distribution of slip amplitude, particularly for spectral acceleration at long periods. The results also give insights on the potential rupture even beyond the seismogenic zone for large magnitude events in active crustal regions.

Partially Nonergodic Region Specific GMPEs for Iran

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Moving towards performing partially nonergodic region specific PSHA, there is a vital need to update GMPEs derived based on the database of Iranian ground motion records. We developed a new set of ground motion prediction equations (GMPEs) to predict both horizontal and vertical ground motion intensity measures (GMIMs) such as peak ground velocity (PGV), peak ground acceleration (PGA), and pseudo spectral acceleration (PSA) at different periods. In this regard, we used a dataset consists of 688 records out of 152 shallow crustal earthquakes occurred within the Iranian plateau. The applicability range of these derived GMPEs is for the moment magnitude of **M** 4.7 to **M** 7.4, the Joyner-Boore distance less than 250 km, and V_{S30} of 200 m/s to 1500 m/s. In this study, we classified the database into three different regions, Alborz, Zagros, and others, regarding their different path characteristics.

In the final functional form, we disregarded the style of faulting term since this decision results in reduction of the total standard deviation by 10%. We used a mixed-effects regression algorithm to estimate the coefficients of the functional form. Moreover, we introduced a random-effects coefficient in anelastic attenuation term to capture the effects of regional variations. The total standard deviation is portioned into between-event, site-to-site, and event-site corrected standard deviations. Significant site-to-site standard deviation reveals that the spatial variability of ground motions exists and the ergodic assumption is violated.

Comparing the coefficients for vertical and horizontal site responses demonstrates that the site effects on vertical component is negligible to horizontal component. Furthermore, comparing the coefficients for vertical and horizontal anelastic attenuation shows that the anelastic attenuation is faster on vertical component than the horizontal component.

Evaluating Fundamental Seismological Parameters for Israel

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Israel is located in a triple junction between the African, Arabian, and Eurasian plates. In this small but complex geological province, a continental transform, continental collision, and subduction processes can be found. 4000 years of historical and archaeological evidence tell us about devastating earthquakes which have destroyed cultural centers in this area. Unfortunately, the recorded ground-motion is scarce due to low seismicity rates and poor station coverage. Therefore, the uncertainty regarding the seismic parameters of the region is high.

This study is part of a broader project which will develop, for the first time, a local GMPE for seismic hazard assessment in Israel. The GMPE is planned to be hybrid, such that it will include both empirical regression and seismological simulations. The study presented herein, contains a detailed evaluation of seismic parameters for this region. Parameters such as geometrical spreading, attenuation, stress drop, and kappa are carefully evaluated. These refined parameters will be later used to perform stochastic point-source simulations and supplement the existing poorly-sampled database, for the derivation of the local GMPE.

Our analysis uses a relocated database of M>2 earthquakes that occurred in the region since 2006, recorded by broadband and short period stations of the Israel Seismic Network. We calculate moment-tensor solutions for M>3 events, for a better constrained analysis. Then, we use the high frequency ground-motion regression technique to construct a model that will predict the spectrum at an average site. We apply a forward modeling to optimize the source excitation, the wave propagation effect in terms of geometrical spreading and attenuation, and the site term. This analysis is an example for the direct use of high level fundamental seismology, to directly advance the applicability of engineering techniques aimed at reducing seismic hazard.

Development of a New Strong Motion Database for Iran

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This study discusses development of a new and high-quality dataset of recorded earthquake ground motions. Here we explain the procedure used to collect and to generate a database of strong motion significant events from Iran and regions with similar tectonic activities. This database may be used in the development and ranking of ground motion models and for hazard and risk analyses. This study focuses on gathering near source shallow earthquakes data from Iran, Eurasia, and California locations with moment magnitudes, from 5.6 to 7.6, and rupture distances, $R_{\text{rup}} \leq 100$ km. For this study, 266 three-component strong motion records are processed from 27 large Iranian earthquake events from 1978 to 2013. We picked strong motion data, from four other regions which have similar tectonic features and shallow earthquake with depth less than 35 km. A raw database is obtained from the Iranian Strong Motion Network (ISMN). Geometrical characteristics were partially obtained from international agencies and the rest processed from seismologic and strong motion databases. This is consistent with the standard worldwide databases.

This study is focused on assembling the most important and applicable parameters included in the database that characterize the earthquake source, the source to site path, and site parameters at the recording station. To determine the database parameters, we have considered the Bommer and Ambraseys (1992) criteria and the Next Generation Attenuation Phase 2 (NGA-West2) project (Bozorgnia *et al.*, 2014) criteria, which constitute the basis of this database. Furthermore, we only used strong motion data recorded at or near ground level—records which have insignificant structural interaction effects (Campbell 2007). The accelerometric data and metadata information are gathered from collections of recordings from national accelerometric data networks, existing global databases, seismological agencies, and various published data.

Testing the Suitability of Global Ground Motion Models for the Western Balkan Region

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In the framework of the Harmonization of Seismic Hazard Maps in the Western Balkan Countries Project (BSHAP), a strong motion database that includes 672 uniformly processed accelerograms from 358 earthquakes recorded in 121 strong motion stations was compiled (Salic *et al.*, 2016). The BSHAP strong motion database also includes the earthquake metadata, source-to site distance matrices, and station information; therefore, it provides a solid base for the ground motion characterization studies in the region. Recently published NGA-West 2 GMPEs and updated models from the Pan-European region (*e.g.* GMPEs developed within the SIGMA project) are tested for the suitability with the magnitude, distance, and site amplification scaling of the regional ground motion database. Details of the testing strategy including the random effects regression analysis and the analysis of the residuals, evaluation of the trellis plots showing comparative ground motion scaling with predictive parameters (distance, magnitude, and period), and ranking based on quantitative model-data comparison methods (*e.g.* log-likelihood and Euclidian-distance methods) will be discussed with the focus on the regional variation of seismological characteristics.

Scaling and Empirical Relationships of Moderate to Large Earthquakes: Re-scaling or Re-thinking?

Poster Session · Wednesday 19 April ·

A Critical Review of Empirical Earthquake Source Scaling Relationships

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The earthquake source scaling relationships are typically regressions of historical and instrumental earthquake datasets, in which seismic moment or magnitude are estimated from geometrical parameters such as fault rupture length and rupture area. The relationships not only provide an insight into the underlying mechanics of the rupture process but also suggest input parameters for seismic hazard estimates. Numerous relationships have been proposed and published during the years using data from different tectonic environments and different forms of the regression equations. The most used regressions for seismic hazard purposes are the well-known Wells and Coppersmith (1994) ones, proposed for various earthquake size and for different kinematics and based on a relatively old dataset.

Following the philosophy of the Wells and Coppersmith (1994) and using the same log-linear regression equations, we propose a review of the relationships based mainly on an update of the earthquake dataset. We compile a worldwide database of earthquakes using most of the available datasets used for the most known published empirical relationships, taking into particular attention the origin of the data and distinguishing, for example, between geological data collected in the field (*e.g.* rupture length and coseismic displacements measured after major earthquakes) and seismological data (*e.g.* source parameters from finite-fault slip models). The database contains 865 worldwide earthquakes, with a moment magnitude range 4.0-9.5. The suggested revised regression equations show good correlation coefficients and have all large numbers of data points, suggesting a better statistical stability. Finally, using the same dataset, we also propose a regression relationship based on the concept of aspect ratio, defined as the ratio between the fault length along strike and the fault length along dip.

Earthquake Scaling Relationship for Volcano-Tectonic Earthquakes: A Case-Study from Mt. Etna (Italy)

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The characterization of magnitude-size scaling relationships to be used in volcanic domains is a key step for assessing seismic hazard induced by low to moderate volcano-tectonic events. Whereas empirical relationships derived for tectonic domains are largely available in the literature both for worldwide applications and regional contexts, those calibrated for active volcanic areas are relatively few. Among them, there are two for thin crust volcano-tectonic contexts and one specifically derived for the Taupo volcanic zone in New Zealand. However since the different magnitude ranges for which relationships have been calculated, they are not really applicable in any volcanic region.

At Mt. Etna (Italy) volcano-tectonic earthquakes feature shallow foci (H<5 km), moderate magnitudes (M_w up to 5.3) and extensive surface faulting with end-to-end rupture lengths up to 6.5 km and vertical offsets up to 90 cm. Systematic historical investigations and recent observations have permitted the compilation of an earthquake rupture catalogue, listing more than 40 coseismic ruptures with associated features.

We present an earthquake scaling relationship calibrated for the Mt. Etna region from original data of surface faulting in the magnitude range M_w 2.9-5.3; results are compared with relationships available for other volcanic domains. In particular, considering a few approximation due to the use of different dimensional parameters (surface fault length for Etna, rupture area for volcanic NZ sources), the agreement with the Taupo relationship covering higher magnitude range, is quite satisfactory.

Finally, the above magnitude-scaling relationships for volcanic domains have been implemented in the software FiSH, a Matlab® routine developed in order to quantify, from geometry and slip-rates of a fault, the related maximum expected magnitude and the associated mean recurrence time.

Family Tree of Magnitude Versus Rupture Size Relationships

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Magnitude versus rupture size is an important element in many seismological and engineering fields, and a key point in probabilistic and deterministic seismic hazard assessment.

The datasets used for deriving empirical relationships or confronting theoretical models gather few hundreds of earthquakes at most; the homogeneity in the metric of the measurements is not always guaranteed, and the accuracy is not declared. Moderate to minor earthquakes are usually less represented in empirical relationships, the divergence of mean values expected to be dramatic in the magnitude range of interest *e.g.* for induced seismicity. Last but not the least, crustal or fault-specific properties are usually taken into account only in terms of focal mechanism.

As a contribution to the discussion given from a European perspective, we mapped a family tree of existing magnitude/rupture size relationships, to depict the kind of data used, the common sources of information, and the original schools of thought developed in about 40 years of literature on this subject.

The map will be proposed in a hands-on and interactive poster, to catch during the meeting all the suggestions, modifications, new entries, and promising ideas of the scientific community that will convene in Denver.

Advanced Empirical Scaling Laws for Earthquake Sources

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We present new empirical scaling laws for rupture width W, rupture length L, rupture area A and average slip D, developed using a large database of rupture models. The database accounts for wide magnitude-range (M_w 5.4 – 9.2) and events of various faulting styles. We apply general orthogonal regression, to account for measurement errors for all variables and to obtain mutually self-consistent relationships.

We find that L grows more rapidly with M_w, compared to W. The fault-aspect ratio (L/W) tends to increase with fault dip, which generally increases from reverse-faulting events, to normal-faulting events to strike-slip events. Subduction-interface events have significantly higher W (hence larger rupture area A) compared to other faulting regimes. For strike-slip events, the growth of W with M_w is strongly restricted, while the scaling of L agrees with the L-model behavior (D correlated with L). However, at regional level where seismogenic depth is essentially fixed, the scaling behavior corresponds to the W-model (D uncorrelated with L). A scaling behavior of $A \propto M_w$ is consistently found, except in case of normal-faulting events. The ratio D/W (a proxy for average stress-drop) tends to increase with M_w, except for shallow crustal reverse-faulting events, suggesting the possibility of scale-dependent stress-drop.

There are substantial differences between our new scaling relationships and those of previous studies. Hence, our study provides critical updates on earthquake-source scaling laws needed in seismic-tsunami hazard analysis and engineering applications.

Source Discovery Using Differential Methods: Applications to Explosion Monitoring

Poster Session · Wednesday 19 April ·

Characterizing Blast Wave Behavior at Solid-Gas Interfaces of Varying Curvature

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Wavefield interactions with cavities and damage zones play an important role in the near-field seismic signals generated by underground conventional and/or chemical explosions. The interactions of blast waves with gas-solid interfaces are studied experimentally to characterize the blast wave response to the presence of interface curvature. The experiments are designed to simultaneously illuminate the wave phenomena in both the gas and solid material. Wave formation and solid response to multiple shocks or rarefactions resulting from interfaces with increased curvature are captured. We report here on blast propagation in four situations: air-only, solid-only, zero-curvature air-solid interface, and non-zero curvature air-solid interface. Polydimethylsiloxane (*i.e.*, Sylgard) is used as the transparent solid material with a known principal Hugoniot and governing equation of state. Wave propagation is visualized with an optical density-gradient based technique (Schlieren imaging) and imaged at 1 MHz. Blast waves (Mach ~ 1- 1.5 in air) are created in the laboratory using exploding bridge wires. Results may better inform models of energy transfer in situations where seismic waves pass through complex near-source and damaged regions.

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Using Short-Period Surface Waves (Rg) as a Yield Estimator at Local Distances

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Estimating yield from explosions is an extensive research question, particularly in the context of a complex urban environment. Although challenging, yield estimation is a crucial step in the post-detonation analysis and a combination of multiple techniques will most likely lead to the lowest uncertainty in yield estimation. The focus of our research is using short-period surface waves (Rg) as a yield estimator, since shallow buried and surface explosions can generate Rg signals at local distances less than 200 km. The method involves calibrating earth models to specific source region geologies, and then using these earth models to calculate synthetic seismograms for both atmospheric and underground explosions for a range of yields (10-10^6 kg). The synthetic seismograms are measured for maximum Rg amplitudes at a given period and then these values are used to construct MRg magnitudes calibrated to the source earth model. Using the Denny and Johnson moment/yield relation we construct site-specific MRg/yield relationships. We tested MRg on a dataset from a surface shot with a yield of 22,374 kg. Using stations at a range of local distances (2-7 km) we estimated a yield of 19,327 kg, utilizing both atmospheric and underground site calibrated MRg/yield relations. The explosion was conducted in saturated alluvium, resulting in slow group velocities (250 m/sec) and high Rg amplification. Outside the range of 7 km, the geology transitioned into weathered limestone and granite resulting in up to 20:1 transmission losses for Rg signals. To correct for these losses we are developing reflection and transmission coefficients based on conservation of energy and displacement continuity, which can compensate for high impedance mismatches across boundaries. As the method is applicable across multiple boundaries it can be extended to tomographic corrections, if shallow tomographic earth models are available for given sites of interest.

Investigation of Seismic-Acoustic Coupling and MRg-Yield Relations through Surface Wave Analysis of Explosive Data in Different Geologies

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Potential terrorist blasts or explosive tests may occur at, near, or above the surface in a variety of geologies and in complex media. Above and near-surface explosive tests were conducted to better characterize the source characteristics and observed coupling differences in materials such as alluvium, granite, limestone, and tuff. The Humble Yellowwood 4 experiments of 2014 included a pair of explosions in weathered granitic geology with a yield equivalent of about 100 kg TNT and depth of burial (DOB) and height of burst (HOB) of 10 meters and 2 meters respectively. Observed seismic coupling differences between the two shots can be compared to previous work done on the Humble Redwood III tests with similar experimental setups in alluvium and limestone geology. The high-frequency fundamental-mode Rayleigh wave Rg is a useful phase for the analysis of near surface explosions due to its sensitivity to depth of burial and other source parameters. We utilize a site-specific method that uses Rg amplitudes and timing to estimate the relation between MRg and explosion yield for best fitting underground or atmospheric explosions (see Napoli et al, this session). In addition to yield information, the code can also invert for geophysical properties such as shear wave attenuation and Poisson's ratio. A specific challenge with the Humble Yellowwood data set is proximity of the observing stations to the source (within 1 km), which can cause overlap between any generated Rg waves with other phases. We show results based on analysis of the Rg phase to demonstrate the utility of the MRg-yield method in providing yield estimates and other source/site information that will allow us to better identify and characterize near-surface explosions.

Discriminating between Shallow, Natural Earthquakes and Blasts near Sussex, New Brunswick, Canada

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Between 19 September and 5 October 2016, a low magnitude earthquake swarm occurred near Sussex in southern New Brunswick, Canada, in igneous rocks of the Appalachians. During this 16 day period, 11 events, the largest of which was magnitude (M_N) 2.3, were well-recorded regionally in part because of increased instrumental coverage intended to monitor potential shale-gas activities (a total of six stations are in operation between 15 and 85 km of the epicenters) . Analysis of the events indicates that they were very shallow (less than 5 km deep). Blasts associated with ongoing road construction nearby were also recorded by the same instruments, providing the opportunity to improve our discrimination capabilities in this non-shield environment. While time-of-day alone can be used to eliminate some events as potential blasts, additional criteria for discrimination is required. Accurate event relocation can aid in separating clustered events and in identifying potential zones of blasting but it may be insufficient in cases of co-located events. For these reasons we also investigated the use of other discriminants such as amplitude ratios between phases and other spectral methods. Despite the shallow focus of less than 5 km, the earthquakes have not been reported as felt by people in this sparsely populated region. Nonetheless, it was decided to use these events for a media outreach exercise with the aims of raising the Department's visibility in the province and of testing our earthquake swarm communication strategy. For comparative data a more active swarm near McAdam in southwestern New Brunswick (2012-2016) 150 km to the SW has provided us with a large and valuable data set of naturally occurring, extremely shallow (~0.1 km) earthquakes recorded at regional distances as well as hypocentral distances as close as 1-2 km. However, in that region we do not have nearby blasts with which to compare them.

Wave Propagation Effects on P/S Ratio at Local Distances for an SPE Explosion and Shallow Earthquake

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The regional high frequency P/S amplitude ratio has proven to be one of the most reliable discriminants between explosions and earthquakes. However, its performance at local and short distances is still a subject of research. At these distances the underlying assumption of similar wave propagation effects between the two sources does not fully hold. In this study we looked at effects of the difference in source depth between a shallow near-by earthquake and an underground explosion, as well as effects of wave scattering, manifested as focusing and defocusing, on P wave radiation patterns and amplitudes of Rg waves.

Using deterministic high-frequency (up to 5Hz) waveform modeling for the SPE-5 chemical explosion and a M1.7 local earthquake at the Nevada National Security Site, we investigated wave propagation effects on the amplitudes of recorded P, S and Rg waves. Ground motion simulations using high performance computing and several regional velocity models that include shallow small-scale complexities with random distributions were used to investigate the correlation between structural complexities and P/S ratio performance at stations covering a distance range of 1-60km. Synthetic seismograms were also used to characterize local wave propagation effects and guide development of possible corrections to P/S ratios needed to account for wave path effects at different frequency bands.

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Amplitude Difference Methods for Source, Site and Path Models Used in Explosion Monitoring Research

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We have shown that waveform-based arrival time differences can be used to obtain accurate absolute locations in cases where ground truth is available (Balapan DOB series) and when it is not (DPRK). Differencing methods are also extremely important for amplitude work. By forming differences (log ratios) appropriately, we can isolate relative source, site and path effects, and absolute levels can be obtained using independent information. To create propagation models for use in high frequency discrimination and yield estimation research, we isolate relative channel site effects, relative site effects within station clusters, and relative source effects for event clusters. We can then reduce the amount of data, and the number of unknowns in the tomographic inversion. These steps also provide critical quality control on the amplitude data. We shift models to absolute levels using independently determined moments from regional studies and teleseismic catalogs, along with corner frequency or stress from well-constrained coda spectral ratio studies. Spectral ratios can also be used to test explosion source models. Local distance seismograms from the SPE series show strong shear waves, and by comparing P and S coda spectral ratios for shots 3 and 5 we see that P and S corner frequencies are similar, in contrast to the well-known Fisk Conjecture, which was formulated using nuclear explosion data, and may involve different physical effects (*e.g.* cavity creation). Of course, amplitude difference techniques rely on having the correct instrument response, which is not always the case with seismic data sets. We track noise amplitudes, and tomography residuals versus time to look for shifts that might indicate intervals with instrument issues, which can then be discarded, treated as separate site terms, or (if we have time) fixed. We are automating this process, and will present results for a global set of stations that we hope will be of use to the research community.

Coda-Wave Interferometry-Derived Source Separation between SPE-1 and -2 and Near-Source Medium Change between SPE-2 and -3

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Differences in the seismic coda of similar events can be used to investigate medium change and source displacement with coda wave interferometry (CWI). We employ CWI to find any change in the source medium due to damage between explosions of the Source Physics Experiment (SPE) and to infer the known relative location between the explosions. We find that damage due to the second SPE explosion, SPE-2, must be confined to a spherical region with radius less than 10 m and velocity perturbation less than 25%, and that the time-shifts calculated from CWI are most consistent with a small error in origin time of one or two samples. Inferred displacement between the first, SPE-1, and second, SPE-2, explosion is between 5 and 20 meters, where the known separation is close to 10 meters. Prepared by LLNL under Contract DE-AC52-07NA27344.

A Dry Alluvium Constitutive Model for Simulating the Source Physics Experiments (SPE)

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We describe a methodology for large scale modeling of wave propagation from chemical underground chemical explosions that will be conducted at the Nevada National Security Site (NNSS) in highly heterogeneous alluvial deposits. The SPE phase II include a series of underground chemical explosions in dry alluvium geology (DAG) sized with different yield deployed at different depths, to understand the genesis of shear motions. Shear motion is one of the main proxies in discriminating between chemical explosions and earthquakes. To build a reliable conceptual model of the subsurface we integrated the geological and geophysical characterizations conducted during the legacy nuclear tests at the NNSS. Simulating the behavior of alluvial deposits under chemical explosive loading requires the use of a constitutive model that includes non-linear material response. The rock behavior is described using an isotropic elastic-viscoplastic model, coupled with a rate-dependent damage mode, and a Mie-Grüneisen equation of state, coupled with a porous compaction-dilation model. Major model parameters are functions of the reference porosity. The constitutive model is implemented in GEODYN, a 3D Eulerian code. Because most strength measurements in rock materials are performed for intact samples under static conditions, the models based on these data need to account for possible scale and rate effects when applied to simulation of the dynamic response of large-scale rock masses. Therefore, laboratory-scale calibrated model is used to perform 3D simulations of chemical explosions with GEODYN, and is further upscaled and calibrated to reproduce the well-known Perret and Bass field correlations. The upscaled constitutive model is then used for a parametric study of the effect of the key geophysical parameters of alluvium on the magnitude of shear motion generation. This work performed under the auspices of the U.S. DOE by LLNL under Contract DE-AC52-07NA27344. LLNL-ABS-716762-DRAFT

Numerical Simulation of near Field Ground Motions Observed during the Source Physics Experiments

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We have performed three-dimensional high resolution simulations of underground explosions in jointed granite as part of the Source Physics Experiment (SPE) being conducted at the Nevada National Security Site (NNSS). The main goal of the current study is to investigate the effect of surface spall due to underground chemical explosions on the seismo-acoustic signature in the far field. Two parametric studies have been undertaken to assess the impact of 1) conceptual geological models including single and two layer models, with and without joints, and with and without varying geomechanical properties, and 2) depth of burst and explosion yields. Through these investigations we have explored not only the near-field response of the explosions but also the far- field responses of the seismic and the acoustic signatures. The near-field simulations were conducted using Lagrangian hydrocode, GEODYN -L, while the far-field seismic simulations were conducted using the elastic wave propagation code, WPP, and the acoustic response using the Kirchhoff-Helmholtz-Rayleigh time-dependent approximation code, KHR. In the near-field simulations we have recorded the velocity field histories 1) at the ground surface on an acoustic-source-patch for the acoustic simulations, and 2) on a seismic-source-box for the seismic simulations. Using the model calibrated for SPE3 and SPE4P experiments we predicted SPE5 and SPE6 seismo-acoustic responses and compared them to measured data. We have extended the parametric study to include various geologic settings around ground zero in order to rank the most important key parameters to be characterized on site to minimize uncertainties in prediction and discrimination.

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A Method for Yield Scaling FFT Velocity Amplitude Spectra from Chemical Explosions

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The Source Physics Experiment (SPE) is a series of chemical explosive shots of various yield detonated at varying depths in a borehole in granite. The near-source ground shock environment for each of these events was recorded with a dense array of in-ground borehole accelerometers at various ranges. One goal of SPE is to develop greater understanding of the explosion phenomenology in all regimes: from near-field non-linear response to the far-field linear elastic region, and connecting the analyses from the respective regimes.

While near-field analysis typically involves review of kinematic response in the time domain to facilitate comparison among events, far-field data analysis more often is based on study of response in the frequency domain to facilitate comparison of event magnitudes. To try to "bridge the gap" between approaches, we developed a scaling law for Fourier amplitude spectra of near-field velocity histories that successfully collapsed data from the first three SPE events ranging in yield from 100 kg to 1000 kg. Next, we developed a simple graphical analysis method to accurately determine the yield of a fourth event of much larger yield (5000 kg). Finally, we use the technique to help identify data quality issues in a subsequent event with a yield of 2200 kg in which a new data acquisition system was being proof-tested.

This approach presents a new way of working with near-field data that will be more compatible with traditional methods of analysis of seismic data and should serve to facilitate end-to-end event analysis. The goal is that this new approach to data analysis eventually result in improved methods for discrimination of event type (*i.e.*, nuclear or chemical explosion, or earthquake) and magnitude.

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Seismic Wave Propagation from Underground Explosions: Influence of Topography on Wave Scattering and Ground Motions.

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Explosions in homogeneous isotropic media are ideally spherically symmetric sources that generate only radially and vertically polarized P-waves. However, recordings from underground explosions commonly contain a significant amount of tangential motion, which may originate from the source itself or converted from radially polarized motions during seismic wave propagation between the source and the receiver. Source effects consist of non-linear material response during high-energy loading in the near source region, while path effects consist of seismic scattering at material heterogeneities and irregular topography. The Source Physics Experiments is a series of ongoing chemical explosions being conducted at the Nevada National Security Site (NNSS) and are aimed at building a physics-based understanding of the relative contributions of these mechanisms. Here we aim to investigate the contribution from path effects. Specifically, we focus on the effects of surface wave scattering due to topography, since it is the only well-determined contributor. We use SW4, an anelastic anisotropic fourth order finite difference code, to run hundreds of simulations of wave propagation through regions with irregular topography obtained from sub-domains of the NNSS. Scattering of surface waves due to topography leads to a significant amount of tangential motion and the presence of coda. We show that the relative significance of these motions is related to the local variance of the topography. We also investigate the effects of source depth, source frequency content, and source type and their sensitivity to topography. The findings of this study can assist in monitoring of explosions in remote, inaccessible areas for which details of the explosive source and seismic velocity structure are unknown, and topography is the only observable, constrained variable.

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Cross Borehole Change Detection Imaging for the Source Physics (SPE) at the Nevada National Security Site (NNSS)

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Quantification of changes in the near-source medium associated with subsequent explosive testing is critical to the Source Physics Experiment (SPE) for differentiating source characteristics from site effects (*i.e.*, localized damage) in far field seismic and infrasound recordings. We have mapped changes in compressional wave velocity attributed to damage associated with five separate chemical explosions of varying yields and depths during the SPE experiments in the Climax Stock at the Nevada National Security Site (NNSS). Each of the five change detection surveys were undertaken with great care ensuring that survey geometry, recording parameters, and equipment were consistent, thereby allowing for direct comparison between the surveys. Data challenges, such as early triggering, were rigorously addressed. For instance, signals were stacked using cross-correlation of a known pre-event impulse before each shot to ensure proper timing. Also, appropriate filters were determined using a Monte Carlo method in a band-pass frequency space to find localized peaks in cross-correlation coefficients. These tomographic surveys used active source signals produced by both an accelerated weight drop (AWD) at the surface and a borehole sparker at depth, producing dense ray path coverage in the ground zero (GZ) region. Source-receiver pairs for each survey range between 29,232 in the first survey to 36,480 in the latest survey. We present five separate models for P-wave velocity (Vp), the four associated changes in Vp (dVp) between each explosion, and the total change in Vp between SPE-3 and SPE-6. Sandia National Laboratories is a multi-mission laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

P-wave Attenuation of Yucca Flat, Nevada National Security Site

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Understanding explosion-source phenomenology is a critical step in improving nuclear explosion monitoring capabilities. Isolating source effects from those caused by path, instrument, etc., is the goal of the Source Physics Experiment (SPE). SPE is a well-recorded set of chemical explosions conducted at the Nevada National Security Site (NNSS). In preparation for SPE Phase II, we present the results of attenuation tomography along two roughly perpendicular transects in Yucca Flat, the location of future SPE tests. Yucca Flat is a sedimentary basin that has been host to more than 800 underground nuclear tests. Data was acquired in an active-source seismic survey that utilized a 13,000 kg impulsive source (a weight-drop source called the Seismic Hammer™). The survey consisted of at least 32 impacts from the Seismic Hammer at each of the 154 shot locations (~5,000 hits). Recovered P-wave quality factor (Q) ranged from 25-180. Anomalies present themselves as local minima in Q that coincide with the depths and locations of past nuclear explosive tests. The material above shot depths for these nuclear tests have an increased (relative to adjacent undisturbed material) Q. We propose that fracturing of the local consolidated alluvium and volcanic rocks near the explosion leads to an increase in attenuation. Collapse of superjacent material into the resultant nuclear explosion cavity (*i.e.* the collapse chimney) decreases the porosity of the native material (mostly alluvium), resulting in higher Q. Sandia National Laboratories is a multi-mission laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

Towards Array Discrimination Using a Large-N deployment at the Nevada National Security Site

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Seismic methods currently provide the best way to detect and discriminate underground nuclear explosions. Studies to date indicate that seismic discriminants based on single-station and network-averaged P/S amplitude ratios typically used at regional distances may not be reliable at local distances (<200km), likely due to significant path and site effects. We investigate the utility of small-aperture seismic arrays in discriminating between earthquakes and explosions from local to regional scales. As part of the Source Physics Experiment (SPE), a Large-N style array was deployed at the Nevada National Security Site (NNSS) in April 2016 for 30 days surrounding the detonation of the SPE-5 shot. The SPE consists of a series of chemical explosions designed to improve our understanding of explosion physics and enable better modeling of explosion sources. We select subsets of instruments from the Large-N deployment to form highly coherent small-aperture arrays that can be exploited at high-frequencies applicable to explosion monitoring. We compare the discrimination performance of beamformed amplitude ratios at single and multiple subarrays to those formed by individual sensors. We theorize that the beamforming process will significantly reduce path and site effects that hamper current discrimination efforts.

Applying Insights from the Nevada Source Physics Experiments to the DPRK Declared Nuclear Test Seismic Signals

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The Source Physics Experiments (SPE) are a series of chemical explosions conducted in Nevada, which are designed to improve the United States ability to detect and identify low-yield nuclear explosions amid the clutter of conventional explosions and earthquakes. The 2.2 ton SPE-6 on October 12th, 2016 was last of the Phase I series of six underground chemical explosions conducted in the same granite borehole. By varying the size and depth of the shots, while recording them on a common sensor network, ranging from near- to far-field, we are able to improve our understanding of the effects of yield, scale depth, scattering and emplacement properties on explosion seismic wave generation. This has resulted in refinements to previous models for explosion P-wave spectra, S-wave generation, P/S discrimination, correlation behavior and more.

Here we apply these SPE results to regional signals generated by the five declared nuclear tests by North Korea (DPRK—Democratic People's Republic of Korea) between October 2006 and September 2016. The SPE results suggest that explosion P-wave spectra deviate from traditional models for small and/or over-buried cases. This affects P-wave explosion model based estimates of DPRK nuclear test depths and yields, particularly for the smaller explosions. The SPE results also show little magnitude dependence and good separation from earthquakes above 4 Hz in the P/S discriminant, which appears to be consistent with the relatively constant P/S values observed for the DPRK tests at regional stations such as MDJ. The SPE results show very good correlation between shots of different sizes and depths, and we can use the spectral models to correct for corner frequency effects. We are examining DPRK correlation behavior in light of these SPE results.

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Relative Energy and Aperture Estimation of the Five Explosions in North Korea

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According to the calculation, the latest nuclear explosion occurred in North Korea had the largest energy at the frequency of 0.1-3 Hz, and in the frequency higher than 3 Hz, the latest event had the same energy with the ones in Jan. 2016, the one in 2013 and even the one in 2009. At 2 Hz, the ratio of the event occurred on Sep. in 2016 to other four events are 40.1, 4.7, 2.0, 1.8 respectively, which have little difference with the results of Wen Lianxing 2016 group, who gave the 17.8kt, 11.3kt, 12.2kt , 7kt, 0.48kt for the five events, and the ratios are 37.1, 2.5, 1.5, 1.6 respectively. According to the calculation, the maximum coefficients of E1609 and E06, E09, E13, E16 is 0.88, 0.98, 0.94, 0.98 in vertical direction. According to Fuqing array-Zhangzhou array analysis in China and the research results of Ingate(1985) and Rindal(1982), we concluded that the aperture of the five events is no large than 3km, the distance of the latest two events is no longer than 1km.

Cross Comparison of Five DPRK Events Using Seismic Data of the International Monitoring System

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The seismic network of the International monitoring system of the Comprehensive nuclear-test-ban Treaty Organization detected seismic signals from five declared underground tests conducted by the DPRK in October 2006, May 2009, February 2013, January and September 2016. These data allow thorough comparison of relative amplitudes and frequency content of detected signals as well as event locations and magnitudes obtained using standard methods adapted at the International Data Centre (IDC) and several techniques based on waveforms cross correlation, which are under development at the IDC. Seismic signals from the bigger events provide high quality waveform templates for detection of missed arrivals from smaller events at less sensitive/remote IMS stations and possible aftershocks with magnitudes by two-to-three units lower than the DPRK events themselves.

Comparative Source Analysis of the DPRK Nuclear Events at Regional Scale: What We Can Learn About the Explosive Nature of the Events from Moment Tensor Inversions and MSVMAX

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The Democratic People's Republic of Korea (DPRK) triggered five confirmed nuclear tests between 2006 and September 2016. These events recorded at regional and teleseismic distances show great similitudes in their waveform content indicating that they are collocated and have similar source description. Using the available regional data and identical processing parameters, we present a comparative analysis of the moment tensor inversions to explore the relative differences among the five events, especially in terms of seismic moment and source decomposition. The collocated sources and similar station coverage highlight the relative source parameters without taking into account the structure at regional scale. The explosive nature of the sources is confirmed by this means. The inversion of the M5.4 earthquake in September 2016 in South Korea using a similar inversion scheme allows us to verify the stability of the inversions and the resulting source decompositions.

In addition, other techniques are used to determine the anthropogenic nature of the sources such as the MSVMAX approach. The study of the differential surface wave amplitudes (and magnitudes) recorded at the regional stations provide useful information regarding the complexities of the sources.

Here, we present results from moment tensor inversions and MSVMAX calculations on the DPRK nuclear tests and show that the explosive nature of the source is successfully revealed. Discussion is provided regarding non-isotropic radiation at the source in regional scale and potential path effects.

Application and Validation of a Relative Relocation Technique for Explosion Monitoring

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Relative arrival times have been used in the past to produce relative relocations of earthquakes and explosions. Precise relocations of explosions have value in the context of the Comprehensive Nuclear-Test-Ban Treaty on-site inspection when data are available for a previous event. The Democratic Peoples Republic of Korea (DPRK) has now conducted 5 declared nuclear tests from 2006-2016. After the declared test in 2009, many researchers applied relative relocation techniques to improve the accuracy and precision of the seismic event locations. Relative relocation methods require multiple events at the same location in order to utilize the differential arrivals between events. There are few locations in which such a scenario takes place with the same source type and similar location. However, there is still the overall unknown of the exact ground truth location for these events. We will demonstrate the application of a straight-forward master event methodology for doing relative relocations for DPRK events, and validate this methodology using a data set where we precisely know the locations of multiple, similarly-located explosive events with arrivals from common stations. Taking advantage of readily available waveforms, we are able to make relative picks for many stations at local, regional, and teleseismic distances, depending on the particular event and data set. Waveforms are manually-aligned on the first few cycles in order to match the initial arrival information. We will compare the relative relocations with those obtained using more recent techniques that involve simultaneous inversion of data from multiple events. The application of the standard master event method consistently provides high relative accuracy and precision, even when the master and test events are separated by tens of kilometers.

SSA-ESC Joint Session on Advances in Geotechnical Borehole Arrays, Data and Analyses

Poster Session · Wednesday 19 April ·

OTNX—A 3D Seismic Observatory for a Geothermal Drilling and Permeability Stimulation Experiment

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We began a project to image geological structure and monitor potential induced seismicity for a geothermal permeability stimulation experiment. The study site is located on the west side of Helsinki, Finland, on Otaniemi Peninsula. We have developed and implemented a (1) 3D arrangement of shallow and deep borehole seismic stations and (2) both passive and active seismic monitoring for this project. The data were collected in near-real time at a central site at the Otaniemi District Heating Plant.

A unique instrumentation aspects of our project were the installation of both an near-surface network and vertical array of stations. The project includes not only passive observation of the stimulation, but also reflection imaging using air hammer drilling noise. This signal was recorded from surface to several km depth.

The near surface net includes 10 stations with new, slim-line, 70 mm diameter 4.5 Hz borehole sondes with tilt tolerance of 12 degrees. These stations were installed in boreholes ranging from 350 to 1200 m in depth. The drill noise was observed with a vertical array of 24 levels of 3-C 15 Hz equally spaced in a 1840 m deep borehole. In the hard basement rocks that outcrop over the entire study area we were able to record a surprising variety of man-made noise and drilling related seismicity—all in the M~0 range.

We view the OTN project as part of an advanced seismic monitoring R&D effort, one aimed at realizing relatively broadband and cost effective borehole instruments and subsurface imaging procedures. We are working toward slim (50 mm diameter) instruments that can cover 10s of seconds to hundreds of Hz, deployable in deep, low cost, PQ (60 mm) boreholes with moderate tilts.

The Evolution of Excess Pore Pressure Generation and Dissipation: Observations from the Wildlife Liquefaction Array

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Unique dense observations of excess pore pressure generation and dissipation during earthquakes are presented from multiple sites within ~100 meters of each other in the confined 5-meter thick silty sand layer at the Wildlife Liquefaction Array (WLA), Imperial Valley, California. In what is the most densely instrumented liquefaction array anywhere in the world, continuous recordings of acceleration and pore pressure are providing in situ empirical evidence documenting the range of ground motion and dynamic strain levels at which the onset excess pore pressure and nonlinear soil behavior begins, augmenting previous case history data, and cyclic tri-axial and centrifuge laboratory testing.

The observations with depth within the liquefiable layer shows the excess pore pressure develop quickly at the top of the layer just below the impermeable clay cap, and then migrate towards the bottom of the layer as the ground motions subside and the pressure dissipates over the course of minutes to hours depending on the level of ground motion. Confirmation of this behavior is provided by monitoring multiple locations within ~100 meters of each other, with 8 transducers at one location and 5 transducers at a second location (both operating for more than a decade now), and 5 transducers at a third location (operating since 2014). The 5 sensors at the third location densely cover the upper two meters of the liquefiable layer, while the sensors at the other two locations sample the top, middle, and bottom of the layer. We will present a comparison of these recordings to demonstrate the spatial variability both with depth in the liquefiable layer as well as within the 100-meter areal distance at the field site. This spatial variability is analyzed with respect to both the fine-scale heterogeneous soil properties (percent fines, relative density, saturation), and also with respect to installation methods and site improvements to potentially increase liquefaction resistance.

The Mw7.8 Kaikoura Earthquake

Poster Session · Wednesday 19 April ·

Source Characteristics of the 2016 Kaikoura and Te Araroa, New Zealand, Earthquake Sequences from Regional Moment Tensor Analysis

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New Zealand experienced two major earthquakes during the second half of 2016. On 01 September the moment magnitude (M_w) 7.1 Te Araroa earthquake occurred off the northeast coast of the North Island, and was followed by the 13 November M_w 7.8 Kaikoura earthquake along the northeast coast of the South Island. Regional moment tensor analysis has been carried out to study the source characteristics of the aftershock sequences for both earthquakes. The Kaikoura earthquake was a complex event involving a number of strike-slip and reverse faults rupturing over a distance of ~180 km, and caused heavy damage over a widespread region along with two fatalities. More than 165 regional moment tensor solutions have been calculated for the Kaikoura aftershock sequence with M_w 3.7–6.5, including four with $M_w \geq 6.0$, and the focal mechanisms are a mixture of strike-slip and reverse faulting reflecting the complexity of the main rupture sequence. The majority of the aftershocks are located northeast of the epicentre, consistent the direction of rupture propagation. While the overall number of strike-slip and reverse faulting mechanisms are roughly equal, the southern region of the aftershock zone has a higher number of reverse faulting mechanisms and the northern region has a higher number of strike-slip faulting mechanisms. 25 moment tensor solutions have been calculated for the Te Araroa aftershock sequence with M_w 4.4–6.0. The focal mechanisms are consistently normal faulting, with the vast majority having one high angle east-dipping fault plane and one low angle west-dipping fault plane, similar to the mainshock. A M_w 5.8 foreshock occurred ~18 hours prior to the mainshock with a similar mechanism to the aftershocks.

Surface Rupture and Slip Distribution of the 2016 Mw7.8 Kaikoura Earthquake (New Zealand) from Optical Satellite Image Correlation Using MicMac

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Remote sensing techniques, like optical satellite image correlation, are very efficient methods to localize and quantify surface displacements due to earthquakes. In this study, we use the french sub-pixel correlator MicMac (Multi Images Correspondances par Méthodes Automatiques de Corrélation). This free open-source software, developed by IGN, was recently adapted to process satellite images. This correlator uses regularization, and that provides good results especially in near-fault area with a high spatial resolution. We use co-seismic pair of ortho-images to measure the horizontal displacement field during the recent 2016 M_w7.8 Kaikoura earthquake. Optical satellite images from different satellites are processed (Sentinel-2A, Landsat8, etc.) to present a dense map of the surface ruptures and to analyze high density slip distribution along all major ruptures. We also provide a detail pattern of deformation along these main surface ruptures. Moreover, 2D displacement from optical correlation is compared to co-seismic measurements from GPS, static displacement from accelerometric records, geodetic marks and field investigations. Last but not least, we investigate the reconstruction of 3D displacement from combining InSAR, GPS and optic.

Imaging the 2016 Mw 7.8 Kaikoura, New Zealand Earthquake with Teleseismic P Waves: A Cascading Rupture across Multiple Faults

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The dextral strike-slip Marlborough fault system (MFS) of South Island, New Zealand, near the town of Kaikoura, comprises a series of NE-SW striking faults and links two oppositely verging subduction zones—the Puysegur and Hikurangi. The MFS was struck by a M_w 7.8 earthquake on November 13, 2016. Here the MW 7.8 Kaikoura, New Zealand earthquake was investigated using teleseismic P-waves. Back-projection of high-frequency P-waves in two frequency bands from two regional arrays shows unilateral rupture of at least three southwest-northeast striking faults with an average rupture speed of 1.4-1.6 km/s and total duration of ~100 s. Guided by these back-projection results, 33 globally distributed low-frequency P-waves were inverted for a finite-fault model (FFM) of slip. The FFM showed evidence of several subevents, however it lacked significant moment release near the epicenter, where a large burst of high-frequency energy was observed. A local strong-motion network did in fact record strong shaking near the epicenter, hence for this earthquake the distribution of back-projection energy is superior to the FFM as a guide of strong shaking. For future large earthquakes that occur in regions without strong motion networks, initial shaking estimates should incorporate constraints from back-projection in addition to FFMs.

Advances in Seismic Full Waveform Modeling, Inversion and Their Applications

Oral Session · Thursday 20 April · 8:30 AM · Governor's Square 15

Session Chairs: Nian Wang, Xueyang Bao, Dmitry Borisov, and Youyi Ruan

3D Ground Motion Simulation of the Ladysmith Earthquake for Kinburn Basin

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Finite Difference technique (AWP-ODC program) was used to model the Kinburn basin in Ottawa, Canada, with a very high (~20) shear-wave impedance contrast between bedrock and soil in comparison to typical impedance contrasts of 3–5 in many other places. Detailed geophysical information was used to model the study basin. The recorded May 17th, 2013 Ladysmith earthquake of M4.6 with different suggested focal mechanisms was used as the seismic source to investigate the 3D basin behaviour. The linear viscoelastic ground motions for the frequency range of 0-1 Hz were used for the modeling. Comparison between recordings from the Ladysmith earthquake and simulation results suggests that the focal mechanism as described by Ma and Audet (2014), provides the best results in time and frequency domain. The simulation proves the role of depth and shape of a basin in ground motion amplification.

Keywords: staggered-grid finite difference scheme, Kinburn basin, Ladysmith Earthquake.

Full Waveform Modeling with Mesh Refinement in SW4

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In this talk we discuss how mesh refinement is implemented in the seismic wave propagation code SW4. Block-structured mesh refinement allows the grid size to approximately follow the seismic velocity structure of the Earth, thus allowing higher frequency content to be modeled with the same computational resources. SW4 is a parallel, open-source, finite difference code for regional ground motion simulations. It is based on 4th order accurate difference stencils that satisfy the principle of summation-by-parts, which guarantees energy stability of the numerical solution. Across mesh refinement boundaries, the energy stability is retained by using special interpolation and restriction stencils. The energy stability holds for both elastic and visco-elastic material models. After verifying the accuracy of the implementation on canonical test problems, we demonstrate how mesh refinement allows the frequency content to be increased in full waveform modeling of seismic events in the San Francisco bay area.

Three-Dimensional Ground Motion Simulations of Moderate Earthquakes and Large Scenario Ruptures in the San Francisco Bay Area

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We are running three-dimensional (3D) ground motion simulations for earthquakes in the San Francisco Bay Area (SFBA). The current best representation of earth structure in northern California is from the United States Geologic Survey (USGS) 3D model of the region used in previous investigations (*e.g.* Rodgers *et al.*, 2008; Aagaard *et al.*, 2010). We are running simulations of moderate (MW 3.5-5.5) earthquakes to evaluate the USGS 3D model and large (MW 5.5-7.5) scenario ruptures to quantify hazard and risk. Ground motions are simulated with SW4, LLNL's open-source anelastic finite difference code for seismic simulations. SW4 has many desirable features for earthquake modeling including attenuation, surface topography and mesh refinement. Moderate events are well recorded by permanent networks operating in the region and have reasonably good constraints on source parameters. For these events, we compare observed and synthetic waveforms to quantify how well the 3D model predicts ground motions as a function of path and frequency content. Previous investigations showed that the 3D model can predict low-frequency features in the data (1 Hz), however higher frequency details will require improvements to the model, including smaller scale structure. This effort lays the ground work for possible future waveform tomography to improve the 3D model of the SFBA. We are also modeling large scenario earthquakes, with emphasis on the Hayward Fault, which presents the greatest seismic hazard to the region. We are comparing computed ground motions with Ground Motion Prediction Equations (GMPEs) to explore consistency of simulations with empirical models heavily used in the earthquake engineering community. For these simulations, we want to include the highest possible frequencies of interest to engineers (5 Hz or higher). Consequently, we are running massively parallel simulations on 100,000's of cores or more. Such large simulations are driving improvements to SW4.

Investigation of Scattered Wavefield by Using Full-Wave Simulations

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Seismic wave amplitudes are affected by scattering which redistributes the energy of waves in a medium with distributed heterogeneities. Classic seismic theories, based on ray theory or single forescattering finite-frequency theory, fail in the prediction of coda waves excited by backscattering. Wave-equation-based numerical treatments, *e.g.*, the 3D finite-difference method, account for the effects of multiple fore/back scattering and phase conversion, and thus can be used to compute the complete wavefield. New insight of the variation of seismic amplitudes can eventually improve the accuracy and resolution of seismic tomography and source moment estimation.

In this study, we simulate and measure the amplitude fields of teleseismic Rayleigh waves traveling through a vertical velocity discontinuity to highlight the effect of backscattering. The amplitudes drastically change at the discontinuity, and oscillate strongly on the incident side with a wavelength depending on the wave period and incident angle, indicating that wave energy is redistributed by backscattering. Based on the simulated full-wave synthetics, we derive an approximate description of backscattering effect using a single-reflection plane wave model, which can help better using surface wave amplitudes in high-resolution seismic imaging for both velocity and intrinsic attenuation.

We also simulate the full-wave field of the recent DPRK nuclear test by including small-scale random heterogeneities and high-resolution surface topography. Synthetic seismograms exhibit high-frequency Pg, Lg, and coda waves, as well as transverse component P-waves, all significantly enhanced by fore/back scattering. We compare observations to the synthetics based on distributed random heterogeneities generated from the power-law scaling of structural wavelength in northeastern Asia. This comparison will provide constraints on the distribution of random heterogeneities and its effects on waveforms and source characterization.

Detection of Voids Using 3D Elastic Full Waveform Inversion

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Detection of voids such as clandestine tunnels or conduits using seismic methods in the near surface (within the first tens of meters) is a challenging problem. One of the difficulties is that the surface waves are not well separated from the body waves, which makes conventional methods such as seismic reflections or refractions methods not effective. On the other hand, the spectral analysis of surfaces waves can provide only 1D profiles of the subsurface. Furthermore, high-frequency seismic energy required for detecting small objects is rapidly attenuated within the weathering layer.

In this proof-of-concept study, we use elastic full waveform inversion to obtain high-resolution three-dimensional maps of voids by simultaneously inverting the whole content of seismic records. An active source survey with different combinations of sources and several lines of multicomponent receivers was acquired over an existing tunnel. The tunnel is 1.5-m wide, 2-m tall and the top of the tunnel is located at about 10 m below the ground surface. Our synthetic and field experiments showed that a low frequency content (below 20 Hz) carries a significant amount of back-scattering surface wave energy from the tunnel, which plays a major role in locating the anomaly. In our inversion results the void itself can be observed as an elongated low S-wave velocity anomaly, and the Vp/Vs ratio helps to reduce the artifacts and further sharpens the structure of the tunnel. We demonstrate that a combination of vertical sources and vertical geophones, which is a typical combination of sources and sensors used in geophysical surveys, can produce adequate results for a detailed image of significant shallow subsurface anomalies. We also demonstrate that using shear sources and horizontal geophones provides additional clarity and definition of the subsurface anomalies.

Structure and Physical Characteristics of the Southern Hikurangi Subduction Zone Derived from Seismic Full Waveform Imaging

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Slip behavior along the megathrust has been shown to be closely related to the evolution of pore fluid pressures at the plate interface. Fluids are released within the subduction zone due to mineral dehydration and tectonic loading and may play an important role in the onset of seismogenesis, in the updip limit of earthquake rupture and transition to aseismic slip. Moreover, various modes of fault slip along the megathrust have been associated to elevated pore fluid pressures including very-low-frequency earthquakes, episodic tremor and slow sleep events.

In recent years, seismic attributes and velocity images obtained from active source seismic data have provided a promising opportunity to infer porosity, fluid pressure and effective stress at the plate interface and within the overlying accretionary wedge. However, due to the limitations underpinning traditional velocity analysis and ray-based tomography approaches, the resolution and accuracy of existing velocity models remain limited. Full waveform inversion (FWI) is a powerful alternative to those traditional approaches. It uses the phase and amplitude information contained in seismic data to produce structurally accurate high-resolution physical models of the Earth.

Here, we applied elastic FWI along a 90-km-long 2D multichannel seismic profile crossing the southern Hikurangi convergent margin, New Zealand. Our processing sequence included: (1) a downward continuation of the seismic data to the seafloor, (2) 2D traveltime tomography, and last (3) full waveform inversion of both refracted and reflected energy. Our final model provides exceptional constraints concerning the structure and physical properties of this convergent margin with sufficient details to interpret and model fault zone physical properties, hydrogeology and a possible origin for hydrocarbon accumulation and gas hydrate formation.

Lithospheric Foundering and Underthrusting Imaged beneath Tibet Revealed by Adjoint Tomography

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Long-standing debates exist over the timing and mechanism of uplift of the Tibetan Plateau, and, more specifically, over the connection between lithospheric evolution and surface expressions of plateau uplift and volcanism. Our new tomographic model from adjoint tomography reveals a T-shaped high wave speed structure beneath South-Central Tibet, interpreted as an upper-mantle remnant from earlier lithospheric foundering. Its spatial correlation with ultrapotassic and adakitic magmatism supports the hypothesis of convective removal of thickened Tibetan lithosphere causing major uplift of Southern Tibet during the Oligocene. Lithospheric foundering induces an asthenospheric drag force, which drives continued underthrusting of the Indian continental lithosphere and shortening and thickening of the Northern Tibetan lithosphere. Surface uplift of Northern Tibet is subject to more recent asthenospheric upwelling and thermal erosion of thickened lithosphere, which is spatially consistent with recent potassic volcanism and an imaged narrow low wave speed zone in the uppermost mantle.

Full 3D Tomography Based on the Discontinuous Galerkin Method

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In this study, we present applications of full 3D tomography (F3DT) based on the discontinuous Galerkin (DG) method to both exploration scale seismic refraction data and continental scale earthquake data. The seismic refraction profile was collected over a critical zone site in Blair-Wallis watershed, Wyoming. Multiple transects of geophysical data including seismic refraction data and electrical resistivity data were collected. The seismic profile in this study is 240 m long and was acquired using Geometrics Geode systems with 40 Hz vertical-component geophones spaced at 2.5 m. A 12-pound steel sledgehammer produced the seismic source by striking a stainless steel plate on the ground. Our image shows small-scale near-surface heterogeneities and important structural features, such as the bedrock-core-stones and the sharp velocity boundaries at the chemical weathering front. The detailed subsurface structures will help us build conceptual models of the Critical Zone. The Vp / Vs ratio calculated from our velocity models show a truly remarkable anti-correlation with the electrical resistivity image of the same cross-section. At the continental scale, we applied our technique to image the upper-mantle structure of China using seismic waveform data from the national stations and regional stations in the Chinese National Digital Seismic Network (CNDSN). At the current stage, we have included about 18,000 seismograms recorded at 110 CNDSN stations from 383 earthquakes with moment magnitude larger than 5.5 between 2003 and 2012 in our modeling volume. About 550,000 frequency-dependent group-delay misfits measured at 31 frequencies between 5 mHz and 35 mHz were inverted in the latest iteration. After 5 iterations, the objective function, defined using the summation of the squares of the group-delay misfits, has been reduced by around 45%. The updated seismic velocity model shows excellent correlation with known geology.

Advances in High Resolution Global Tomography of the Earth's Deep Mantle Using Numerical Wavefield Computations

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We have recently constructed the first global whole mantle radially anisotropic shear wave velocity model based on time domain full waveform inversion and numerical wavefield computations using the Spectral Element Method (French *et al.*, 2013; French and Romanowicz, 2014, 2015). Salient features of this model are broad chimney-like low velocity conduits, rooted within the large-low-shear-velocity provinces (LLSVPs) at the base of the mantle, and located in the vicinity of major hotspots. The robustness of these features is confirmed through several non-linear synthetic tests.

We discuss the characteristics of these plumes and their consequences for deep mantle dynamics. In particular, their morphology indicates a significant change in rheology across the top of the lower mantle. Also, the roots of these not-so-classical "plumes" are regions of more pronounced low shear velocity. While the detailed structure is not yet resolvable tomographically, at least two of them contain large (>800 km diameter) ultra-low-velocity zones (ULVZs), one under Hawaii (Cottaar and Romanowicz, 2012) and the other one under Samoa (Thorne *et al.*, 2013). Through 3D numerical forward modeling of Sdiff phases down to 10s period, we show that such a mega ULVZ also exists at the root of this plume. Because of the intense computational effort required for forward modeling of trial structures, to first order this ULVZ is represented by a cylindrical structure of diameter ~900 km, height ~20 km and velocity reduction ~20%.

To further refine the model, we have developed a technique which we call "tomographic telescope", in which we are able to compute the teleseismic wavefield down to periods of 10 s only once, while subsequent iterations require numerical wavefield computations only within the target region, in this case, around the base of the Iceland plume. We briefly introduce the method and preliminary results of its implementation.

Global Adjoint Tomography

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Elastic heterogeneity, anisotropy, and anelasticity provide important constraints on the state of Earth's interior. Resolving the fine structure of these properties in seismic tomography requires accurate simulations of seismic wave propagation in complex 3D Earth models. On the supercomputer "Titan" at ORNL, we are employing a spectral-element method to accurately calculate theoretical seismograms. They are combined with an adjoint method to obtain Frechet derivatives for model updates. In a pilot study, Bozdag *et al.* (2016) iteratively determined a transversely isotropic earth model, GLAD_M15, using 253 carefully selected events. To achieve higher resolution, we have expanded our database to more than 4,220 events in the magnitude range M_w 5.0–7.0 from 1995 to 2014. We are experimenting with a hybrid method of source encoding and stochastic optimization by drawing subsets of 10-30% of the entire database to achieve faster convergence while reducing computational costs. For good coverage of the deep mantle, we randomly draw events from three categories: deep (>500 km), intermedia and shallow (<150 km) earthquakes with a ratio of 5:3:7. Using synthetic seismograms recalculated in the latest model with updated CMT as reference, we select time windows that show good agreement with data and make measurements. From the measurements we further assess the overall quality of each event and station and exclude bad measurements based upon certain criteria. Using very conservative criteria, we have assimilated more than 8.0 million windows from 1,200 earthquakes in three period bands to fuel the first few iterations. In the inversion, dense array data (*e.g.*, USArray) usually dominate model updates. We introduced weighting of stations and events based upon their geographical distribution to strike a balance between contributions from dense arrays and sparse ocean island stations in the Frechet derivatives. We present a summary and preliminary results of the global tomography

Characterization of the Stress Field and Focal Mechanisms for Earthquake Source Physics and Fault Mechanics

Oral Session · Thursday 20 April · 1:30 PM · Plaza D

Session Chairs: Patricia Martínez-Garzón, Jeanne L. Hardebeck, Martha Savage, and Marco Bohnhoff

Heterogeneities of Stress and Strength and its Relationship With Induced Seismic Activities Associated With the Tohoku-Oki Earthquake

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After the 2011 M9 Tohoku-Oki earthquake, a great number of earthquakes are induced even in the inland regions separated by more than several hundred kilometers from the large slip area. Because of the very large size of this earthquake, it is expected that we can investigate detailed characteristics of the induced seismicity, which will help improve our understanding of its generation mechanism. In this study, we investigated the seismicity, focal mechanisms and stress fields in northeastern Japan to understand the causes of the induced seismicity.

On the spatial distribution of the induced seismic activities, they tend to concentrate in several locations as clusters rather than distribute widely. Many of these clusters in northeastern Japan are located in regions where seismicity was inactive before the 2011 earthquake. Stress tensor inversion results before and after the earthquake are significantly different from each other. In addition, the stress orientations after the earthquake are quite similar to those of the static stress change [Yoshida *et al.*, 2012]. This suggests the following two possibilities. a) Stress orientations rotated after the 2011 Tohoku EQ by its static stress change. b) Static stress triggered earthquakes in regions where stress orientations are different from the typical stress orientation in the surrounding areas but is consistent with the static stress change.

To distinguish these two possibilities, we reinvestigated the stress orientations before the Tohoku-Oki earthquake by using data of Tohoku University for the period of 1980-2002 and those by Yoshida *et al.* (2015a). In the arc and the backarc in northeastern Japan, it has been known that the compressive stress orientations are oriented WNW-ESE homogeneously in space. However, several regions were detected, where stress orientations are different from the regional orientation. Some of the regions have favorable stress orientations for the induced earthquake focal mechanisms there. Thi

What Makes Seismic Events Grow Big?: Insights from the Analysis of *b*-Value and Fault Roughness Variations During Laboratory Stick-Slip Experiments

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Earthquake magnitude prediction is a fundamental goal in seismology but the many inherently non-linear processes that govern fault-system behavior complicate magnitude forecasts. In contrast, the potential of seismic events to grow to relatively larger sizes can be evaluated statistically by variations in the Gutenberg-Richter *b*-value, which describes the proportion of small to large magnitude events. The *b*-value is thought to vary significantly if stress changes are large; however other parameters such as crustal heterogeneity may also contribute to such variations. We examine the influence of fault roughness on *b*-value, focal mechanisms and spatial localization of acoustic emission (AE) events in laboratory stick-slip experiments. Since both roughness and stress variations are expected to influence b, we strive to isolate roughness contributions by analyzing only AE events close to peak stress. The experiments are conducted on Westerly granite surfaces with a spectrum of roughness from planar, polished to irregular, fractured surfaces. Differences in roughness strongly influence the spatial distribution of AE events so that roughened and fractured surfaces exhibit spatially more distributed seismicity. Rougher faults also lead to more heterogeneous near-fault stresses, inferred from focal mechanisms of AE events, while focal mechanisms of smooth surface are largely aligned with the applied macroscopic stress field. Our results suggest that an increase in fault-roughness changes AE event characteristics in three ways, namely rougher faults are associated with: 1) more distributed seismicity within the fault damage zone, 2) higher b-values and 3) a high degree of variability in focal mechanisms, likely due to heterogeneous, underlying stress fields at the micro-scale. Thus, seismic events are expected to preferably grow to larger sizes if they nucleate on smooth faults and within a more homogeneous stress field.

Delineating the Seismic Record of Off-Fault Deformation near the Southern San Andreas Fault Using Crustal Deformation Models

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Some recorded earthquakes along the southern San Andreas Fault (SAF) show focal mechanisms that disagree with the expected long-term dextral loading of the fault. Non dextral focal mechanisms along the southern SAF may be related to the local fault complexity, which can generate significant off-fault deformation. If this off-fault strain has different principal stress orientation than the regional loading, it could produce non-strike-slip events that are recorded in the seismic catalog. To investigate the off-fault deformation signal in the seismic catalog, we compare the focal mechanism inversions to two end member crustal deformation models representing 1) the interseismic loading of the southern SAF system and 2) the steady-state deformation across multiple earthquake cycles. While the interseismic models simulate the overall loading of faults between earthquakes, the steady-state models simulate crustal stresses that are not relieved by earthquake events. The accumulation of this residual stress can produce permanent off-fault deformation such as evidenced by microseismicity. The 3D models include >30 regional faults from the SCEC Community Fault Model and has been validated with good match to geologic slip rates. We compare the slip rakes from high quality focal mechanisms to the model predicted slip sense (Aphi) calculated from stress tensors at the locations of each focal mechanism. Within regions near fault tips, bends along faults and where faults have significant slip gradient the focal mechanism rakes have better match to stresses within the steady-state models that capture off-fault deformation than the stresses within the interseismic models that simulate long term dextral loading. These results suggest that within regions of high fault complexity, the seismic catalog may include events that record permanent off-fault deformation rather than long-term fault loading, compromising the effectiveness of the seismic catalog in assessing seismic hazard.

Spatiotemporal Variations of Seismic B-Value along the North Anatolian Fault Zone in Northwest Turkey

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We studied spatiotemporal b-value variations along the North Anatolian Fault Zone (NAFZ) in northwestern Turkey with a focus on the combined 1999 Izmit and Düzce rupture and the eastern Sea of Marmara. We used a local seismicity catalog of the Izmit-Düzce region and the eastern Sea of Marmara and consistently calculated moment magnitudes to ensure a homogeneous dataset and applied strict quality criteria. This allows studying variations of b-values throughout the region and time. With a standard gridding technique we calculated b-value maps, depth sections and time series for different regions and times (pre-, inter-, and post-seismic) and observe a very heterogeneous b-value distribution in the study area. The variety of b-value observations cannot be interpreted unambiguously, given that the b-value most likely depends on a combination of fault-zone characteristics like local stress conditions, heterogeneity of the crust and damage distribution. By presenting a comprehensive set of possible interpretations we point out that a biased discussion of the results towards stress or another individual parameter may lead to erroneous conclusions. Furthermore, the applied data discretization scheme influences the appearance of the final b-value distribution leading to potential misinterpretations.

Using Coseismic Slip Models, Focal Mechanisms, and Topography to Constrain Seismogenic Stresses

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Stress is a fundamental physical control on crustal deformation and earthquake slip. Considerable effort has been devoted to the inference of stress from fault slip data over the last several decades. In the last few years, we have undertaken to estimate the stresses that led to several large earthquakes within a Bayesian estimation framework and using all available fault slip data. Using slip data alone, either focal mechanisms or coseismic slip models, the orientations of principal stresses are relatively well constrained. The larger the disparity of slip data, due to variations in focal mechanism types and/or differences in slip directions and fault orientations in coseismic slip models, the tighter the constraints on the posterior stress solution. If the slip data is insufficiently disparate, there is an ambiguity between the intermediate compressive stress and either the most or least compressive stresses. On the other hand, if too disparate, the posterior collapses to a delta function, with only a single stress orientation consistent with the observed data. In contrast to the directions, the relative magnitudes of the principal stress are more weakly constrained and the absolute magnitude of stress can not be determined. Consideration of the stresses due to topographic loading along with the slip data can greatly increase the resolution of the relative magnitudes of the principal stresses, and bracket the absolute stress magnitude. In this presentation, we discuss how our method addresses some of the challenges associated with the inference of stress from slip data, introduce a radial basis function-finite difference method to calculate topographic stresses, and use information criteria to judge the support of disparate slip data for variations in stress in space and/or time. We also show results from several of our focus regions, and discuss interactions between topographic stresses and heterogeneities in fault slip during large earthquakes.

Imaging Rupture Threshold Variations along Subduction Faults

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Subduction faults accumulate stress during long periods of time and release it suddenly, during earthquakes, when the stress reaches a threshold. This threshold is called shear strength and its distribution controls the occurrence and magnitude of earthquakes. We use a 2D analytic model [Bletery *et al.*, Science, 2016] and estimates of the stress field orientation in Japan [Hardebeck, Science, 2015] to image the distribution of shear strength along a subduction fault. We further image the spatial variations of shear strength by computing its gradient. We find that the M_w9.0 2011 Tohoku mega-earthquake ruptured a fault portion of particularly homogeneous shear strength. Shear strength is more likely to be exceeded simultaneously over large areas if its spatial distribution is homogeneous. Imaging spatial variations of shear strength along large faults may reveal the location of possible future large earthquakes.

Correlations Between Stress Orientation and Seismic Coupling in Subduction Zones

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Subduction zone megathrust faults range from being completely locked to continuously creeping. The locked regions pose the greatest seismic hazard because they accumulate stress that is often released in large earthquakes. We find that the creeping versus locked behavior of subduction zone megathrust faults correlates with the apparent frictional strength of these faults as inferred from their orientation in the regional stress field inverted from moment tensors. Our global investigation of stress orientations in subduction zones finds that the average angle between the maximum compressive stress axis and the subduction interface is significantly correlated with the average seismic coupling. The most coupled subduction zones exhibit a maximum compressive stress axis at angles of 20°-45° to the megathrust, well oriented for failure with a typical laboratory friction coefficient. The least coupled zones have angles in the range of 40°-65°, less well oriented, and implying reduced frictional strength. Comparisons between existing maps of stress orientations and geodetically-derived coupling models for the Japan Trench show a similar correlation: the locked patches on the megathrust fault are on average at lower angle to the maximum compressive stress axis than the creeping patches. Our new finer-scale model of stress orientations in the Japan Trench reveals additional complexity. Much of the plate interface exhibits angles near 30°, consistent with the overall coupling of the Japan Trench in the global subduction zone context. Exceptions are shallow zones of geodetically-inferred creep and deep locked zones, which are at angles closer to 45°, suggesting they are weaker. Our observations, excluding the deep locked zones of the Japan Trench, suggest that creeping megathrust faults have on average lower frictional strength than locked megathrust faults.

Constraining Uncertainties of Stress Tensor Inversion with Data-Driven Focal Mechanism Cluster Analysis

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Earthquake focal mechanism solutions (FMS) form the basic data input for all common stress tensor inversion routines. In these applications the FMS data are usually binned spatially or in predetermined ranges of rake and dip based on expert elicitation. However, due to the significant increase of FMS data in the past decade an objective data-driven cluster analysis of FMS is now possible. We present the method ACE (Angular Classification with Expectation-Maximization) that identifies clusters of FMS without a priori information. The identified clusters can be used for the classification of the Style-of-Faulting and as weights for data binning in the FMS catalog.

As an application example we use ACE to identify FMS clusters according to their Style-of-Faulting that are related to certain earthquake types (*e.g.* subduction interface, strike-slip along major faults). We use the identified clusters and weights as a priori information for a stress tensor inversion for selected regions and show that uncertainties of the stress tensor estimates are reduced significantly.

A Refined Methodology for Stress Inversions of Earthquake Focal Mechanisms

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In this study we elaborate on an improved methodology for reliable high-resolution inversions of focal mechanisms to background stress field orientation and stress ratio R in two or three dimensions. The earthquake catalog is declustered to remove events likely affected strongly by local stress interactions rather than reflecting the large-scale background stress field. The declustered data are discretized with the k-means algorithm into groups containing a number of focal mechanisms between a minimum number Nmin and 2Nmin. Synthetic tests indicate that Nmin ≈ 30 provides stable inversion results under different stress regimes and noise conditions when R ≈ 0.5, while Nmin ≈ 45 is needed for R near 0 or 1. Additional synthetic tests compare the performance of selecting the fault plane of each focal mechanism using (a) the plane with lowest misfit angle between the slip vector from the focal mechanism and shear traction from the stress tensor and (b) the plane with highest instability coefficient representing proximity to the optimally oriented fault for given stress field and friction coefficient. The instability criterion is found to provide more accurate inversion results under all tested stress regimes, stress ratios, and noise conditions. The refined inversion methodology combines selecting fault planes using the instability criterion iteratively with a damped simultaneous inversion of different focal mechanism groups. Results characterizing neighborhoods of discretized domains merged during the damped inversion provide high-resolution information independent of the discretization. Some aspects of the methodology are illustrated with synthetic sets of focal mechanisms created under specified stress states, pore pressure and friction coefficients, as well as with focal mechanism data from the San Jacinto Fault Zone in Southern California.

Spatio-Temporal Variations of Stress Parameters in the San Jacinto Fault Zone

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We discuss stress parameters and seismicity in the San Jacinto Fault Zone based on a refined stress inversion methodology (Martínez-Garzón, 2016) employing a focal mechanism catalog for the years 2000-2015 (Yang *et al*. 2012, extended to 2015). The stress inversion provides the maximum horizontal compressive stress direction (SHmax) and the stress ratio parameter $R = (\sigma1-\sigma2)/(\sigma1-\sigma3)$. Potential temporal changes associated with the 2010 M_w 7.2 El Mayor-Cucapah earthquake are examined by analyzing two sub-catalogs for the years 2008-2009 and 2011-2012.

The obtained spatial distribution of stress parameters is in general in agreement with the tectonic setting and the regional geology. Clear variations of SHmax and R-value are observed with depth, reflecting overall changes from strike-slip towards transpressional and transtensional regimes. The R-value is lowest in the depth range 9 to 12 km representing transtensional stress regime. Furthermore, the R-value exhibits larger variations and SHmax rotates clockwise with increasing depth. The median rotation angle from the surface to 18 km in the entire examined region is 25 degrees.

The SHmax orientation along the fault remains generally the same before and after the El Mayor-Cucapah earthquake, showing oblique faulting in the Hot Springs and Trifurcation areas. The R-value remains about the same in the Hot Springs region but changes toward transpressional regime in the Trifurcation area after the El Mayor-Cucapah earthquake.

The derived stress parameters exhibit correlations with some fault properties and seismicity features. The initial results show significant correlations between the R-values and coefficients of friction selected by the stress inversion technique. The number of events in seismicity clusters at different locations correlates with the fault instability coefficient representing proximity to optimally oriented fault in the derived stress field. Updated results will be presented in the meeting.

Earthquake Complexities Revealed by Kinematic and Dynamic Modeling and Multiple Geophysical Data Sets

Oral Session · Thursday 20 April · 8:30 AM · Plaza D

Session Chairs: Wenyuan Fan, P. Martin Mai, and David D. Oglesby

Intraslab Rupture Triggering Megathrust Rupture Co-Seismically in the December 17, 2016 Solomon Islands Mw 7.9 Earthquake

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The December 17, 2016 Solomon Islands earthquake (M_w 7.9) initiated ~103 km deep in the subducting Solomon Sea slab near the junction of the Solomon Islands and New Britain trenches. Most aftershocks are located near the Solomon Islands plate boundary megathrust west of Bougainville, where previous large interplate thrust faulting earthquakes occurred on August 16, 1995 (M_w 7.7) and July 14, 1971 (M_w 8.0). Teleseismic body wave modeling indicates that the initial 30 s of the 2016 rupture occurred over depths of 90 to 120 km on an intraslab fault dipping ~30° to the southwest, almost perpendicular to the dipping slab interface. The next 50 s of rupture took place at depths of 32 to 47 km in the deeper (Domain C) portion of the overlying megathrust fault dipping ~35° to the northeast. This is the first well-documented case of intermediate depth intraslab faulting triggering large interplate faulting, and demonstrates an additional level of hazard from intermediate depth earthquakes. High triggering susceptibility in the region accounts for this compound rupture of two separate fault planes. A prior intraslab rupture in 2005 of comparable mechanism, seismic moment, and rupture dimensions to the intraslab portion of the 2016 event did not activate the megathrust, indicating that the additional 11 years of strain accumulation loaded the 1971/1995 rupture zones to near their critical failure stress, allowing triggering to occur.

Imaging Complex Fault Slip History of 2016 Taiwan and Japan Earthquakes with Geodetic and Seismic Data

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We made kinematic fault slip models for the complex fault ruptures for the February 2016 MeiNong earthquake in Taiwan and the April 2016 Kumamoto earthquake sequence in Japan, using combined analysis of of InSAR, SAR pixel offset tracking, GPS, and seismic waveforms. We used SAR data from the Copernicus Sentinel-1A and Sentinel-1B satellites and the JAXA Advanced Land Observation Satellite-2 (ALOS-2) satellite. We combine pixel offset tracking and burst overlap double-difference interferograms on ALOS-2 ScanSAR pairs, including the along-track component of surface motion, with SAR interferometry (InSAR) measurements in the radar line-of-sight direction to estimate all three components of the surface displacement for the events.

Joint inversion of S1A and ALOS-2 InSAR, GPS, and strong motion seismograms for the M_w6.4 MeiNong earthquake shows that the main thrust rupture with N61°W strike and 15° dip at 15-20 km depth explains nearly all of the seismic waveforms but leaves a substantial uplift residual in the InSAR and GPS offsets estimated 4 hours after the earthquake. We model this residual with slip on a N8°E-trending thrust fault dipping 30° at depths between 5-10 km. This fault strike is parallel to surface faults and we interpret it as fault slip within a mid-crustal duplex that was triggered by the main rupture within 4 hours of the mainshock. In addition, InSAR shows sharp discontinuities at many locations that are likely due to shallow triggered slip.

The Kumamoto earthquake sequence in Japan started with M_w 6.2 and 6.0 earthquakes on 14 April (UTC) followed on 15 April by the M_w 7.0 mainshock. JAXA acquired one ALOS-2 scene between the foreshocks and mainshock that enables some separation of the surface deformation. InSAR shows M6 foreshocks were deeper, while M7 mainshock ruptured surface. Main M7 rupture terminated at edge of Aso volcanic complex, possibly due to change in crustal structure.

Rupture Process of the 2016 Kumamoto Earthquake Revealed by Waveform Inversion with Empirical Green's Functions

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In this study, the rupture process of the main shock of the Kumamoto earthquake was investigated, with special reference to the generation of strong ground motions in the frequency range relevant to structural damage, based on the inversion of strong ground motions. Strong motion records in the near-source region were mainly used, because the authors were interested in the generation mechanism of damaging ground motions in the near-source region. Empirical Green's functions (EGFs) were used to avoid uncertainty in the subsurface structure model. Four cases of inversions were conducted using different combinations of small events to investigate the dependence of the inversion results on the selection of the small events. It was found that the dependence of the final slip distribution and the peak slip velocity distribution on the selection of the EGF events was basically small. The results clearly indicate that a region of significantly large slip and slip velocity existed approximately 15 km north-east of the hypocenter. No "asperity" existed between the hypocenter and Mashiki Town. Thus, it is not appropriate to interpret that the large amplitude pulse-like ground motion in Mashiki Town was generated by the forward directivity effect associated with the rupture of an asperity. As far as the source effect is concerned, the ground motion in Mashiki cannot be interpreted as the worst case scenario. On the other hand, the rupture of the "asperity" 15 km north-east of the hypocenter should have caused significantly large ground motions to regions close to the asperity. The significant damage to highway bridges in the region can potentially be attributed to the rupture of the asperity.

Directivity and Rupture Velocity of Small Earthquakes

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It is well known that many larger earthquakes have highly complex sources with significant variation in slip and stress drop over the rupture plane. As the quantity and quality of data increases, similar complexity is being observed in sources of well-recorded smaller earthquakes. We find evidence for both directivity, and variability of slip in earthquakes of M2-5 in a range of different settings, both tectonic and induced.

The EGF-based method developed by Abercrombie *et al*. 2017 to calculate and model source spectra also calculates source time functions (STFs). The approach includes strict selection criteria for EGFs, and stacks over them to stabilize the results. Azimuthal variation in the source can be retrieved for earthquakes with multiple EGFs, recorded at stations over a wide range of azimuth. The STFs (and corresponding source spectra) reveal that many small earthquakes involve regions of varying slip. Following Prieto *et al*. [2017] we systematically stretch the time-axis of STFs at each station in turn to find the best correlation between pairs of stations. This provides a measure of the azimuthal variation of the source duration, without the need to pick start and end points of the STFs. We then model this azimuthal variation in duration using bilateral and unilateral line sources to find which fits best, and the best fitting orientation.

To date, we have applied this approach to earthquakes from the Hikurangi subduction zone, New Zealand, two sequences of induced earthquakes in Oklahoma (Guthrie and Prague), and to the shallow tectonic sequence beneath Mogul, Nevada. For example, of the 40 best-recorded earthquakes in the Mogul sequence (M2.4-4) about half are modelled significantly better with a unilateral, rather than a bilateral source; minimum rupture velocity is ~0.4-0.7Vs. The line source orientations coincide well with nodal planes when a mechanism is available, enabling the fault plane to be identified.

Uncertainties in Teleseismic Rupture Models Using a Monte Carlo Approach: The Mw 7.3 Papanoa, Mexico Subduction Earthquake of 18 April 2014

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The use of teleseismic waveforms for the modeling of the extended properties of the earthquake source has become relatively common due to the general availability of worldwide digital broadband data. The results of these studies are used to characterize the earthquake source and to examine the potential for large, damaging earthquakes in seismically-active regions. However, the degree to which teleseismic rupture models represent the actual temporal and spatial distribution of the coseismic slip has not been fully evaluated. Uncertainties in the inferred slip models result from errors in the assumed fault parameterization, crustal structure and station distribution. In this study, we use a Monte Carlo procedure to examine the uncertainties in teleseismic finite-fault rupture models resulting from errors in the input fault parameters including the source geometry, the hypocentral depth and the rupture velocity. We apply the Monte Carlo procedure to the large M_w 7.3 interplate, thrust earthquake of 18 April 2014 in Papanoa, Mexico by considering the expected variations in the input strike, dip, rake, depth and rupture velocity. We conduct several hundred finite-fault inversions using 70 teleseismic P and SH waveforms to compute uncertainties in the slip amplitude resulting from errors in the input fault parameters. The Monte Carlo approach provides insight into the accuracy of teleseismic rupture models that would be useful for identifying realistic bounds on the properties of the earthquake source for the simulation of expected ground motions.

Multiscale Probabilistic Imaging of Tsunamigenic Seafloor Deformation During the 2011 Tohoku-oki Earthquake

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Inferring detailed earthquake source processes is often met with challenges in characterizing epistemic uncertainties and exploring nonunique model solutions. In the case of the great 2011 M_w 9.0 Tohoku-oki earthquake, the style of near-trench seafloor deformation and fault slip remains one of the least constrained source features, despite the wide range of available datasets and a myriad of source studies.

To explore this issue, we develop a probabilistic approach to image the spatiotemporal evolution of coseismic seafloor displacement from near-field tsunami observations alone. In a Bayesian framework, we sample ensembles of nonlinear source models parameterized to focus on near-trench features, adopting minimal a priori assumptions of model roughness and incorporating the uncertainty in forward modeling of dispersive tsunami waves in addition to nominal observational errors. Spatial smoothing of posterior solutions enables a multiscale analysis of the resolution and uncertainty, not only for the inferred source models, but also in explaining scale-dependent features in the waveform data.

Our models indicate that seafloor in the region of the earthquake was broadly uplifted and tilted seaward approaching the trench. Over length scales of ~40 km, seafloor uplift peaks at 5±0.6 m near the inner-outer forearc transition and decreases to ~2 m at the trench axis over a distance of 50 km, corresponding to a seafloor tilt of 0.06±0.02 m/km. Over length scales of ~20 km, peak uplift reaches 7±2 m at the similar location, but uplift at the trench is less constrained. While these results are qualitatively well supported by semi-analytical solutions derived in a quasi-static tsunami problem, the kinematic source models provide quantitatively improved estimates with tighter constraints. These probabilistic estimates allow for further interpretations of the near-trench coseismic slip deficit and plausible slip mode of the shallow subduction zone in this region.

The 2011 Mw 9.0 Tohoku Earthquake: Dynamic Rupture with Rupture Reactivation and Ground Motion Simulation

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Rupture reactivation may be a mechanical process of earthquakes exhibiting large slip, as was the case of the 2011 M_w 9.0 Tohoku Earthquake. The source features of this mega-event have been inferred by several kinematic inversions models (*e.g.* Lee et al, 2011) and backprojection techniques (*e.g.* Honda et al, 2011). These studies suggest the presence of two sequential rupture fronts starting at the same hypocenter area. Here we present the dynamic rupture model for this earthquake presented by Galvez *et al.* (2016), in which has been proposed a mechanical model that generates rupture reactivation governed by a slip-weakening friction with two sequential strength drops, the second one being activated at large slip. This friction model has been earlier proposed by Kanamori and Heaton (2000) suggesting that melting or fluid pressurization induced by frictional heating can further reduce fault strength at large slip. Such frictional behavior has also been observed in laboratory experiments (*e.g.* O'Hara *et al.*, 2006) and attributed to pressurization of fault-zone fluids by mineral decomposition reactions activated by shear heating, such as dehydration and decarbonation. Our dynamic rupture model is composed by asperities consisting of two main asperities constrained by source inversion models and several deep small asperities constrained by backprojection source imaging studies. This rupture model produces ground-motion patterns along the Japanese coast consistent with observations and rupture patterns consistent with a kinematic source model featuring rupture reactivation. Results suggest that the deep small asperities serve as a bridge to connect the two main asperities, and the rupture reactivation mechanism is needed to reproduce the observed ground-motion patterns as well as it may have provided a second breath to the rupture enhance the final slip size. This double slip-weakening friction offers a plausible model for the rupture process of the 2011 Tohoku earthquake.

Dynamic Models of Large Ruptures on the Southern San Andreas Fault

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The southern San Andreas Fault—defined here as the section between Cholame and the Salton Sea—is a heterogeneous structure. Despite being a primary plate boundary fault, it has major variations in along-strike geometry in the Big Bend and San Gorgonio Pass, as well as substantial variation in dip. Maximum horizontal compressional stress orientation also varies considerably along strike. The historic earthquakes of 1857 and 1812 may have had at least one rupture endpoint at a point of stress or geometrical complexity, and paleoseismic records suggest that many prehistoric events also exhibit geometrical segmentation. However, the possibility of a wall-to-wall rupture from Cholame to the Salton Sea is allowed by paleoseismic records and multi-cycle models, and is considered in hazard assessment. In this study, I use the 3D finite element method to conduct models of dynamic rupture on the entire southern San Andreas Fault. I implement stress orientations from seismicity literature, but vary initial stress amplitudes in order to determine which values are necessary to replicate historic or well-documented paleoseismic ruptures, as well as which values and nucleation locations are necessary to produce a wall-to-wall rupture.

Pulse-Like Property and Complex Fault Geometry on Dynamic Rupture Models of the 2015 Mw7.8 Nepal Earthquake

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The entire Main Himalayan Thrust (MHT) is capable of hosting giant earthquakes. In particular, the section on the Nepal region experienced large (M_w>7.5) events in 1833 and 1934, and just recently, the April 15th, 2015 M_w 7.8 Gorkha earthquake. The unusual observations from this earthquake provide an impetus to understand the event itself and to better characterize seismic hazard on the MHT. Seismic and geodetic kinematic inversions imply multiple stages of rupture in this event, with rupture front acceleration and deceleration, a complex spatial distribution of high-frequency radiation, but no surface rupture. Considering that this earthquake occurred on a very shallowly dipping MHT fault, local complex fault geometry, proximity of the free surface and the bi-material nature of the fault will introduce asymmetry of stress and strain field crossing the fault. Dynamic rupture simulations of the Nepal earthquake on a realistic structural model of MHT yield earthquake parameters comparable to those from kinematic inversions, including seismic moment, slip rate and rupture velocity. Pulse-like rupture characteristics have been inferred in some source inversion studies, and the dynamic rupture simulations reproduce this behavior, predicting pulse widths in agreement with observations, and supporting an interpretation in which this pulse-like rupture is principally controlled by fault geometry. Dynamic simulations also suggest that multistage processes indicated by some back-projection imaging may be related to a hypocentral location on a steep ramp lying downdip from the main, shallow-dipping rupture surface. The simulations also reveal how reflected seismic waves from the free surface, nonplanarity, and material contrasts lead to time-dependence of normal stress on the fault, modifying both rupture propagation and slip.

Towards a Hybrid Broadband Ground Motion Simulation Model for Strong Earthquakes in the South Iceland Seismic Zone

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A seismological model for the hybrid simulation of the three largest recorded earthquakes in the South Iceland Seismic Zone (SISZ) is presented. This addresses the relative lack of a region-specific physical ground motion model applicable over a broad frequency bandwidth relevant for engineering purposes. A part of the issue may be that only three strong earthquakes (M6-6.5) have been well recorded in the region and for which static slip distributions exist, and geotechnical information on the complex subsurface structure is sparse. Therefore, we employ a physical modeling approach to the earthquake source and the corresponding strong-motions by combining long-period deterministic synthetic seismograms with high-frequency stochastic seismograms to simulate broadband (0-20 Hz) ground-motion time series from the three earthquakes. We employ the Specific Barrier Model (SBM) in simulating the high-frequency waves and a deterministic model in a 1D subsurface structure in the context of the kinematic approach for the long-period waves. The deterministic representation of fault rupture is described by spatially heterogeneous slip, rupture speed and rise time using an approximated Yoffe-type source time function. The model is calibrated to strong-ground motion records, aided by the existing finite-fault static slip distribution models, and path and site effects constrained using records of several smaller earthquakes. Most model parameters were constrained jointly through a Bayesian approach using informative prior densities for them. The synthetic strong-motion time histories fit the recorded data well. Moreover, on the basis of insight into the physical earthquake source parameters provided by the SBM, the presented models are expected to be representative of strong earthquakes in South Iceland. That in turn provides the basis for future earthquake scenario modeling of larger earthquakes and has potential implications for seismic hazard estimates.

Earthquake Geology and Paleoseismic Studies of the Intermountain West: New Methods and Findings on Seismic Hazard Characterization of Low Slip Rate Faults

Oral Session · Thursday 20 April · 1:30 PM · Plaza F

Session Chairs: Seth Dee and Stephen Angster

Paleoseismic Investigation of the Teton Fault at Leigh Lake

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The Teton fault is the major range bounding normal fault along the eastern flank of the Teton Range in western Wyoming. The 72 km-long fault has an estimated slip rate of 0.7 to 1.3 mm/yr and is the major contributor to regional seismic hazard. However, uncertainty in the history of large earthquakes on the fault remains because previous paleoseismic data are limited to a single site on the southernmost of three sections of the fault. To improve the spatial distribution of paleoseismic data and improve estimates of earthquake timing, rupture length, and fault slip rate, we excavated two paleoseismic trenches at the Leigh Lake site on the central section of the fault. The trenches crossed the easternmost two of three subparallel scarps on a latest Pleistocene deglacial surface that individually record ~1.4–1.6 m of vertical surface offset. We interpret two to three latest-Pleistocene to Holocene surface-faulting earthquakes at the site based on faulted glacial till and a total of three scarp-derived colluvial wedges exposed in the trenches. Using estimates of stratigraphic displacement and surface offset, we estimate a total of 4–5 m of down-to-the-east vertical displacement across the Leigh Lake deglacial surface. However, because of complex distributed faulting in the easternmost trench, we cannot rule out a component of lateral motion. We plan to use ages from six radiocarbon and nine luminescence samples to constrain the timing of individual earthquakes at Leigh Lake and compare our results to the existing paleoseismic history for the southernmost part of the fault. These data will help resolve the timing and extent of ruptures on the Teton fault and permit a more accurate characterization of the earthquake hazard in western Wyoming.

Paleoseismology of the Corner Canyon and Alpine Sites: Insight into Normal Fault Segmentation of the Wasatch Fault Zone

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Prominent structural discontinuities, such as fault step-overs and gaps along normal fault systems, are thought to play an important role in limiting the lateral extent of individual surface-rupturing earthquakes. For example, structural boundaries along the 350-km-long Wasatch fault zone (WFZ) in Utah have classically been used to define 10 individual fault segments. To test the assumption that these boundaries arrest laterally propagating ruptures, we evaluated the history of large earthquakes at companion sites near the Traverse Mountains salient (TMS), long considered a barrier to ruptures on the Salt Lake City segment (SLCS) and Provo segment (PS) of the WFZ. Six earthquakes ruptured the Corner Canyon site (southern SLCS) since ~4.9 ka. Six earthquakes ruptured the Alpine site (northern PS) since ~5.5 ka. Four earthquakes at ~3.1, ~1.3, ~0.6, and ~0.4 ka were observed at both sites, indicating possible rupture through the TMS. Synthesis of paleoseismic data suggests multiple rupture modes in the post-6 ka history of the SLCS and PS, including two separate ruptures of the SLCS, two separate ruptures of the PS, four spillover ruptures across the TMS, and at least one rupture centered on the TMS. Our results indicate that although the TMS has influenced Holocene rupture extents, it cannot be considered a complete barrier to rupture. Consequently, rupture length and magnitude for the SLCS and PS are larger than previously reported. Using these data, we propose a model in which structural segment boundary maturity influences normal-fault rupture length. Sites near structurally mature boundaries may have elevated probabilistic seismic hazard due to more frequent ruptures at or near the boundaries. Our results complement analysis of WFZ segmentation using paleoseismic data for the five central WFZ segments and the Stringing Pearls method to objectively build rupture scenarios.

Forecasting Large Earthquakes along the Wasatch Front, Utah: Final Results from the Working Group on Utah Earthquake Probabilities

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In the first comprehensive study of its kind outside of California, the Working Group on Utah Earthquake Probabilities (WGUEP) has assessed the likelihood of large earthquakes in the Wasatch Front region. The WGUEP forecast includes the probability of one or more earthquakes of a specified magnitude range in the region in the next 30, 50, and 100 years. Both time-dependent and time-independent models were used to characterize the probabilities for the central segments of the Wasatch fault zone and two segments of the Great Salt Lake fault zone. Only time-independent probability estimates were made for the other 45 faults and fault segments and background earthquakes within the Wasatch Front.

There is a 43% probability that the Wasatch Front region will experience at least one moment magnitude (M) 6.75 or greater earthquake in the next 50 years. This total probability for the entire region is based on new geologic information on the timing and location of large prehistoric earthquakes on known faults in the region. For example, the WGUEP's review of paleoseismic investigations of the Wasatch fault zone indicates that at least 22 large prehistoric earthquakes have ruptured parts of this fault between Brigham City and Nephi in the past 6000 years. The probability of at least one M 6.75 or greater earthquake on the Wasatch fault zone is 18% in the next 50 years and 6% on the Oquirrh-Great Salt Lake fault zone. The probability of one or more M 6.75 or greater earthquakes on the other 45 faults or fault sections is 25% in the next 50 years.

There is a 57% probability of one or more M 6.0 or greater earthquakes in the region in the next 50 years. This total probability is based on the probability of M 6.0 or greater earthquakes on known faults and a reevaluation of the size of historical earthquakes that have occurred since the settlement of the region. There is a 14% probability of a M 6.0 or greater background earthquake occurring in the next 50 years.

Time-Dependent Probabilistic Hazard along the Wasatch Front, Utah Using the Working Group on Utah Earthquake Probabilities Model

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The Working Group on Utah Earthquake Probabilities (WGUEP) has assessed the likelihood of one or more large earthquakes in a specified magnitude range in the Wasatch Front region for a range of time periods. Both time-dependent and time-independent models were used to characterize the probabilities for the five central segments of the Wasatch fault zone and the two southern segments of the Great Salt Lake fault zone. Only time-independent probability estimates were made for the other 45 faults and fault segments and background earthquakes within the Wasatch Front. There is a 43% probability that the Wasatch Front region will experience at least one moment magnitude (M) 6.75 or greater earthquake in the next 50 years. The probability of at least one M 6.75 or greater earthquake on the Wasatch fault zone is 18% in the next 50 years and 6% on the Oquirrh-Great Salt Lake fault zone. The probability of one or more M 6.75 or greater earthquakes on the other 45 faults or fault sections is 25% in the next 50 years. We have implemented the WGUEP time-dependent and time-independent modeling of the Wasatch fault zone and the Great Salt Lake fault zone in a probabilistic seismic hazard analysis to evaluate the impact on seismic hazard at several major cities along the Wasatch Front. Three central segments demonstrate the range of impact of the time-dependent modeling: the Brigham City segment whose elapsed time (2,500 yrs) is now more than 2 times the segment's mean recurrence interval (MRI) of 1,100 yrs; the Salt Lake City segment whose elapsed time is 1,400 yrs ago (MRI 1,300 yrs); and the Nephi segment whose most recent earthquake (MRE) was only 300 years ago (MRI 900 yrs). To model the time-dependent behavior of faults, the Brownian Passage Time model was used. For implementation into hazard analyses, equivalent Poisson rates are computed. The probabilistic hazard results to illustrate the impact of time-dependent behavior will be presented in this paper.

Estimating Rates of Slip within the Central Walker Lane Using Multiple Geochronometers

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The Walker Lane is a well-known intraplate shear zone that trends along the eastern Sierra Nevada and accommodates a significant portion of North American-Pacific Plate relative transform motion. At the latitude of Walker Lake in Nevada, ~8 mm/yr of northwest directed transtensional dextral shear in geodetically observed and distributed across north-south trending basin bounding normal faults in the western portion, and northwest striking right-lateral faults of the central Walker Lane in the eastern portion. Prior studies have identified the Benton Springs, Petrified Springs, Gumdrop, Indian Head, and Agai-Pah faults as the main Quaternary active faults and provide qualitative rates of slip from for only some, using soil chronosequences and standard field techniques. We are currently attempting to place quantitative limits on the slip rates for each of these faults by combining multiple geochronometers, including soil profiling and modern dating techniques of 10Be and 36Cl terrestrial cosmogenic nuclide dating and optically stimulated luminescence, to place better age constraints on previously identified and newly observed offset geomorphic features. Optimal measures of offset at each site are further constrained using digital elevation models produced from newly acquired airborne lidar data and self-produced Structure from Motion surface models and with LaDiCaoz, a MATLAB GUI. Here, we anticipate presenting offset measurements and preliminary results of the ages.

Earthquakes and Tsunamis

Oral Session · Thursday 20 April · 10:45 AM · Governor's Square 12

Session Chairs: Rich Briggs and Gavin Hayes

Advancement of Seismological Datasets at ISC

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The International Seismological Centre (ISC) is a non-governmental organization based in UK and funded by 66 research and operational institutions in 49 countries, including the NSF, USGS and IRIS in United States.

The ISC produces the global definitive Bulletin of earthquakes and other seismic events based on reports from ~140 seismic networks worldwide. The ISC Bulletin remains the most long-term and comprehensive source of information covering the period from 1904 to 2017. We are currently rebuilding the Bulletin to improve the locations and magnitudes and insert previously missing bulletin data from permanent networks and temporary deployments. The data for the 1960s has been recently updated and the work on the 1970s is progressing well.

We also maintain and distribute several derivative datasets designed for specific applications:

The **ISC-EHB bulletin**—a groomed subset of the ISC Bulletin containing well-recorded teleseismic events; it is widely used in studies of seismicity and structure of the Earth.

The **IASPEI Reference Event List (GT)**—a bulletin of events with the hypocentral information known with high confidence (to 10km or better); used for a variety of calibration purposes, especially in nuclear monitoring studies.

The **ISC-GEM catalogue**—the most homogeneous and complete record of large instrumentally recorded earthquakes over the 110-year period; designed for use in global and regional assessment of seismic hazard.

The **ISC Event Bibliography**—an interactive facility that enables searches for references to scientific articles devoted to specific natural and anthropogenic seismic events that occurred within a region and time period of interest; widely used in education and by scientific article authors, reviewers and journal editors.

We describe major advances recently made by the ISC to extend and improve these datasets that are openly available and widely used in different fields of geophysical research.

Seismic Catalog of the Dominican Republic Period 2013-2016

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The island of Hispaniola, home to the nations of the Dominican Republic (DR) and Haiti, is located in the northern Caribbean, where the interaction between the Caribbean and North American plates transitions from subduction (in the east) to transcurrent (to the west). Regional stresses have produced strains that are partitioned into subduction and transform faults. Several of these fault systems are known to be capable of producing significant earthquakes (the Septentrional, Bonao, Enriquillo-Plantain Garden faults, among others) but additional faults are likely to be discovered as a result of comprehensive, continuous monitoring. These features make the island tectonically complex and the expose the population expose high levels of seismic hazard.

Until 2013, the Dominican Republic's national seismic network consisted of few stations, limiting its ability to record and analyze local earthquakes. With the installation of 16 broadband stations, between mid-2013 and early 2014, improvements in communications, and the installation of modern software, we are now routinely acquiring continuous data in real time from ~20 stations. We will present preliminary results regarding a new velocity model, re-located events for a new, comprehensive catalog, and focal mechanisms for events that exceed M3.5.

This work is part of the Project "Seismic structure and anisotropies of the earth's crust and tectonic processes present in the north-central part of the Caribbean Plate", which is funded by the Autonomous University of Santo Domingo, University of Puerto Rico at Mayaguez and Baylor University under the auspices of the FONDOCYT of the DR Ministry of Higher Education, Science and Technology in its 2015 call.

Seismic and Tsunami Hazard Assessment of Ecuador following Observations from the 2016 Mw7.8 Muisne Earthquake

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Ecuador is located on an active seismic region with a unique mixed tectonic setting of a subduction zone with crustal earthquakes and volcanism. The subsurface conditions often include thick, soft, and plastic deposits that can generate large soil amplification or loose granular fills that can liquefy or loose strength after strong shaking. The Geodynamics of the coastal area make it susceptible to tsunamis due to deep earthquakes generated in the ocean, but also earthquakes with epicenter inland that can create deep seated landslides that can cause tsunamis. Historically, the subduction zone along the Ecuador and Peru-Chile has produced destructive earthquakes including the largest ever recorded earthquake of 1960 with M_w9.5. In the past two centuries, the Ecuadorian shoreline has experienced several tsunamis of various intensities.

The 4/16/16 M_w7.8 earthquake struck northern Ecuador about 29 km southeast of Muisne, at a hypocentral depth of 21 km. The event was caused by shallow thrust faulting on or near the boundary where the Nazca plate subducts beneath the South American plate and produced a tsunami registered by NOAA 32411 and 32413 DART buoys in the Panama and Peru basins, respectively. The tsunami was registered 2 and 3 hrs after the earthquake, when the waves reached the buoys. Observations indicate that the tsunami had a period of about 40 min with an amplitude close to 1 cm. The tsunami impact occurred at low tide. This is a reason that no inundation occurred and considerable physical effects at the coastlines were absent. However, this case could have been catastrophic, as some authorities, soon after the main event did not issue a tsunami warning due to the false assumption that a tsunami would not be generated because the epicenter was in the continental rather than the marine side.

This paper presents seismological and tsunami observations from the Muisne Earthquake and recent developments in the overall seismic and tsunami hazard of coastal Ecuador

"Sequencing" of Tsunami Waves, or Why the First Wave is Not Always the Largest

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We discuss what contributes to the 'sequencing' of tsunami waves in the far field, *i.e.*, to the distribution of maximum sea surface amplitude inside the dominant wave packet making up the primary arrival at a distant harbor. Based on simple models of sources for which analytical solutions are available, we show that, as range is increased, the pattern evolves from a regime of maximum amplitude in the first oscillation to one of delayed maximum, where the largest amplitude occurs during a subsequent oscillation. In the case of the simple, instantaneous uplift of a circular disk at the surface of an ocean of constant depth, the critical distance for transition between those patterns scales as r0**3/h**2 where r0 is the radius of the disk and h the depth of the ocean. This behavior is explained from simple arguments based on a model where sequencing results from frequency dispersion in the primary wave packet, as the width of its spectrum around its dominant period T0 becomes dispersed in time in an amount comparable to T0, the latter being controlled by source size and ocean depth. The general concepts in this model are confirmed in the case of more realistic sources for tsunami excitation by a finite-time deformation of the ocean floor, as well as in real-life simulations of tsunamis excited by large subduction events, for which we find that the influence of fault width on sequencing is more important than that of fault length. Finally simulation of the major events of Chile (2010) and Japan (2011) at large arrays of virtual gauges in the Pacific correctly predicts the majority of the sequencing patterns observed on DART buoys during these events. Our results stress the importance, for civil defence authorities, of issuing evacuation orders of sufficient duration to prevent otherwise unsuspected hazard from delayed wave-trains, as was case in Hilo (Chilean event, 1960) and Crescent City (Good Friday tsunami, 1964).

Improving Earthquake Resilience in Developing Countries through Seismology

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As part of capacity building and joint research under the U.S. Department of Energy's Seismic Cooperation Program (SCP), Lawrence Livermore National Laboratory (LLNL) is helping assess seismic hazard and modernize building codes in the Middle East, Central Asia and the Caucasus. The project is multi-faceted as it helps countries under its portfolio to: 1) improve seismic monitoring, thereby improving event locations and magnitudes, and allowing more advanced seismological and geophysical analyses, 2) improve existing earthquake catalogues in former Soviet republics by digitizing millions of seismic arrivals archived in paper-based seismic bulletins across the Caucasus and Central Asia, 3) relocate past earthquakes using the new digitized data by BayesLoc algorithm, 4) utilize coda calibration technique to directly calculate moment magnitudes down to magnitudes of about 3, thereby vastly improving M_w quality (compared to conversions from other magnitude scales), 4) conduct seismic source and ground motion characterization specific to these regions, 5) conduct probabilistic seismic hazard assessments for each country to feed into their national hazard mapping and building codes, and finally 6) create the necessary knowledge base and analysis results for modernization of building codes in the area, which are generally based on 1970s Soviet-era seismic hazard and engineering concepts. All these efforts are largely undertaken by the locals themselves, LLNL's role being limited to coordinating, and providing support, regular training and workshops for the local seismologists, geologists, and engineers to work together. The goal is for the locals to be able to update their own seismic codes regularly in the future, thereby significantly improving the disaster resilience of their communities. This presentation provides an overview of these projects, including an example from a recently finished project.

Emerging Opportunities in Planetary Seismology

Oral Session · Thursday 20 April · 1:30 PM · Governor's Square 12

Session Chairs: Sharon Kedar, Steve Vance, and Nicholas Schmerr

Emerging Opportunities in Planetary Seismology

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In the coming years and decades, NASA may launch missions to explore Mars, our Moon, and the Ocean Worlds of the Solar System (*e.g.*, Europa and Enceladus, and Titan). The InSight mission that will land on Mars in 2018 will be the first Mars lander to place an ultra-sensitive broadband seismometer on the planet's surface, and the first planetary seismometer since the Viking missions (1976). The Lunar Geophysical Network, identified as a high-priority mission concept in the Planetary Science Decadal survey, would seek to understand the nature and evolution of the lunar interior from the crust to the core. Other concepts are being developed to explore the interior of Venus, asteroids and comets.

The objectives of these missions vary. While InSight and the Lunar Geophysical Network are primarily geophysical missions, missions to the Ocean Worlds would focus on the detection of life and habitability. Despite these differing emphases, seismological mapping the shallow and deep interior of planetary bodies is essential, as their interiors hold the clues for understanding their planetary evolution and for determining their thermal and chemical make-up.

The seismological community faces multiple challenges in introducing seismological exploration to planetary mission concepts. Most landed missions concentrate on habitability or detection of biochemical traces, and are therefore focused on the near surface. Consequently, most of our knowledge of rocky planets' interiors is deduced from gravitational measurements derived from orbital mechanics, and are inherently non-unique. Moreover, seismometers, are perceived as complex and adding risk to inherently already complicated lander missions. Finally, due to the long breadth required in the planning and execution of planetary seismology missions, it is challenging to invest effort and resources in an endeavor that may not materialize for decades. We will discuss these challenges and approaches to overcoming them.

InSight/SEIS: One Year Prior to Beginning the Seismic Investigation of Mars

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InSight is the next NASA Discovery mission, planned for launch in May 2018 and landing on Mars about 6 months later. The payload comprises a geophysical observatory, with a seismometer (SEIS), a heat flow experiment, a geodesy experiment, and a suite of environmental sensors measuring the magnetic field and atmospheric temperature, pressure and wind. SEIS is the primary instrument of the mission and consists of a 3-axis Very-Broadband (VBB) instrument and a 3-axis Short Period (SP) instrument mounted on a leveling system, protected by a wind/thermal shield and connected to the instrument electronics by a tether. The VBBs are enclosed in an Evacuated Container (EC). A leak detected in the EC late in 2015 forced postponement of the launch from 2016 to 2018, with a redesign of the EC to prevent a recurrence.

Despite efforts with the Viking seismometers in 1976, SEIS is expected to provide the very first seismic records of Mars. Thus implementation of the science goals is very challenging due to the almost complete lack of information on the seismic structure of Mars as well as the levels of seismic activity and noise. In parallel to the instrument development by the SEIS technical team, SEIS science team efforts have concentrated on three challenges: single-station seismic analysis methodology; pre-launch estimation of the seismic and station-generated noise; and amplitude of seismic and gravity signals generated not only by quakes but also by non-seismic sources (*e.g.*, meteorite impacts, atmosphere, Phobos tide).

We present the status of the SEIS experiment as well as the expected performance of the seismic payload following its characterization during the 2016-17 Flight Model delivery campaign. We then summarize and review the most recent analyses predicting the seismic performance of the SEIS experiment in the Martian environment, and update estimates of seismic signals, noise (including environmental decorrelation) and prospects for planetary structure inversion.

Investigating the Interior of Icy Worlds with Short Aperture Seismic Arrays

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The interiors of the icy outer satellites may support the largest volume of habitable space within the Solar System. A key parameter is the presence of liquid water oceans beneath the frozen surface, thus geophysical investigations of the interior are crucial for understanding the structure, dynamics, and evolution of these liquid water reservoirs. Our present understanding of the seismic signals produced by Icy Worlds is limited, with the level of seismic activity at the surfaces likely driven by tidal processes. The harsh operating environments will limit mission observation times, making it is essential that the seismic information returned from a surface mission be of high fidelity in resolving key questions about the internal environment of an Icy World.

Here we present new field observations and modeling results that demonstrate the improved knowledge provided by a short aperture seismic array. We define a short aperture array as a deployment of multiple 3-component seismometers, with a separation between instruments of 1-10 meters. We will present 3D synthetic modeling results that demonstrate sensing requirements and the primary advantages of such a seismic array over a single station, including the improved ability to resolve the location of the source through detection of backazimuth and differential timing between stations, ambient noise techniques, as well as the ability to improve the signal to noise ratio by additive methods such as stacking and velocity-slowness analysis. We also compute a series of modeled noise functions for Europa and Enceladus based upon periodic tidally induced stress on surface faults to estimate the types of signals and noise that would be observed by a seismic station. These results will inform future missions and planning of landers on the surfaces of Europa, Enceladus, Titan, and other objects in the outer Solar System.

A Broadband Silicon Seismic Package for Planetary Exploration

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The Silicon Seismic Package (SSP) is compact, 0.3 ng/rtHz sensitivity silicon microseismometer based on the hardware successfully delivered to the InSight Mars 2018 mission. The SSP provides a sensitivity and dynamic range comparable to significantly more massive broadband terrestrial instruments in a robust, compact package. Combined with a high resolution radiation-hardened digitiser also under development, the SSP offers high performance seismic monitoring under a range of planetary environments.

The sensor is micromachined from single-crystal silicon by through-wafer deep reactive-ion etching to produce a non-magnetic suspension and proof mass. It is robust to high shock (> 1000 g) and vibration (> 30 grms). For qualification SP units have undergone the full thermal cycles of the InSight mission and has been noise tested down to 208K and up to 330K, with no degradation in the performance in both cases. In addition, the sensor has been tested as functional down to 77K. The total mass for the three-axis SP delivery is 635g while the power requirement is less than 400 mW.

The SSP has particular advantages for a planetary deployment. All three axes deliver full performance over a tilt range of ±1 m/s^2 which allows for operation without levelling. With no magnetic sensitivity and a temperature sensitivity below 2E-5 m/s^2, there is no need for magnetic field monitoring and the additional resources for thermal isolation are also much reduced.

In terms of performance the SSP has fast initialisation, reaching a noise floor below 1 ng/$\sqrt{\text{Hz}}$ in less than a minute from an untilted configuration. The noise floor is 0.3 ng/rtHz from 10 s to 10 Hz, with a long period noise below 10 ng/rtHz at 1000s. This allows tidal measurements as well as seismic monitoring for a number of proposed planetary missions.

Development of a Planetary Broadband Seismometer for Geophysical Exploration of the Moon and the Ocean World

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We have designed a Planetary Broadband Seismometer (PBBS) with sensitivity of over 10 times that of the current state of the art. This PBBS could be deployed in some of NASA's future missions to better determine the structure and composition of the interiors of planetary bodies.

The PBBS is based on the Electrostatic Frequency Reduction (EFR) Technology invented by H. J. Paik [1], where the resonance frequency f_o of the suspended mass of a seismometer is reduced to near zero by applying opposing electrostatic forces at its surfaces. In a traditional seismometer, f_o is reduced by mechanically changing the configuration of the suspension system. With EFR, this can be achieved remotely or autonomously by a voltage adjustment. This capability is particularly important for planetary operations. For example, when springs in the seismometer become stiff when cooled to cryogenic temperatures of Europa, f_o can be brought back to zero by EFR.

When the ground moves at a frequency below f_o, the test mass tends to move with the ground, and sensitivity degrades since there is little displacement between them to be measured by the electronics. Moreover, high frequency seismic waves are attenuated strongly with distance. Far from the source, only low frequency waves are detected. Hence a seismometer with lower f_o will be able to detect weaker signals from farther away.

We discuss test results of a PBBS prototype deployed next to two STS-2 seismometers, showing performance close to the current state of the art. We also describe the design of a more sensitive next-generation 3-axis PBBS based on lessons learned from these tests.

[1] Griggs, C.E. *et al*. (2007), Nucl. Phys. B (Proc. Suppl.) 166, 209-213.

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Fault Mechanics and Rupture Characteristics from Surface Deformation

Oral Session · Thursday 20 April · 16:00 · Governor's Square 16

Session Chairs: Lia Lajoie, Kendra Johnson, and Edwin Nissen

Managing the Explosion of High Resolution Topography for Active Fault Research

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Centimeter to decimeter-scale 3D sampling of the Earth surface topography coupled with photorealistic coloring of point clouds and texture mapping of meshes enables a wide range of science applications. The configuration and state of the surface is valuable, and repeat surveys enable quantification of topographic change. We are in an era of ubiquitous point clouds from both active sources such as laser scanners and radar as well as passive scene reconstruction via structure from motion (SfM) photogrammetry. With the decreasing costs of high-resolution topography (HRT) data collection, the number of researchers collecting these data is increasing. Applications of these data to active tectonics and earthquake fault rupture are proven. There is great opportunity for further utilization of these data as they become easier to acquire and access. The U.S. NSF funded OpenTopography (OT) Facility employs cyberinfrastructure including large-scale data management, high-performance computing, and service-oriented architectures to provide efficient online access to HRT datasets, metadata, and processing tools. With over 225 datasets and 15,000 registered users, OT is a widely utilized resource including data related to active tectonics. This presentation will highlight recent developments and new datasets in OT, including: 1) New HRT data from New Zealand in the epicentral region of the November 14, 2016 Kaikoura earthquake. 2) The OT "Community DataSpace", a service built on a low cost storage cloud to make it easy for researchers to upload, curate, annotate and distribute their HRT datasets. The ingestion workflow extracts metadata from data uploaded; validates it; assigns a digital object identifier (DOI); and creates a searchable catalog entry, before publishing the data via the OT portal. It enables wider discovery and utilization of these HRT datasets, promotes citations, and most importantly increases the impact of investments in data to catalyze scientific discovery.

Shallow Fault Physics Constrained by Active-Source Seismic Imaging, Fault-Zone Drilling, and Mechanical Testing

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The recent proliferation of high-resolution, near-field geodetic techniques provides unprecedented opportunities to relate surface displacements to fault slip and related deformation in the very shallow crust (<1 km depth). Such analysis, however, is limited by uncertainty in the mechanical behavior of the shallow crust, particularly in response to an earthquake. Following the 2014 M_w 6.0 South Napa Earthquake, Mobile Laser Scanning (MLS) with centimeter-level accuracy was used to image deformed vine rows within 300 m of the fault rupture. Typical vine rows are deflected right-laterally across ~10- to 30-m-wide zones, accumulating 10s of centimeters of fault-parallel displacement. We used Abaqus to construct 3D finite element models to compare surface displacements resulting from linear elastic and Drucker-Prager elastoplastic rheologies with the MLS data. Non-uniqueness of the normalized model results indicates that surface displacements alone cannot diagnose rheology in typical settings where slip and burial depth are not known a priori. Instead, we propose a multidisciplinary approach, incorporating active-source seismic imaging, fault zone drilling, and mechanical testing, to characterize fault-related deformation in the shallowest ~20 m. We conducted high-resolution (1 m geophone/shot spacing) active-source seismic surveys at two sites dominated by co- and post-seismic slip, respectively. A preliminary Vp/Vs model from the post-seismic site shows an ~25-m-wide anomalous velocity zone (Vp/Vs>7) buried ~10 m beneath the surface. We plan to collect continuous cores through the fault zone at the two sites to be analyzed using multi-sensor core logging. Additionally, we aim to measure the frictional and plastic mechanical properties of these materials using rock mechanics experiments. This synthesized perspective on shallow fault physics may better enable the use of near-field surface data to infer fault properties at shallow depths.

Characterizing Near-Surface Fractures in Radar Interferograms

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Repeat-pass SAR observations from an aircraft or satellite often reveal secondary faulting in a wide zone around a large earthquake. Interferograms from a single viewing angle provide a limited, but important means of characterizing this fault motion. When a second view angle interferogram is available, one can separate vertical and horizontal motion, but the information is still incomplete. The images are also large, so searching by hand for features of interest is tedious. We have implemented means to automatically scan interferometric images for surface and near-surface fractures and use simple functional forms to derive information of substantial interest. Gradient-based methods such as Canny edge detection rapidly identify fractures, but cannot distinguish the amplitude of the deformation pattern from the width of the surface shear zone. Using detected edges as a reduced data set for deeper analysis, we automatically fit sigmoid functions in orthogonal directions and derive a candidate locking depth and shear amplitude suitable for strike-slip motion. Information from seismicity and, when available, a second viewing angle provide means to estimate dip angle, as encountered for common blind slip events. These methods are illustrated using UAVSAR data covering recent California earthquakes.

Statistically Preferred Hypocenter Location, Slip Variability, and Surface Rupture Patterns from Fractally Rough Fault Structure

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Fault zone structure is well known to exert strong controls on earthquake properties including seismic slip distribution, rupture directivity, and hypocenter location. It has also been well-established that the principal slip surface, which accommodates the majority of earthquake displacement, exhibits roughness at all scales following self-affine fractal distributions. Until now, only the largest-scale features of fault roughness have been correlated to earthquake properties. Here we present direct statistical links between fault roughness and specific earthquake properties including slip, hypocenter location, and directivity. First we procedurally generate fractally rough faults using von Karman autocorrelation with different fractal dimensions. Next we simulate 10,000 years of earthquakes using the physics-based earthquake simulator RSQsim, placing the faults in a homogeneous elastic solid with a homogeneous initial stress state and applying pure right-lateral shear at a constant rate. For each fault geometry, we generate millions of earthquakes including thousands of events with M>6.0 which rupture the surface. The patterns of surface rupture in these large events follow self-affine fractal distributions with consistent fractal dimension related distinctly to the fractal dimension of the fault. In addition, the hypocenters of these large events occur in predictable locations where the longest wavelength structure produces a stress asperity (*i.e.*, restraining bend). Medium-sized events (M4 to M6) have complementary hypocentral locations, while the smallest events (M below 3.5) occur as aftershocks at the boundaries of large ruptures and as background seismicity at small-scale asperities. These patterns all vary systematically and predictably with fault roughness, thus providing a link between a quantity that is directly measurable on active faults (roughness) and the properties of future earthquakes, with important implications for earthquake hazard assessment.

Epistemic Uncertainty in Thrust Fault Slip as Revealed by 62 Vertical Offsets along the Cucamonga Fault

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Maps of earthquake ground surface ruptures imply that displacements along strike are spatially variable. As a result, latest Quaternary slip rates developed from a small number of displacement measurements may misrepresent slip rate behavior. The Cucamonga thrust fault in southern California is unusual in that numerous fault scarps are well expressed on alluvial fans along its length. The 33 ka Qyf1 fan surface includes nearly the entire 25 km fault and all its strands. Younger fans provide patchier coverage. Using airborne lidar in combination with GPS surveys, we measured vertical separation (VS) at 62 locations in order to quantify along-strike variability and to refine late Quaternary slip rates, which are important for hazard assessment in the Los Angeles region. We focus on VS, rather than dip-slip, because VS does not require inferring fault dip angle.

Our results show that along-strike variance greatly exceeds measurement error. For example, VS in the Qyf1surface varies along strike: 1.5(±1.0) m to 16.9(±1.6) m for fault strand A, 3.4(±0.1) m to 5.6(±1.1) m for strand B, and 3.3(±0.2) m to 13.4(±1.5) m for strand C. We also considered VS measurements amalgamated along strike at sites with lengths of ~5 km. Total maximum VS of Qyf1 ranges from 23.2 m to 30.2 m at four sites with >5 measurements each. These values are lower than previous estimates (27 to 36 m) and show no trend along strike. Local variation at each site exceeds variation among site averages and among site maxima. This may result from local variations in fault dip, strain partitioning, and scarp erosion, as well as the distribution of VS associated with individual earthquake ruptures. Given the short spatial scale of variance, our results do not support significant slip rate differences along the Cucamonga fault. Care should be taken when comparing slip rate estimates: rates derived from small sample sets likely include uncertainty that significantly exceeds measurement error.

Importance of Long-Period Ground Motions in Seismic Design of Structures.

Oral Session · Thursday 20 April · 16:00 · Governor's Square 12

Session Chairs: Erdal Safak and Eser Cakti

Observed and Calculated Response of Long-Period Structures to Surface Waves

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Records from instrumented structures clearly show that long-period ground motions are an important factor affecting the response of flexible structures, such as tall buildings, long bridges, and base-isolated structures. Large earthquakes can generate surface waves that can travel long distances, far beyond those considered in seismic hazard studies, without significant attenuation.

In this paper, we will first give some examples of the observed response of instrumented long-period structures to surface waves, including tall buildings, suspension bridges, and minarets. We will then show analytically the significance of long-period response of such structures, in terms of the duration of vibration, human comfort, number of stress cycles, ductility demand, accumulation of damage, and deterioration of structure.

We conclude that surface waves generated by large earthquakes can be critical for long-period structures, even when they are located hundreds of km away from the source. Having the period of surface waves close to the period of a structure causes resonant vibrations in the structure, characterized by long-duration of vibrations and a large number of stress reversals. Such vibrations can create low-cycle fatigue failures in steel structures, and further deteriorations in concrete and masonry structures that are already damaged. There is a need for a better characterization of long period ground motions in seismic design codes.

Use of 3D Physics-Based Numerical Simulations in the Development of Long Period Ground-Motion Maps for Los Angeles

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The Utilization of Ground Motion Simulation (UGMS) committee of the Southern California Earthquake Center (SCEC) has developed risk-targeted Maximum Considered Earthquake (MCER) spectral acceleration maps for the Los Angeles region. The long period (T > 2-sec) values for these maps are based on a weighted average of MCER spectral accelerations derived from (1) 3D numerical ground-motion simulations using the CyberShake computational platform, and (2) empirical ground-motion prediction equations (GMPEs) from the Pacific Earthquake Engineering Research (PEER) Center NGA-West2 project. CyberShake simulated suites of earthquake scenarios for ~40,000 ruptures (M ≥ 6) in Southern California from the UCERF2.0 earthquake recurrence model and generated ~440,000 ground motions for each of ~300 regional sites. The response spectral accelerations computed from these simulations are valid for periods of 2-sec and longer. For both the simulated and GMPE-based motions, the corresponding MCER spectral accelerations for each site were computed following the site-specific procedures in Chapter 21 of the ASCE 7-10 standard; then the final MCER response spectra were obtained as the weighted geometric average of the two sets of spectra. For periods less than 2 sec, the MCER response spectra were computed solely from the NGA-West2 GMPEs. A web-based lookup tool has been developed so users can obtain the MCER response spectrum for a specified latitude and longitude and for a specified site class or 30-m average shear-wave velocity, VS30. The acceleration ordinates of the MCER response spectrum are provided at 21 natural periods in the 0 to 10-sec band; values of SDS and SD1, per the requirements in Section 21.4 of ASCE 7-16, are also listed. The MCER response spectra are being considered for possible inclusion as an amendment to the ASCE 7-16 edition of the Los Angeles City Building Code.

Highlights of Recorded Responses of Two Tall Buildings to Long-Period Earthquake Motions from Distant Sources

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The first example: A 55-story building in Osaka, ~770 km from the epicenter of the M9.0 Tohoku, Japan, earthquake of March 11, 2011, was subjected to ~1000 s of prolonged long-period shaking. Records show that: (1) average drift ratios reached ~0.5%, a damage threshold in Japanese building codes, (2) damping ratios for the building were low (<1.6%) and beating is present in the response, (3) observed resonance in the motions likely is tied to similarity between the building's fundamental frequencies (0.17 Hz in both principal directions) and the site frequency (0.15 Hz) determined for the records from the nearby strong-motion Kik-net station, OSKH02. Concerns about how the building might respond to similar shaking in the future prompted a retrofit that included dampers and buckling restrained braces (BRBs). Subsequently the building was shaken by the M_w7.3 Kumamoto earthquake of April 16, 2016 that occurred at ~478 km distance. Small but significant increases in fundamental frequency (~0.01 Hz) and damping were identified, although resonance and prolonged shaking of the building were not ameliorated.

The second example: A 52-story building in Los Angeles (LA), CA, built on the LA basin. A site transfer function computed using the SCEC velocity model CVM-H version 5.3 indicates a fundamental site frequency of ~0.12-0.13 Hz. Several recorded earthquake responses (particularly the 1992 M7.3 Landers and 1994 M6.7 Northridge events) reveal that: (1) NS, EW and torsional fundamental frequencies of the building are the same (0.17Hz), thus indicating coupling of the modes, (2) these frequencies are similar to those determined by Ventura and Ding (2000) using different earthquakes, and (3) damping is small (<2% for Landers and Northridge) and beating is observed.

In summary, hazard and risk to tall buildings from long-duration, long-period motions from distant earthquakes are significant. Design codes for tall buildings should take into account these effects and risks.

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

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The Cascadia Subduction Zone (CSZ) can produce long-duration, large-magnitude earthquakes that could severely affect structures in the Pacific Northwest (PNW). The long-period (1-10 seconds) ground motions from these earthquakes are expected to be amplified by deep sedimentary basins that underlie several cities in the Puget Sound region. The effects of long durations and basins are poorly understood for the CSZ because no recordings are available for M8-9 earthquakes in this region.

To compensate for the paucity of recorded subduction events in the PNW, a research team at the University of Washington and the USGS is generating synthetic ground motions for magnitude 9 megathrust earthquakes using finite-difference simulations and a 3D seismic velocity model for the Cascadia subduction zone, which includes several sedimentary basins (*e.g.*, Puget Lowland basin). Ground motions are generated for many earthquake rupture scenarios using a variety of hypocentral locations, down-dip rupture extents, slip distributions, and magnitudes and locations of high stress drop sub-events.

The effects on structural response due to the rupture scenarios are quantified using engineering demand parameters (EDP, *e.g.*, inter-story drift). The sensitivity of EDP to the rupture parameters is quantified by subjecting archetypical structures to motions from multiple scenarios. The severity of the EDP values is correlated with key ground-motion intensity measures that quantify spectral acceleration, duration, and spectral shape. The long-period (1.5-4s) spectral acceleration and shape are amplified by basins and, for many scenarios, are shown to be larger than what is considered in structural design. For all scenarios, the significant duration is shown to be 7 to 10 times longer than for M6-7 crustal earthquakes, which leads the archetypes to exhibit severe cyclic strength degradation. Finally, we evaluate the archetypes' performance and discuss appropriate design recommendations.

Significant Duration of Earthquake Ground Motion for Subduction Zone Earthquakes

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Developing an understanding of duration of strong-shaking is important when characterizing engineering ground motion because the duration of strong shaking is correlated to critical damage indices in the performance-based design of civil engineering structures. Most existing empirical models for duration are for crustal earthquakes. Using the Next Generation Attenuation Subduction Zone Database, we derived an empirical model for duration for subduction zone earthquakes. In evaluating the subduction data from large magnitudes (M>8), we found that the commonly used measure of duration based on the time between 5% and 75% of the Arias intensity does not work well if the ground motion has multiple sections of strong shaking that are separated in time. In crustal earthquakes, the slope of the Arias intensity is approximately constant over the 5%–75% range. With the concept that the parameter of interest is the actual duration for which the shaking has significant energy, we computed the slopes of the Arias intensity in 5% increments (5-10%, 10-15%, etc) and then summed the durations of the 14 increments with the largest slopes. In other words, we skipped the time increments with small slopes (low energy). This new method provides a better measure of duration because it captures the duration of strong shaking in large subduction earthquakes but remains consistent with the current definition for typical ground motions without large separations in the strong shaking in the recording. Using this new definition, we derive empirical models for the duration for subduction earthquakes in Japan and Taiwan. Compared to the duration models for crustal earthquakes, the subduction duration model shows stronger distance dependence and weaker magnitude dependence.

Induced Seismicity—The European Perspective

Oral Session · Thursday 20 April · 16:00 · Plaza E

Session Chairs: Manfred Joswig, Joshua White, and Mariano Garcia-Fernandez

Hydrocarbon Induced Seismicity in Northern Netherlands

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The northern Netherlands has been regarded aseismic until the first earthquakes started in 1986, after more than 25 years of gas production from the one of the largest on-shore gas-fields in the World, the Groningen field, and accompanying smaller gas fields. Due to the shallow sources, at 3 km depth, even small magnitude events cause considerable damage to buildings in the region. Since the largest recorded event in the Groningen field in 2012 with ML= 3,6, more than 50.000 damage claims were received by the mining company. Since 1995 a seismic monitoring network is operational in the region, consisting of 8 200m deep boreholes with 4 levels of 3C 4,5 Hz geophones. The network was designed for a location threshold of ML=1,5 over a 40x 80 km region. Average station separation was 20 km. Since 2003 a new mining law is in place in the Netherlands, which requires for each gas field in production a seismic hazard and risk analysis. At the same time an increase in the activity rate was observed, leading to the development of new hazard models and a re-assessment of parameters like the maximum magnitude. More recently these models are extended to seismic risk, where also the fragility of the regional buildings is taken into account. Understanding the earthquake process is essential in taking mitigation measures. Continued research is focused on reducing the uncertainties in the hazard and risk models and is accompanied by an upgrade of the monitoring network. In 2014 a new dense network was designed to monitor the Groningen gas field in this region (30*40 km) with an average separation of 4 km. This allows an improved location threshold (M>0,5) and location accuracy (50-100m). A detailed P- and S- velocity model is available for the region. In total 70 new 200m deep boreholes are operational in 2017. At each borehole an accelerometer is placed at the surface. In addition two deep downhole tools (3 km depth) are operational since 2013.

Modeling of Induced Seismicity in Producing Gas Fields in the Netherlands

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In several dozen of the onshore producing gas fields in The Netherlands, including the giant Groningen gas field, seismicity has been recorded during production. These seismic events are induced by pore pressure changes in the reservoir rocks, which cause stress changes on faults within and nearby the gas reservoir. Magnitudes of seismic events up to M_w 3.6 have been recorded in the Groningen field. Moreover, in the Groningen gas field a trend of increasing seismic activity and magnitudes with ongoing production and compaction is observed. For the assessment and mitigation of the seismic risks of future gas production, it is crucial to understand the underlying processes of fault rupture and seismicity. Here, we present an approach to model the seismic rupture on faults, intersecting a producing gas reservoir, and the resulting outward propagation of seismic waves towards the surface. Our approach consists of three components. We use a static numerical geomechanical model to analyze the onset of fault reactivation caused by the reservoir pressure changes and the compaction of the gas reservoir. Once the nucleation of a seismic event is observed, we use the same geomechanical model in dynamic mode to simulate the dynamic fault rupture process. The geomechanical models enable us to analyze the effects of reservoir and fault geometry (*e.g.* offset) and fault strength on the nucleation of seismic events and the main characteristics of the fault rupture in terms of fault slip, slip velocity, rupture area, event duration and stress drop. The near fault deformation computed in the dynamic model is transferred to SPECFEM2D by means of an equivalent force field. The wavefield is then propagated to the surface. This way, we can determine the expression of specific source characteristics, *e.g.* resulting from different fault geometries, in seismic records at varying distances from the source, which will allow a better interpretation of observed earthquake data.

3D Mechanical Analysis of Complex Reservoirs for Induced Seismicity: A Novel Numerical Approach

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For complex reservoirs, it is a major challenge to build geomechanical models, in particular if many faults need to be included. A clear example is the Groningen gas field in the Netherlands. The field is marked by over 1000 mapped faults with offsets which potentially contribute to seismicity, but it is hardly feasible to incorporate them all in a geomechanical model. Furthermore, the models are computationally intensive and therefore difficult to adopt in a probabilistic seismic hazard assessment.

In order to improve predictive capability and to provide physics based understanding of the reservoir seismicity we developed a novel way of calculating stress and slip and associated moment response for structurally complex reservoirs as the Groningen field. Our methodology deploys a mesh-free semi-analytical approach for stress calculation and seismic moment prediction. For the stress calculation on the faults we introduce a high-performance, high-resolution computational method, based on Green's function for stress response for nuclei of strain. Key is the deployment of an octree representation and calculation scheme for the nuclei of strain, in close agreement with the topology and spatial variability of the mesh for reservoir pressure depletion. For the seismic moment prediction, we use semi-analytical methods based on the elastic solution in step 1. We do not take into account stress interactions from one fault to another as stress effects due to slip are restricted spatially to the vicinity of a single fault.

We demonstrate the capability of the novel calculation workflow, dubbed as MACRIS (Mechanical Analysis of Complex Reservoir for Induced Seismicity) through benchmarks with finite element model (FEM) solutions. We show that it can easily handle the 1000 faults contained in the Groningen field, and we highlight performance and first order correspondence of the spatio-temporal characteristics of the seismic moment predicted by the model and observations.

Recent Seismicity in the Northern German Gas Fields—Induced and Tectonic?

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In the northern German gas fields, production of conventional plays started in the 60s, and was enhanced by some 300 tight gas fracks. Since then, several ML 2 to ML 3 earthquakes per year happened in a previously quiet area but none could directly be related to the fracking operations. The 2004 ML 4.5 Rotenburg earthquake is the largest event so far recorded in an area of reservoir depletion. Seismicity is generally bound to some 5 km depth corresponding to the exploited gas reservoirs in the Rotliegend. Thus this seismicity is assumed to be probably related to the conventional gas extraction. For liability claims, the regional seismic monitoring has improved recently by several new stations operated for BVEG—an industry consortium of gas producers—and BGR—the German federal governmental agency for geosciences and resources.

In the context of the DGMK research project 761, Stuttgart university has installed an additional, small-scale seismic network that monitored the Rotenburg region for the last three years. For our monitoring, we combined two 10-station arrays with two tri-partite small arrays and three 3C single stations. Our installation covers an area of 15 by 20 km achieving a detection threshold of ML 0.5 as verified by 50+ events in a distance range of up to 100 km. In spite of this sensitivity just one small event ML 1 was observed so far near Rotenburg.

Reprocessing BVEG and BGR data from the past by cross correlating seismograms from the bulletin earthquakes we found more events also clustering at 5 km depth. Additionally we discovered four singular, deeper earthquakes at 25 km to 30 km depth which previously were overlooked in regional monitoring due to the many noise bursts by military shooting. Most likely, these deeper earthquakes are related to the stress release from postglacial isostatic relaxation, and fit to the observed, regional seismicity of singular, mid- to lower crust earthquakes.

Monitoring an Underground Gas Storage in a Seismic Area: The Case of Collalto (Northeastern Italy)

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Italy has about 15 sites devoted to underground gas storage (UGS) activity. All sites are on-shore and use depleted natural gas reservoirs. UGS is crucial for the Italian energetic policy, in order to support gas demand fluctuations and to guarantee strategic supply for extraordinary demand. Being Italy heavily exposed to natural seismicity, these activities often are opposed by part of the local population, the possibility to trigger earthquakes exists, and the possible interaction with existing seismogenic faults must be accurately monitored. As recognised by the Italian Guidelines for monitoring published in 2014, high-sensitivity seismic monitoring allows recognising the occurrence of induced seismicity at the early stage, and intervening in case of seismicity anomalies.

The Collalto gas storage is located in NE Italy, on the foothills of Southern Alps, and exploits a depleted natural gas reservoir 1.5 km deep. The activity is managed by Edison Stoccaggio S.p.A. since 1994. The gas storage is monitored by OGS through the Collalto Seismic Network (RSC) since 2012, as imposed by local and national administrators, when the company requested to inject gas up to 160 bars (*i.e.* the original pressure). RSC consists of 10 stations deployed at increasing distance from the reservoir and equipped with borehole broadband sensors and surface accelerometers.

In more than 5 years, RSC has detected and located a thousand of microearthquakes, also with negative magnitude. The high-quality monitoring is demonstrated by a completeness magnitude of about 0 in a 20 km wide area around the reservoir. The located seismicity is not correlated with injection/extraction operations either in time or in space, as shown by pore-pressure diffusion modeling. On the other hand, the 3D seismicity pattern depicts the deep geometry of the Alpine compressive front, reveals the activity of the local thrusts, and suggests the natural origin of all events.

Intraplate Earthquakes: Central and Eastern North America and Worldwide

Oral Session · Thursday 20 April · 1:30 PM · Governor's Square 15

Session Chairs: Lillian Soto-Cordero, Christine Powell, and Will Levandowski

A New Paradigm for Large Earthquakes in Stable Continental Plate Interiors

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Large earthquakes within stable continental regions (SCR) show that significant amounts of elastic strain can be released on geological structures far from plate boundary faults, where the vast majority of the Earth's seismic activity takes place. SCR earthquakes show spatial and temporal patterns that differ from those at plate boundaries and occur in regions where tectonic loading rates are negligible. However, in the absence of a more appropriate model, they are traditionally viewed as analogous to their plate boundary counterparts, occurring when the accrual of tectonic stress localized at long-lived active faults reaches failure threshold. Here we argue that SCR earthquakes are better explained by transient perturbations of local stress or fault strength that release elastic energy from a prestressed lithosphere. As a result, SCR earthquakes can occur in regions with no previous seismicity and no surface evidence for strain accumulation. They need not repeat, since the tectonic loading rate is close to zero. Therefore, concepts of recurrence time or fault slip rate do not apply. As a consequence, seismic hazard in SCRs is likely more spatially distributed than indicated by paleoearthquakes, current seismicity, or geodetic strain rates.

Repeating Large Holocene Earthquakes in the Central and Eastern U.S. Warrant Continuing High Hazard Characterization

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Collectively the Wabash Valley, New Madrid, and Charleston seismic zones account for about 15 M7–7.5 intraplate earthquakes in the Central and Eastern U.S. (CEUS) in the Holocene. These seismic zones are primary contributors to seismic hazard and are the best studied in the CEUS, with substantial pre-historic earthquake chronologies based on liquefaction and trenching data. These data show that the New Madrid seismic zone (NMSZ) accounts for about 10 of these large earthquakes during the last 4000 years. Other studies in the NMSZ show that there are an additional 15 Quaternary faulting localities around the NMSZ revealing a more widespread and complex hazard than just the M7-7.5 earthquake sequences in 1811–1812, ~1450 A.D, ~900 A.D., and ~2200 B.C. The pre-Holocene NMSZ earthquake history is unknown, although seismic reflection data provide evidence of long-term recurrent faulting. Liquefaction features also identify two large (M6.7–7.3) late Pleistocene to Holocene earthquakes approximately 6000 and 12,000 years ago in the Wabash Valley seismic zone (WVSZ). No historic-era earthquakes of this magnitude are known in the WVSZ, although the region has hosted possibly 10 M5–5.6 earthquakes since about 1800. The Charleston seismic zone is defined by a M6.9–7.3 earthquake in 1886 as well as liquefaction evidence for multiple strong ground shaking events into the mid-Holocene. Consensus opinion currently explains the lack of long-term surface deformation in these seismic zones, and other regions of the CEUS, as resulting from intermittent earthquake activity through time, which may be caused by transient stress changes. While the causes of earthquakes in these regions is an active area of research, the uncertainty of where we are within these clusters and the earthquake record necessitate sensible measures of preparedness and earthquake engineering design in these high-hazard areas.

The Geodynamics of Intraplate Stresses within Central and Eastern North America

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Central and eastern North America have experienced large intraplate earthquakes. The 2011 Mineral, Virginia M5.8 earthquake is a reminder that intraplate stresses continue to produce events of permanent strain within the plate interior. Yet, at present there is no comprehensive model to explain passive margin stresses, strains and seismicity. Although there is agreement that some of these earthquakes occur along favorably oriented ancient rifts and other major strength contrasts, there is no consensus on the sources of intraplate deformation and earthquakes. Proposed models include glacial isostatic adjustment (GIA), ridge push effects and large scale convection. Recent studies have also argued that dynamic topography impact the passive margin. We present a self-consistent model of the dynamics of eastern North America that explains the stress field responsible for these intraplate earthquakes. The earthquakes represent slow, ongoing deformation associated with forces arising from a combination of lithosphere topography and structure, coupled together with the effects of density driven mantle flow. We test the effects of lateral strength contrasts within the lithosphere. Important features involve a strong craton interior, a weaker lithosphere east of the craton boundary, comprised of Appalachian terranes, along with strong oceanic lithosphere east of the stretched continental margin of North America. Models with a strength contrast along the ancient suture between Laurentia and accreted Appalachian terranes show a rotation of stresses from NE-SW maximum compressive stress directions west of the boundary, roughly E-W maximum compression within the boundary zone, and NE-SW compression within the oceanic plate. This stress rotation pattern appears to be supported by the bulk of moment tensor solutions of small to moderate-sized earthquakes that lie within continental lithosphere east of the Laurentian margin, including the Mineral, Virginia earthquake.

Evidence for Hydrous Mantle beneath the New Madrid Seismic Zone: A Potential Explanation for an Intraplate Enigma

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The origin of the New Madrid seismic zone (NMSZ) remains an intriguing question facing scientists concerned with central and eastern U.S. tectonics and seismic hazard. New insights regarding the role that mantle heterogeneity plays in the generation of NMSZ earthquakes may improve our understanding of why the zone exists and the likelihood of future seismic activity. Tomographic images obtained using teleseismic data recorded by the EarthScope Transportable Array and the FlexArray Northern Embayment Lithosphere Experiment reveal an isolated region of thinned lithosphere below the Mississippi Embayment (ME), including the NMSZ. Additionally, low Vp and Vs in the mantle under the NMSZ extend from near the Moho to the top of the transition zone (410 km). The magnitudes of the Vp and Vs anomalies—up to 6%— are similar, which is inconsistent with a purely thermal perturbation. Instead, this finding argues for the presence of hot, wet mantle. In light of increasing observational and experimental evidence that subducted slabs can transport water into the transition zone, we speculate that these conditions are produced by the dewatering of a flat portion of the Farallon slab in the transition zone below the ME. A similar hypothesis exists for the East North China Craton, another locus of intraplate seismicity. Fluid flux from subducted material into the overlying mantle can influence rheology and flow, resulting in lithospheric thinning and the influx of low velocity, hydrated material at lithospheric depths. Preexisting lithospheric-scale faults inherited from Eocambrian rifting could focus fluids and associated metasomatism beneath the NMSZ compared to surrounding areas. Numerical modeling based upon a surface wave Vs model suggests that the presence of low mantle viscosities may strongly affect earthquake nucleation and rupture processes in the NMSZ. If crustal strain is localized by hydrous mantle, then future seismic activity may be focused within the NMSZ.

Control of the Lithospheric Mantle on Intracontinental Deformation: Revival of Eastern U.S. Tectonism

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Southeastern United States is a product of earlier episodes of arc accretion, continental collision and breakup. This region is located in the interior of the North American Plate, some 1500 km away from the closest active plate margin. However, there is ongoing tectonism across the area with multiple zones of seismicity, rejuvenation of the Appalachians and Cenozoic intraplate volcanism. The mechanisms controlling this activity and the modern-day state of stress remain enigmatic. Recent improvements in broadband seismic data coverage in the region associated with the South Eastern Suture of the Appalachian Margin Experiment (SESAME) and EarthScope Transportable Array make it possible to obtain detailed information on the structure of the lithosphere in the region. Here we present new tomographic images of the upper mantle beneath the Southeastern United States, revealing large-scale structural variations in the upper mantle. Our results indicate fast seismic velocity patterns that can be interpreted as ongoing lithospheric foundering. We observe an agreement between the locations of these upper mantle anomalies and the location of major zones of tectonism, volcanism and seismicity, providing a viable explanation for modern-day activity in this plate interior setting long after it became a passive margin. Based on distinct variations in the geometry and thickness of the lithospheric mantle, we propose that piecemeal delamination has occurred beneath the region throughout the Cenozoic, removing a significant amount of reworked/deformed mantle lithosphere. Recent geological observations from the region indicate that the foundering of lithosphere could possibly be related to post-rift, long-term thermal instability of the passive margin. Therefore, ongoing lithospheric foundering beneath the eastern margin of stable North America could present a possible mechanism for passive margin tectonism, volcanism and variations in geological stability across the region.

The January 2017 Barrow Strait Earthquake Sequence, Arctic Canada

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At 23:47 UT on 8 January 2017, a magnitude (M_W) 5.9 earthquake occurred just offshore of Somerset Island, in Barrow Strait 92 km from Resolute in northern Canada. The earthquake, which occurred near the Boothia Uplift of the Boothia-Ungava Seismic Zone, was one of the largest to occur in eastern Canada during the last 50 years. It was recorded on scale by the newly refurbished seismograph in Resolute (RESN). An earthquake of this size is expected about once every 300 years based on the statistics for the Somerset-Cornwallis Island seismic source zone; the rate for Barrow Strait by itself is higher than for the larger region. The mainshock was followed by a rich and currently ongoing aftershock sequence. As of 10 January 2017 there were seven aftershocks of magnitude 3.0 or greater with the largest being a magnitude 5.1 event that occurred at 17:55 UT on 9 January. We note that swarm activity is common in this area but it is too soon to determine whether this is a typical mainshock-aftershock sequence or a swarm. Moment tensor inversion of the mainshock indicates that it was a predominantly thrust faulting event on a northwest-striking plane consistent with past events in Barrow Strait including the magnitude 5.2 event in 1987 that occurred 30 km NW of the January 8 mainshock. We will discuss the characteristics of the mainshock, seismotectonics of the region, an analysis of the aftershock sequence, depth estimation using a variety of methods such as moment tensor inversion and analysis of teleseismic depth phases, and analysis of INSAR data for possible surface deformation and confirmation of source parameters.

Influence of the 2011 M9.0 Tohoku-Oki Megathrust Earthquake on Intraplate Seismicity around the Korean Peninsula

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Megathrust earthquakes produce large permanent lithospheric displacements as well as strong transient ground shaking up to regional distances. The lateral permanent displacements construct stress shadows in a wide backarc region. The Korean Peninsula is placed in the far-eastern Eurasian plate that belongs to a stable intraplate region with a low earthquake occurrence rate and diffused seismicity, and is located in the backarc at ~1300 km in the west from the epicenter of the 11 March 2011 M9.0 Tohoku-Oki earthquake. The seismicity around the Korean Peninsula was increased significantly after the 2011 M9.0 Tohoku-Oki earthquake, which is not consistent with the expected seismic-quiescence. Strong seismic waves cause large dynamic stress changes, incurring fluid migration and increasing pore fluid pressure in the media. The lithospheric displacements directing to the epicenter on the convergent plate boundary develop transient radial tension field over the backarc lithospheres. The seismic velocities in the lithosphere changed abruptly up to ~2 % after the megathrust earthquake, which recovered gradually with time for several years. The pore pressure growth and radial tension field decrease the Coulomb failure stress, increasing episodic increases of seismicity in both fault zones and intact media. The ambient stress field is recovered gradually as the induced stress field diminishes with time by tectonic loading. The seismicity changes with the temporal evolution of stress field. A series of moderate-size earthquakes and earthquake swarms occur as a consequence of medium response to the temporal evolution of stress field. The long-term evolution of seismicity is expected to continue until the ambient stress field is fully recovered.

Faults and Lineaments of the St. Lawrence Rift System

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The St. Lawrence Rift System (SLRS) is an important component of the geological model used to define seismic hazard in eastern Canada. The SLRS includes most of the St. Lawrence valley, plus the Ottawa-Bonnechere (OBG) and the Saguenay (SG) grabens. Regional faults along the SLRS are not located in most geological maps which is problematic for seismic hazard assessments. For this reason, this project aims at producing a digital map of the faults and lineaments of SLRS. The digital map will help defining the relationships between earthquakes and faults, including when new sizeable earthquakes occur within the SLRS. Since most SLRS earthquakes occur in the Precambrian Shield rocks, only the lineaments and faults of the Grenville Province are considered.

The project integrates the results of the existing structural geology mapping along the SLRS, most notably along the OBG on the Ontario side and along the SG. Additional lineaments were interpreted mostly from the Digital Elevation Model (DEM) of the Canadian National Topographic Data Base (NTDB) at a scale of 1:250,000. Only the brittle structures were considered; the ductile structures of the Grenvillian orogeny were not mapped. Brittle structures are generally linear whereas ductile structures are curved or present a distinct pattern. Also, only the lineaments with a length greater than 5 km were considered. From this first detection pass, regional scale lineaments were drawn by interpolating between segment of lineaments where the topography was subdued and did not create a conspicuous trace. Where possible, other sources of data such as magnetics, gravity, bathymetry and Lidar (for Charlevoix) will be included in the final product. During the last few months, we have concentrated our efforts on the lineaments of the Western Quebec Seismic Zone and of the Quebec North Shore region. This paper will present an up-to-date status of our mapping effort.

Eastern Tennessee Seismic Zone Paleoseismology—Alignment of Faults Displacing Quaternary Sediments, and Bedrock, and Liquefaction Features, Confirm Strong Earthquakes in the Past 15 ka

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The eastern Tennessee seismic zone (ETSZ) extends from SE KY through E TN and NW GA to NE AL. It is the second most active in the E US; seismicity is localized 5-15 km deep in the basement. No historic earthquakes (EQ) larger than M_w 4.8 have been recorded. We have concentrated on Quaternary river sediments up to 800 ka resting on Paleozoic shale to eliminate misinterpretation of Quaternary karst features formed on carbonate rocks. During the past 8 yrs, we have identified a 125 km-long 060 line of thrust, strike-slip, and normal faults with displacements of 1-2 m parallel to a local trend of maximum seismicity. These displacements require one or more EQ of M_w >6.5. We also have identified EQ-generated liquefaction features at several localities in E TN and NW GA. A listric thrust fault on Douglas Lake E of Knoxville truncated an alluvium-filled 045 fissure dated at ~15.4 ka. Two sizable EQ likely produced these structures. Another thrust fault N of Maryville, TN, (S of Knoxville) had two episodes of faulting separated by sedimentation. A third zone of thrust faulting occurs SW of Maryville near Vonore, TN, 1.5 km NE of a 1-2 m displacement normal fault. Another intensely fractured zone occurs near Tellico Plains, TN, off the 060 trend, but on a N-S spur off the main trend of seismicity. Conjugate thrust faults occur here, but displacements are unknown. Faults are commonly filled with red sandy-clay gouge.

This fault system may be related to: an interrelated stepover system of faults from a master fault at depth; an array of localized coseismic faults and fractures that developed above an active basement fault; or by another mechanism. Each option is likely the product of one or more M_w>7.0 EQ. Taken separately, they require EQ of M_w >6.5 in the ETSZ to produce the observed displacements and structures. We have confirmed that EQ of M_w >6.5 have occurred here, and our incomplete data set suggests a recurrence interval of 7.5 ka or less.

PSHA Source Modeling: Approaches, Uncertainty and Performance

Oral Session · Thursday 20 April · 1:30 PM · Governor's Square 14

Session Chairs: Peter Powers and Christie Hale

PEER PSHA Code Verification Project

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Probabilistic Seismic Hazard Analysis (PSHA) has become the primary tool in estimating seismic hazard and is used both on a site-specific basis for critical facilities and on a national scale for building codes. Meanwhile, a series of comprehensive hazard characterization projects have resulted in the development of increasingly complex source and ground motion models, which necessitate implementation into the PSHA codes. With important decisions being made based on seismic hazard results, and the rapidly increasing sophistication of the source and ground motion models, there is a need to ensure that the codes used in PSHA calculations are tested and verified. Through the PEER PSHA code verification project, participants ran a suite of tests on their own codes, results were compiled, and meetings were held to discuss the results and understand the modeling approaches leading to differences in reported hazard.

Through several iterations, and many changes to the PSHA codes, consensus results were reached and a set of standardized tests and benchmark answers were developed for the majority of the tests. For some of the more advanced tests, the project provided an opportunity to identify the questions that the code developers faced when implementing more complex source and ground motion models. For a bending fault, how is the geometry of the fault handled at the bends where gaps or overlaps may form, and how is the perpendicular distance Rx calculated when this distance changes as the rupture bends? How far out on the tails of the ground-motion distribution can the codes reliably compute probabilities of exceedance, and when do we see a difference in hazard between the standard lognormal distribution and a mixture-model distribution for ground motions? This presentation focuses on how these issues lead to different modeling approaches within the PSHA codes, and the associated sensitivity of the calculated hazard.

Some Sources of Modeling Uncertainty for Area Source Zones in Probabilistic Seismic Hazard Analysis

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Area source zones or distributed seismicity sources are used to model the spatial distribution of earthquakes in areas of low seismicity or to represent background seismicity that cannot be correlated to mapped faults in the region of interest. A recent verification project carried out by PEER compares capabilities available in several PSHA codes to model area source zones. The project identifies sources of modeling uncertainty due to different approaches currently used by practitioners. This study describes some of the findings of this project and expands the discussion to the potential impact of these findings in the Central and Eastern U.S. Seismic Source Characterization Model sponsored by U.S. Department of Energy, U.S. NRC and EPRI in 2012.

Different approaches to model the rupture within the seismogenic area are reviewed. Sensitivity of the hazard results to the spacing of point source/virtual fault grid, and magnitude increment used for the integration of the hazard is assessed. The impact on the hazard is calculated from 1E-2 to 1E-7 mean annual frequency of exceedance. This range covers design requirements in building codes and probabilistic risk assessment of critical structures like nuclear power plants.

Exploring Source Modeling in the GEM Hazard Models Database

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One of the most important goals of Global Earthquake Model (GEM) Foundation's second implementation phase (2014-2018) is the construction of a global earthquake hazard model. The paradigm adopted by GEM for its construction relies to the largest extent possible on the use of publicly-accessible models developed within large multinational projects and well-recognized scientific organizations operating at national and international level. The result is a mosaic of PSHA input models sharing a common format which conforms to the one used to describe PSHA input models in the OpenQuake Engine, GEM's hazard and risk calculation engine. Examples of models found in this database include the ones for Europe, Middle East, Central Asia, South America, Sub-Saharan Africa regional as well as national models such as the Australian, the U.S. National

Model (2008) and the Taiwan model (for a comprehensive list please consult the OpenQuake Platform at https://platform.openquake.org/). New models are in the process of being included, such as the UCERF3 model for California and the 2014 U.S. National model, the HERP (2014) model for Japan and new national models for various nations including, for example, New Zealand.

Overall, the set of PSHA models so far collected and implemented presents a comprehensive spectrum of modeling choices for the description of earthquake occurrence in time and space for the purpose of assessing hazard. In this presentation we illustrate the main content of the GEM hazard models database and we appraise the main characteristics of the earthquake source models it includes. We discuss more quantitative comparisons aimed at understanding similarities and differences between earthquake sources included in different models and belonging to, for example, similar tectonic contexts. Ultimately these comparisons provide a summary of current state-of-practice in earthquake source models currently used for assessing hazard at regional and national scales

Slab Models for PSHA

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"Slab" earthquakes are defined as those occurring in downgoing, subducting oceanic plates. For hazard characterization, these are important because they often occur directly below populated areas on the overriding plate, and appear to produce relatively higher ground motions than other sources. Slab events are observed to occur from 30–50 km depths down to about 650 km. The rate of activity decreases down to about 450 km. Earthquakes deeper than this appear to have different source characteristics than the shallower ones, and due to their distance from sites on the earth surface and lack of information on the ground motions they produce, are generally not considered in PSHA analyses. Most focal mechanisms indicate normal faulting on steeply dipping planes parallel to the arc, due to gravitational stress ("slab pull"). Hypocenters tend to occur in the top 40 km of the slab, in the central part of the rupture plane, with planes dipping about 45 degrees with respect to the slab dip. Maximum magnitudes of slab events appear to be M_w 7.9–8.2. For the PEER PSHA Code Verification tests, participants were asked to model a two-segment slab model and compute probabilistic ground motions. Modeling approaches included 3D areal zones filled with point sources or virtual faults, listric faults within the slab, and virtual faults within the 3D slab volume. Large variations in results were observed, especially at the longer return periods, which appear to be due to varying distance and depth distributions. Current slab peak ground motion attenuation models appear to be very sensitive to rupture depth and distance, and saturation effects at higher magnitudes are not well known. If high-resolution seismicity data are available, a slab model incorporating both observed geometry and magnitude rates can be developed. An example from Alaska includes slab segmentation geometry and Gaussian-smoothed seismicity rates.

Parameterizing Directivity in PSHA

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The PEER Working Group on Directivity generated five models that can be implemented in probabilistic seismic hazard analyses (Bayless and Somerville 2013, Chiou and Spudich 2013, Rowshandel 2013, Shahi and Baker 2013, and Spudich and Chiou 2013). The differences between these models can be large in some cases and thus the epistemic uncertainty due to directivity cannot be ignored. To account for this epistemic uncertainty more than one directivity model must be included in the PSHA. This increases run times for PSHA as each ground motion prediction equation must be run with each directivity model selected.

Additionally, all of the PEER Directivity Working Group models require the distance to the hypocenter as an input. Incorporation of these models within PSHA thus necessitates including the distribution of hypocenter locations within the hazard calculation. Run times for PSHA can dramatically increase depending on how finely sampled the hypocenter locations are. The accuracy of the directivity models is also dependent on the sampling of hypocenter location, and the total effect is dependent on the distribution of hypocenters on the fault plane.

The effects of hypocenter distribution, hypocenter sampling and model selection are examined using the hazard code Haz45.2 for a number of PEER Directivity Working Group models as well as the Watson-Lamprey (2017) directivity model, which does not require the inclusion of hypocenter distribution within the hazard analysis. Recommendations are provided for hypocenter modeling and directivity model selection that capture the epistemic uncertainty due to directivity and maximize the accuracy of the calculations while minimizing run times.

Epistemic Uncertainty in the National Seismic Hazard Mapping (NSHM) Project Models

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Complex probabilistic seismic hazard analysis (PSHA) systems such as the National Seismic Hazard Mapping (NSHM) Project utilize multiple ground motion models and complex models for seismicity, combined through logic trees, to address scientific or epistemic uncertainties. This treatment of epistemic uncertainty alters the weighted average or consensus "mean" that is reported, but also produces dispersion in the results, and this dispersion generally goes unreported. Consequently, users may attribute undue precision to the results, sometimes with significant consequences.

In this study, we utilize a method called Robust Simulation [Lee et al, 2014, 2015; Taylor, 2015] to examine the impacts of epistemic uncertainty in the UCERF3 source models and NGA West2 ground motion models (GMMs) to the results of the NSHM. The method preserves and displays separate coherent track of the logic tree, as well as the "mean" solution, presented in a set of hazard curves. We examine the epistemic dispersion in hazard results for major seismic regions in the U.S., *i.e.*, Southern California, Northern California, Pacific North-West, Utah (the Wasatch Fault Zone) and the New Madrid Seismic Zone. We identify regions where the dispersion of scientific results is greatest. For sites in California, we also examine the epistemic dispersion on NERHP B/C and D site conditions, accounting for diverse soil amplification models from GMMs directly.

Modeling Virtual Faults in PSHA

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There is no scientific consensus on how virtual faults should be modeled in the probabilistic seismic hazard analysis (PSHA) of gridded seismicity and area sources. Often pragmatic implementation decisions are made out of convenience or computational efficiency. These decisions are generally not evaluated to understand their impact on the PSHA results. To better understand how differences in modeling virtual faults impact seismic hazard, we evaluate several methods of characterizing such faults: (1) a point-source approach wherein no virtual faults are used, (2) a simplified approach used by the US Geological Survey to develop the 2014 National Seismic Hazard Maps, and (3) two approaches in which either the top or the centroid of a set of randomly-oriented 3D virtual fault planes are centered on the source grid point. We propose a new, more efficient method of modeling the random strike of a virtual fault by assuming that the location and orientation of the 3D fault plane is fixed and a series of virtual sites with the same point-to-point distance as that between the actual site and the source grid point is rotated around the source grid point, thus eliminating the need to create multiple versions of the fault plane. We use the UCERF3 seismic-source model, the NGA-West2 ground-motion prediction equations (GMPEs), the OpenSHA PSHA platform, and a site located in Sacramento, CA to calculate the hazard used in the study in order to peg the results to a real-world example. In addition to evaluating the different approaches used to model virtual faults, we also perform analyses to show the sensitivity of the results to the number of azimuths used to define a randomly-oriented fault, the distance cutoff used to define when a fault (whether virtual or geologic) is included in the PSHA, and the local site conditions used to evaluate the GMPEs. Our results show that there can be relatively large differences in seismic hazard depending on how gridded seismicity is modeled.

UCERF3 Implementation for Site-Specific Probabilistic Seismic Hazard Analysis

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We present our methodology for implementing the Uniform California Earthquake Rupture Forecast, version 3 (UCERF3) seismic hazard model for site-specific applications. The UCERF3 procedure represents a departure from the traditional approach of developing a seismic source model and then computing probabilities of exceedance, in that it begins with a set of seismic source characterizations with full variability and then performs a state-wide inversion to best fit observed data. This allows the UCERF3 model to incorporate multi-fault rupture scenarios while honoring observed seismicity, geodetic, and paleoseismic data; however, the computationally intensive inversion is impractical to reproduce and refine for site-specific applications. UCERF3 model inputs include spatial geometry for fault sources, but magnitude frequencies are derived from the inversion and cannot be used directly for site-specific PSHA. Further, UCERF3 may not include potentially significant fault sources in the immediate proximity of the project site, or may lack sufficient detail for local sources.

Our methodology uses UCERF3 model inputs for fault sources and key inversion outputs for magnitude-recurrence. Publicly available Magnitude-Frequency Distributions (MFD) and "participation" data for each fault section, in conjunction with fault geometry, incorporate all the epistemic and aleatory uncertainty in the UCERF3 model. To adjust UCERF3 MFD for site-specific PSHA, we identify fault systems with control sections and dependent sections. Ruptures on a fault system are attributed to the section closest to the site and subtracted from MFD for adjacent participating sections to avoid double counting. Local faults are added to the model by way of scaled proxy MFD, and background grid MFD are reduced accordingly below added faults. Our methodology has been used and reviewed on recent projects, including for the Sanitation Districts of Los Angeles County and the Lawrence Livermore National Laboratory.

Probabilistic Fault Displacement Hazard Analyses—Evaluation of Empirical Relationships for Fault Displacement

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Probabilistic fault displacement hazard analysis (PFDHA) is a relatively new tool for assessing design displacements for projects that cross or lie astride active faults. While the availability of slip distributions for all three types of faulting, strike-slip, reverse, and normal, significantly improves the applicability of PFDHA for different tectonic environments, the available models, empirical relationships, and details of the methodology require numerous explicit choices by the practitioner to perform PFDHA. One of the choices in PFDHA is the type of displacement estimate, for expected maximum or the expected average displacement on the fault. This study provides sensitivity analyses of the effects of different empirical relationships for maximum and average displacement that may be used to evaluate the expected fault displacements at a site.

Available relationships for estimating maximum and average displacement are based on ordinary least squares regressions (OSL, e.g, Wells and Coppersmith, 1994). OLS regressions based on new average and maximum displacement data sets provide more reliable but not significantly different results than previous OLS regressions. A more important choice is consideration of alternatives such as orthogonal regression (OR). OR appears to be applicable to data sets of earthquake source parameters, and they are convenient because they apply to both parameters as the dependent variable. However, as OR minimizes errors in both variables, rather than minimizing error in the dependent variable, it is not clear which form is more appropriate for engineering application. OR for average displacement and magnitude provide slightly lower to similar results to OLS regressions at moderate magnitudes (M 6.0-7.0) but provide increasingly larger displacements with increasing magnitude (greater than M 7.0). Thus, the choice of regression is important for engineering application where large earthquakes and large fault displacements may occur.

Incorporating Uncertainty in Kernel Density Models of Distributed Seismicity into Hazard Assessments

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A key focus of probabilistic seismic hazard analyses is to identify, quantify, and incorporate the epistemic uncertainties associated with seismic source characteristics. Kernel density estimates are commonly used to model the spatial distribution of background seismicity in a source zone or region. The kernel density represents a statistical estimate of the spatial distribution of future earthquakes, and is based on the assumption that the observed distribution of seismicity is a good model for the distribution of earthquakes in the future.

Two techniques are commonly applied in probabilistic seismic hazard assessment: one in which the kernels have a fixed size (*e.g.*, Frankel, 1995; Petersen *et al.*, 2008, 2014), the other in which the kernel size varies depending on the distances to the nearest earthquakes (*e.g.*, Petersen *et al.*, 2014) or on the local seismicity density (*e.g.*, Stock and Smith, 2002). Using adaptive kernel methods, the size of the kernel is larger in areas of sparse seismicity and smaller where earthquakes are concentrated.

Regardless of the approach, the computed kernel density represents an estimate from a finite sample of earthquakes. In this study we explore the statistical uncertainty in that estimation and its impact on the uncertainty in the resulting seismic hazard. Using the adaptive kernel smoothing technique based on the work by Stock and Smith (2002), uncertainty in the kernel density estimates is assessed by a bootstrapping procedure. The initial adaptive kernel density function produces a value of the kernel bandwidth parameter for each earthquake. Using these values in 2-D Gaussian distributions centered on each earthquake, alternative synthetic earthquake catalogs are simulated. Each simulated catalog is then refit with an adaptive kernel density function. The effect of using alternative spatial density models in seismic hazard analysis will be illustrated through a series of examples from regions of low and high seismicity.

Recent Advances in Very Broadband Seismology

Oral Session · Thursday 20 April · 8:30 AM · Governor's Square 16

Session Chairs: Adam Ringler, David Wilson, and Robert Anthony

Physical Mechanisms of Seismometer Site Noise and Self-Noise

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Ideally any seismometer installation should have a noise level corresponding to a predefined specification, to ensure the noise level is below the signals of interest. In practice seismic data may contain unforeseen noise artifacts and may vary widely in quality from one station to another due to particular site conditions, problematic installation methods, or a defective or unsuitable instrument. Also some modes of ground motion can be considered as noise, for example local vibration or tilt motion obscuring teleseismic signals.

In this study we present an analysis of the physical phenomena which most commonly cause noise artifacts in broadband seismic data, based on data from controlled laboratory experiments as well as field installations. Each different physical mechanism gives rise to noise with particular distinguishing characteristics which can enable the user to diagnose noise symptoms, trace them to a root cause, take corrective action, and evolve towards best practices for particular environments and use cases.

Installation Techniques Used to Maximize Data Quality at Global Seismographic Network Stations

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As the Global Seismographic Network (GSN) was constructed, considerable investment was made in sensor emplacement and infrastructure to maximize the quality of the data collected from the GSN's observatory-grade very broadband (VBB) sensors. These investments included drilling of boreholes where traditional tunnels and mines did not exist, packing techniques to suppress convection currents in those boreholes, mechanical isolation of instruments installed on conventional piers, and liberal use of thermal insulation to stabilize thermal conditions in the sensor's recording environment. Now that more than two decades of data from these installations are available, the effectiveness of these investments can be examined and the knowledge gained can be applied to the current program for modernizing the GSN's infrastructure.

Using GSN data from inception to the present, we will present analyses that demonstrate how successful these sensor emplacement strategies may have been and describe ongoing experiments at GSN testing facilities to evaluate the best, most cost effective strategy to renovate existing GSN facilities

A Portable Fiber Optic Gyroscope—Performance and First Field Tests

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We present the performance characteristics of BlueSeis-3A instrument, the first fiber optic gyroscope (FOG) especially designed for the needs of seismology. BlueSeis-3A was developed by iXBlue (France) in close collaboration with the European Research council project ROMY (Rotational motions—a new observable for seismology).

We first present the performance of the new sensor by quantifying the sensor self-noise using operating range diagrams. Next, we present the first results of two experiments with collocated measurements of translational acceleration and rotation rate. One experiment was conducted as an aftershock measurement close to the October 2016 Norcia sequence. Using the co-located measurement, we are able to estimate local wave field properties as *e.g.*, the back azimuth of the incoming wave field and the SH-wave velocity, respectively.

The second experiment took place at Giotto's bell tower in Florence, Italy, and served to explore the benefit of having a direct measurement of rotation rate in structural health monitoring.

Progress in the Development of an Optical Seismometer

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Optical interferometry offers displacement sensing with the unusual combination of high sensitivity, linearity, and wide dynamic range. We have applied interferometric technology to inertial seismic instruments and tested them in a 60 m borehole at the Albuquerque Seismological Laboratory with excellent results.

In our optical seismometer, we measure the positions of two pendulums (for the horizontal components) and a spring-supported mass (for the vertical components) with interferometry. Rather than using feedback to maintain constant positions of the test masses, we allow them to oscillate naturally. Knowing their free periods and damping, we can solve for ground motion from the records of the mass motions. This has two main advantages: first, only optical fibers between the sensors and the surface electronics are required, eliminating the need for downhole electronics; and second, the sensor bandwidth extends to DC. The simplicity and longevity of the metal and glass borehole sonde make it suitable for permanent cementation into a borehole to achieve good coupling and stability. The result is a seismo-geodetic sensing system that provides three components of observatory quality seismic recordings, two components of tilt, and gravity, all in a single borehole sonde linked to the surface with optical fibers.

Seismogeodetic Instruments as Broadband Seismometers for Local Earthquake Early Warning and Rapid Response

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Ground motions can exceed the dynamic range of near-field broadband seismic instrumentation (clipping) for large events of interest to earthquake and tsunami early warning systems. Strong motion accelerometers, designed with low gains to better capture strong shaking and that do not clip, are typically deployed with broadband seismometers. However, integrating accelerations to displacements is problematic because it amplifies small "baseline" errors, creating unphysical drifts that must be eliminated with a high pass filter. In this process the permanent displacement is lost. Direct measurements of displacement by GNSS/GPS networks in the near-source region of significant earthquakes, are not affected by instrumental limitations and magnitude saturation experienced by local seismic networks. However, GNSS/GPS displacements by themselves are too noisy for strict earthquake early warning (P-wave detection). We describe the optimal combination of high-rate GPS (1-5 Hz) and very-high-rate (100-200 Hz) strong motion accelerometer data using a Kalman filter, referred to as seismogeodesy. The result is a broadband instrument that does not clip in the near field, is impervious to magnitude saturation, and that measures accurate real-time static and dynamic displacement and velocity waveforms. We give examples of seismogeodetic combinations that are derived from observatory-grade as well as inexpensive MEMS accelerometers for earthquakes up to M_w9.0. Even with the MEMS sensors, we can detect the P-wave for local earthquakes of magnitude 4 and above. Using the seismogeodetic data we can generate a hierarchy of products, including automatic P-wave picking, hypocenter estimation, S-wave prediction for early warning, magnitude scaling relationships based on P-wave amplitude and peak ground displacement, finite-source CMT solutions and fault slip models within 2-3 minutes of earthquake onset time.

Horizontal Seismometers—Determining Orientation and Self-Noise

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The Berkeley Digital Seismic Network (BDSN) operates a variety of broadband sensors at its sites. Most sites also have a collocated accelerometer. The confirmation and/or determination of both orientation and self-noise of horizontal channels is a particular challenge. This is especially true for STS1 seismometers, which are separate units, in contrast to more modern seismometers, in which the three components are embedded by the manufacturer in a single package. Using the advantage provided by a collocated sensor—in the case of most BDSN stations a three-channel accelerometer, we have developed a method to determine the relative orientations of the two horizontal channels and to validate the orthogonality of STS1s at BDSN sites, assuming that the reference accelerometer sensors are orthogonal. For example, in BKS, the Byerly Vault on the UC Berkeley campus, we are currently testing a plethora of broadband seismometers in parallel with the operation of the station's STS1s and Episensor accelerometer. Orientations of the North and East channels relative to the Episensor's N and E orientation are: STS1 (1.487, -0.172), STS2 (0.999, -0.509), Reftek151B (0.841, -0.007), and Guralp CMG-3T (2.094, 0.658). Positive angles indicate counter-clock-wise rotation in degrees. We will report analysis in particular for the BDSN's STS1 seismometers at BKS, CMB, HOPS, KCC, MHC, ORV, SAO, SCZ and YBH. A second problem is to determine the self-noise of horizontal sensors, as the co-orientation must be precise to better than 0.001 degree. We collect data for triplets of seismometers from two time intervals, between which the relative orientations of the sensors have been changed. Using the method described above, we rotate the recordings for each of the two intervals to produce horizontal recordings with the same orientations and determine the "self-noise" for the pseudo-sensors. Using these 2 determinations, we rotate the self-noise back to assign it to the original components.

Coherence and Spectra Analysis of the USArray TA PY Posthole Test Array

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In 2014, a 13-element broadband array was installed at Pinyon Flat Observatory to test installation options and characteristics for the EarthScope USArray TA project in preparation to deployment in Alaska. In this array, each element uses a broadband posthole sensor (STS-5 or Trillium 120PH) and either a Setra 278 barometer or an Episensor strong motion accelerometer. Each posthole is about 3 meters deep in cased holes emplaced in decomposed granite by a light weight portable drill developed for the TA using a hammer bit. Continuous data from has been collected at 1, 40, and 200 sps on the broadband sensors. The array has an aperture of 1 km with a minimum station spacing of 40 meters. This array presents a unique opportunity to study the noise and coherence characteristics of the seismic signals from this new generation of broadband seismic installation technique. We will present results from multitaper spectra from seismic noise as well as from local, regional, and teleseismic events recorded on the array. These spectra will be compared to the existing ANZA and GSN PFO stations as well as with the standard lower-48 style TA_TPFO stations. We will complement the spectra results by presenting multitaper coherence analysis between various combinations of sensors.

Reliability and Repeatability in High Frequency Ground Motion Records

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The ability to characterize seismic amplitudes is fundamentally limited by the accuracy and precision with which scientists calibrate sensors and characterize instruments responses. Historically, most calibration efforts, if performed at all, have focused on constraining the long-period corner of broadband sensors using a known source injected into the calibration coil. However, several stations with co-located sensors within the Global Seismographic Network show substantial deviations in acceleration power spectral densities at higher frequencies ($\geq \sim$ 5 Hz). It is unclear how much of these differences are due to true variations in ground motions from local, near-field noise sources versus unresolved discrepancies in the sensitivity and response of the seismic instrumentation. Here, we evaluate the extent to which individual sensor responses vary from the manufacturer specified nominal responses through the calibration of several types of seismic instruments (both broadband and short-period sensors) at high frequencies. We then co-locate the calibrated sensors on a single pier and characterize the frequency dependent coherency between station pairs in the presence of various sources of high frequency signal (*e.g.*, drop tests, etc.) and high frequency noise. Such analysis will provide valuable insight on the ability and limitations of seismic instrumentation to recover true ground motion at high frequencies.

Performance of Shallow Drill Emplaced Broadband USArray Seismic Stations

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A specially designed portable drill has been used to deploy broadband seismic stations in Alaska and Western Canada as part of the EarthScope Transportable Array (TA) project. 111 stations were built or upgraded in 2015 and 2016, with another 73 planned for the 2017 field season. The 268 station network will operate through 2018 and be removed in 2019 and 2020 with an approximate spacing of ~85 km across vast swaths of previously uninstrumented land. The drill is primarily transported via helicopter due to the remote locations of many sites, but can also be loaded on a truck for road accessible locations. Nanometrics Trillium-120PH and Streckeisen STS-5A broadband posthole seismometers are emplaced in 2-3 meter steel cased postholes. At this depth, many sensors are below the active layer and can approach the noise floor of benchmark GSN stations especially at long periods. We explore the performance of stations using the data collected through 2017 and metrics calculated and provided by the IRIS DMC MUSTANG web service. We offer detailed procedures including embedding material, grouting technique and orientation method. In addition to the best-performing stations, we also investigate stations that have little to no improvement to determine if alternative site selection could affect data quality. These results can inform potential improvement of existing regional networks such as the Central and Eastern United States Seismic Network (CEUSN) as well as drive future developments toward continental-scale efforts like the Subduction Zone Observatory (SZO).

Estimating Noise and Wave-Propagation Effects from a 3D Array at the Sanford Underground Research Facility

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A novel three dimensional array of 24 seismometers has been deployed in and around the Sanford Underground Research Facility, formerly the Homestake Gold Mine in South Dakota, USA, with several instruments as deep as 1.5 km. The deployment provides a unique opportunity to compare event waveforms in 3D, solving for waveform differences relating to free surface reflections, scattering and attenuation, both characterizing the importance of such effects in wave propagation and testing the frequencies to which they might be resolved with an array of this spacing. In a related signal processing approach, we build on previous methods to design a Wiener filter with the array; while determining a transfer function between two stations is already common practice in earthquake engineering characterizations, transfer functions between every station in the 3D array as a whole should provide a better prediction of expected signals at one station based on information from all others. With both methods, we attempt to quantify how much information is gained by including stations at depth.

The array also provides an opportunity to explore the ambient noise field at depth. In addition to providing deep and quiet sites, the 3D nature of the array should allow for a characterization of the different modes of seismic energy (P, S, Rayleigh, Love) contributing to the ambient noise field, and the role of scattering between such wave types. Long term goals for the project include improving our understanding of how the seismic-noise field affects the measurements of gravity-wave interferometers, as any perturbations to nearby mass (*i.e.*: the ground) will contaminate such measurements.

Recent Moderate Oklahoma Earthquakes: Widely Felt and Often Damaging

Oral Session · Thursday 20 April · 1:30 PM · Plaza E

Session Chairs: William Yeck, Robert Williams, and Justin Rubinstein

Local Effort for Global Contribution: Seismic Observations of Recent Oklahoma Moderate Earthquake Sequences and for Future

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In 2016, the state of Oklahoma encountered three M5+ earthquakes, although the total number of felt earthquakes decreased compared to 2015, which is attributed to the reduction of the total injection volume. As local institutions, the School of Geology and Geophysics and the Oklahoma Geological Survey at the University of Oklahoma quickly responded to these events, and we deployed seismometers for aftershock observations along with other agencies (*e.g.*, USGS, Georgia Tech, Cornell, Lamont, OSU). We processed observed data for seismicity analyses including fore/aftershock detection/location, source characteristics and statistical interpretation. For the Fairview and Pawnee earthquakes, we deployed 28 and 31 stations, respectively, and these stations greatly improved the spatiotemporal resolution of aftershock acquisition and our understanding of the earthquake sequences. The Cushing earthquake was clearly observed by the Pawnee network. In addition, some companies are willing to provide their data to us (broadband, short-period, geophone-array networks). In this talk, we share our effort of the observation of these earthquake sequences and discoveries using these datasets. We will also discuss our future plan of observation.

Diverse Earthquake Responses to Wastewater Disposal near Fairview, Pawnee, and Cushing, Oklahoma

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It is generally accepted that the increase in seismicity and its associated hazard in Oklahoma that began in about 2009 is largely the result of wastewater disposal by deep injection (*e.g.*, Ellsworth, Science, 2013) including the three earthquakes of magnitude 5 and greater, near Fairview, Pawnee, and Cushing, which occurred during 2016. All three earthquake sequences appear to have been induced by high-volume wastewater disposal within about 20 km of each main shock epicenter and the total moment release is close to, or below, the limits inferred from the respective volumes of injected fluid (McGarr, JGR, 2014). The three earthquake magnitude distributions, however, are quite different. The Fairview M5.1 main shock was part of an extensive sequence that resulted from more than 4 million cubic m of fluid injection; the main shock accounted for a bit less than half of the total moment release, with the remainder distributed among about 150 earthquakes of M3 or greater. The M5.8 Pawnee earthquake was the result of somewhat more than 5 million cubic m of fluid injection, but was preceded by large changes in injection rate that may have introduced local slip-inducing stress perturbations on the fault; the other earthquakes in the sequence were too small and too few to contribute significantly to the cumulative moment release. The M5.0 Cushing earthquake in November is part of a sequence that includes 46 earthquakes of M3 or greater. The Cushing main shock accounts for about 75% of the total moment release. The Cushing area may warrant a high level of concern because there are 41 disposal wells within 20 km that have each injected more than 100,000 cubic m of wastewater for a total injected volume of about 14.5 million cubic m. This area has already exhibited earthquakes on reactivated faults in response to fluid injection (*e.g.*, McNamara et al, 2015) and so the possibility of an induced earthquake of M5.7, or so, near Cushing cannot be ruled out.

InSAR Constraints on Recent Induced Earthquakes in the United States

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Interferometric synthetic aperture radar (InSAR) observations have played an increasingly important role in estimating the subsurface slip of earthquakes. The near-source imaging capabilities of InSAR allow for the spatial extent of slip to be mapped with higher precision and confidence than is commonly possible with seismological observations. In turn, source inversions can be used to further investigate the role of local geology on earthquake rupture and the relationship between slip and aftershock distributions. The recent launches of the Sentinel-1 satellites have increased the spatial and temporal coverage of InSAR observations in active regions of induced seismicity- regions where InSAR observations were previously sparse or absent altogether. We present analysis of recent earthquakes in Oklahoma and Colorado, including the 2011 M_w5.3 Trinidad, CO, 2016 M_w5.8 Pawnee, OK, and 2016 M_w5.0 Cushing, OK earthquakes. We conduct finite-fault inversions of the InSAR observations to determine the depth and spatial distributions of slip during these earthquakes to address whether these events occurred within the crystalline basement beneath production fields, and whether high-quality aftershock locations provide a proxy for the spatial extent of co-seismic slip. Additionally, we highlight the magnitude of surface deformation generated by these earthquakes that could potentially impact surface and shallow production infrastructure, and we explore the degree to which these earthquakes fit within common earthquake scaling relationships.

Geodetic Slip Model of the M5.8 3 September, 2016 Pawnee, Oklahoma, Earthquake: Evidence for Fault Zone Collapse

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The M5.8 3 September, 2016 Pawnee earthquake in northern Oklahoma is the largest earthquake ever recorded in Oklahoma. The coseismic deformation was measured with both InSAR and GPS, with measureable signals of order 1 cm and 1 mm, respectively. We derive a coseismic slip model from Sentinel 1A and Radarsat-2 interferograms and GPS static offsets. It is characterized by distributed left-lateral strike slip up to one meter on a primary WNW-ESE trending sub-vertical plane. Although strike slip is concentrated near the hypocenter (5.6 km depth), significant slip below the hypocenter evidently extends to about 9 km. Based on systematic misfits of observed interferogram line of sight displacements (LOS) with LOS based on shear-dislocation models, a few decimeters of fault zone collapse are inferred in the hypocentral region where coseismic slip was largest. This may be the result of postseismic migration of large volumes of fluid away from the high slip areas, enabled by the enhanced permeability of the reactivated fault.

Hidden Faults: Rupture of an Immature Fault System in the 2016 Mw5.8 Pawnee, OK Earthquake

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Induced seismicity mitigation often relies upon maps of fault orientation and the resulting estimated likelihood of fault rupture in a perturbed stress field. This approach requires that fault segments capable of hosting significant earthquake are known and mapped. However, the largest earthquake ever recorded in Oklahoma, the September 3 2016 M_w5.8 Pawnee earthquake, occurred on an unmapped fault. Here we show that the Pawnee earthquake occurred on a series of discontinuous, en echelon fault segments rather than on the adjoining, mapped large faults. Furthermore, we show that the set of faults that ruptured was effectively hidden, implying that other such hidden basement faults 1) are also capable of damaging earthquakes, 2) may be present throughout Oklahoma and 3) need to be accounted for in mitigation of induced seismic risk. The Pawnee earthquake occurred on multiple short fault segments < 2 km in length, offset laterally by northeast-southwest fault jogs of up to five hundred meters. The coseismic deformation pattern indicates that 90% of the slip was concentrated within 6 km of the mainshock location. Despite rupturing short fault segments, the earthquake released substantial seismic moment and caused damaging ground motions. We propose that fluid pressure from active wastewater disposal wells, including regionally elevated pore pressure, may have enabled rupture across segments within an immature fault zone that would not otherwise rupture jointly. Away from the mainshock rupture zone, numerous closely-spaced faults strands north and south of the mainshock rupture activated in the aftershock sequence, illuminating the pervasive faulting present throughout continental crust, also observed in seismic rupture in north-central Oklahoma. The strong seismic moment release achieved by rupture across an unmapped series of fault segments underscores the challenges in estimating the risk for induced seismicity.

Seismotectonics

Oral Session · Thursday 20 April · 16:00 · Plaza F

Session Chairs: Rich Briggs and Gavin Hayes

Anthropogenic Influences in USA Intraplate Earthquakes

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In this paper, we carry out an investigation about the enhancement of intraplate earthquakes in USA last seven years. We also search for the possible impact of the human activity in several different locations that developed an unusual seismological activity at the same time. Intraplate earthquakes do not share a consensus about how they are generated and why they continue to occur over many earthquakes cycles. This research required a division of the country in three main regions, western, midcontinent and eastern. The Midcontinent is partially covered by the Great Plains which developed an uneven area being thicker than western or eastern. This thickness is the discrepancy of the Earth's crust that in the USA has a significant variation from west to east in an interval 25–45 km -25 km.

The earthquakes enhancement in the mid-continent since some years ago had as main cause the anthropogenic exploration in the area. Small earthquakes are not only intraplate occurrence affecting other regions with increasing intensity.

The biggest topic nowadays is the earthquakes happening in Oklahoma a place since 2009 increased the events in frequency and magnitude. Here the main issue is the deep wastewater disposal used to recycle the water-contaminated withdrawal from the gas and oil wells. We also discussed why not all the waste wells are going to create higher magnitude earthquakes. This study showed that most of the small earthquakes not only in Oklahoma but also in the entire USA is due to the human actions. We also explained the reason they do not occur in every place researched.

Keywords: earthquakes, wastewater wells, anthropogenic, Earth's crust

New Bedrock Evidence for Overall Offset on N-S Faults in the Vicinity of Historic Earthquakes in Little San Bernardino Mtns; Implications for Interactions Between the San Andreas Fault and the Eastern California Shear Zone

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Bedrock mapping in the epicentral areas of the 1992 Joshua Tree earthquake (M_w 6.1), 1948 Desert Hot Springs earthquake (M_w 6.0) and 1992 Landers aftershocks (M_w 5.7, 5.8) has further delineated the geometry, distribution, and relative chronology of brittle structures in the northern Little San Bernardino Mts. Of particular interest are (1) the interactions of the Dillon Shear Zone Fault Set (DSZFS) of NW-trending faults with four younger N-S striking dextral faults (W to E): Long Canyon, Wide Canyon, Eureka Peak and California Riding Trail (CRT); and (2) the kinematic roles of the DSZFS and the N-S faults in relation to the San Andreas Fault (SAF) and the Eastern California Shear Zone (ECSZ).

Our mapping documents dextral offsets on the four N-S faults: Long Canyon (500 m), Wide Canyon (~300 m), Eureka Peak (~ 400 m), CRT (750 m) and a splay of CRT the Deerhorn (115 m). Calc-silicate rocks, marble, and gabbro-diorite intruded by monzogranite are key units for documenting offsets. Cumulative dextral offset across the four N-S faults totals almost 2 km. The fault zones consist of breccia and fault gouge which are flanked by damage zones; faults of the DSZFS are also associated with pseudotachylyte.

Epicenters of 1992 Joshua Tree and 1948 Desert Hot Springs earthquakes are located along the Eureka Peak Fault and have hypocentral depths that coincide with the fault plane of the Mission Creek strand of the SAF which dips ~ 60 NE under the LSBM. This geometry suggests a tectonic link between the N-S faults, the SAF and the ECSZ. Low-T, thermochronologic data (Sabala, 2010) indicate an abrupt boundary between rapid rock uplift close to the SAF and slower uplift to the north. We integrate the thermochronologic data together with the DSZFS, SAF, and the N-S faults to hypothesize that a regional-scale flower structure extends parallel to the SAF from Long Canyon Fault to Eureka Peak Fault This flower structure responds to strain transfer between the SAF and the ECSZ.

The Seismologically Detected Taan Fiord Landslide and Tsunami of 17 October 2015: Preliminary Findings

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On 17 October 2015, the Global CMT Project seismically detected an unusually large landslide in the St Elias Mountains of southern Alaska. Satellite images revealed a landslide in Taan Fiord, only 3 km from the inferred location, that it had entered the ocean, and generated significant tsunami runup. A tsunami was observed at the closest two tide gauges—145 and 345 km away by sea. A single-force inversion model calculated a slide mass of 100-150 billion kg. In the summer of 2016, teams of scientists documented physical aspects of the landslide, tsunami, and deposits. Data include LiDAR and SfM topography, swath bathymetry, tsunami runup, and seismic profiles. Tsunami runup reached a maximum of 190 m directly across from the landslide. The rest of the 17-km-long fiord has a trimline that tapers gradually to 15 m at its mouth. Flow depth of the tsunami on a spit between Taan Fiord and adjacent Icy Bay was about 5 m. Comparison of August 2012 IfSAR and May 2016 LiDAR elevations show a landslide volume of ~56 million m^3, equivalent to a mass of ~132 billion kg, a value remarkably similar to the seismologically estimated value. Approximately 93% of the slide volume entered the fiord, which explains why it was so efficient at generating a tsunami. Landslide blocks are imaged on the fiord bottom up to 2.5 km from where the landslide entered the fiord. However, the seismic profiles show blocks likely extending to a distance of 3 km and fiord-bottom deformation extending to 6 km. These features are hidden by post-landslide suspended sediment deposition. Some landslide debris was deposited as a 2-4 m thick blanket on the toe of the Tyndall Glacier, which has caused accelerated terminus failure. The overall setting of this landslide and subsequent tsunami is related to retreat of the Tyndall Glacier and debutressing of the fiord walls. These studies highlight the robustness of rapid seismological detection and characterization of landslides even in remote regions.

Moho Temperature and Compositional Controls on Lithospheric Bending Strength in the Western United States

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We use measurements of mantle P-wave velocity from the Moho refracted phase, Pn [Buehler and Shearer, 2012, 2014], and mineral physics [Schutt and Lesher, 2006, 2010] to estimate temperature in the uppermost few km of the western U.S. mantle. Relative to other approaches to modeling the deep geotherm, or mapping surface wave velocities to temperatures, Pn requires fewer assumptions and provides a less uncertain temperature within a tightly-constrained depth. Moho temperatures are lowest in the high-plains region of Wyoming and western Kansas/Nebraska, while highest temperatures are observed under recent (<10 Ma) volcanic provinces where they generally exceed 850C. Moho temperatures east of the Laramide deformation front are also quite hot—~850C, but crustal thicknesses here are 10-20 km thicker than in the Basin and Range, so these temperatures are not surprising.

Using a range of estimates of crustal heat production values, surface heat-flow measurements are extrapolated to depth under the assumption of steady-state conduction, and with the constraint that Pn velocity observations are fit. Preliminary results are very encouraging, and also provide an indication of where Pn velocities are modulated by composition rather than temperature or where the assumption of steady-state heat flow is invalid.

These geotherms are used to predict lithospheric bending strength parameterized as effective elastic thickness, Te, for various assumed rheologies. The model predictions are compared to measurements [Lowry and Pérez-Gussinyé, 2011], to show that a weak, hydrous rheology and/or hydrous partial melt is required to fit observations in the westernmost U.S. The hydrous rheology zone significantly overlaps with the part of North America formed from accreted terranes over the last 300 M.y. To the east of this region, a dryer and stronger rheology is needed to fit the Te observations.

Meager Mountain Seismicity—Magmatic or Not?

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Meager Mountain, in southwestern BC, is the most recently active volcano in British Columbia, Canada. It is a stratavolcano composed of lava domes and vents in a volcanic massif that last erupted 2360 years BP; it is characterized by explosive eruptions. The modern day complex is extremely unstable with over 10 historic rock avalanche or landslide events since the 1970's. In 2010 a landslide failed with a volume of 49,000,000 cubic meters. During July 2016, three fumaroles were spotted on Meager, venting through the glacier covering the mountain. In September 2016, a new seismic station was installed across the valley to the east of Meager Mountain, in order to monitor the mountain and its seismicity and to improve earthquake depth determinations.

Seismicity since 1985 clusters around the Meager volcanic complex. Seismicity rates were from one to ten events per year until 2013, when the rates began to climb to a maximum of more than 50 events in 2014, then dying back down to background levels in 2016. The majority of the increased activity clusters between July 2014 to October 2015, with the events occurring during the day and night. The events are all less than or equal to magnitude 2.5 and the majority of events are shallow, although depth determination of those events is poor as the closest seismic station, at that time, was located in Whistler, BC, approximately 100 km away. Most of the events lie to the south of Meager Mountain, itself. The b-value for the 2013-2016 cluster of events is greater than 1. It is unlikely that the events are due to magma movement as they are of small magnitude, are predominantly shallow, and have substantially lower seismicity rates than active volcanoes, which may have hundreds to thousands of earthquakes per day. There are three known springs in the area and it is likely that the seismicity is due to hydrothermal fluid circulation.

The Future of Past Earthquakes

Oral Session · Thursday 20 April · 8:30 AM · Plaza F

Session Chairs: David Schwartz, Ramon Arrowsmith, William Lettis, Koji Okumura, Daniela Pantosti, and Thomas Rockwell

Geometric Complexity in Past Ruptures and Lessons for Hazard and Future Ruptures

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Systematic analysis of surface ruptures of past earthquakes has led to new understanding of the efficacy of steps and bends in fault trace to arrest rupture. Overall, strike-slip ruptures stop at steps of 1 km or more about 46% of the time. Large steps are crossed only in large earthquakes: only ruptures longer than 50 km push through steps of 3 km, and only ruptures >100 km pass steps of 4 km or larger. Step size affects its passing ratio, $PR = 1.89 - 0.31$*step width (km); a step of 3 km is equally likely to be passed or to arrest rupture, and none are expected to pass at 6 km. Dip slip ruptures pass larger surface steps, up to 12 km in our event set. Bends in surface traces measured on a 5-7 km scale have similar predictive qualities for strike-slip ruptures, but bend angles in dip-slip fault traces do not help predict where ruptures may end.

New relationships from past earthquakes between fault complexity and rupture propagation improve our ability to assign probabilities among rupture alternatives for hazard and risk estimation purposes. Future analysis of past ruptures may help with remaining questions. For example, we measured steps from surface trace separation; is there predictive power in knowing fault separation at depth? Can probabilities of arrest be usefully extended to smaller steps than 1 km? Can we make better use of regional stress orientation in predicting rupture extent? More broadly, past earthquakes alert us to the possibility of exceptional events. The 1957 Gobi-Altai earthquake included 10's of km of reverse rupture, connected at a right angle to the strike-slip main trace. We would doubtless learn more if the event could be flown with modern LiDAR. Should future forecasts in California or elsewhere include such ruptures, or might an accurate hazard estimate be developed without them? We still have much to learn from past earthquakes.

The Mechanics of Multifault Ruptures and the Keystone Fault Hypothesis

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Most large earthquakes activate slip on more than one fault, but the genesis of multifault ruptures remains poorly understood, and classical applications of static yield criteria are inadequate to describe the mechanical conditions required to prepare multiple faults with diverse orientations to fail simultaneously in a single earthquake. This is mainly because the critical stress level for fault failure depends greatly on fault orientation and is lowest for optimally oriented faults positioned approximately 30° to the greatest principal compressive stress. Yet, misoriented faults whose positioning is not conducive to rupture are also commonly activated in large earthquakes.

The 2010 El Mayor-Cucapah earthquake of magnitude M_w 7.2 propagated through a network of high- and low-angle faults producing the most complex rupture ever documented on the Pacific-North American plate margin. Using stress inversions of surface displacement and seismic data, we find that the El Mayor-Cucapah earthquake initiated on a fault, which due to its orientation, was among those that required the greatest stress for failure. Although other optimally-oriented faults must have reached critical stress earlier in the interseismic period, Coulomb stress modeling shows that slip on these faults was initially muted because they were pinned, held in place by misoriented faults that helped regulate their slip. In this way, faults of diverse orientations could be maintained at critical stress without destabilizing the network. We propose that regional stress build-up continues until a misoriented keystone fault reaches its threshold and its failure then spreads spontaneously across the network in a large earthquake. In addition to explaining the mechanics of multifault ruptures, our keystone fault hypothesis provides new understanding for the seismogenic failure of severely misoriented faults like the San Andreas Fault and the entire class of low-angle normal faults.

Multi-Disciplinary Paleoseismic Investigations of Complex Earthquake Ruptures: Characterising the Predecessors of the 2010 Mw 7.1 Darfield Earthquake in New Zealand

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The 2010 M_w 7.1 Darfield earthquake in New Zealand produced a 30 km-long surface rupture trace across a low relief alluvial landscape. The surface rupture was sourced from at least three geometrically distinct crustal faults (Greendale Fault East, Central, and West) with overlapping parabola-shaped surface displacement distributions and maximum co-seismic horizontal displacements exceeding 5 metres. Our investigations found no unambiguous surface evidence of predecessor ruptures, suggesting that paleoearthquake surface ruptures are likely to have been buried and / or eroded. The central Greendale Fault has been studied using airborne LiDAR and field-based mapping, trenching and dating-based paleoseismic investigations, ground penetrating radar, fault zone guided waves, and seismic reflection surveys. To understand variations in the width and complexity of the observed surface rupture we also used purpose-built analogue models monitored with particle imaging velocimetry. Our prevailing unified hypotheses from these investigations are that (i) the penultimate earthquake on the central Greendale Fault occurred between 20,000 to 30,000 years ago, (ii) coseismic surface slip on some Riedel fractures in the penultimate event was the same as that measured in the 2010 Darfield earthquake, (iii) the deformation zone width and en-echelon Riedel fractures reflect low finite slip and infrequent faulting of the ca. 200-300 meter thick loosely consolidated Quaternary sediments, and these structural features and deformation zone widths extend to depth in the Quaternary section, (iv) the complex arrays of obliquely-oriented near-surface fractures reflect faulting of a cohesive gravel and soil cap layer strongly influenced by pedogenic processes, including cementation, rather than seismogenic processes at depth. Coulomb stress modeling is used to extend source models of the complex Darfield earthquake, which involved at least 7 distinct faults, into the paleoseismic realm.

Large Magnitude Earthquakes in New Zealand: What is the Norm?

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Analysis of moderate to great historical earthquakes since 1840 and paleoseismic data for active faults indicate what future earthquakes might be expected in New Zealand. Historical earthquakes can suffer stationarity issues while paleoseismic records are incomplete. This incompleteness arises because not all events rupture the ground surface and surface-ruptures for low slip rate faults (<1 mm/yr) with long recurrence intervals (> 10 ka) can be eroded or buried. Despite these sampling limitations, collectively the available data sets support the following conclusions. 1) About half of $M_w \geq 7$ earthquakes rupture faults that, based on today's state of knowledge of active fault locations, would not have been identified as active prior to the event. 2) Approximately three quarters of earthquakes occur on low to moderate slip rate (*i.e.*, ≤4 mm/yr) faults primarily because they constitute a greater proportion of the total active-fault population and collectively have greater rates of occurrence than high slip-rate faults. 3) Historically multi-fault ruptures have been important and likely contributed to the paleoseismic record, although are not yet specifically incorporated into the New Zealand Seismic Hazard Model. These conclusions are consistent with fault rupture in the recent M_w 7.8 Kaikoura earthquake and support the view that earthquakes on unidentified active faults, on low-moderate slip-rate faults and associated with multiple-fault ruptures are closer to being the norm than previously thought. Our observations emphasise the importance of background seismicity models for complementing paleoseismic data sets at magnitudes of M_w >7.

New Scenarios for Paleoseismological Ruptures Based on the 2016 Central Italy Earthquake Sequence

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The 2016 normal faulting earthquake sequence in central Italy counts >40,000 events and 3 mainshocks: Aug 24 M_w 6.0, Oct 26 M_w 5.9, Oct 30 M_w 6.5. They involved NW-trending and SW-dipping normal fault systems, for an overall length >40 km. The first shock caused >5 km surface faulting with 0.1 m average throw, and similar effects were observed for the 26 Oct event. Conversely, the M_w 6.5 event produced a complex and impressive surface faulting pattern, overprinting the previous coseismic ruptures, involving both mapped faults and previously unknown strands, on limestone bedrock and loose deposits with throws locally >1.5-2 m, for a total length of ≈30 km.

The 2016 sequence proved that surface ruptures can re-occur on the same portion of a fault system even within a few days/months, a scenario that has been seldom documented so far. From a paleoseismic perspective, we learn that: 1) the paleoearthquake record that we interpret as due to discrete slip events may actually represent the cumulative effect of more events very close in time; 2) widespread morphotectonic features in the Apennines like bedrock fault scarps mostly form during M>6 earthquakes; 3) at surface the slip is partitioned along a main rupture and subsidiary splays in a 2-3 km wide zone; 4) The 2016 central Italy ruptures are certainly an extreme as they occurred within a handful of days, whereas we know from the 2009 L'Aquila earthquake study case (Cinti *et al.*, 2011), that if enough time separate events (*e.g.* 500 yr), even small slip (order of 10 cm) events can be isolated in trenches. Under this light what are the scenarios that we may face in interpreting a paleoseismic trench? In a young tectonic environment with slip partitioning, the maximum displacement observed along a main strand is a recurring behaviour? How can we estimate the uncertainties in our model? These issues are additional insights for paleoseismological research also in areas of moderate seismicity, as central and western Europe.

Segmentation and Supercycles: Earthquake Cycle Complexities and the Sumatran Sunda Megathrust as a Behavior Catalog

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Paleoseismic records are a key component of tectonics-based earthquake forecasting, and the longest, most detailed records provide the most complete understanding of the range of fault behavior. A concept that has come into focus recently is that rupture segmentation and cyclicity can be complex, and that the simple characteristic earthquake model is inadequate. The term "supercycle" has been used to describe repeating longer periods of strain accumulation that involve multiple fault ruptures. However, this term has become broadly applied, lumping together several distinct phenomena that likely have disparate underlying causes. We divide earthquake cycle behavior into four major classes, each having different implications for seismic hazard and fault mechanics: 1) quasi-periodic characteristic rupture, 2) clustered similar ruptures, 3) clustered complementary ruptures, and 4) superimposed cycles in which neighboring fault patches have cycles with different recurrence intervals. Rupture segmentation can be either persistent over many cycles or transient (changing from cycle to cycle). We discuss the paleoseismic evidence currently available for each of these types of behavior on major faults worldwide. Though paleoseismic records for some faults now stretch for many millennia, it is typically difficult to determine the rupture extent for each event, which is required to evaluate which types of behavior have occurred. Due to the unique level of paleoseismic and paleogeodetic detail provided by the coral microatoll technique, it has been possible to reconstruct seismic cycle deformation with high spatial resolution over multiple cycles along the Sumatran Sunda megathrust. Thus, the Sumatran Sunda megathrust provides a catalog of types of seismic cycle behavior, exhibiting nearly all of the different phenomena we delineate. Researchers should expect to discover similar behavior styles on other megathrust faults and perhaps major crustal faults around the world.

Paleoseismology of the Collision Plate Boundary on the Himalayan Front

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The Himalayan front in Bhutan, Nepal, India, and Pakistan is the most extensive plate boundary fault zone on land, extending more than 3000 km. Though the extent of the plate boundary and size of mega-thrust earthquakes are smaller than those of subduction zones, the seismic risks are much higher along Himalayan front because the Himalayan front and adjacent Hindustan Plains are extremely densely inhabited by more than a half billion people. In order to assess the risks, information on the geology of earthquakes are critical. Like as the Sunda subduction zone where 2004 M 9 earthquake was a big surprise, historic records of large earthquakes along the Himalayan front before 17th century are rather sparse, and the seismicity after 17th century seems to be rather mild. Our knowledge on the full-size collision front earthquakes are still limited. In the past two decades, paleoseismological studies have been carried out at more than 30 locations (1 in 100 km), however, only few trenches exposed multiple events and we barely know the rupture length or the magnitude of the past earthquakes. For example, the authors' trench near Ramnagar exposed possible 1803, 1505, and an older large events. 1803 event is not known in any other trench. 1505 is reported from only one trench in western Nepal. Since the interpretations of sparse historic records have rather large uncertainties, we need concrete evidence from geologic investigations. Though revealing the geologic evidence of penultimate events is often hindered by a large slip of the most recent event and high-energy fluvial sedimentation, it is necessary to determine the timing and extent of multiple events. Beside the history of the surface ruptures on the frontal faults, we have learned upper plate faulting events as 1905 Kangra earthquake and large deep earthquake on the interface are sometimes hard to differentiate from front-rupturing earthquakes. We need further integrated studies.

Integrated Seismic Hazard Investigations and Progressive Reduction of Uncertainties: The North Anatolian Fault as a Case Example

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The North Anatolian fault (NAF) has been an open laboratory for international research collaborations and new paleoseismic techniques for decades. Despite well-documented 20th century westward migrating fault rupture behavior of the NAF, understanding of the temporal and spatial behavior for this significant dextral fault continues to evolve. Case examples from western, central, and eastern sections of the NAF provide insights for refinement of location, timing, and offsets of past events. Integrated onshore and offshore multi-technique investigations at the western termination of the 1999 Izmit surface rupture provides an example of reduction of uncertainties for fault location, geometry, and deformation pattern along the western NAF. Based on new data collected since 1999 we have progressively revised fault geometry, segmentation models, and seismic hazard estimates. On the central NAF, geochronologic dating of offset geomorphic features with radiocarbon, cosmogenic nuclides, and dendrochronology in combination with historical and paleoseismic earthquake data not only facilitates refinement of geologic slip rates but also facilitates revision of average slip per event assumptions. An average late-Holocene geologic slip rate of approximately 20 mm/yr is relatively constant over the length of the fault but slower (about 20%) than geodetic slip rates. Closely-spaced paleoseismic trench sites with multiple exposures of high-resolution peat stratigraphy on the eastern NAF documents infrequent very large magnitude earthquakes as well as relatively regular large magnitude events suggesting a bi-modal (or greater) earthquake recurrence behavior. Combination of these field findings spanning millennial scales and their comparison to decadal remote sensing data hints at possibly non-linear fault behavior through earthquake cycles.

Earthquake Cascade along Large Strike-Slip Faults, Rule or Exception?

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A significant part of continental deformation is accommodated by major strike-slip faults. Understanding time and spatial distribution of earthquakes along faults is key to mitigate seismic hazard. The Altyn Tagh fault (ATF), in China, and the Dead Sea fault (DSF), in Middle East are stunning example of such major faults. They are recognized as active fault, with slip-rate of respectively 1 to 2 cm/yr and 5 mm/yr. Rate at different time scales, from geodetic rate to rate over Quaternary period, show that slip-rate does not vary over short-time period. In addition, geodetic measurements suggest that if aseismic creep occurs on these faults, it accommodates only a marginal part of the deformation. Nevertheless, seismic activity remains surprisingly limited along these two faults, and in the case of the ATF, even historical events are almost unknown. We present new paleoseismological data on the ATF and on the DSF that clearly demonstrate that each fault has generated significant earthquakes in the past. In the case of the ATF at least 2 events occurred in a period of few hundred years, about one thousand years ago. Previous sequence seems to date about 2000 years earlier. No evidence for earthquake is found for the last millennium. Along the DSF, recent trench investigation indicates that large earthquakes occur irregularly as well, with series of events rupturing the entire fault in a short period. Hence, these new observations show that these two large strike-slip faults seem to alternate between intense periods of earthquake activity and long quiescent periods. These results add up to previous observations along other large strike-slip faults, such as the North Anatolian fault, in Turkey, or the Kunlun Fault, in China, to suggest that temporal clustering with periods when the entire fault would rupture in a cascade of earthquakes, separated by long seismically quiescent periods might be the rule rather than the exception along continental strike-slip faults.

Using Displacement and Paleoclimate Data to Overcome Age Uncertainties in Rupture Histories of the Southern San Andreas Fault

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The Carrizo, Big Bend, and Mojave sections of the southern San Andreas Fault last ruptured in the 310-km-long, M_w7.9, 1857 earthquake. These sections contain four sites with 700 year records of dated per-earthquake displacement measurements obtained in trenching investigations. Here I add these dated, single earthquake displacement measurements to the catalogue of 450 undated geomorphic offsets from Zielke *et al.* (2012) to refine rupture lengths previously estimated by earthquake age correlation alone in Scharer *et al.* (2014). I also use similarities in the depositional history at trench sites to overcome broad ranges in paleoearthquake ages. For example, a reduction in depositional rate and change to more wetland-type deposits occurs from 1300 to 1450 AD, coinciding with a transition from the Medieval Warming Period to the Little Ice Age in regional paleoenvironmental studies. Despite overlapping earthquake ages at proximal sites, the stratigraphic position of the event horizons relative to the climactic transition shows they are not the same rupture. Specifically, the Mojave sites ruptured before and the Big Bend site ruptured after this transition, requiring at least two earthquakes rather than one long rupture. In combination, the data provide a model of maximum rupture lengths and variability of displacement along strike for eight ruptures. No simple alternating or unzipping patterns emerge, but the timing of long quiescent periods is intriguing. Like the current 160-year open interval, which occurred after a 200-year period with three major earthquakes, a 150-year quiescent period followed a similar 100-year long, three-earthquake sequence that includes the only permissible repeat of an 1857-length rupture. The temporal-spatial patterns and the average rupture length (215 km), displacement (3 m) and magnitude (M_w7.5) should provide useful tests against the earthquake patterns provided by physics-based simulators and seismic hazard forecasts.

Theoretical and Methodological Innovations for 3D/4D Seismic Imaging of Near-surface, Crustal, and Global Scales

Oral Session · Thursday 20 April · 8:30 AM · Governor's Square 12

Session Chairs: Marco Pilz and Nori Nakata

Time-Lapse Changes in Seismic Velocity Log-Time Recovery of Earth Materials

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With the increasing application of seismic interferometry, and in particular coda wave interferometry, our ability to measure changes in the seismic velocity has improved dramatically. In the Earth's near-surface the seismic velocity depends on the seasons, rainfall, and past deformation. The dependence of the seismic velocity on these parameters is poorly understood, which is a lost opportunity because Earth is performing perturbation experiments for us! We typically observe a recovery of the velocity after deformation that varies as log-time. Such a time-dependence is, strictly speaking, not possible because the logarithm is singular for zero and infinite times. We show how the log-time dependence, and a regular behavior for zero and infinite time, can be explained by a superposition of exponential decay mechanisms over a variety of time-scales.

A New Approach to Constrain Near-Surface Seismic Structure Based Upon Body-Wave Polarization

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Various seismic imaging methods have been developed, such as traveltime, waveform, and noise tomography, improving our knowledge of the subsurface structure and evolution. Near-surface structure, in particular, is important in understanding earthquake and volcano hazards; seismic speed is directly related to the level of ground shaking, and monitoring its temporal change is valuable in volcanic hazard assessment. Here, we introduce a novel technique to constrain near-surface seismic wave speed based upon the polarization measurements of teleseismic body-wave arrivals.

Polarization analysis of three-component seismic data has been widely used until about two decades ago for detection and identification of different types of seismic arrivals (*e.g.*, compressional and shear waves). Today, we have good understanding of the expected polarization for any given seismic wave arrival based upon a reference seismic model such as PREM, and deviation from the predicted polarization provides constraints on the elastic wave speed immediately beneath the station. By comparing the observed and predicted polarization directions, we can obtain the near-surface wave speeds.

This approach is applied to the High-Sensitivity Seismograph Network in Japan, where the results are benchmarked against the borehole well data that are available at most stations. There is a good agreement between polarization-based estimates and the well measurements, confirming the efficacy of the new method. This technique provides reliable, non-invasive, and computationally inexpensive estimates of near-surface elastic properties, and can be expanded into 3D by examining the frequency dependence and 4D by analyzing earthquakes from different time periods.

Analysis of Non-Diffuse Characteristics of the Seismic Noise Field in Southern California Based on Neighboring Frequency Correlation

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Non-diffuse characteristics of the ambient seismic noise wavefield recorded at 154 broadband stations in southern California are analyzed by computing the correlation matrix of power spectral values at neighboring frequencies. The similarity of the derived correlation matrices are compared by choosing a different reference station at a time. The data recorded by the different stations are classified into five groups using a hierarchical clustering algorithm based on the similarity of the correlation matrices. Stations belonging to different groups are clustered spatially in the Los Angeles basin, mountains and regions farther from the coast. The deviations from diffuse wavefield in the correlation matrices of representative stations from the five groups are inverted for dominant cross-frequency components. These are used to derive power spectral ratios of non-diffuse noise and fully diffuse noise. The similarity maps for different reference stations and the inverted cross-frequency components provide information on properties of the noise sources and propagation/scattering characteristics in the different regions.

An Investigation on Time-Frequency Domain Phase Weighted Stacking and its Application to Phase Velocity Extraction from Ambient Noise Based Empirical Green's Functions

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The time-frequency domain phase weighted stacking (tf-PWS) technique based on the S transform has been employed in stacking empirical Green's functions (EGFs) derived from ambient noise data, mainly due to its superior power in enhancing weak signals. Questions such as the induced waveform distortion and the feasibility in phase velocity extraction are yet to be thoroughly explored. In this study, we investigate these issues by conducting extensive numerical tests with both synthetic data and USArray TA ambient noise data. We find that the bias on the measured phase velocity associated with waveform distortion caused by the tf-PWS method is less than 0.1%, sufficiently small such that the measured phase velocities can be safely used in regular surface wave tomography. We also find that tf-PWS implemented with a time inversion S transform (IST) tends to cause large waveform distortion, leading to the extracted phase velocities at long periods from the corresponding stacked EGFs systematically larger than those measured from linearly stacked ones by as much as ~0.4%. If tf_PWS is used in stacking EGFs, The frequency IST needs to be adopted to transform the stacked elapse time spectra back to the time domain for the stacked EGFs.

New High-Resolution 3D Imagery of Fault Deformation and Segmentation of the San Onofre Trend in the Inner California Borderlands

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The Inner California Borderlands (ICB) is situated off the coast of southern California and northern Baja. The structural and geomorphic characteristics of the area record a middle Oligocene transition from subduction to microplate capture along the California coast. Marine stratigraphic evidence shows large-scale extension and rotation overprinted by modern strike-slip deformation. Geodetic and geologic observations indicate that approx. 6-8 mm/yr of Pacific-North American relative plate motion is accommodated by offshore strike-slip faulting in the ICB.

The farthest inshore fault system, the Newport-Inglewood Rose Canyon (NIRC) fault complex is a dextral strike-slip system that extends offshore approx. 120 km from San Diego to the San Joaquin Hills near Newport Beach, California. Based on trenching and well data, the NIRC fault system Holocene slip rate is 1.5-2.0 mm/yr to the south and 0.5-1.0 mm/yr along its northern extent. A rupture of the entire length of the system could produce an M_w 7.3 earthquake.

West of the main segments of the NIRC system is the San Onofre Fault Trend along the continental slope. Previous work concluded that this was part of a strike-slip system that eventually merged with the NIRC complex. Others have interpreted this trend as deformation associated with a blind thrust fault purported to underlie most of the region.

In late 2013 we acquired the first high-resolution 3D P-Cable seismic surveys (3.125 m bin resolution) of the San Onofre Trend. Analysis of these data provides important new insights and constraints on the fault segmentation and transfer of deformation. Based on this new 3D seismic data, our preferred interpretation for the San Onofre Fault Trend is a transpressional feature associated with a westward jog along a right lateral fault strand of the NIRC fault. Such a scenario also is consistent with observations from the 3D data volume along the upper slope that images westward stepping faults splaying off the NIRC system.

Toppled and Rotated Objects in Recent, Historic, and Prehistoric Earthquakes

Oral Session · Thursday 20 April · 1:30 PM · Governor's Square 16

Session Chairs: Klaus-G. Hinzen and Rasool Anooshehpoor

Engineering Seismological Aspects of Toppled and Rotated Objects in Past and Recent Earthquakes

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The study of objects toppled or rotated during recent earthquakes for which detailed instrumental and macroseismic data are available offer an empirical approach to evaluate estimation of ground motions during ancient earthquakes based on similar objects. Since Vivenzio described two obelisks rotated during the 1783 Calabria earthquake, such effects have been analyzed using seismology, and many more examples have been documented. Toppled or rotated objects (TROs) can be profitably employed as seismoscopes and, in some instances, remain the only artifacts providing physical evidence that an earthquake occurred. However, the sensitivity of these objects remains an unknown quantity, hampering any quantitative conclusion about the nature of the causative ground motions. Numeric models can help to set limits to the ground motion parameters if the shape and material of the TROs is sufficiently well known, a technique similar to that applied to precariously balanced rocks.

Analog and numeric models indicate that rotation of vertically oriented objects is possible without the introduction of rotational ground motions components. Observed rotation and toppling behavior of monuments and tombstones during recent earthquakes can be explained by appropriate discrete element models. Such models also increase the understanding of the principal behavior of building elements which are parts of ancient constructions and key objects in archaeoseismology.

We summarize results of studies from the past decade and formulate key questions for future research.

Could the Collapse of a Massive Speleothem be the Record of a Large Paleoearthquake?

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We used non-conventional methods, such as the so-called "Fragile Geological Features", and in particular cave speleothems, for assessing and improving existing paleoseismological databases and seismic hazard models. We present a detailed study of a massive speleothem found collapsed in the Cola Cave (Abruzzo region, Central Apennines, Italy) that could be considered the record of a large paleoearthquake. Laboratory analysis included radiometric dating of the speleothem and geotechnical measurements to characterize its mechanical properties. We performed theoretical and numerical modeling in order to estimate the values of the horizontal ground acceleration required to failure the speleothems. In particular we used a finite element method (FEM), with SAP200 software, starting from the detailed geometry of the speleothem and its mechanical properties. We used several individual seismogenic source geometries and four different ground motion prediction equations to calculate the possible response spectra. We carried out also a seismic noise survey to understand and quantify any amplification phenomenon. The results suggest two faults located in the Fucino area as the most probable causative sources of the cave speleothem collapses, recorded ~4-5 ka ago, with an inferred M_w=6.8 ± 0.2, and values of peak ground acceleration included between 0.54g and 0.63g. Furthemore, in order to bracket the age of co-seismic event, we performed U/Th and radiocarbon dating. The results, compared with published paleosismological data from geological studies allowed us to detect at least three large shocks during the last 12.5 kyr. Our approach contributes to assess the existence of past earthquakes integrating the classical paleoseismological trenches techniques and can give an important contribution to improve the investigation of active tectonic processes in relation to the seismic cycle.

Fragile Geologic Features in Coastal California

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We provide a precis of our studies of fragile geologic features in the vicinity of Avila Beach, coastal central California. Precariously-balanced rocks (PBRs) present on uplifted paleo-seastacks are studied to determine the fragility (threshold ground motions for toppling) and the fragility age (time since PBRs achieved their present fragile geometries). We obtain apparent (assuming zero erosion and no inheritance) cosmogenic 10Be dates in chert (SiO2) of ~22-65ka for six samples that bound the age of one of the PBRs, and interpret 22 ± 5 ka to approximate the fragility age. This fragility age is consistent with the relatively pristine morphology of the paleo-seastacks (similar to the "active" seastacks in the nearby surf zone), and the relative scarcity of rubble on the Pleistocene marine terraces at the base of the paleo-seastacks. This fragility age suggests that the PBR is old enough to have survived repeated large earthquakes on local active faults.

Photogrammetry is used to generate 3D models for three PBRs and allow the estimation of their fragilities. Unexceeded peak ground accelerations, estimated based on the dynamic toppling acceleration of the PBRs, are estimated as 0.2g, 0.4g, and 0.6g. We also quantify fragilities for these PBRs by way of the Purvance *et al.* method, which jointly utilizes the ground motion parameters of peak ground acceleration and velocity. We develop toppling probabilities for scenario Hosgri Fault earthquakes (M7.5 at about 10km distance) as a function of ground motion epsilon. The results show Hosgri motions less than 2-3 epsilon are compatible with survival of the PBRs, whereas motions greater than 2-3 epsilon result in high toppling probabilities. Future studies will investigate the toppling probabilities for other local faults, and obtain fragility ages for additional PBRs. Our results and the associated methods will have utility in constraining probabilistic seismic hazard models in coastal California and elsewhere.

Earthquake Rotated Objects Associated with Ground Motion during the Mw 6.0 2016 Amatrice (Central Italy) Earthquake

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The M_w 6.0 normal faulting Amatrice earthquake, occurred on 24th August 2016 in the Central Apennines (Italy), produced a significant (60 observations at 35 different sites) number of rotational effects (EROs—Earthquake Rotated Objects) on vertically organized objects such as chimneys, pillars and capitals. Following the path of studies already carried out for the L'Aquila (M_w 6.3, 2009) and Emilia (Ml 5.9 and Ml 5.8, 2012) past seismic events, we investigate the relations between EROs occurrence and a number of customary seismological and geological observables, such as intensity, epicentral distance, distribution of seismicity, potential amplification of the seismic shaking at the site, heterogeneities of the rupture on the fault and directivity effects, and peak ground accelerations. Our results show a significant convergence between EROs distribution and damage, and highlight the importance of the geological and geomorphological conditions at a particular site for the occurrence of the earthquake-induced rotational effects. The EROs observed following the 2016 Amatrice earthquake are the last data added to the World Catalog of Earthquake Rotated Objects, that presently counts more than 2200 observations relative to 205 seismic events occurred between 1349 and 2016. We therefore provide a comparison between the data from the Amatrice earthquake and from the whole dataset of the catalog, and see how those data fit with the empirical relations on the EROs distribution presented there. Finally, also the 2016 data confirm the importance of the rotational effects for studies of earthquake engineering as they can produce relevant deformations in buildings or part of buildings.

The Ruin of the Roman Temple of Kedesh, Israel; Example of a Precariously Balanced Archaeological Structure Used as a Seismoscope

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In certain regions and under favorable geologic conditions, precariously balanced rocks may form. These types of unusual formations have been used to estimate yield ground motions. Because such balanced rocks have not been 'unbalanced', they can be used as a rough estimate for ground motions which have not been reached or exceeded since the balanced formation achieved its contemporary state. We hypothesize that other ancient manmade structures, delicate in terms of stability and particularly those that have survived earthquake ground motions intact, can be used in the same manner. We therefore suggest that these structures act as a highly local seismoscope for determining maximum upper ground motion bounds. We apply the concept of the study of precariously balanced rocks to the ruin of the Roman temple of Kedesh, located in close proximity to a branch of the Dead Sea Transform Fault. The delicate-looking ruin was surveyed with a 3D laser scanner. Based on the point cloud from that survey, a discrete element model of the remaining temple wall was constructed. To test the stability of the model we used 54 analytical ground motion signals with frequencies ranging from 0.3 to 2 Hz and PGAs between 1 and 9 m/s2 and simulated and measured strong ground motions of eight earthquakes. Two hypothetical local earthquake scenarios, five of which are historical earthquakes of the region and one is a strong motion record of the 1999 Taiwan Chi Chi earthquake were also used to test the hypothesis. None of the simulated earthquakes (historical or assumed) toppled the ruin; only the strong motion record collapsed the structure. The simulations reveal a surprisingly high stability of the ruin of the Roman temple of Kedesh mainly due to the small height to width ratio of the remaining walls.

Understanding and Modeling Ground Motions and Seismic Hazard from Induced Earthquakes

Oral Session · Thursday 20 April · 10:45 AM · Plaza E

Session Chairs: Annemarie Baltay, Daniel McNamara, Eric Thompson, and Mark Petersen

2017 One-Year Seismic Hazard Forecast for the Central and Eastern United States from Induced and Natural Earthquakes

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We produced a one-year 2017 seismic hazard forecast for the central and eastern United States from induced and natural earthquakes that replaces the one-year 2016 forecast and evaluated the 2016 seismic hazard forecast to improve future assessments. The 2016 forecast indicated high seismic hazard (greater than 1% probability of damaging ground shaking in 1 year) in Oklahoma/Kansas, Colorado/New Mexico, northern Texas, Arkansas, and New Madrid. During 2016, several damaging induced earthquakes occurred in Oklahoma within the highest hazard region of the 2016 forecast; all of the 23 $M > 4$ and 3 $M > 5$ earthquakes occurred within the highest 5%-12% probability of damage contours shown in the 2016 forecast. Outside Oklahoma two moderate earthquakes with $M \geq 4$ occurred near Trinidad, Colorado but no earthquakes with magnitudes $M \geq 2.7$ were observed in northern Texas or Arkansas. Several observations of damaging ground shaking levels were also recorded in the highest hazard region of Oklahoma. The 2017 hazard model applies the same methodology and input logic tree as the 2016 forecast, but with an updated earthquake catalog. The 2017 seismic rates are lower in almost all regions of induced activity due to lower rates of earthquakes in 2016 compared to 2015, which may be related to decreased wastewater injection, caused by regulatory actions or by a decrease in unconventional oil and gas production. Additional research on ground shaking, earthquake rates, and tests of the maps will improve future forecasts.

Comparison between the 2016 USGS Induced-Seismicity Hazard One-Year Forecast and the 2016 "Did You Feel It?" Data Archive

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For 2016, the U.S. Geological Survey (USGS) developed a one-year probabilistic seismic hazard forecast for the Central and Eastern U.S. from induced and natural earthquakes (https://pubs.er.usgs.gov/publication/ofr20161035). The hazard forecast is primarily based on the earthquake catalog from 2014-2015. Previous analysis by the authors retrospectively compared "Did you feel it?" (*DYFI?*) and instrumental data from 2014-2015 to the 2016 hazard forecast. The previous study led to the development of a process to compare *DYFI?* to hazard models and revealed a number of necessary steps to make the data and models comparable. These steps include converting the hazard model from peak ground acceleration (PGA) to Modified Mercalli Intensity (MMI), using only *DYFI?* data from the declustered catalog used in the hazard model, and applying site condition adjustments (V_{S30} topography based) to the hazard model. The results, focused on Oklahoma and southern Kansas, showed agreement between the model and data in areas with sufficient population to have a complete *DYFI?* catalog, thereby providing a baseline for future prospective comparisons. Here, we apply the same comparison method using the *DYFI?* archive from 2016 and the 2016 hazard model. The mean annual ground motion exceedance rates from the hazard model output are directly compared to the calculated (observed) exceedance rates from zip code and geocoded *DYFI?* data. The differences between the modeled and observed exceedances are complicated, as they may be influenced by economic and regulatory influences on industry activity. Nevertheless, completing the prospective comparison can potentially inform any future induced seismicity hazard modeling and more formal testing of the results.

A Better Understanding of the Seismic Hazard of Induced Earthquakes from High-Resolution Structure, Crustal Anisotropy, and Source Properties of the M_w 5.7 Prague Earthquake

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In addition to the level and type of anthropogenic activity, key factors controlling seismic hazard from induced earthquakes include the locations of potential sources (faults), the source properties (magnitude and stress drops), and orientation of local stresses. By using data collected during a temporary deployment following the 2011 M_w5.7 Prague earthquake, we can develop a comprehensive picture of an induced earthquake sequence from the imaged fault structures, source properties, and shallow anisotropy. Keranen *et al.* (2013) provided an overview of the three major fault structures involved in the sequence; we augment that catalog with additional detections using newly developed template-matching techniques to help define smaller sub-structures. We also report that measured crustal anisotropy shows fast directions align with the local maximum compressive stress orientations (N80E to E-W). Anisotropy measurements also show some heterogeneity in fast direction orientations near several segments of the major fault structures, suggesting either minor stress rotations or structure-controlled anisotropy. A detailed understanding of stress orientations provides insights into whether the various fault segments involved in the Prague sequence are well oriented (or not) to fail in the local stress field. Finally, we estimate stress drops for the sequence using two methods: Brune spectral fitting of individual spectra and Empirical Green's function spectral ratios. Analysis of individual spectra suggests that stress drops are low compared to intraplate regions (median stress drop of 0.2 MPa; Sumy, Neighbors *et al.*, in review). We continue our study and report on estimates of preliminary stress drops from applying Brune spectral fitting to spectral ratios.

Evaluation of the Fitting Accuracy for the Source Parameter Estimation of Potentially Induced Earthquakes in Oklahoma

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Stress drop is important factor for evaluating the seismogenic environment; however, precision measurement is challenging. Signal bandwidth is often inadequate to evaluate small events. In this study, we use the misfit between model spectrum and data for spectral ratio measurements to evaluate the quality of source parameter estimates for earthquakes in Oklahoma.

We use small events (M_L < 3.5) located within 2 km of larger events (M_w ~4) in Oklahoma from March to August in 2016 as empirical Green's functions. We compute mean spectral ratios by stacking all components of 4 USGS and OGS stations. To remove the directivity effect, we use a 5.12 window taken after 2.5 times of the S wave arrival (coda). Frequency range for the fitting was 0.5 to 40 Hz, and we evaluate a range of corner frequencies between 1 and 60 Hz. Both Boatwright and Brune model were used as source models. Although there is sometimes a difference between the two models, residual sum of squares (RSS) do not favor one model over the other. We evaluate the trade-off of the corner frequencies with a residual map spanning the range of considered corner frequencies. The low corner is generally well-resolved, while the higher corner frequency is not. We also examine the residual as a function of frequency. When the residuals are zero mean the in high frequency range (> 10 Hz), the fitting accuracy for the smaller event corner is improved.

For the precise fitting and selection of the spectral model, a combination of residual trade-off, RSS, and absence of bias in the low and high frequency range appears to be effective. Most stress drops we determined are under 100 MPa in this study.

Examining Earthquake Source Properties and Scaling of Recent Seismicity in Southern Kansas

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Seismicity rates have risen sharply in regions of oil and gas production in the Central and Eastern United States. A better understanding of the source properties of these earthquakes would yield insight into their nucleation and rupture processes and their influence on observed ground motion. Here we apply a new spectral decomposition technique to analyze the source spectra and source properties of earthquakes in an 1,800 km^2 region of southern Kansas recorded during 2014 and 2015 by the temporary deployment of a 14-station USGS array. We derive source parameter estimates, including corner frequency and (Brune-type) stress drop, for more than 1300 earthquakes with magnitudes ranging from M1 to M5. We find that these earthquakes are characterized overall by relatively low stress drops (median values < 1 MPa) that increase mildly with seismic moment. We observe complex temporal and spatial variations in the inferred source parameters, with relatively high stress drops before and during the November 2014 M_w 4.9 Milan earthquake sequence. We further note a significant increase in corner frequency and stress drop for events occurring in the deeper portion of the basement rock (> 6 km), suggesting a depth-dependent change in the rupture properties of these events. In future work, we hope to consolidate our understanding of the stress-triggering processes driving seismicity in this region, and provide constraints for future hazard and ground motion analyses, by exploring in detail the spatiotemporal relationship between the anthropogenic stressing from oil and gas production and the source properties of these events.

Using Simulated Ground Motions to Constrain Near-Source Ground Motion Prediction Equations in Areas Experiencing Induced Seismicity

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Recent increases in seismic activity in historically quiescent areas such as Oklahoma, Texas, and Arkansas have spurred the need for investigation into expected ground motions associated with these seismic sources. The neoteric nature of this seismicity increase corresponds to a scarcity of ground motion recordings within ~20 km of earthquakes M_w 3 and greater. To aid the effort of constraining near-source ground motion prediction equations (GMPEs) associated with induced seismicity, we develop a framework for integration of synthetic ground motion data from simulated earthquakes into the GMPE development process. We demonstrate this framework by developing a GMPE for a target region encompassing north-central Oklahoma and south-central Kansas. We gather a catalog of recorded ground motions from M_w 3+ earthquakes that occurred in the target region. Using constraints on the region's material structure, including well log data that provides insight into the characteristics of shallow sedimentary layers, we perform simulations intended to mimic a selection of recorded earthquakes from the target region.

For M_w 3-4 earthquakes, we use point source simulations where sources are constrained by available moment tensors and locations. For M_w 4+ earthquakes, we employ finite fault sources that aim to capture the complexities of intermediate and large earthquakes. Once we determine that our simulations produce realistic ground motions, we combine recorded and synthetic ground motion data to produce a hybrid ground motion catalog. We use this hybrid catalog to develop a regionally-specific GMPE for our target region. This framework can be exported to other regions where near-source ground motion data are sparse and can be used to improve constraints on near-source GMPEs, which could directly benefit seismic hazard estimates.

Ground Motions from Induced Earthquakes in Oklahoma and Kansas

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Recent efforts to characterize seismic hazard from induced earthquakes in Oklahoma and Kansas (OK-KS) highlight the need for regionalized ground motion characterization. To support these efforts and provide insight into the ground motions from induced earthquakes in this region, we compared pseudo-spectral accelerations (PSA; 5 percent damping) from a recently developed database of induced ground motions in OK-KS with the PSA from three suites of ground motion prediction equations (GMPEs) from the western U.S. and the central and eastern U.S. We made no attempt to correct the ground motions for site response because little is known about the shallow seismic velocity structure of the region; however, our focus on the distance-scaling of the residuals is not dependent on accurate characterization of site effects and GMPE-predictions employed Vs30=760 m/s. Total ground motion residuals (PSA, 0.1–5 s) were computed and decomposed into intra-event, inter-event, and fixed terms using mixed-effects regressions. The fixed terms, for all GMPE suites, exhibit a positive correlation with period beyond about 0.5 s; at shorter periods, the fixed residuals appear to depend on the assumed attenuation of the shallow subsurface (*i.e.*, "kappa"). Intra-event residuals exhibit a strong distance dependence, resulting from faster near-source distance-attenuation of the ground motions than is predicted by any of the GMPE suites and higher than predicted ground motions at larger distances. The large-distance, long-period misfit may be explained by strong surface waves. The effect of the observed near-source distance attenuation is significant for ground motion prediction and seismic hazard assessments in the region because seismic hazard from induced events is strongly controlled by local sources. These observations highlight a fundamental deficiency in the parameterization of modern GMPE suites for induced earthquakes in OK-KS and will be critical for future GMPE development.

A Ground Motion Prediction Equation for Induced Oklahoma Earthquakes

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We present a ground motion prediction equation (GMPE) for induced earthquakes in Oklahoma, where hazard contributions from induced seismicity is of particular interest. We first examine regional source and attenuation attributes based on the peak ground motions and response spectra obtained from induced Oklahoma events. The compiled ground-motion data is limited for deriving a robust predictive model for moment magnitudes M>5. In order to ensure seismologically robust predictions for moderate-to-large magnitudes, we adopt a "plug-and-play" generic GMPE (Yenier and Atkinson, 2015, BSSA) that is adjustable for use in any region by modifying a few key model parameters. We determine stress parameters of induced events based on the observed spectral shape, and compare to those from natural events in central and eastern North America. We modify the model parameters of generic GMPE in accordance with the observed source and attenuation attributes, and determine an empirical calibration factor that accounts for the overall differences between the generic model and the recorded data in the region. This provides a fully-adjusted GMPE for induced events in Oklahoma. Finally, we investigate the spatial and temporal variation of stress parameters to gain insights into the source characteristics of induced events in the region.

Are Ground-Motion Models Derived from Natural Events Applicable to the Estimation of Expected Motions for Induced Earthquakes?

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Natural earthquakes in western North America can be reasonable proxies for induced earthquakes in central and eastern North America, because of the opposing effects that source depth and tectonic setting have on the stress parameter that scales high-frequency ground-motion amplitudes. It is critical that ground-motion prediction equations selected as induced-event proxies have appropriate near-distance scaling behavior for small-to-moderate shallow events. We describe the conditions under which natural-earthquake models are suitable for induced seismicity applications. Using examples from Oklahoma and Alberta, we identify at least three models (Atkinson, 2015 BSSA; Abrahamson *et al.*, 2014 Earthquake Spectra; Yenier and Atkinson, 2015 BSSA) that are reasonable proxy estimates of median motions from induced earthquakes in the east, for the magnitude-distance range of most concern to hazard estimation from such events: M 3.5 to 6 at distances to 50 km. The first two models (Atkinson, 2015; Abrahamson *et al.*, 2014) were developed from the Next Generation Attenuation (NGA) West2 database while the third (Yenier and Atkinson, 2015) was developed from the NGA-East database.

Ground Motion Prediction Equation for Small-To-Moderate Earthquake Events in Texas, Oklahoma, and Kansas

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The observed increase in seismicity in Texas, Oklahoma, and Kansas during the last 10 years has made the evaluation of the seismic hazard in these States increasingly pertinent. Such evaluation requires the development of ground motion prediction equations (GMPEs) that are tuned to the characteristics of the observed, and potentially induced, seismicity. Accordingly, we use 4,258 ground motions recorded during M>3.0 events in Texas, Oklahoma, and Kansas, to develop a GMPE for this region. The GMPE uses the reference empirical approach to modify the Hassani and Atkinson (2015) Central and Eastern North America (CENA) GMPE to account for differences between the regional ground motion observations and the reference GMPE for CENA. The developed model includes site effects based on updated VS30 values derived from the P-wave seismogram method (Zalachoris *et al.* 2017) or regional geologic-slope proxies (Parker *et al.* 2017). The predicted response spectral accelerations at short distances ($R \leq 20$ km) for Texas, Oklahoma, and Kansas can be up to 2.5 times larger than those predicted by the reference GMPE. The VS30 scaling for the newly developed model predicts less amplification at VS30 < 200 m/s, about 35% less at T < 0.3 s and about 70% less at T = 1.0 s . This effect is likely due to the generally thinner sediments in the study area. Finally, for M>4.5 events, the new model predicts spectral accelerations about 60% smaller than those predicted by the reference GMPE, possibly due to lower stress drops associated with the potentially induced seismicity in Texas, Oklahoma, and Kansas.

Verification and Validation of Earthquake Occurrence and Hazard Forecasts

Oral Session · Thursday 20 April · 8:30 AM · Governor's Square 14

Session Chairs: Seth Stein, John Rundle, and Mark Petersen

Nowcasting Earthquakes: Applications and Sensitivity Testing

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The term "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). Nowcasting is a term that originated in economics and finance, referring to the process of determining the uncertain state of the economy or markets at the current time by indirect means. We have applied this idea to seismically active regions, where the goal is to determine the current state of a regional system of faults, and its current level of progress through the earthquake cycle (http://onlinelibrary.wiley.com/doi/10.1002/2016EA000185/full). We wish to estimate how far the fault system has progressed through the "cycle" of large recurring earthquakes.

We use the global catalog of earthquakes, using "small" earthquakes to determine the level of hazard from "large" earthquakes in the region. As an application, we can define a small region around major global cities, for example a "small" circle of radius 150 km and a depth of 100 km, as well as a "large" earthquake magnitude, for example M6.0. The statistics are computed from a "large" 10º x 10º region surrounding the "small" 150 x 100 km circle. The current count of earthquakes that is used to compute the nowcast is obtained from small earthquakes in the small region. The basic assumption is that both the "large" and "small" regions are characterized by the same Gutenberg-Richter magnitude frequency statistics.

If one defines a "model" as a calculation system in which there exist free parameters that must be optimally fit to data, then it can be said that there is no model involved in our nowcasting analysis, only data interpretation. We have used these techniques to compute the relative nowcast rankings of large global cities at risk for damaging earthquakes. We also discuss the results of sensitivity analyses of the rankings to variations in the selected magnitude, small and large regions.

Insights from Population Forecasting for Earthquake Hazard Forecasting

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Statisticians have questioned earthquake hazard forecasts for issues including: how expert opinion is used, how probability is used, how uncertainty is measured, and how probabilistic forecasts should be interpreted. Some insight into these issues can be obtained from another complex endeavor: population forecasting. Population forecasting is both easier than earthquake hazard forecasting, in that data are more readily available to check models, assumptions, and forecasts, and harder in that population growth is a non-stationary process. The population forecasting literature has examined how complex models perform versus simple models, where complexity refers not only to the mathematical form and spatio-temporal detail of the model but also to the diversity of data on which the model fitting depends. Research has also examined how much weight to give expert opinion as a supplement to data. Accuracy of population forecasts commonly is estimated in two different ways, one involving propagation of error in models of underlying stochastic processes whose parameters must be estimated, and the other involving comparison of forecasts with observed population sizes. Probabilistic forecasts of population are seeing increased development and application for social insurance programs such as Social Security in the U.S. and public pension plans in Europe. The probabilistic aspects of the forecasts are communicated in an interpretable way to improve their uses by decision makers. We discuss insights from population forecasting with an eye toward improving seismic hazard forecasts and their uses.

Probabilistic Framework and Experimental Concepts for Testing Earthquake Forecasting and Seismic Hazard Models

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To account for the randomness (aleatory variability) and limited knowledge (epistemic uncertainty) of earthquake processes, we must formulate and test seismic hazard models using the concepts of probability. Probabilistic seismic hazard analysis (PSHA) gives the chance that a specified seismic intensity will be exceeded at a particular site during some future time window. Because knowledge of that chance is uncertain, a complete PSHA estimate must be expressed as a probability distribution. Owing to limited observations, this epistemic uncertainty is often quantified by expert opinion. The conceptual objections to PSHA stem primarily from the unsatisfactory treatment of the aleatory-epistemic duality in probabilistic inference. In the subjective (Bayesian) framework, all probabilities are epistemic, whereas in the frequentist framework, all probabilities are aleatory; PSHA models cannot be entirely formulated and tested within either framework. We propose an augmented framework that resolves the testing issue by adding a 3rd level of uncertainty, which we term "ontological" (PNAS, 111, 11973, 2014). A complete probabilistic model is sufficient to pose an ontological null hypothesis, which states that the aleatory representation of future earthquake activity—the seismic behavior of the real Earth—samples the probability distribution of aleatory representations that describe the model's epistemic uncertainty. We can test, and possibly reject, the ontological null hypothesis by employing an "experimental concept" that identifies collections of data, observed and not yet observed, judged to be exchangeable (*i.e.*, with joint probability distributions invariant to data ordering) when conditioned on a set of explanatory variables. These conditional exchangeability judgments specify data sequences with well-defined frequencies. Bayesian models that predict such long-run frequencies can thus be tested for ontological error by frequentist methods, *e.g.*, using p-values.

How Good Should We Expect Probabilistic Seismic Hazard Maps To Be?

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Recent earthquakes that caused shaking much stronger than shown in probabilistic seismic hazard (PSH) maps have stimulated discussion about how well the maps forecast shaking. Although maps are designed for certain goals, we know little about how they actually perform. This issue has two parts. Verification involves how well maps implement the PSH algorithm ("have we built the map right?"). Validation asks how well the map forecasts shaking ("have we built the right map?"). We explore verification by simulating shaking histories for an area with assumed distribution of earthquakes, magnitude-frequency relation, Poisson temporal occurrence, and ground-motion prediction equation (GMPE). The fraction of sites where shaking should exceed that on the map is $p = 1 - \exp(-t/T)$, where t is the duration of observations and T is the map's return period. Exceedance occurs in infrequent large earthquakes, as in reality. The distributions of fractional exceedance have mean equal to that predicted, so the PSH algorithm appears verified. The fractional exceedances show scatter about the mean decreasing with increasing t/T and a-value and independent of GMPE uncertainty. The scatter decreases as the largest earthquakes occur in more simulations. Our results are important for evaluating the performance of a map based on misfits in fractional exceedance and assessing whether such misfit arises by chance or from bias in the map. We determined confidence intervals on allowed misfits in fractional exceedance and thus on the map bias that can be detected by comparison with observed shaking histories. Since in reality we only have one shaking history for an area, these results indicate that if a map misfits observations, it is difficult to assess its veracity, especially for low-to-moderate-seismicity regions. Because our model is a simplified version of reality, additional uncertainty or complexity will widen these confidence intervals.

Improving Earthquake Forecasts with Crustal Deformation Observations

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Geodetic imaging techniques provide a wide range of measures of the spatio-temporal behavior of faults and the crust, useful for improving earthquake hazard assessment and forecasting. GPS measurements provide rate estimates of <1 mm/yr, and InSAR measurements provide displacements at the cm level. Topographic measurements, derived from lidar or structure from motion measurements, at >1 sample per square meter, provide geomorphic constraints on fault zones. Adding geodetic imaging to earthquake forecasts can reduce the uncertainty of potential earthquake location and magnitude. Observations in California show that large earthquakes can cause transient deformation up to three fault dimensions from the source earthquake that may persist for years. Key questions that can be addressed with geodetic imaging include 1) How is plate boundary deformation distributed across the active fault network in California? 2) How do faults within the plate boundary interact before, during and after earthquakes? 3) What fraction of strain accumulation is relieved aseismically and does this provide limits on seismic moment release? Both GPS and InSAR measurements from NASA's airborne UAVSAR platform show crustal deformation rate changes and triggered slip on faults up to 100 km away from large earthquakes. The 1994 M6.7 Northridge earthquake affected the Sierra Madre fault near JPL for several years after the event and the 2010 M7.2 El Mayor-Cucapah earthquake triggered slip on a network of faults ranging up to the Eureka Trend just south of the Eastern California Shear Zone. UAVSAR observations suggest coseismic shallow slip on several faults associated with earthquakes, which may reflect release of still locked deeper accumulated strain providing opportunity to assess seismic potential. We will also present results that indicate deeper aseismic slip on portions of the San Andreas fault, and off fault deformation, which could improve estimates of earthquake hazard.

Seismic Hazard Prediction or Forecasting in the Central United States

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Recent earthquakes, such as the 2008 Wenchuan (China), 2010 Haiti, and 2011 Christchurch (New Zealand) and Tohoku (Japan) earthquakes, showed that seismic hazard prediction or forecasting is not only a great challenge, but also an obligation for earth scientists. This is particularly demonstrated by the prosecution of six scientists in Italy for "inadequate communication of seismic hazard and risk" or "failure to predict the earthquake" in Italy before the 2009 L'Aquila quake. Thus, seismic hazard prediction or forecasting has been a major topic for debate and discussion at the annual meeting of the Seismological Society of America. Seismic hazard prediction or forecasting has also become a major topic for debate and discussion among earth scientists in the central United States since the famous prediction by Iben Browning that there would be a major earthquake in the New Madrid Seismic Zone in December 1990. The difficulty for seismic hazard prediction or forecasting in the central United States is not only the lack of observations, but also in communicating the low probability of seismic hazard, less than 1 percent for any given day, to the stakeholders and general public.

Assessing Earthquake Hazard Map Performance for Natural and Induced Earthquakes

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Assessing the performance of earthquake hazard maps for natural and induced seismicity is conceptually similar but has practical differences. One approach is to compare the fraction of sites at which shaking exceeds the mapped level to the expected fraction of such sites. Another is to compare the maximum observed shaking to the forecasted shaking. The first metric is sensitive to the overall level of shaking, whereas the second is sensitive to spatial variations. Although we have only short periods of data since hazard maps began to be made, maps that have return periods of hundreds or thousands of years— as commonly used for natural seismicity— can be assessed using historical intensity data. Comparing historical intensity catalogs for Italy and Japan to earthquake hazard maps shows intriguing differences from modeled behavior. The cause of these differences is unclear because of possible biases in intensity assignment, biases in space-time sampling, and the fact that the comparisons are hindcasts rather than forecasts. Several different features stand out when assessing the USGS 2016 seismic hazard model for the Central and Eastern United States from induced and natural earthquakes. First, the model can be assessed as a forecast in one year, because event rates are sufficiently high to permit evaluation with one year of data. Second, because these models are projections from the previous year thus implicitly assuming that fluid injection rates remain the same, misfit can reflect changes in human activity. Hence misfits can give useful insight into how and where to adopt injection policies to reduce the hazard. We present initial comparisons of observations to hazard models. We plan to compare models produced with differing key parameters including maximum and minimum magnitude, ground motion prediction equations, and assumptions such as whether and how to decluster the observed seismicity, to gain insight into the model uncertainties involved.

Are Large Global Earthquakes Temporally Clustered?

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In order to study temporal clustering of earthquakes a relatively large number is required (say 50-100). On the world-wide basis, there will typically be a large enough number of earthquakes as large as $M > 8$. However, a significant number of these earthquakes will be aftershocks of the largest events. No satisfactory method of declustering the aftershocks in clock time is available. However, the use of "natural time" (event count) eliminates the need for declustering. The event count we utilize is the number of small earthquakes that occur between large earthquakes. The small earthquake magnitude is chosen to be as small as possible such that the catalog is still complete based on Gutenberg- Richter statistics. For the global CMT catalog we take this magnitude to be $M > 5.5$. We then utilize the concepts of nowcasting, a new method of statistically classifying seismicity and seismic risk introduced by Rundle *et al.* (2016), to obtain the temporal statistics of occurrence of the large earthquakes. The number $M > 5.5$ earthquakes that occur between each pair of $M > 8$ earthquakes is obtained and is presented as a time series. The statistics of the time series and the statistics of the distribution of interevent natural time intervals will be presented and discussed.

Modeling Earthquake Clusters as Resulting From Long-Term Fault Memory

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A major challenge for earthquake hazard assessment 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 unlikely soon. Clusters are intriguing because faults are presumably being loaded by steady plate motion, so we would expect quasi-periodic earthquakes rather than clusters. Earthquake hazard assessments typically employ one of two models. In one, earthquake probability is modelled as Poissonian, so an earthquake is equally likely at any time. The fault has no "memory" because when a prior earthquake occurred has no bearing on when the next will occur. Another common model is an earthquake cycle in which the probability of an earthquake increases with time until one happens, after which the probability resets to zero. Because the probability is reset after each earthquake, the fault "remembers" only the last earthquake. We propose an alternative, Long-Term Fault Memory (LTFM), a modified earthquake cycle model where the probability of an earthquake increases with time until one happens, after which it decreases, but not necessarily to zero. Hence the probability of the next earthquake depends on the fault's history over multiple cycles, giving "long-term memory". Physically, this reflects an earthquake releasing only part of the elastic strain stored on the fault. Damage rheology models feature similar LTFM at the expense of heavy computation. We use the LTFM to simulate earthquake clustering along the San Andreas Fault, Cascadia, the Dead Sea Transform and in Australia. In some portions of the simulated earthquake history, events would 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.

Validation of Aftershock PSHA in Central Italy

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We present the development and validation of an aftershock probabilistic seismic hazard model for the region of Central Italy, following the Amatrice M6.2 earthquake of August 24th, 2016 which resulted in 298 casualties.

The aftershock hazard is modeled using a fault source with a realistic geometry, based on literature data and field investigation of the surface ruptures carried out in the days following the August mainshock. We calibrate earthquake activity rates using data from the first weeks after the earthquake following an Omori-Utsu decay curve, and the magnitude distribution of aftershocks is assumed to follow a Gutenberg-Richter distribution. We apply uniform and non-uniform spatial distribution of the seismicity across the fault source, by modulating the rates as a decreasing function of distance from the mainshock. The hazard results can be computed for any exposure period (*e.g.* 1 month) and are intrinsically time-dependent; they may be considered valid after the learning period of the O-U decay curve, but before the occurrences of the similar size ruptures of October events (M6.1 Oct 26th, M6.6 Oct 30th).

We perform a validation test of our model from mid September to mid October, *i.e.* before the new major ruptures. The Amatrice earthquake and aftershocks were recorded by both national and regional networks. Using the wealth of strong motion records available, we compare the observed ground motions at sites within our study area to the results of our hazard analysis.

Advances in Seismic Full Waveform Modeling, Inversion and Their Applications

Poster Session · Thursday 20 April ·

Finite-Difference Algorithm for 3D Orthorhombic Elastic Wave Propagation

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An orthorhombic elastic medium, characterized by three mutually orthogonal symmetry planes, constitutes a realistic representation of seismic anisotropy in shallow crustal rocks. This symmetry condition typically arises via a system of vertically-aligned microfractures superimposed on a layered horizontal geology. Mathematically, the elastic stress-strain constitutive relations for an orthorhombic body contain nine independent moduli, which can be determined from nine independent P-wave and S-wave phase speeds along different propagation directions. We are developing an explicit time-domain finite-difference (FD) algorithm for simulating three-dimensional elastic wave propagation in a heterogeneous orthorhombic medium. The components of the particle velocity vector and the stress tensor are governed by a set of nine, coupled, first-order, linear, inhomogeneous partial differential equations called the velocity-stress system, discretized with centered and staggered FD operators possessing second-order temporal and fourth-order spatial numerical accuracy. Simplified FD updating formulae for the stress components are obtained by restricting the principle axes of the modulus tensor to be parallel to the global rectangular coordinate axes. Novel perfectly matched layer (PML) absorbing boundary conditions, specifically designed for orthorhombic media, effectively suppress grid boundary reflections. Initial modeling results with a homogeneous body reveal well-established anisotropic seismic waveforms. Recent implementation of an orthorhombic stress-free surface enables investigation of the azimuthal dependence of surface wave propagation speeds, polarizations, and waveforms.

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Far-Field Seismic Signals from Coupled Nonlinear-To-Linear Propagation Codes

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Explosions within the earth nonlinearly deform the local media, but at typical seismological observation distances, the seismic waves can be considered linear. Although nonlinear algorithms can simulate explosions in the very near field well, these codes are computationally expensive and inaccurate at propagating these signals to great distances. A linearized wave propagation code, coupled to a nonlinear code, provides an efficient mechanism to both accurately simulate the explosion itself and to propagate these signals to distant receivers. To this end we have coupled Sandia's nonlinear simulation algorithm CTH to a linearized elastic wave propagation code by passing information from the nonlinear to the linear code via time-varying boundary conditions. The distance at which the coupling is implemented can affect far-field wave amplitudes and shapes and should be placed where particle motions are small enough that linearized approximations to the governing equations are sufficiently valid. We will explore the optimal distance for this coupling region for a variety of earth materials based on simulation studies. From a computational perspective, limiting the domain size of the expensive nonlinear algorithm as much as possible is desirable; thus, we will also investigate the sensitivity of the far-field waveforms to variations in the coupling distance. These results will be used to quantify uncertainty in the far-field seismic signals generated from numerical simulations of explosions.

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3D Passive-Source Reverse Time Migration Imaging of the Mantle Transition Zone in the Yellowstone Region

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The common-conversion-point (CCP) stacking method has been widely used in receiver function studies to image velocity discontinuity structures. However this method does not account for complex wave phenomena such as wave scattering and focusing/defocusing. With advance of computational power, wave equation base imaging methods have been proposed. During the past few years we have developed a 3D passive-source reverse time migration (PS-RTM) method using receiver functions to image complex structures. Here we applied this method to image the mantle transition zone boundaries in the Yellowstone region. We used an iterative deconvolution method to calculate vertical, radial and transverse component receiver functions. We calculated receiver functions of about 1743 teleseismic events (between epicentral distances of 28-98 degrees) at 243 stations. 222 events with high average signal to noise ratio (SNR>10) receiver functions were selected for imaging purpose. We binned the selected events by back-azimuth (5 degrees) and ray parameter (0.003139s/km) and stacked the weighted receiver functions of different events in each bin. We used a cubic-spline method to interpolate the receiver functions from sparse and unevenly distributed stations onto numerical grids to construct a wavefield covering the model surface. Then we used the PS-RTM method to image the structure with interpolated receiver functions and combined the images from all the azimuthal and ray parameter bins to generate the finial image. We used both 1D and 3D velocity models for the migration and will show some preliminary results.

Nonlinear Moment Tensor Inversion of the Envelopes and Cumulative Energy of Regional Seismic Waveforms

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Moment-tensor inversion of seismograms recorded at regional distances for earthquakes of M4 or greater is a routine process to determine seismic moment, focal mechanism and depth of moderate and large magnitude earthquakes. We are working to extend the inversion of regional waveforms for the moment tensor and focal depth to smaller magnitude events, which are rich in high frequency content but lacking in observable longer period surface-wave energy. We are developing a nonlinear moment-tensor inversion scheme to invert processed seismic waveforms for smaller seismic events. In the inversion, we fit either the envelopes or the cumulative energy curves of the seismograms, both of which preserve some element of the high-frequency part of the signal but still present a relatively simple waveform for the inversion after frequency filtering. The proposed scheme extracts the desired source information of regional earthquakes within epicentral distances of 70-400 km in the frequency band of about 1-3 Hz after the seismograms have been processed to their envelopes. We start with a coarse grid search to find a set of the starting source parameters (focal depth and moment tensor) near the optimum solution and proceed with either a finer grid search or a nonlinear inversion to find the optimum solution. We have tested several Mineral aftershocks down to M2.5 to find how close the starting model has to be to the optimal solution in order to get the desired results. The method shows good results for events below M3.0. We also are testing the method using a "cut-and-paste" approach to match separate sections of the waveforms such as the P-wave window, S-wave window, surface-wave window or even seismogram sections with multiple phases.

Topographic Influence on Near-Surface Seismic Velocity in Southern California

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It has been suggested that the spatial distribution of Vs30 [time-averaged shear-wave velocity (Vs) in the top 30 m of the crust] values can be inferred based on rock types and topographic slope. To address the local variability of Vs30 values, we estimate Vs30 values from P-wave seismic tomography (Vp) data using the Brocher (2005) Vs-Vp relation and compare Vs30 to the measured spatial distribution of near-surface seismic velocity at granitic rock sites in the San Gabriel Mountains (SGM), the San Bernardino Mountains (SBM), and the San Jacinto Mountains (SJM). Our results show that Vp of bedrock sites vary significantly depending on locations and do not linearly correlate with topographic slope. In addition, we observe significant variations in Vp within the near-surface of hillslopes in mountainous sites. For example, the Vs30 values inferred from Vp at a SGM site is 25% faster beneath the valley portion of the site than that beneath the hillslope. Overall, we observe slower Vs30 values in the SBM and SJM regions than in the SGM. Slower Vs30 values may result from a greater depth of weathered and/or fractured zone in subsurface bedrock. These results suggest that the local variability of near-surface seismic velocity distribution may depend on subsurface weathering structures that are affected by various factors including chemical composition of bedrock, erosion rates, groundwater flow, bedrock fractures, and topographic stresses.

Using Exponentiated Phase in Regional and Global Seismic Tomography

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Seismic tomography is at the threshold of a new era of massive data sets. Improving the resolution and accuracy of Earth structure by assimilating as much information as possible from every seismogram, remains a challenge. We propose the use of the "*exponentiated phase*", a type of measurement that robustly captures the information contained in the variation of phase with time in the seismogram. We explore its performance in both conventional and double-difference (Yuan, Simons and Tromp, *GJI*, 2016) adjoint seismic tomography. We introduce a hybrid approach to combine different objective functions, taking advantage of both conventional and our new measurements. We initially focus on phase measurements in global tomography. Cross-correlation measurements are generally tailored by window selection algorithms such as FLEXWIN. However, it is difficult to select all usable portions of the seismogram in an optimal way, such that much information may be lost, particularly the scattered waves. Time-continuous phase measurements, which associate a time shift with each point in time, have the potential to extract information from every wiggle in the seismogram without cutting it into small pieces. One such type of measurement is the *instantaneous phase* (Bozdağ, Trampert and Tromp, *GJI*, 2011), which thus far has not been implemented in realistic seismic-tomography experiments, given how difficult the computation of phase can sometimes be. The *exponentiated phase*, on the other hand, is computed on the basis of the normalized analytic signal, does not need an explicit measure of phase, and is thus much more practical for real-world applications. To deal with cycle skips, we use the exponentiated phase to take into account relatively small-magnitude scattered waves at long periods, while using cross-correlation measurements on windows to select distinct body-wave arrivals without complicating measurements due to non-linearities at short periods.

Full-Wave Velocity and Attenuation Sensitivities of Seismic Waves Based on the Scattering-Integral Method

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To date developments of seismic attenuation models of the Earth have lagged behind those of velocity models. This is partly due to difficulties in isolating waveform perturbations caused by attenuation and velocity heterogeneities, and partly due to different theories (*e.g.* ray theory, finite frequency theory, etc) used in most previous and current studies to approximate sensitivity kernels and invert for the attenuation structure. We present in this paper the 3D velocity (VP and VS) and attenuation (QP and QS) Fréchet kernels based on the scattering-integral method. The isotropic anelasticity in the medium is approximated by the rheological model of the generalized Maxwell body, which allows us to take the effects of physical dispersion and dissipation into account. We apply the collocated-grid finite-difference method in waveform simulations, in which the time-dependent strain green tensor is saved for the calculation of sensitivity kernels for each data functional. For each source, we carry out one forward simulation and for each station, we carry out three 'backward' simulations for the three displacement components based on source-receiver reciprocity. In contrast to the adjoint wavefield method, we don't need to use a negative time step to reconstruct the 'reverse' wavefield, which helps us to avoid numerical instability problems in calculating anelastic sensitivity kernels. Finally, we show several benchmark examples at regional and global scales to validate our developments.

Attenuation of High Frequency Body Waves in the New Madrid Seismic Zone

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We estimated the attenuation characteristics of body waves in the New Madrid seismic zone (NMSZ) from 157 seismograms of 46 earthquakes with moment magnitudes less than 4.1 and hypocentral distances out to 60 km. Seismograms were obtained from local earthquakes in the NMSZ, recorded by the Center for Earthquake Research and Information (CERI) at the University of Memphis.

We used the coda normalization method to derive Q values at 13 center frequencies. We found that assuming $1/R^{1.0}$ as the geometrical spreading function yields a better fit to the data than $1/R^{1.3}$.

We used a mixed-effects regression algorithm to find Q values. Results demonstrate that the attenuation characteristics of West Tennessee, East Arkansas, and South Missouri are very similar. The Q_P estimates increase with increasing frequency from 354 at 4 Hz to 729 at 24 Hz, and Q_S values vary from 426 at 4 Hz to 1091 at 24 Hz. By fitting a power law equation to the Q estimates, we found the attenuation models for the P-waves and S-waves in the frequency range of 4 to 24 Hz as $Q_P = (115.80 \pm 1.36) f^{(0.495\pm0.129)}$ and $Q_S = (161.34 \pm 1.73) f^{(0.613\pm0.067)}$, respectively. For frequencies less than 4 Hz, Q estimates have a huge uncertainties due to the effects of sedimentary basin as well as the effects of radiation pattern, the effects of background ambient noise, and the effects of contamination of surface waves with coda portion. Thus, we disregarded Q values for frequencies less than 4 Hz to obtain frequency dependent quality factor. $Q_S/Q_P > 1$, for $4 \le f \le 24$ Hz, suggests that the crust beneath the NMSZ is partially fluid-saturated. Further, the relatively high attenuation of *P*- and *S*-waves indicates a high level of heterogeneities inside the crust in this region.

Attenuation of Lg Waves in the New Madrid Seismic Zone Using Coda Normalization Method

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Lg waves are trapped waves propagating through the crust and are the dominant phase in seismograms in regional distances. This study estimates the frequency dependent quality factor of *Lg* waves using the coda normalization method. 121 seismograms from 122 events from 2000 to 2009 are captured by 11 broadband stations of the CERI network, with hypocentral distances from 120 to 400 km and moment magnitudes, M_w, from 2.5 to 5.2. The coda normalization method is a time domain method that takes advantage of unique properties of coda waves. Coda waves are body waves that are backscattered by random lateral heterogeneities of the crust and are captured by the seismograms. Studies show that the code wave spectral shape is approximately dependent on the lapse time from the origin time, regardless of the source to site distance and magnitude (at least for small to moderate magnitudes). In this approach, the amplitude of the *Lg* windows of bandpass filtered seismograms is normalized by the coda window amplitude to isolate the source and the path functions and to eliminate site effects and the instrument response to set up the inverse problem. Using a singular value decomposition algorithm, the quality factor of *Lg* waves at center frequencies from 3 to 12 Hz are obtained. Q values are regressed using a power law equation, $Q(f) = Q_0 f^{\eta}$.

In this study, we obtain $Q^V_{Lg}(f)=(410\pm38) f^{0.49\pm0.05}$ for the vertical component and $Q^H_{Lg}(f)=(390\pm26) f^{0.56\pm0.04}$ for the horizontal components. Below 3 Hz Q values are unreasonably high. This may be due to contamination of the low frequency surfaces waves. Site effects may also aggravate the situation. The quality factors obtained in this study are compared with Erikson *et al.* (2004), Zandieh and Pezeshk (2010), and Chapman *et al.* (2014).

Lg Attenuation in Oklahoma and Its Surrounding Regions

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Increased seismicity in the Oklahoma and surrounding regions since 2008 and the passing of the EarthScope USArray through the region provides an opportunity to better define Lg attenuation in that region. Initial tomography results at 1 Hz by Gallegos *et al.* (2014) and a study of the location of the boundary between mid-continental low attenuation and Gulf Coast higher attenuation regions at 1.0 and 5.0 Hz by Cramer and Al Noman (2016) and Cramer (2017) provide insight into the problem of defining Lg attenuation in the Oklahoma region. The location of the mid-continental/Gulf Coast Q boundary in Oklahoma is complicated by other crustal structures, such as the Southern Oklahoma Rift. We address this problem using Lg Q tomography and increased raypath coverage from M3 earthquakes surrounding the study region. We determine frequency dependent attenuation models Q(f) for the Oklahoma and surrounding region using direct Lg waves at regional distances of 100 to 1500 km. Using automated processing we extracted the Lg-wave amplitude spectra between 0.05 and 10.0 Hz from horizontal and vertical waveforms recorded at 178 TA stations from 106 crustal earthquakes (M>3.5). We simultaneously determined the Q_{Lg} distribution, source and site functions at different frequencies from the geometrical spreading corrected Lg amplitudes using a tomographic regularized inversion. The 1°x1° checkerboard test with synthetic data shows good resolution coverage over the region. Preliminary results at 1.0 Hz and 5.0 Hz show a trend of lower Q estimates near the Gulf Coast region while the central Oklahoma part reveals a higher Q estimate. We expect to locate the boundaries for higher attenuating (low Q) Gulf-Coast region and other crustal structures by investigating the spatial variation of regional frequency dependent Lg attenuation.

Characterization of the Stress Field and Focal Mechanisms for Earthquake Source Physics and Fault Mechanics

Poster Session · Thursday 20 April ·

Analysis and Stress Modeling of the March 21, 2009 (M=4.8) and September 26, 2016 (M=4.3) Bombay Beach Earthquake Swarms

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From March 21, 2009 through April 9, 2009, an earthquake swarm occurred near Bombay Beach, which is located on the eastern side of the Salton Sea near the southern end of the San Andreas Fault. During this period, over 460 earthquakes were recorded, and the largest of which had a magnitude of 4.8. The M4.8 moment tensor solution showed left-lateral, strike-slip motion with a preferred nodal plane strike of N57E which is consistent with faults orthogonal to the San Andreas fault in this area. The 2009 swarm events were relocated using hypoDD and the SCEDC CVM. The seismicity consisted of two swarms, both striking about N57E, with dimensions of 4-6 km in length and 1 km in width, and the depth range was 2-8 km. The first swarm, to the northwest with M=4.8, seems to have triggered the second swarm (M=4.0) located 4km to the south-

east. The September 26, 2016 (M=4.3) swarm is oriented NE-SW and located to the southeast of the 2009 swarm. The M4.3 event exhibited left-lateral strike-slip motion along a nodal plane at N47E. Modeling stress changes and triggering with Coulomb 3.3 for the M=4.8 swarm shows minor stress changes to the southeast towards the second 2009 swarm, and possibly the 2016 swarm. These swarms illustrate possible book-shelf faulting associated with the extension of the Extra Fault Zone (EFZ) from the San Jacinto fault to the west of the Salton Sea to the San Andreas fault at Bombay Beach. In addition, published seismic reflection data in the Salton Sea area near Bombay Beach show NE trending, near-vertical dipping faults possibly resulting from a young pull-apart basin from the interaction of the San Andreas and other regional faults.

The State of Stress at Intermediate Scales

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The state of stress in the Earth's crust is a fundamental physical property that controls both engineered and natural systems. The stress field is the sum of several components: tectonic forces, the gravitational field, pore-pressure, local stress concentrations due to slip on faults, and dynamic stresses from earthquakes and earth tides. Tectonic forces act over the largest scales (up to 1000s of km), whereas gravitational forces act at smaller scales (up to 100s of km). Local stress concentrations and pore pressures generally contribute to the stress field at more local scales. The stress field is reasonably well known at the upper end of the scale by modeling plate boundary and mantle convection forces, and at the lower end of the scale by borehole measurements. In between these two scales, at 10s to 100s of km, plate scale models have too little detail and borehole measurements are often too sparse and reflect only the very local stress field.

We will present our latest results characterizing the state of stress in the Earth at scales relevant to local and regional applications such as natural and induced seismicity, wastewater disposal and CO2 storage, and hydro-fracking. Two important components of the state of stress are the orientation and magnitude of the stress tensor, and a measure of how close faults are to failure. We jointly invert seismic (body and surface waves) and gravity data for a self-consistent model of elastic moduli and density and use the model to calculate the contribution of local material heterogeneity to the total stress field. We then combine local and plate-scale contributions, using local indicators for calibration and ground-truth.

Relative P- and S-Wave Amplitudes at Close Stations near the San Jacinto Fault Zone Dictated by Focal-Mechanism

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The peak and relative amplitudes of P- and S-waves are dictated to some degree by the earthquake source focal mechanism, in addition to other source, site and path effects. In theory, seismic stations located close to the nodal planes record smaller P-wave amplitudes than non-nodal stations, while S-wave amplitudes differ and are largest near the nodal planes. Here, we explore differences in waveform characteristics created by sampling different parts of the focal sphere. We use data within 30 km of a relatively deep (7-9 km) left-lateral fault in southern California. This short ~5 km fault is conjugate to the primary right-lateral trending faults in the region, orienting perpendicular (fault strike of ~50°) to the San Jacinto Fault. We focus on 25 events along this fault that occurred between 2001-2007, which belong to the same cluster when relocated by Hauksson *et al.*, 2012. We track the peak absolute velocities of vertical, radial and transverse recordings, for both the P-wave and the S-wave individually. Using ANZA network data, we find, as expected, that at a given station larger magnitude quakes produce larger amplitude waveforms and that stations RDM and KNW at ~30 km from the fault record similar amplitudes. However, two stations both located ~5 km from the fault produce vastly different peak ground velocities (PGVs). Station FRD (at an azimuth 32° counter clockwise from fault strike), records much smaller PGVs than station BZN (azimuth 102° counter clockwise from fault strike). At station BZN the radial component consistently produces the largest PGVs, whereas the vertical component PGVs are the largest at station FRD. We attribute these differences to sampling different parts the focal sphere, and suggest that these types of observations can be incorporated into site-specific seismic hazard estimates to devise a more informed focal mechanism or rupture directivity correction factor in regions where strike-slip faults are the dominant fault structures.

Seismotectonic Setting of the Marmara Segment of the North Anatolian Fault Zone from Local Stress Inversion Based on a Refined High Precision Hypocenter Catalogue (2006-2016)

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The Sea of Marmara (SoM) is located towards the western end of the North Anatolian Fault Zone (NAFZ), Turkey. Here the fault has forked into several branches hosting clusters of seismic activity in which normal as well as right-lateral strike-slip faulting mechanisms have been observed. The northern branch of the western NAFZ lies under the SoM and it is an ongoing debate whether this segment in the direct vicinity of the Istanbul metropolitan area represents a single through-going strike-slip fault capable of hosting an up to M_w 7.4 earthquake in the near future or rather decomposes into a segmented transtensional pull-apart environment.

We here present results on the local stress field orientation calculated from direct inversions of first-motion polarities associated to 2700 seismic events obtained from the analysis of a decade of seismic data (2006-2016) recorded by four permanent seismic networks around the SoM.

We employ a largely automatized processing scheme. P- and S-phase readings were automatically determined using higher order statistics, polarization analysis and the Akaike Information Criterion (AIC). An iterative travel-time inversion rejects outlying phase readings while attempting to retain as much information as possible in order to maximize the coverage of the focal sphere.

Nevertheless, the large network aperture with lacking permanent stations immediately above the fault prevents the calculation of well-constrained individual focal mechanisms for the majority of events. We therefore employ the MOTSI inversion code (Abers and Gephart, 2001) allowing the stress field inversion directly from first motion polarity readings.

A density-based clustering approach breaks the distribution of epicenters into nested and overlapping seismicity clusters allowing to test for the hypothesis of stress homogeneity for most of the seismically active strands of this key segment of the NAFZ and to identify their current state of stress.

Analysis of In-Situ Stress during EGS Development at The Geysers Geothermal Field, California

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We have developed a seismic moment tensor and focal mechanism catalog for seismicity at the Enhanced Geothermal System (EGS) study area at The Geysers geothermal field in northern California. The catalog consists of 168 events with M_w ranging from 0.7 to 3.8 and is sufficient for use in temporal inversions for the stress tensor and to investigate possible temporal changes resulting from the fluid injection. Two approaches to invert for the stress tensor (Martinez-Garzon *et al.*, 2014; Vavrycuk, 2014) have been used in this analysis. The results demonstrate the quality of the seismic moment tensor catalog through the relatively small uncertainties in the recovered stress tensors. We find that there is an approximate 15-degree counterclockwise rotation of sigma 3 and a rotation of sigma 1 toward the vertical as the injected volume of water increased. The magnitude of these rotations is consistent with other nearby empirical observations (Martinez-Garzon *et al.*, 2013) and thermo-hydromechanical simulation results (Jeanne *et al.*, 2015). We find that there is a systematic reduction in the stress shape factor, R, as injected volume increases, indicating an evolution toward a more tensile stress state.

Microseismic Event Relocation Based on PageRank Linkage at the Newberry Volcano Geothermal Site

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The Newberry Volcano has been stimulated two times using high-pressure fluid injection to study Enhanced Geothermal Systems technology. Several hundred microseismic events were generated during the first stimulation in the fall of 2012, showing events in two distinct depth ranges where microseismicity does not clearly outline subsurface structures due to large event location uncertainties (Foulger and Julian, 2013). From this stimulation we explore the spatial and temporal development of microseismicity, which is key to understanding how it modifies stress, fractures rock, and increases permeability. We use an application of Google's PageRank (Aguiar and Beroza, 2014) to assess signal-correlation topology for the micro-earthquakes. We create signal families and compare these to the spatial and temporal proximity of associated earthquakes. We relocate events within families using the Bayesloc approach (Myers *et al.*, 2007) which show tight spatial clustering of event families, as well as changes in cluster affiliation for some events. We also find that signal similarity (linkage) at several stations, not just one or two, is needed in order to confidently determine that events are in close proximity to one another, suggesting the importance of good seismic station coverage. We show that indirect linkage of signals using PageRank is a reliable way to increase the number of events confidently determined to be similar to one another, suggesting an efficient and effective grouping of earthquakes with similar physical characteristics (ie. location, focal mechanism, stress drop). We will apply this analysis to the stimulation performed in 2014 and compare the results to clusters found in the initial stimulation. This will allow us to determine whether changes in the state of stress and/or changes in the generation of subsurface fracture networks can be detected using PageRank topology as well as aid in the event relocation to obtain more accurate subsurface structure.

Characterizing Recent Northern Walker Lane Earthquake Sequences: Complexities in Geometry and Source Processes

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Recent earthquake sequences in the Northern Walker Lane (northern Nevada and northeastern California) have caught the attention of the general public and the scientific community. Our aim is to understand this seismicity and the complexities of local earthquake sequences, specifically their structures and source properties, to determine seismic hazard implications. We use GrowClust (Trugman *et al.*, 2016) to compute relative relocations of four recent sequences: Thomas Creek (202 events; 2015-2016; largest event = M_w 4.3); Herlong (260 events; 2016; largest event = M_w 4.5); Virginia City (429 events; 2010-2016; largest event = ML 3.2); and Carson City (149 events; 2012-2015; largest event = ML 2.9). Relocation results for each sequence show well-defined primary fault structures with additional and more complex off-fault structures. HASH (Hardebeck and Shearer, 2002) short-period focal mechanisms help constrain structures and their orientations at depth. Additionally, we compile measurements of stress drop for the larger events, in each sequence. These help characterize Reno urban seismicity and supplement results from analysis of Mogul earthquake stress drops (a shallow swarm in 2008 in the west Reno urban area; Ruhl *et al.*, 2016, presentation at this meeting) to provide input to ground motion models. Preliminary results of the stress drop measurements for the Thomas Creek sequence and the Herlong sequence show average stress drops of 15 MPa and 24 MPa respectively. Of the events tested, 67% do not fit the simple circular source model, and show evidence of complex ruptures.

Conveying Uncertainties of Focal Mechanism Parameters on Focal Spheres: Probability Densities of Compressional and Tensional Axes

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Focal mechanisms provide a summary of fault orientation and slip during a particular earthquake but uncertainties with focal mechanism parameters are not easily conveyed on a map. Computing a focal mechanism for a small-to-moderate magnitude earthquake from first motions and amplitude ratios usually produces a set of nodal planes that fit the observations equally well. To extract useful information about tectonic processes, it is therefore important to characterize the set of solutions in terms of a probability density distribution. However, a distribution of nodal planes cannot be summarized neatly on a focal sphere. A distribution of compressional (P) and tensional (T) axes can be presented on focal sphere and placed on a map. A catalog of earthquakes can be compared readily to see which orientations of the axes are compatible with some or all of the earthquakes and which orientations are not admissible.

The Kamb method, typically used in fracture analysis, was adapted to plot densities of the multiple P and T axes calculated from each possible fault plane for each focal mechanism. Density distributions are plotted on focal spheres to facilitate tectonic interpretations and to provide information concerning parameter uncertainties that would need to be satisfied in a formal stress inversion.

We applied this new method to intermediate-depth earthquakes in the Northeast Caribbean. Acceptable fault planes for 30 events with focal depths of 50 km to 180 km and magnitudes larger than 3.8 were calculated using the program HASH. P and T axes were then determined for hundreds of fault planes per earthquake and the densities of axes were plotted. The mechanisms of these intermediate-depth events are consistent with north-south oriented compression, which points to the collision of Hispaniola with the Bahamas Platform as the most likely cause. Surface and body-wave tomography are underway to elucidate the relationships of P and T axes in intermediate-depth earthquakes.

Understanding Resolution and Uncertainties of Stress Drops of Repeating Earthquakes at Parkfield

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Earthquake stress drop is an important parameter that directly link to ground motion predictions and earthquake source physics. Estimating stress drop from corner frequency is superficially easy but subject to significant uncertainty. In the Parkfield segment, Abercrombie [2014] analyzed three repeating clusters, and found that the sampling rate and source complexity significantly affect the reliability of source parameters. Specifically speaking, low sampling rate from the surface stations is insufficient to resolve corner frequencies for small earthquakes when the corner frequency is beyond the Nyquist frequency. In this study, we aim at resolving the uncertainty in source parameters systematically by comparing results from stacking methods that averaging over many event-station pairs, and results from individual pair analysis methods that look into details for each earthquakes.

We begin with the double-difference catalog in Northern California, and a catalog of repeating earthquakes. Then we search for suitable EGF events for each repeating cluster. Our current analysis is focused on two selected clusters that have wide magnitude range (from 0 to 3), including a repeating sequence extends from 1 to 2, that are recorded on both borehole network (sampling rate of 250 Hz) and surface network (sampling rate of 100 Hz). We will apply both improved stacking analysis methods and individual pair analysis to the selected clusters, and systematically assess their consistency and difference. Updated results will be reported at SSA meeting.

Earthquake Complexities Revealed by Kinematic and Dynamic Modeling and Multiple Geophysical Data Sets

Poster Session · Thursday 20 April ·

Mach Wave Coherence in the Presence of Source and Medium Heterogeneity

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We investigate Mach wave coherence for heterogeneous kinematic supershear ruptures embedded in 3D random media, considering: 1) source heterogeneity specified in terms of spatial variations in slip, rise time and rupture speed; 2) medium heterogeneity parameterized as combinations of three correlation lengths and two standard deviations assuming a von Karman autocorrelation function with fixed Hurst exponent (H = 0.2); 3) source and medium heterogeneities jointly. Ground-motion simulations are performed by solving the elastodynamic equations of motions using a generalized finite-difference method, such that the maximum resolved frequency is ~5 Hz.

We discover that Mach wave coherence is diminished in near fault distances (< 10 km) due to source heterogeneities. Beyond this distance, Mach wave coherence is predominantly affected by wavefield scattering due to small-scale heterogeneities in Earth structure. Based on our numerical simulations and a theoretical derivation we demonstrate that the standard deviation of the medium heterogeneities controls the wavefield scattering, rather than the correlation lengths in case of small Hurst exponent (H< 0.2). In addition, we find that peak ground accelerations for combined source and medium heterogeneities are consistent with empirical ground motion prediction equations for all distances, suggesting that observed ground shaking amplitudes for supershear ruptures are not elevated due to complexities in the rupture process and seismic wave-scattering. Based on our simulations, we speculate that local super-shear ruptures may be more common in nature then reported, but are very difficult to detect due to the strong seismic scattering.

The Spatial Interdependence of Kinematic Rupture Parameters as Evidenced by Dynamic Ruptures on Rough Faults

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We investigate correlations between different kinematic parameters of earthquake rupture, namely slip, rise-time (total duration of slip), acceleration time (time-to-peak slip velocity), peak slip velocity, and rupture velocity. We extract these parameters from dynamic rupture models generated by simulations of spontaneous rupture on faults with varying degree of surface-roughness. In general, we observe that the spatial interdependences between these parameters are better described by non-linear correlations (that is, on logarithm-logarithm scale) instead of linear ones. Slip and rise-time are positively correlated, while these two parameters are seen uncorrelated with acceleration time, peak slip velocity, and rupture velocity. On the other hand, peak slip velocity correlates positively with rupture velocity, but negatively with acceleration time. Acceleration time correlates negatively with rupture velocity. However, the observed correlations could be attributed to weak heterogeneity of the slip distributions of the rough-fault dynamic models used in this study. Therefore, the spatial interdependences could be specific to the parts of rupture plane with weak slip heterogeneity if an earthquake-rupture associate highly heterogeneous slip distributions as given by the source inversions. Our findings will help to improve pseudo-dynamic rupture generators for efficient broadband ground-motion simulations for seismic hazard studies.

Complex Slip Distributions on Complex Fault Geometries

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The frequencies of waves radiated by an earthquake, above the corner frequency, are linked to the heterogeneities of the geometry of the fault or the complexity of the rupture process. The variations of geometry have a wide spectrum from the bend of a subduction zone up to the roughness observed on fault scarps. On the other hand, if the accepted seismic radiation model is an omega square, then it is demonstrated that a self affine distribution of the slip on a simple fault is sufficient to explain this behavior. Often one of two end-member approaches are taken: the complexity is introduced through a rough geometry with a simple rupture process or through a rough rupture process on a simple geometry. The scope of this study is to present a strategy to apply a complex, but organized rupture process (*e.g.* a slip distribution with a k-2 spectra) on a complex fault geometry (*e.g.* a complex slab). This strategy relies on a geodesic distance matrix computed on the fault surface and using it with a composite source methodology. We evaluate this technique comparing our results with analytical solutions for specific cases. An example of complex rupture process is also presented on a realistic fault geometry.

Dynamic Models of Earthquake Rupture along Branch Faults of the Eastern San Gorgonio Pass Region in CA Using Complex Fault Structure

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Compilation of geomorphic and paleoseismic data have illustrated that the right-lateral Coachella segment of the southern San Andreas Fault is past its average recurrence time period. On its western edge, this fault segment is split into two branches: the Mission Creek and the Banning fault strands of the San Andreas. Depending on how rupture propagates through this region, there is the possibility of a through-going rupture that could lead to the channeling of damaging seismic energy into the Los Angeles Basin. The fault structures and rupture scenarios on these two strands are potentially very different, so it is important to determine which strand is a more likely rupture path, and under which circumstances rupture will take either one. In this study, we focus on the effect of different assumptions about fault geometry on the rupture process to test those scenarios and thus investigate the most likely path of a rupture that starts on the Coachella segment. We import the geologic map from the SCEC Community Fault Model version 4.0 to define the geometry of the faults and create a 3D finite element mesh. This mesh is then incorporated into the finite element method code FaultMod to compute a physical model for the rupture dynamics. We use the slip-weakening friction law, and we consider different assumptions of background stress such as constant tractions, regional stress regimes, and the results of long-term stressing rates from quasi-static crustal deformation models that consider time since last event on each fault segment. Preliminary results from the constant stress distribution show that it is easier for the rupture to jump to Mission Creek compared to the Banning fault segment. However, for the regional stress distribution, we encounter cases where the rupture jumps on both the Mission Creek and Banning faults. The fault connectivity at this branch system seems to have a significant impact on whether a through-going rupture is more likely to occur or not.

Modeling Earthquake Rupture and Corresponding Tsunamis along a Segment of the Alaskan-Aleutian Megathrust

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Motivated by the 2011 M_w 9 Tohoku-Oki event, we explore the effects of realistic fault dynamics on slip, free surface deformation, and the resulting tsunami generation and local propagation from a hypothetical M_w 9 megathrust earthquake along the Alaskan-Aleutian (A-A) Megathrust. Firstly, we demonstrate three scenarios: a spatially-homogenous prestress and frictional parameter model and two models with rate-strengthening-like friction (*e.g.*, Dieterich, 1992). We use the 3D finite element method (Duan and Oglesby, 2006; Barall, 2009) and time-weakening friction (Andrews, 2004) to dynamically model the rupture and slip process along a portion of the A-A subduction zone. Given geometric, material, and plate-coupling data along the A-A megathrust assembled from the Science Application for Risk Reduction (SAFRR) team (*e.g.*, Bruns *et al.*, 1987; Hayes *et al.*, 2012; Johnson *et al.*, 2004; Santini *et al.*, 2003; Wells at al., 2003), we are able to inform our dynamic rupture models. Adding frictional-strengthening to a region of the fault reduces both average slip and free surface displacement above the strengthening zone, with the magnitude of the reductions depending on the strengthening zone location. Secondly, we incorporate random prestress distributions (Andrews and Ma, 2016) to examine effects on slip and sea floor displacement. Preliminary models are qualitatively similar to the homogeneous scenario in that they produce relatively smooth slip distributions weighted updip. Corresponding tsunami models, which use a finite difference method to solve the long-wave equations (*e.g.*, Shuto, 1991; Satake, 2002), match sea floor displacement, in time, to the free surface displacement from the rupture models. Tsunami models show differences in local peak amplitudes and beaming patterns between the different slip distributions. Given these results, other heterogeneous parameterizations, with respect to prestress, friction, and fault geometry, still need to be examined.

Simulating Impacts of Rupture Variability on Near-Fault Strong Motions

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Observations from past earthquakes demonstrate that the rupture process can be complex, exhibiting significant spatial variations in rupture speed, slip and slip rate, as well as geometric roughness of the faulting surface. Incorporating these features within kinematic ground motion simulations is challenging due to uncertainty in the expected ranges and potential inter-correlations of the required parameters. Here, I calculate a suite of broadband ground motion simulations for the 1989 Loma Prieta earthquake to help constrain appropriate ranges for key rupture parameters. The simulated motions are computed using the Graves and Pitarka (2010) method and are compared with near-fault ($R < 40$ km) recorded motions using the validation criteria described by Goulet et al (2015). A total of 240 rupture scenarios are examined, with individual scenarios consisting of random realizations generated using the approach of Graves and Pitarka (2016). In addition to spatial variability in slip and fault roughness, each realization randomly samples from uniform distributions of slip standard deviation (expressed as coefficient of variation, S_{cov}), average rupture speed (expressed as fraction of local shear wave velocity, V_r/V_s), down-dip fault width (F_{wid}) and moment magnitude (M_w). I find the results with smallest misfit tend to be for ruptures with S_{cov} ~ 0.75-0.85, F_{wid} ~ 16-18 km, V_r/V_s ~ 0.81-0.84, and M_w ~ 6.96-7.00. However, the results exhibit significant scatter and there are various combinations of parameters across the specified ranges that can produce equally good (and equally poor) fits to the observations. These results reinforce the importance of adequately sampling ranges of rupture parameters when performing validations with past earthquakes, as well as when simulating ground motions for future events.

Strong Motion Simulation of the 2016 Kumamoto Earthquake (Mw7.0) Using Pseudo Point-Source Model and Empirical Green's Functions

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The pseudo point-source model (Nozu, 2012) approximates rupture process on the faults with multiple point sources for simulating strong motions. Waveforms are synthesized by combining the source model with path spectrum, empirical site amplification factor, and empirical phase characteristics. This method has been validated by simulating earthquakes such as 2011 Tohoku earthquake.

The 2016 Kumamoto earthquake, occurred on April 16, 2016, with M_w 7.0. Large surface ruptures appeared due to the earthquake and some records in the northeast of the hypocenter were considered affected by rupture directivity. In fact, some source process analyses indicate that the rupture proceeded mainly northeast from the hypocenter. In this study, a strong motion model was developed and the generation mechanism of the strong motions and the applicability of the pseudo point-source model for the large earthquake were investigated.

Parameters of the simulation were determined by forward modeling. As a result, three subevents (point sources) were placed on a fault plane. Synthetic Fourier spectra and velocity waveforms generally explained the main features of the observed records except for underestimation in the low-frequency range. The underestimation is presumably due to following two reasons. One is that the pseudo point-source model does not simulate crustal deformation, or fling steps. Another reason is that the current version of the pseudo point-source model does not consider the rupture directivity effect. Consequently, strong pulses were not reproduced enough at stations northeast of the hypocenter, where the effect of rupture directivity was significant, while the amplitude was well reproduced at most of the other stations. This result indicates the necessity for improving the pseudo point-source model so that it can simulate fling steps, and incorporate the effect of rupture directivity by, for example, introducing azimuth-dependent corner frequency.

Joint Inversion of Continuous GPS, InSAR and Seismicity Data to Constrain the Spatiotemporal Evolution of Strain Release of the 2016 Kumamoto Earthquake Sequence: Implications for the Shallow Slip Deficit and the Role of Aseismic Slip

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Estimates of coseismic slip at depth from finite-fault inversions provide important information about faulting mechanics, and empirical constraints for dynamic rupture simulations. However, due to the lack of spatially dense and temporally continuous geodetic data it has been difficult to assess reliably i) whether large ruptures typically exhibit a deficit of shallow slip (where lack of near-field surface data in finite-fault inversions has been shown to bias and significantly underestimate shallow slip, Xu *et al.*, 2016), and ii) whether shallow slip primarily occurs co- or post-seismically. Here we investigate the spatiotemporal evolution of strain release during the 2016 Kumamoto sequence, Japan, that was composed of a prolonged foreshock sequence followed by a M_w 7.0 mainshock. We jointly invert for fault slip using Sentinel 1 and ALOS-2 InSAR InSAR timeseries and pixel-tracking, 170 continuous GPS stations that provide dense spatial and temporal coverage of surface motion, and optical image correlation results which capture details of the near-field surface deformation pattern. We filter the GPS data using principal component analysis which allows for detection of subtle ground motion, revealing a significant aseismic slip transient that preceded the mainshock. We find this spatiotemporal filtering approach helps significantly improve constraints on the magnitude and spatial distribution of slip at depth and gives better insight into the contribution of aseismic slip to the overall slip budget. We also present preliminary results using relocated seismicity and the network inversion filter of Bekaert *et al*. (2016 JGR) inverting GPS and InSAR, to further constrain the migrating pattern of aseismic strain release. Understanding whether ruptures exhibit a shallow slip deficit holds significance for how strain is released through the seismic cycle, and allows for generating realistic synthetic rupture simulations important for hazard analysis.

Finite Rupture Process and Ground Shaking of the 2014 Mw5.1 La Habra Earthquake

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The chances for medium size (M5-6) earthquakes occurring in urban areas are much larger than that for the more damaging events. Nonetheless, such events are big enough to produce meaningful strong ground shaking observations that are useful in preparing for the future larger events (*e.g.* M>7). The 2014 M_w5.1 La Habra earthquake in LA basin is such an event that has been well recorded by both the strong motion network and InSAR observations. Eight strong motion recordings were obtained within 10 km epicentral distance with the largest peak ground acceleration and velocity being 687 cm/s/s and 32 cm/s. InSAR observations were obtained with two look directions, roughly east and west, from the COSMO-SkyMed and TerraSAR-X satellites. Combining strong motion and InSAR observations in the inversion can provide better constraints on the finite rupture process of the earthquake because of the complementary temporal and spatial coverage of these datasets. The trade-off between slip distribution and other source parameters can be reduced in the joint inversion, which is of particular importance for medium size earthquakes due to their limited rupture dimension. Our joint inversion of eight nearby strong motion stations and two satellite InSAR images results in a bilateral rupture within a zone having dimensions of 6km along strike and 2km down dip, and centered 5km depth. This depth is consistent with the centroid depth obtained by long period focal mechanism inversion and the along strike rupture dimension also agrees with that defined by the aftershocks. The average rupture speed obtained by joint inversion is about 1.5 km/s and most of the moment was released in the first 2 s. The peak slip amplitude is about 30cm, with average risetime of ~0.3s, corresponding to average slip rate of ~1 m/s.

Three-Dimensional Multi-Episode Directivity Analysis for Complex Ruptures

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Rupture properties, such as rupture direction, length, propagation speed and source duration, provide important insights into earthquake dynamics, and one approach to estimate these properties is to investigate the rupture directivity effect using the body-wave duration measurements. The earthquake directivity effect is often treated in two dimensions, *i.e.*, horizontal or a pre-defined fault plane, with the unilateral rupture assumption, which is insufficient if multiple faults are involved or rupture propagates in different directions.

In order to resolve earthquake complexities, we implement the directivity analysis in three dimensions and expand its framework to include multiple episodes. This new approach is first used to demonstrate that the conventional two-dimensional analysis can considerably bias the rupture parameters. The multi-episode formulation shows that directivity effect of complex ruptures needs to be studied with caution, *e.g.*, the shortest observed duration cannot be used to identify the rupture direction, and averaging duration measurements leads to an overestimated source duration.

Based upon the new framework, we introduce an optimization scheme to obtain the timing and the three-dimensional locations of multiple episodes, and apply the technique to a deep-focus event in the Sea of Okhotsk region, an M_w 8.3 event from 2013 May 24. The duration measurements show significant deviation from a simple sinusoidal pattern associated with the unilateral propagation, indicating that the unilateral rupture cannot explain the data. When the multi-episode analysis is applied, two propagation directions are obtained, one towards the southwest and another towards southeast that occur at similar times, during the first 33 seconds of the event. The two-episode model gives a better fit to the data than the unilateral model, and is compatible with our back-projection analysis, demonstrating that the rupture propagation of this event is complex.

Investigation of Back-Projection Uncertainties with M6 Earthquakes

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Back-projection is one of the primary tools to investigate large earthquake rupture propagation. Because the method makes few prior assumptions, back-projection can resolve complex earthquake behavior, such as variable rupture velocity, multiple events, frequency-dependent radiation, and very early aftershocks. However, quantifying back-projection image uncertainties is important because biased energy burst locations may lead to erroneous interpretations of rupture physics. Constraining the uncertainties is challenging because back-projection relies on stacking instead of optimizing a misfit function. Therefore, special care must be taken to avoid imaging artifacts. The robustness of back-projection images is often assessed using synthetic tests, resampling of the data, or back-projection of smaller events near the mainshock of interest. One issue for large earthquakes is the degree to which empirical timing corrections for the epicenter computed from the initial P-wave arrival are applicable to other parts of the rupture. We have begun exploring back-projection resolution by imaging M6 earthquakes within the Japan subduction zone. By studying the spatial correlation lengths among the timing corrections for these events, and by imaging events using timing corrections derived from other events, we can quantify how much the stacking incoherence grows as a function of epicentral distance for large ruptures and estimate limits on the spatial resolution of the images. These results will vary both with the array geometry (regional versus global) and with the frequency content. Systematic investigation of the resolution limits will provide guidelines for interpreting back-projection results in the region. We hope to be able to quantitatively evaluate current back-projection source models as a basis for obtaining robust kinematic source parameters.

Earthquake Geology and Paleoseismic Studies of the Intermountain West: New Methods and Findings on Seismic Hazard Characterization of Low Slip Rate Faults

Poster Session · Thursday 20 April ·

Characterizing the Quaternary Expression of Active Faulting along the Olinghouse, Carson, and Wabuska Lineaments of the Walker Lane

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The Walker Lane accommodates a significant portion of the dextral motion along the North American-Pacific transform plate boundary. It is a structurally complex zone composed of northwest-trending right-lateral, north-trending normal, and northeast trending left-lateral faults and lineaments. In the vicinity of Reno to Hawthorne, NV, the Walker Lane accommodates 5-7 mm/yr of northwest directed dextral shear in the absence of right-lateral strike-slip faults. Previous studies have suggested that left-lateral slip on the northeast striking Olinghouse, Carson, and Wabuska lineaments is accommodating dextral shear through the clockwise rotation of intervening crustal blocks. Observations from newly acquired lidar data (0.5 m/pixel) combined with low sun-angle aerial photography and observations from previous studies show the presence of late Pleistocene-Holocene faulting along each of these lineaments. Fault scarps along the Carson and Wabuska lineaments are discontinuous and sparse, and show evidence for left-lateral faulting, evident by linear fault traces, alternating scarp face directions, and lateral offsets of small gullies and ridges within late Pleistocene alluvium along the Carson lineament, and Holocene alluvium along the Wabuska. The trends of the scarps that define these lineaments also appear to link at their western ends with north trending normal faults. In this manner, it appears that the 5-7 mm/yr of slip taking place across the Walker Lane at this latitude is being accommodated by the combined processes of basin opening in the west and block rotation to the east. This mode of slip transfer differs from the Excelsior Domain of the Central Walker Lane that also exhibits east trending left-lateral faulting, where Walker Lane slip is transferred to the east, in the form of a right step, from the right-lateral faults of the southern Walker Lane to the right-lateral faults of the central Walker Lane.

Insights into the Seismogenic Relation between the West Valley and Wasatch Fault Zones, Utah—New Data from the Airport East Trench Site

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The intrabasin West Valley fault zone (WVFZ) in Salt Lake Valley, Utah, is antithetic to the range-bounding Wasatch fault zone (WFZ) to the east. The WVFZ comprises two subparallel main strands which, along with their associated subsidiary strands, are known as the Granger fault (western strands) and Taylorsville fault (eastern strands). To better characterize the WVFZ earthquake chronology and improve our understanding of the mechanical interaction between the WVFZ and WFZ, we conducted a fault-trench investigation at the Airport East site on the Taylorsville fault. Our trenches revealed stratigraphic and structural evidence for three surface-faulting earthquakes on the Taylorsville fault, as well as earthquake-related deformation (local folding and liquefaction) in a fourth event that may or may not have resulted from slip on the Taylorsville fault. Radiocarbon and optically stimulated luminescence ages provide temporal constraints on earthquake timing, which was probabilistically modeled using OxCal software. Our preliminary modeling indicates the surface-faulting earthquakes occurred at ~ 0.4, 0.6, and 2.1 ka, and the liquefaction event occurred at ~ 5.1 ka. Comparing these earthquake times ($\pm 2\sigma$) with the existing Granger fault and WFZ chronologies yields the following observations: (1) the three dated Taylorsville-fault earthquakes do not correlate with any known Granger-fault earthquakes, but the 2.1 and 0.6 ka earthquakes have very similar timing to earthquakes on the adjacent Salt Lake City and nearby Weber segments, respectively, of the WFZ; (2) timing of the liquefaction event at 5.1 ka is very similar to that of earthquakes on the Granger fault and Salt Lake City segment; and (3) six of eight dated WVFZ earthquakes have very similar timing to earthquakes on the Salt Lake City and Weber segments. Our preliminary results support the hypothesis that slip on the WVFZ occurs largely in response to slip on the WFZ, and independent WVFZ earthquakes are rare.

Refining the Rupture Length of the MRE and Timing of the Penultimate Earthquake along the Simpson Park Mountains Fault, Central Great Basin Nevada

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The Simpson Park Mountains fault in the central Great Basin is a low slip rate fault that accommodates long-term Basin and Range extension and is clearly expressed along the southeastern margin of Grass Valley, Nevada. Geomorphic evidence of active late Quaternary deformation is expressed along the entire length of the fault, including prominent scarps, springs, vegetation lineaments, over-steepened mountain-front facets, and greater amounts of offset along progressively older deposits. Measured offsets and the relative age of faulted deposits suggest a poorly constrained extension rate of ~0.12 mm/yr.

A paleoseismic trench study was conducted at a site ~4 km north of Walti Hot Springs across a 1.8-m-high scarp and indicates the occurrence of two earthquakes. The trench spans a recessional shoreline of pluvial lake Gilbert and exposed a penultimate colluvium, overlain by near-shore pluvial deposits and beach gravels. The offset shoreline is lower than the high stand of Lake Gilbert, which may correlate to the timing of the high stand of Lake Lahontan, suggesting that the MRE postdates 13 ka. Diffusion analyses of a scarp profile surveyed across the scarp suggests that the MRE occurred around 6.5 ka. The penultimate event occurred prior to the high stand of Lake Gilbert and prior to the accumulation of carbonate in the penultimate colluvium, suggesting a long inter-event time.

Here, I present new observations on the length of the Holocene earthquake identified in the trench based on analyses of orthorectified photomosaics and field work. Ongoing analyses of optically stimulated luminescence samples will provide dates to estimate the age of the penultimate colluvium and provide constraints on recurrence interval. The combined observations will contribute to a better characterization of paleoseismic parameters and improve seismic hazard characterization.

Kinematic Observations of the Manastash Ridge and Boylston Ridge; Implications for Connectivity between Primary Structures in the Yakima Fold and Thrust Province, Washington

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Formation of the Yakima Fold and Thrust (YFT) province is due to north-directed contraction in the back-arc of the Cascadia Subduction Zone (CSZ). Geodetic and paleomagnetic data indicate that the CSZ is deforming in response to clockwise rotation of the Pacific Northwest. This model predicts differential rates of motion between the forearc and the back-arc, suggesting that the forearc and back-arc are accommodating a complex pattern of deformation across the arc. Multiple fault orientations are expected to accommodate this deformation in the YFT. We present field evidence from the Manastash range front and the adjacent Kittitas Valley to the north that indicate multiple fault orientations are accommodating regional strain: 1) a primary set of left-stepping, west-northwest striking thrust faults associated with growth of the Manastash anticline; and 2) a secondary set of shorter strike-slip faults orthogonal to the primary faults. Aeromagnetic, Quaternary geologic mapping and LiDAR mapping of the Manastash range front document the primary frontal fault, which is observed for ~25km along the range front. In addition, LiDAR scarp analysis and aeromagnetic data of the Manastash Ridge and Boylston Ridge area to the northeast delineate several north-northeast striking secondary faults. We postulate that these shorter orthogonal faults in the Kittitas Valley transfer slip between the primary thrust structures associated with Boylston Ridge/Saddle Mountains and the Manastash Ridge. Furthermore, kinematics of these multiple fault systems suggest a component of wrenching within the YFT province.

A Decade of USGS Seismic Monitoring of the Teton Fault

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The USGS has been operating a digital broadband and strong motion seismic network (IW) in the vicinity of the Teton Fault in Western Wyoming for more than a decade, and prior to this, the U.S. Bureau of Reclamation operated an analog short-period network. The Teton Fault is an east dipping normal fault located within the seismically active Intermountain Seismic Belt. Observed seismicity rates on or near the Teton Fault have been noted to be relatively low compared to what would be expected from the paleoseismologically derived recurrence rates. We address whether the observed seismicity rates are accurate or potentially biased by network detection thresholds, instrument failures, station noise, data availability, or earthquake detection and reporting. We examine the potential impacts of these biases on seismically derived recurrence rates for the Teton Fault. For example, if several stations in the IW network are down some events could go undetected causing the seismicity rates to appear lower for the Teton Fault. We use an automatic phase identification system and event associator to examine microseismicity within the region and compare those results to the theoretical capabilities of the IW network. We examine the performance and capabilities of the IW network and how those capabilities may impact observed seismicity rates within the area around the Teton Fault.

Earthquakes and Tsunamis

Poster Session · Thursday 20 April ·

Caribbean Regional Tsunami Early Warning Using W-Phase Source Inversion

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Puerto Rico and the Virgin Islands are located in the Northeastern Caribbean, a seismically active zone. The historical records show that large damaging earthquakes occurred in 1867 (M 7.3), 1918 (M 7.3) and 1943 (M 7.5). At least two of these earthquakes generated tsunamis. Consequently, determining timely and accurate source parameters of an earthquake: location, magnitude and fault geometry, is key for tsunami warning purposes. The W-phase source inversion method takes advantage of the very long period (100–1000s) signal and arrival times between the P and the S-waves to provide a rapid and robust determination of the source parameters for moderate to large earthquakes in teleseismic and regional distances. The purpose of this work is to investigate the applicability of the W-phase source inversion to earthquakes with magnitude equal or greater than 6.0 in the Caribbean region using data from regional broadband instruments from the CARIBE-EWS virtual network. The CARIBE-EWS is an Intergovernmental Coordination Group for Tsunami and other Coastal Hazards Warning System for the Caribbean and Adjacent Regions that was established in 2005 as a body of the IOC-UNESCO to provide efficient assistance on tsunami risk reduction. With this purpose, we focus our research in five events: 2007, Cuba (M_w=6.2), 2009, Honduras (M_w=7.3), 2014, Puerto Rico (M_w=6.4), 2015, Panamá (M_w=6.5) and the recent 2016, El Salvador (M_w=7.0) and simulate real time operations by computing a solution available 14 min. after the origin time. For validation purposes, the inversion results are systematically compared with the ones published in the Global CMT project (GCMT). Based on the consistency of the results, and after a detailed revision of the station metadata, we conclude that the method is suitable to be implemented into the CARIBE-EWS. It is recommended to review the latency, delays and dropouts of data from the stations contributing data to the virtual network.

Tsunamis Obey Snell's Law: Simulations and Real Data

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We study the effect of a wide continental shelf at the receiver end of a far-field tsunami, by using conventional seismic beaming techniques across arrays of receivers, in order to define a two-dimensional slowness vector expressing the phase velocity of the tsunami and its azimuth of passage over the array.

In the Pacific Ocean, we first target two wide shelves fronting the Alaska Panhandle and Central America, and simulate tsunamis based on recent events in Chile and Japan, across arrays of several hundred virtual gauges located both on the shelves and in the nearby abyssal plains.

In all cases, we recover phase velocities compatible with their values expected under the Shallow Water Approximation (160-185 m/s in deep water and 30-40 m/s on the shelf), while the azimuths of arrival show severe refraction (of up to 55 degrees) between the two environments. The resulting ray parameters ($p = \sin i / v$) are found to vary by less than 20%, and thus to verify Snell's law, despite the grossly simplified model of a linear continental shelf break separating two homogeneous media.

We also apply this approach to real data recorded by ad hoc arrays of hydrophones operated as part of temporary OBS/OBH deployments during the past ten years in various coastal and abyssal areas of the Pacific Basin.

Fault Mechanics and Rupture Characteristics from Surface Deformation

Poster Session · Thursday 20 April ·

Spatial Distribution of Surface Displacements in the 1983 M 6.9 Borah Peak Earthquake and Prehistoric Ruptures of the Warm Springs and Thousand Springs Sections of the Lost River Fault Zone

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The 1983 M 6.9 Borah Peak earthquake ruptured ~36 km of the 130-km-long multisegment Lost River fault zone (LRFZ) in central Idaho. Normal-faulting surface rupture occurred on (1) the entire 24-km-long Thousand Springs section, (2) the southern 8 km of the 16-km-long Warm Springs section to the north, and (3) a ~4 km-long fault splay that branches 50° from the main trace of the LRFZ. Rupture of the fault splay continues into the Willow Creek hills, a prominent bedrock ridge that forms a structural boundary between the Thousand Springs and Warm Springs sections. To improve our understanding of the 1983 rupture and the role of structural complexities along normal fault systems in arresting laterally propagating ruptures, we acquired low-altitude aerial imagery using unmanned aircraft systems to generate high-resolution (5–10-cm-pixel) digital surface models. From this dataset, we measured vertical surface offsets across both 1983 and prehistoric scarps along the northernmost 15 km of the 1983 rupture. Estimates of 1983 displacement (n=99) along the Warm Springs section imply a decrease in displacement to the north, from 0.5 ± 0.4 m near the Willow Creek hills, to 0.2 ± 0.1 m where the rupture terminates. We also measured vertical offsets (n=37) for prehistoric surfaces displaced by the Warm Springs section. Prehistoric multiple-event scarps yield vertical-offset populations of ~1.5–2.0, ~2.5–3.0, and ~3.5–4.5 m, likely reflecting increases in the number of events recorded and total displacement for progressively older surfaces. Differences in these estimates suggest that previous ruptures of the Warm Springs section had a maximum of 1.0 ± 0.5 m of vertical displacement; however, surface ages and the timing of individual prehistoric events remain unconstrained. Ongoing analyses near the Willow Creek hills structural boundary will allow us to further compare 1983 and prehistoric displacements and evaluate structural controls on normal-faulting rupture length.

Ground Motions and GMPEs

Poster Session · Thursday 20 April ·

A Model for Estimating Amplification Effects on Seismic Hazards and Scenario Ground Motions in Southern Ontario

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Site amplification effects in southern Ontario are highly variable and strongly influence felt effects and damage potential. Site parameters such as shear-wave velocity in the top 30 meters of soil (V_{S30}), traditionally used to estimate site amplification, are not well known in this region. Thus, regional maps of shaking potential and seismic hazard are often overgeneralized.

In this study, we compare a site amplification model based on peak frequency (f_{peak}) to one based on V_{S30}, as given by the 2015 National Building Code of Canada (NBCC). Earthquakes and scenario events are used to estimate ground motions and shaking intensities. We conclude that the NBCC and f_{peak}-based models generally predict similar felt intensities but can differ significantly in their predicted amplification of ground motions as a function of frequency. The results of this study support the use of f_{peak} as a site response variable for estimating amplification effects in southern Ontario.

Comparison among the Graizer-Kalkan (GK15) GMPE and Two NGA-West2 GMPEs

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We compare the Graizer-Kalkan (2015; hereafter referred to as GK15) ground-motion prediction equation (GMPE) with the Next Generation Attenuation-West2 project (NGA-West2) GMPEs of Abrahamson *et al.* (2014) and Boore *et al.* (2014). The comparisons were conducted in terms of median predictions, standard deviations, and analyses of total residuals with respect to the near-field (within 20 km of the fault) and far-field (beyond 20 km of the fault) ground-motion records from six major earthquakes in California including the 1979 moment magnitude (M) 6.5 Imperial Valley, 1989 M6.9 Loma Prieta, 1992 M7.3 Landers, 1994 M6.4 Northridge, 1999 M7.1 Hector Mine, and 2014 M6.0 South Napa earthquakes. Among these events, the Hector Mine and South Napa earthquakes are not included in the NGA-West2 database (Ancheta *et al.*, 2014). We also used a near-source (within 80 km of the fault) subset of the NGA-West2 database, covering 1,260 ground-motion data from 84 Californian events ranging from M4.27 to M7.36 in order to compare inter and intra-event residual distributions between GMPEs. These comparisons reveal that the scaling characteristics of the GK15 and other two GMPEs are in general similar in terms of distance attenuation and linear site response but differ in terms of scaling with magnitude, style of faulting, and nonlinear site effects. However, these differences are not found to be statistically significant. As a result, we propose that the GMPE of Graizer-Kalkan (2015) can be used to estimate ground motions in California as accurately and precisely as the two considered NGA-West2 GMPEs.

An Energy-Based Seismic Response Evaluation of Simple Structural Systems with Simulated Ground Motions

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In recent years, there has been a strong interest on energy-based design and assessment methods for structural systems. The underlying research has been mostly performed using real ground motion records taken from existing earthquakes worldwide. Results may involve bias due to lack of homogeneity of the available ground motion dataset in terms of magnitudes, source to site distances or soil conditions. For this purpose, in this study a large set of ground motion records are simulated within a parametric exercise to investigate the effect of different intensity measures on the energy-based response of simple single degree of free-dom structures. To generate simulated records, stochastic finite-fault methodology which is effective in simulating a wide range of frequencies including those that influence the built environment is used. The simulations are performed on active faults around Duzce city center located on the western segments of North Anatolian Fault zone in Turkey. The simulated records cover a wide range of moment magnitude, source-to-site distances and soil conditions. To assess the response statistics on SDOF models, time history analyses with simulated records are performed. Input energy, damping energy and hysteretic energy are considered as the main output parameters. The results of this study reveal that energy is a more stable parameter than the other response parameters such as displacement and force. However, it is important to dissipate the estimated input energy through damping and inelastic action. Finally, it is believed that conducting parametric seismic analysis based on simulated records yield realistic results since these records provide variability in seismic demand.

Data Processing with Non-Causal Zero-Phase Filters Under Predict NGA 2 GMPEs

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The Lucerne record from the 1992 M7.3 Landers earthquake had motions too large to be accommodated by the San Bernardino Law and Justice Center, even though this structure was designed for maximum ground motion with triple pendulum base isolators. By investigating the predictions for 10-second response spectral displacements, we found that NGA 2 GMPEs under-predict long-period near-source motions from large earthquakes. The under-prediction may be due to the conventional data processing method used in the NGA ground-motion database, which is a non-causal zero-phase Butterworth filter at a corner frequency corresponding to the expected level of noise in the record. Theoretically, a non-causal zero-phase filtered response is approximately half the value of the response with no filter, as we can see by filtering a unit step function with this method. While non-causal zero-phase filtering leaves the acceleration unchanged, the effect of the corner frequency in this filtering is noticeable on the displacement. Therefore, when long period components of the recorded ground motion contain valuable information, it is critical to choose the appropriate period of the non-causal zero-phase filter.

We examine the strong motion data from recent large earthquakes, such as the 1999 M7.7 Chi-Chi, 2015 M7.8 Nepal, 2016 M7.0 Kumamoto, and 2016 M7.8 New Zealand earthquakes. By taking the uncorrected records, we apply the baseline correction, account for the linear trend in velocity, and integrate for the peak displacement. Using long periods of 10 seconds and 60 seconds, we then compare the unfiltered and non-causal zero-phase filtered spectral displacement. Ultimately, we take these broadband ground motion records containing long period effects and conduct both linear and nonlinear response analyses of tall buildings.

A New Generation of Ground-Motion Prediction Equations Using an Integrated Database for Iran

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New ground-motion prediction equations (GMPEs) are derived by considering various regional characteristics for Iran. For the development of the new GMPEs, we will use a newly developed high-quality dataset of earthquake ground motions recorded in the near source of shallow earthquakes occurred in Iran, Eurasia, and California from 1978 to 2013 for the region with 266 three-component strong motion records processed from 27 large Iranian earthquakes with moment magnitudes between greater than 5.6, and rupture distances $R_{rup} \leq 104$ km. This newly database is combined with existing high quality databases for Iran to generate an integrated database with moment magnitudes **M** ranging from 4.5 to 7.6 and shortest distances to the fault, R_{rup}, of less than 200 km for shallow earthquakes with depths of 35 km or less. The new GMPEs are derived for the peak ground acceleration (PGA) and 5%-damped pseudo-acceleration response-spectral ordinates at periods ranging from 0.01 to 10 s, moment magnitudes (**M**) ranging from 4.5 to 7.6. The GMPEs are developed for a reference site defined as soft-rock with $V_{S30} = 760$ m/s where V_{S30} is the time-averaged shear-wave velocity in the top 30 m the distributions of Inter-Event and Intra-Event residuals demonstrate that there is satisfactory performance of the results. Furthermore, a comparison of the newly developed GMPEs will be provided with the recent published GMPEs for the Iranian region.

On the Bayesian Inference of Random Effects in the Recalibration of Ground-Motion Models to Icelandic Earthquakes

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Ground-motion models (GMMs) describe various aspects of earthquake ground motion as a function of earthquake magnitude, site-to-source distance, local site conditions and other seismic parameters. Typically, empirical GMMs have been fitted to the recorded data by different regression methods such as the ordinary least-squares, the weighted nonlinear least-squares, the two-stage maximum-likelihood and the random-effects regression methods. However, these methods are not able to decrease the bias introduced by the uneven distribution of recordings in regions with sparse data. In many cases, the information contained in the recorded ground-motions is also not sufficient to properly constrain all regression coefficients for a given functional form. To this end, the Bayesian statistical method can be applied to combine prior information of the model parameters with the likelihood of the observed data, summarized in a posterior density. This feature has made it beneficial for the estimation of GMMs in regions like Iceland where due to both limited number of recordings and their narrow earthquake magnitude ranges, magnitude-and-distance dependent saturation terms cannot be constrained by data. Moreover, to account for uneven sampling of the different earthquakes and correlations of the recorded ground-motion from a single event, the aleatory variability is partitioned into inter-event and intra-event components. In this study, a Bayesian random effects model that uses a Markov Chain Monte Carlo algorithm for inference is presented to recalibrate different GMMs. In addition to the inter- and intra-event variability, the correlation coefficients between the model parameters are assessed. The recalibrated GMMs fit the recorded data very well and, due to the uncertainties and correlations between the model parameters now being quantified, they can be used in future seismic hazard analyses in Iceland with much greater knowledge of the quality and confidence in the results.

Development of Source-To-Site Distance Conversion Equations for the Extended-Fault Sources

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One major concern in performing a probabilistic seismic hazard analysis (PSHA) within the areal sources is to convert source-to-site distances defined in GMPEs. The Joyner-Boore distance and the rupture distance are defined to capture the effects of extended-fault sources on ground motion amplitudes, while the areal source configurations almost include point-source distance metrics such as epicentral distance, and hypocentral distance for seismicity distribution in the PSHA studies. Therefore, using the extended-fault source distances in the GMPEs relative to point-source distances for the areal seismic sources may lead to significantly underestimating the ground motions in the PSHA study, particularly at low probability of exceedance.

In this study, we develop a new analytical approach to derive source-to-site distance conversion equations for the various distance metrics defined in the GMPEs. A bathtub shape is first defined around an extended-fault source on which all sites have identical Joyner-Boore distances. Then, the source-to-site conversion equations are analytically derived using laws of sines and cosines. Magnitude-distance polynomial functional forms are derived to obtain their associated uncertainties for a particular fault-dip angle. Furthermore, the results are combined with a site-specific geometric spreading equation to convert the Joyner-Boore distance into the effective epicentral, hypocentral, and rupture distances. These effective distances should finally be used in the GMPE distance conversions or ground-motion simulations since they reflect the total energy released from the entire fault rupture during a large earthquake.

As an application, a PSHA study are performed within a simple circular areal source zone using the GMPEs developed for the CEUS and the source-to-site distance conversion equations developed in this study to demonstrate the effects of inconsistent source-to-site distance metrics on the hazard curves at a given site.

Implications of the Inter-Period Correlation of Strong Ground Motions on Structural Risk

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We test the hypothesis that the character of the inter-period correlations within strong ground motions have a meaningful impact on structural response variability, making the correlations an essential component of ground motion simulation validation. In this study, we investigate the implications of the inter-period correlation of simulated strong ground motions on structural response, and therefore structural risk.

We generate large suites of ground motion simulations using the point source stochastic method (Boore, 2003). Two compatible suites are developed; one with inter-period epsilon correlations sampled randomly from a standard normal distribution (*i.e.* without inter-period correlation), and one with inter-period epsilon correlations sampled from a normal distribution having covariance specified by our empirical inter-period correlation model for Fourier amplitude spectra (FAS). Both suites of simulations have equivalent median and standard deviation in Fourier amplitude space. The Fourier amplitude spectra are then translated to the time domain assuming random phase angles.

Both suites of acceleration time histories are applied in dynamic nonlinear structural analyses, using the open source finite-element platform, OpenSees (OpenSees, 2009). We evaluate the response using multiple nonlinear structural models, and develop fragility curves for each structure based on maximum inter-story drifts. The fragility curves are combined with generic seismic hazard curves for California to calculate the seismic risk. We conclude that the suite of simulations with the imposed inter-period correlations leads to a larger variability in structural response, flatter fragility curves, and higher seismic risk. This conclusion supports our hypothesis and corroborates the importance of inter-period correlation of epsilon of FAS in ground motion simulations, which have not been validated up to now.

Site Response of the Vertical Ground Motion and Its Correlation with Alternative Profile Proxies

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The vertical component of ground motions and specifically its site response are poorly understood. Most vertical ground motion prediction equations (GMPEs) still use Vs30 as a proxy for site characterization, although studies have shown that P-waves may contribute as much as the S-waves to the vertical ground motion and possibly even more. Because the vertical site-response is controlled by both S-wave and P-wave velocities (Vs and Vp respectively), and because Vp are sensitive to the presence of water, we suggest that other profile parameters may be more effective in site-characterization for the vertical component.

The purpose of this study is to identify a predictive proxy, to be used in seismic hazard studies of the vertical ground motion for describing the site-response component. To do so, we use data from the NGA-West2 ground-motion database in California and supplement it with Vp30 and the Ground Water Level (GWL) at most of the stations in the database. The vertical amplification is calculated with respect to a baseline GMPE regressed on surface ground motion recordings in California. Vp30 is calculated from measured Vp profiles at the same locations. Finally, measured ground-water levels from the USGS ground-water database are interpolated, to evaluate the GWL at the locations of the ground motion recording stations.

Correlations between the site amplification and different profile proxies are explored in order to identify the most appropriate proxy. We find that while Vs30 alone cannot fully represent the vertical site-response, it still offers the best first-order approximation of the overall site-response. We also see strong correlation between the amplification at short periods and the GWL. While the Vs30 scaling is sensitive to distance, the GWL scaling is mostly sensitive to magnitude. This is due to the relative contribution of S and P waves within the soil column. This topic will be further explored in future research.

Never Fear Velocity Reversals

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It is a common assumption that the shear-wave velocity of geologic layers will increase with depth, mostly due to overburden pressure. In some cases, however, velocity reversals can be observed in the subsurface. These reversals are considered as complicating factors, and are often avoided when performing simulations of real data and synthetic velocity profiles, in the context of site effects. Here, we try to identify in which cases velocity reversals have a minor effect on the amplification, and in which cases they cannot be ignored.

We generate synthetic 3-layer profiles, all with the same shear wave velocity (Vs) of the bottom layer (L3) – the half space, of 900 m/s. The combined depth of the upper two layers is always 50 meters, and we change the Vs of the uppermost layer (L1), the Vs of the middle layer (L2), and the thickness ratio (TR) between them, when TR is defined as the thickness of L1 to the thickness of L2 (L1/L2). We then calculate the linear transfer function of these profiles, and examine the amplitude at resonance frequency, as a function of the impedance ratio (IR) between L2 and L3, and the TR.

We observe that for a low TR, *i.e.* 10/40, a change in the Vs of L1 has hardly any influence on the amplitude. However, for a high TR, namely 40/10, a change in the Vs of L1 affects the amplitude greatly. It seems as if the amplitude "sees" the thicker layer of the two. This leads us to introduce the concept of the "effective" IR (IR_eff), which is the impedance ratio between L3, and a 50 meter thick layer, with the time-averaged velocity of L1 and L2 (Vs50). Using IR_eff allows us to account for both velocities and thicknesses when comparing amplifications from different profiles. This approach allows us to determine the cases in which the velocity reversal effect on the amplitude, and hence on the site-response, is significant.

Hybrid Empirical Ground-Motion Prediction Equations for the Gulf Coast Region

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The main purpose of this study is to develop GMPEs for the Gulf Coast region using a hybrid empirical method (HEM). The HEM uses stochastically simulated ground motion intensity measures (GMIMs) in the host and target regions to develop adjustment factors that are applied to empirical GMIM predictions in the host region. The Gulf, the target region in this study, is a wide sedimentary region, which is centrally located between the eastern Rocky Mountains (western side) and the Appalachian Mountains (eastern side). Considering western North America as the host region, we will use five new NGA-WEST2 GMPEs developed by the Pacific Earthquake Engineering Research center (PEER). For the required seismological parameters in WNA, we will use Zandieh, Pezeshk, and Campbell (2017) results in which a set of point-source inversions have been performed to match the median NGA-West2 GMPEs for moment magnitudes ($\mathbf{M}$) of 3.0–8.0, rupture distances (R_{rup}) of 1–300 km, spectral periods (T) of 0.01–10 sec (f = 0.01–100 Hz), and NEHRP B/C site conditions. For the Gulf coast region, we will use the most recent available seismological parameters in the literature. A moment magnitude range of 4.0 to 8.0 and rupture distances of up to 1000 km will be considered. The new GMPE will be derived for the 5%-damped pseudo-acceleration response spectra for a reference hard-rock site with V_{S30} =3000 m/s.

Relationships among Various Definitions of Horizontal Spectral Accelerations in Central and Eastern North America

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A single ground motion intensity measure, typically spectral acceleration (S_a), is required as the main input in deriving empirical Ground Motion Prediction Equations (GMPEs). Traditionally, a single horizontal orientation has been used in calculating Sa for all periods. The spectrum changes with orientation, and using a single orientation to represent two dimensional ground motions leads to loss of useful information regarding the variation of Sa with orientation. Different techniques have been proposed in the literature to combine the two horizontal components of ground motions into a scalar horizontal definition. The ratios between different definitions of horizontal component of ground motions have been studied because of the urgent need of using multiple GMPEs combined in a logic-tree framework in the preliminary stages of performing probabilistic seismic hazard analysis, or at further stages where the uniform hazard response spectrum is required to be converted to another spectrum for a different horizontal definition. While the most recent studies produced similar results using different subsets of the NGA-West2 database, it is possible that such directionality results may differ for other earthquake datasets and is region specific. The purpose of this study is to derive ratios between median values and the associated standard deviations for different definitions of the horizontal component of ground motions in Central and Eastern North America using a subset of the NGA-East database. The computed median ratios are similar to the ratios provided in recent studies for other regions with a shift in some period ranges with noticeable differences between the standard deviations. The results of this study fulfill the engineering requirements of considering the maximum direction elastic response spectrum for design of structures.

Comparison of Different Approaches to Incorporate Site Effects and Associated Uncertainties in Probabilistic Seismic Hazard Analysis: Application for a Liquid Natural Gas Tank

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This study presents a comparison of a hybrid approach and a fully probabilistic approach for incorporating site effects in a Probabilistic Seismic Hazard Analysis (PSHA). To fulfill the scope of this study, the weaknesses and strengths of the employed approaches is highlighted focusing on performing a site-specific PSHA for a Liquid Natural Gas (LNG) tank located in the Gulf Coast region. In the employed hybrid approach the amplification factors are computed by performing equivalent linear site response analysis for two separate earthquake scenarios controlling the low- and the high-frequency portion of the rock ground motion. The obtained rock hazard is then multiplied by the computed amplification factors to define the surface ground motions. The considered fully probabilistic approach is characterized by higher levels of sophistication in which the rock hazard is convolved with the probability density function of the amplification functions. For both approaches, the uncertainties associated with the site characterization are addressed via Monte Carlo randomization. The seismic analysis of a LNG tank is a challenging and complicated task because a wide range of frequencies should be considered covering both the fundamental frequency of the structure (typically 2 to 10 Hz) and a sloshing frequency of around 0.1 Hz. Furthermore, the considered site is located in the Gulf Coast region where the thick sediments exhibit significantly different ground-motion attenuation in the region. The employed approaches resulted in a very similar soil hazard, which reveals that increasing the level of sophistication in the numerical ground response analyses might not be always required. Finally, the obtained results are used to develop the design spectrum for the Operating Basis Earthquake and Safe Shutdown Earthquake levels in accordance to the NFPA 59A-2001 requirements.

Importance of Long-Period Ground Motions in Seismic Design of Structures.

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Examples of Observed Response of Tall Structures in Istanbul to Long-Distance Earthquakes

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As part of structural health monitoring activities in Istanbul, Turkey, four tall buildings and two minarets are instrumented with accelerometers operating in real time. They are the 123 m high Kanyon Tower (26 floors), 152 m high Polat tower (42 floors), 181 m high Is Tower (52 floors), 238 m high Sapphire Tower (62 floors), 70 m high Maltepe minaret, and the 73 m high Hagia Sophia Minaret. The M_w 6.9 Gokceada earthquake of 24 April 2014, which took place 300 km away from Istanbul, was recorded by the monitoring networks in these buildings. In this contribution, we draw attention to the long-duration and large amplitudes of recorded vibrations from such a long-distance earthquake. By comparing the records with those from other earthquakes with varying magnitudes and distances, we suggest that these phenomena are a function of structural properties and earthquake source parameters.

Evaluation of Accidental Eccentricity in Symmetric Buildings Due to Wave Passage Effects in the Near-Fault Region

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This study investigates the characteristics of the accidental eccentricity in symmetric buildings due to torsional response arising from wave passage effects in the near-fault region. The soil-foundation-structure system is modeled as a symmetric cylinder placed on a rigid circular foundation supported on an elastic halfspace and subjected to obliquely incident plane SH waves simulating the action of near-fault pulse-like ground motions. The translational response is computed assuming that the superstructure behaves as a shear beam under the action of translational and rocking base excitations, whereas the torsional response is calculated using the mathematical formulation proposed by Luco (1976). A broad range of properties of the soil-foundation-structure system and ground motion input are considered in the analysis, thus facilitating a detailed parametric investigation of the structural response. It is demonstrated that the normalized accidental eccentricity is most sensitive to the pulse period (T_p) of the near-fault ground motions and to the uncoupled torsional-to-translational fundamental frequency ratio (Ω) of the structure. Furthermore, the normalized accidental eccentricities due to simplified pulse-like and broadband ground motions in the near-fault region are computed and compared against each other. The results show that the normalized accidental eccentricity due to the broadband ground motion is well approximated by the simplified pulse for longer period buildings, while it is underestimated for shorter period buildings. For symmetric buildings with values of Ω commonly used in design practice, the normalized accidental eccentricity due to wave passage effects is less than the typical code-prescribed value of 5%, except for buildings with very large foundation radius.

Induced Seismicity—The European Perspective

Poster Session · Thursday 20 April ·

Mitigating Induced Seismicity While Optimizing Production/Injection Strategy of Gas Fields

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Pore pressure changes caused by the production of gas result in reservoir compaction, stress changes on faults, and might induce earthquakes. This seismic activity is expected to be affected by the amount of pressure change, the spatial distribution of the pressure changes relative to the distribution of the faults and the rate at which the pressure changes occur. One of the options to mitigate seismicity in the field during ongoing depletion is to reduce production in areas of high seismicity rates and/or to maintain pressures by local injection. Therefore, seismic activity can potentially be reduced by optimizing the production strategy of a field.

We have developed a dual-optimization workflow that aims to find optimized production strategies that are attractive from an economic perspective and acceptable from a hazard perspective.We use a seismological model that relates reservoir strain, differential strain and strain rate (*i.e.* cumulative compaction and compaction rates) to the rate of seismicity. Other, more advanced types of seismological models, for example based on stress developments in the reservoir, can also be incorporated.

We have implemented an optimization scheme based on approximate gradients, that is flexible, allows for many opererational parameters, and can account for all kinds of uncertainty. The optimization workflow is applied to a gas field model that is inspired by an existing gas field in the Netherlands. The performance of the optimization is demonstrated in a series of experiments in which we constrain total production or let the total production be determined during the optimization by balancing with the objective to minimize seismic risk. The results of these experiments demonstrate the potential for model-based reservoir management workflows to contribute to safe production of hydrocarbon resources.

Modeling Induced Seismicity by Gas Depletion in a Postglacial, Prestressed Regime

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In northern Germany earthquakes which are felt by humans, or even cause minor damage, are rare. But over the last few decades, around 60 events occurred in Northwest Germany with magnitudes mostly under 3.0 ML, and single events up to 4.5 ML. Most epicenters are located in the vicinity or inside of produced conventional gas fields. A few other earthquakes with hypocenters at about 30 km depth can clearly be classified as natural, tectonic events. The 2004 ML 4.5 Rotenburg earthquake is the largest event associated with gas depletion, but depth constraint at that time was poor due to the low density of the seismic network. Modeling shall help to investigate the seismicity of the region further. Here we present a 3D numerical model with hydro-mechanical coupling using finite difference software FLAC3D. In this modeling approach, the mechanical behavior of the rock formation is based on poroelastic theory and Mohr-Coulomb failure criterion. Griffith's fracture criterion is used to determine whether the faulting process has stopped. Our investigation not only considers the local effect of depletion, but also the regional stress changes due to post-glacial isostatic adjustment. To adjust the modeling approach, a calculation based on production data for a gas field from northern Germany has been applied. Numerical results compare fairly well to measured reservoir pressures and observed earthquake data.

Forecasting Magnitude Frequencies and Magnitude Occurrence Probabilities Using the Seismogenic Index Model—Application to Production and Injection Operations in Hydrocarbon and Geothermal Reservoirs

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We study and test the performance of the seismogenic index model for forecasting magnitude frequencies and their occurrence probabilities of induced earthquakes. The seismogenic index model incorporates several parameters: the injected and produced fluid volume, the b value of the Gutenberg-Richter magnitude scaling, the seismogenic index, and the p value of a modified Omori law to capture seismicity induced after shut-in. We apply this forecast model to compute retrospectively magnitude frequencies of seismicity induced by hydraulic stimulation of geothermal reservoirs, by hydraulic fracturing operations in hydrocarbon reservoirs, by production of gas, and by production of geothermal energy in hydrothermal systems. We include time dependency in our forecast tests, it means we consider so-called learning periods and forecast periods, as well as we account for times after shut-in of the operations. Furthermore, we compute total cumulative seismic moment release for 34 injection operations using the seismogenic index model. Both, computed magnitude frequencies and computed total seismic moment well agree with the observed magnitude distributions. Hence, the seismogenic index model performs well and the obtained results prove its reliability for forecasting induced event magnitudes. We combine this forecast model with the homogeneous Poisson process (HPP) which enables to compute the occurrence probability of a given magnitude event. Analyzing the statistics of interevent-times and interevent-volume distributions confirm the use of the HPP model to compute occurrence probabilities. We find that the maximum magnitudes observed in the here considered case studies of fluid injection and production operations had probabilities of occurrence of up to 95 per cent.

Underground Seismic Monitoring and Seismic Hazard Assessment in Bobrek Coal Mine, Poland with the Use of Flameproof Seismic Observation System SOS

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In 2008, 64 channel flameproof Seismic Observation System SOS was developed in GIG and installed in Bobrek coal mine in the Upper Silesia area, Poland. One of the main features of this system is integrated software which enables analysis and interpretation of recorded seismic events. The software is specifically useful for fast 3D seismic event location, seismic energy and seismic source parameters calculation and passive tomographic imaging. The system comprises of mobile *i.e.* very easy to install and relocate uniaxial and triaxial seismic borehole sensors making it possible to surround the area of the mine with high seismic activity. The location of seismic events utilizes onset times of P and S seismic waves and 3 modern optimization algorithms: gradient based Davidon-Fletcher-Powell algorithm and derivative free simplex and modified Powell algorithms. Seismic energy is calculated as averaged sum for P and S seismic waves recorded at each seismic stations. Seismic source parameters are obtained automatically from displacement power spectra of P and S seismic waves assuming Brune's source model. Bent-ray passive tomographic imaging utilizes recorded induced seismicity in Bobrek mine and is based on very fast Levenberg-Marquadt optimization algorithm. In 2011 more than 3000 seismic events were recorded in seismically active coal panel no 6 using SOS seismic system. In July 19th 2011 strong seismic event with rock burst effect took place. This situation provides opportunity for spatial and temporal analysis of seismic hazard in area of coal panel 6 in Bobrek mine utilizing the integrated software of the SOS system. Seismic hazard assessment has been determined with the use of following methods: tomographic P-wave velocity images, 3D distribution of seismic events, peak particle velocity (PPV) values and temporal changes of b value of Gutenberg-Richter relation.

Intraplate Earthquakes: Central and Eastern North America and Worldwide

Poster Session · Thursday 20 April ·

Magnitudes at Close and Very Close Distances in Eastern Canada

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The Nuttli, M_N, magnitude scale for eastern North America consists of two equations with distance determining which is used. In Canada, only the greater distance equation is used based on Wetmiller and Drysdale (1982), a short ES-SSA abstract never followed by a full paper. Their recommendation is re-evaluated with a larger data set. M_N values at 50 km- 4 deg. were compared to magnitudes for the same events at distant stations. A single equation does result in a better match between the two distance ranges (difference reduced from 0.35 to 0.16) but, in both cases the close magnitudes are greater than the distant ones. The discrepancy may arise from an inappropriate attenuation relation and/or calculating magnitudes at too high frequencies. At very close distances, less than 50 km, the Lg-based Nuttli scale is not defined. The Richter, M_L, scale is used instead although it is not calibrated for eastern North America and was never intended for use at extremely close distances. Magnitude data from all regions of eastern Canada were evaluated. For distances of 5-50 km, the M_L, magnitudes are consistently about one magnitude unit smaller than , M_N magnitudes calculated at appropriate distances. Calculating M_N for very close stations results in a better match to the regional values. At distances less than 5 km the differences become less consistent and may vary with source region. Methods, such as spectral scaling, may be the best option in general but they cannot be easily applied when the larger and smaller earthquakes were recorded by different stations. Examples from the McAdam, New Brunswick swarm, highlight the issue but similar problems may arise in any region where stations were installed to monitor recent activity, such as aftershocks or induced seismicity, but where the largest events occurred prior to the installations.

Effectiveness of Subspace Detectors to Assess the Occurrence of Repeating Earthquakes and to Lower the Magnitude Threshold in the Mid-Atlantic US

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Global analysis of intraplate earthquakes suggests some common characteristics: intraplate events seem to be spatially and temporally clustered, episodic, and to migrate in space, although diffuse seismicity is observed outside these seismic zones. Global studies of seismicity in stable continental interiors also hint to the occurrence of repeating earthquakes with similar magnitudes and waveforms. Intraplate seismicity in our study area, the Mid-Atlantic US, has been proposed to cluster into three main seismic zones: Central Virginia (CVSZ), Reading-Lancaster (RLSZ), and Ramapo (RSZ). Previous studies interpret the proposed clustering as resulting from potential zones of lithospheric weakness, local stress concentration, and/or long-lived aftershock sequences.

To assess possible mechanisms for the spatio-temporal distribution of seismicity we are analyzing a dataset (1568-2016) of tectonic earthquakes comprised by locations from the 2014 US NSHM, ISC, ANSS, and USArray ANF. Preliminary cluster analysis shows: (1) seismicity spatially concentrates in a region of transition from thicker to thinner crust, and (2) seismicity in Virginia clusters in a well-defined zone (CVSZ) while it appears to be semi-continuous from northern Maryland to New York. The lack of clustering of seismicity between central Virginia and northern Maryland could be attributed to the short historic earthquake record relative to the low strain rate, short observation period with modern instrumentation and/or poor station coverage.

We are applying subspace detectors to tease out smaller magnitude events recorded by local and EarthScope USArray TA stations from 2013-2015. This technique allows us to examine the earthquake magnitude threshold for the Mid-Atlantic US, evaluate the occurrence of repeating earthquakes as has been documented in other intraplate regions and assess the lack of seismicity clustering between Virginia and northern Maryland observed in our preliminary analysis.

Improving Earthquake Detection in New England (USA)

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Seismicity is low in the northeastern USA, but when moderate earthquakes occur they cause higher levels of damage than in more earthquake-prepared regions. The low level of seismicity, and the historically low density of seismic stations means that we know little about the active structures in the region. By locating more (smaller) earthquakes we can investigate seismically active structures and identify locations where seismicity goes undetected. The arrival of the USArray in 2013 doubled the number of stations in the region. Many of these stations were then adopted into the Central and Eastern US Network, contributing to a much increased level of monitoring. We use these greater numbers of stations in New England, and modern waveform analysis methods to detect and locate previously un-catalogued earthquakes in northeastern USA. We employ both the beam-formed network response and waveform template-matching approaches developed for low-frequency earthquakes in subduction zones. We start with a small region of (relatively!) high seismicity in New Hampshire. On an example day in 2013, we find 10 matches using a cataloged M2 earthquake as a template at the nearest stations. Extending these methods to more distant stations will require modifications as the signal duration and the shape of the waveforms change with distance.

In this seismically sparse region, we need to identify earthquakes by other methods to increase our catalog of template earthquakes. We explore both filtered-waveform and kurtosis-based approaches to improve the detection of arriving phases. We migrate and stack the processed records at each station using a grid search over expected arrival times from an array of source locations to identify and locate real earthquakes. We identify a further earthquake on the example day that is not in the catalogue, nor close enough to the M2 event to be detected using template-matching. We present our improving catalog of New England seismicity.

Intensity Correlations with Regional Q, Stress Drop, and Induced and Natural Seismicity in the Central US

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Hough (2014) proposed that earthquake intensity data in the central and eastern US (CEUS) is not correlated with regional Q but is correlated with stress drop for potentially induced earthquakes (PIE). We have completed a regional Q study of the Gulf Coast region and to the west and north in Kansas, Oklahoma, and Texas (Cramer and Al Noman, 2016; Cramer, 2017a). I have also examined stress drops from PIE and natural earthquakes in central and eastern North America (CENA) (Cramer, 2015, 2016, 2017b). Atkinson and Boore (2014) estimate an average mid-continent Q(f) for CENA as a Qo of 525 and eta of 0.45. We estimate Gulf Coast regional Q(f) as a Qo of 259 and eta of 0.715 (Cramer and Al Noman, 2016; Cramer, 2017a). West and north of the Gulf Coast region we see low 5 Hz Q in central Kansas, central Oklahoma, and northern Texas similar to Gulf Coast 5 Hz Q, but mid-continent Q at 1 Hz. Smaller basins and rifts may be responsible for the Q pattern west of the Gulf Coast region and east of the Rocky Mtns. The intensity patterns of Hough and Page (2015) for the 1957 M5.7 El Reno, OK and 2011 M5.6 Prague, OK earthquakes show decay with distance patterns that correlate with our regional Q pattern. This is also true for the 2016 M_w5.8 Pawnee and M_w5.0 Cushing, OK earthquakes. This suggests that intensities are strongly correlated with region Q in the central US (CUS). Hough's (2014) differences between moment magnitude and intensity estimated magnitude (Mie) are also strongly correlated with regional Q, supporting strong Q/intensity correlation in the CUS. My study of CENA stress drops shows that there is no difference between PIE and shallow natural earthquakes. Regional variations in CENA stress drops are more significant. Based on observations I conclude that intensity observations are strongly correlated with region Q and not correlated with PIE stress drops, the opposite of Hough's (2014) assumptions.

Magnitude Estimates for the 1811-1812 New Madrid Seismic Zone Earthquakes Using Large Scale Numerical Simulations: Implications for the Seismic Hazard in Urban Areas around the Mississippi Embayment

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The earthquake magnitudes whose values range between 7.1 and 8.0, controlling ground motion levels in the New Madrid Seismic Zone have large uncertainties, and are based on controversial magnitude estimates of the 1811-1812 earthquakes in the region. Improvements in our knowledge of the historical sequence's magnitudes and associated ground motions, made using large scale simulations, offer an alternative to previous work on the seismic hazard at regional and city levels by reducing uncertainties associated with the ground motion variability. This project improves estimates of the magnitudes of the three main shocks of the sequence by using broadband simulations generated at sites with reported

MMIs, and comparing MMI values derived from the simulations with the observed intensities. Our work builds on the work of Ramirez-Guzman *et al.* (2015), who used 3D simulations out to distances of about 500 km. We used 1D simulations out to 1,800 km to span the entire region over which MMI intensities were reported. We used the Southern California Earthquake Center (SCEC) Broadband Simulation Platform (BBP) to perform the simulations. We used the Atkinson and Kaka (2007) and Dangkua and Cramer (2011) ground motion intensity correlation equations to estimate MMI from the ground motion simulations so that they could be compared with the observed intensities. We compared simulations of magnitude 7 earthquakes with simulations of larger events. For the larger magnitudes, the NM1 scenarios (December 16, 1811) had a magnitude of 7.7, the NM2 scenarios (January 23, 1812) had a magnitude of 7.4, and the NM3 scenarios (February 7, 1812) had a magnitude of 7.6. There is a slight preference for the larger magnitudes, which are systematically higher than those described by Hough and Page (2011) and comparable to those reported by Cramer and Boyd (2014).

Eastern North America Passive Margin Earthquakes and Mesozoic Rift Structures

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Modern earthquake activity in central and eastern North America generally is thought to occur as reactivations in the modern stress field of pre-existing zones of weakness in the crust, but the identification of which specific faults can be reactivated is not very advanced. Work in the 1990s showed that the largest intraplate earthquakes in stable-craton regions primarily take place in previously rifted crust, and most such earthquakes occur in crust that underwent Mesozoic or younger rifting. This is true in eastern North America, where many of the small earthquakes occur around or within some of the Mesozoic basins. Also, many of the modern small earthquakes have been centered near or on faults not associated with a Mesozoic basin but nevertheless were active during Mesozoic time. Offshore along the Atlantic coast of North America, earthquakes have been detected out to the continental rise. In some recent cases, the passive margin earthquakes appear to have nucleated on faults that were active in the Mesozoic but then those ruptures propagated away from the Mesozoic faults, presumably driven by the modern tectonic stress field. The damaging earthquakes in eastern North America that have occurred during historic and recent time all have had some association with structures that show Mesozoic activity. Most of the smaller earthquakes in the region also occur on or near structures that were active in Mesozoic time. These observations suggest that all of the Mesozoic basins and faults that were active during Mesozoic or later time should be considered as potential source zones of future large earthquakes.

New Constraints on the Late Quaternary Slip Rate of the Cheraw Fault, Southeastern Colorado

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The Cheraw fault (CF) is one of the few Quaternary-active faults expressed at the surface in the Central and Eastern U.S. Our recent investigations of the CF have expanded evidence of Quaternary surface deformation and verified the connection between surface scarps and basement structure. To address uncertainties in the fault's late Quaternary slip rate, we conducted a paleoseismic trench investigation near Haswell, CO. We exposed deformed deposits mapped as Early (?) Quaternary Nussbaum Alluvium and Cretaceous Niobrara bedrock. Three samples were dated using Infrared stimulated luminescence (IRSL) dating (feldspar) to establish stratigraphic age control for the Nussbaum Alluvium. The stratigraphically lowest sample, collected from sandy alluvium in cross bedded channel deposits ~1 m above the basal strath, give an age of >160 ka. These basal channel deposits are capped by overbank deposits and loess; both deposits contain multiple unconformities and two well-developed buried and truncated soils. Two ages from sandy alluvium that unconformably overlies the loess are 159 ±11 ka and 126 ±11 ka.

Based on our studies, we conclude that: 1) The entire CF scarp is closely associated with an underlying bedrock fault and fold structure. 2) Nussbaum Alluvium at the Haswell site is deformed and its basal contact is vertically offset ~9 m. Internal stratigraphy within the Nussbaum Alluvium is deformed in the same manner as its basal contact with bedrock, suggesting that all deformation postdates the youngest Nussbaum strata at the site. 3) IRSL ages suggest that this slip on the CF occurred after ~126 to 159 ka, yielding a minimum vertical slip rate of ~0.06 to 0.07 mm/yr. The similarity between vertical offsets we observe near Haswell and those for surfaces of presumed similar age along the southern and central portions of the fault implies a pulse of post-120 ka slip after a period of much longer quiescence or may reflect the entire Cenozoic extensional history of the fault.

Constraining the Northern Boundary of the Charleston Uplift Using Seismic Reflection Methods

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The Charleston uplift is a recently discovered, approximately 30 km long by 7 km wide, anomalous stratigraphic high that has been interpreted as a northeast extension of the New Madrid North fault based on its N46°E alignment and coincidence with contemporary microseismicity. Borehole logs and seismic walk-away soundings found varying stratigraphic offset extending between the top of Paleozoic bedrock and the Paleogene–Quaternary unconformity. The observed offset through the post-Paleozoic section supports a structural rather than an erosional origin. However, the northeast extent of the uplift is unknown because the subsurface database was truncated just west of the Mississippi River. Additional seismic-reflection walkaway soundings have been acquired across the uplift's northeast bounding fault projection, across the Mississippi River and into western Kentucky. Initial results from the soundings, as well as a shallow common-midpoint seismic-reflection profile, indicate the fault extends into westernmost Kentucky; however, the temporal extent of stratigraphic deformation remains unknown. Ongoing geophysical imaging, including ground-penetrating-radar, may provide better constraint. Improved temporal and spatial understanding of a potential seismogenic structure reduces the uncertainty for seismic hazard calculations.

PSHA Source Modeling: Approaches, Uncertainty and Performance

Poster Session · Thursday 20 April ·

Approach for Modeling Creep in Probabilistic Seismic Hazard Analysis

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Creep reduces the seismic moment available for brittle earthquake rupture, but there is no accepted approach for modeling the spatial distribution of earthquake ruptures on a creeping fault in a probabilistic seismic hazard analysis (PSHA). The spatial distribution of ruptures is important because it is used to determine the source-to-site distances. While there is some consensus regarding computation of the earthquake rates, there is no established method for developing spatial rupture models since spatial models of creep and locked asperities are generally unavailable. PG&E has facilities near the Bartlett Springs fault which has a high creep rate and is using an approach to compute hazard from creeping faults that differs from the UCERF3 approach. For the earthquake rate adjustment, both PG&E and UCERF3 use an R factor that represents the fraction of the moment-rate released in earthquakes. For spatial distribution of ruptures, PG&E assumes earthquakes distribute over the full fault width, and a full rupture dimension with a reduced slip rate (S' = SR) is used. UCERF3, on the other hand, applies the creep reduction to the area (A'=AR), and the rupture is limited to the bottom part of the rupture plane. These two approaches lead to very different hazard estimates for sites near the Barlett Springs fault due largely to differences in source-site distances and depth scaling of the ground motion prediction equations (GMPEs). To evaluate these two different approaches, we use depth distributions of asperities from small earthquakes on the fault, mindful that evaluation of the depth distribution of earthquakes for use in PSHA also needs to consider the definitions of distances used in the GMPEs. Because distance metrics used in GMPES, such as closest distance, are based on the distance to the rupture with non-zero slip, and not the distance to the high slip region, low slip regions need to be included in the spatial distribution of ruptures on creeping faults.

Modeling Background Seismicity in Japan

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The National Seismicity Hazard Maps (NSHM) for Japan were prepared and recently updated by the Headquarters for Earthquake Research Promotion (HERP) in 2015. These are the most up-to-date Probabilistic Seismic Hazard Maps (PSHM) for Japan and much of the data is provided publicly. There are many different sources modeled for these hazard maps, such as: the Nankai Trough, Japan Trench, known/mapped crustal faults, and background seismicity. In this presentation, we will look closely at the background seismicity in the HERP report, and discussing how we will implement this data into a risk model. In addition, we will also examine the background seismicity following the magnitude 9 Tohoku earthquake, and discuss the increase seismicity following this event.

When building a risk model, the focus is on loss. This means our focus is on the areas of high population, industrial centers, etc. To implement the HERP rate sets for risk modeling we first created a variable resolution grid (VRG). This is a grid based on exposure data, to determine the density of our sources over a given area. For each grid cell, we model a randomly selected set of faults. The orientation is based from the regional tectonic trend, and historic events. We use the maximum magnitudes and rates from the HERP 2015 report, and a magnitude length relationship from Matsuda (1975).

The HERP 2015 maps use earthquake catalog data up to 2010 to calculate the rates for the background seismicity. This is done explicitly to avoid the increased seismicity following the Tohoku, and assumes the long-term background rate is best represented by the earthquake catalog prior to Tohoku. We look at the catalog seismicity in the years following the Tohoku event, and find that it is still slightly elevated. Therefore, we analyze the earthquake catalog to create a short-term alternative view of the background rate for this region that accounts for this increase.

Sensitivity of Hazard to Gridded Seismicity Source Modeling

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The U.S. Geological Survey National Seismic Hazard Model uses gridded and smoothed seismicity sources to represent the hazard posed by randomly located earthquakes that are not associated with any named or mapped fault. To generate a long-term rate model from a catalog, we use one or more smoothing algorithms to redistribute the rate of observed earthquakes over a grid with 0.1° spacing given the observation that earthquakes in the catalog usually occur in the vicinity of prior earthquakes, but not always. For the conterminous U.S., this yields a rate grid with approximately 153,000 cells. The rate in each 0.1° cell represents the earthquake rate over a ~100 km^2 area. For performance reasons, we have historically applied the cell rate to a point-source earthquake model anchored in some way at the center of the cell and have applied a variety of optimizations to minimize computational demands. Over a broad area and at a map resolution of 0.1°, this yields an adequate estimate of the hazard contribution from gridded seismicity sources. However, at a smaller scale such coarse gridding yields artifacts and local variations in hazard that do not reflect any variability in the underlying rate data. For instance, if one increases the resolution of a map without a commensurate increase in discretization of the gridded rate model, an unnatural waffle-pattern emerges: hazard is higher at the center of each cell and decreases towards the edge. We explore the sensitivity of hazard to various point-source modeling choices with particular focus on grid source discretization, hypocenter randomization, the handling of strike, dip, and rake variability, and the use of distance corrections. We frame our results in the context of the broader uncertainties associated with a hazard model and the performance considerations necessitated by the particular hazard product required (*e.g.* map vs. web-service).

On the Sensitivity of Various Distance Metrics to the Uncertainties of Fault Rupture Model Parameters

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One of the main predictive variables for ground motion prediction equations (GMPEs) is the earthquake source to site distance. This can be determined by assuming a point or extended model for earthquake source. Considering a point source model, ground motion intensities grow by approaching to the source. For larger events and at short distances; however, distance metrics based on a point-source model are not appropriate. This is because of the slower attenuation trend at close distances for large events compared to small events. Assuming an extended source, the observed intensity remains constant in near-source region. As a result, GMPEs have used extended source to site distance metrics in their functional forms. Yenier and Atkinson (2014) have recently proposed equivalent point source modeling to capture saturation effect due to large earthquakes. They ended up with introducing an effective distance metric, which depends on the magnitude saturation term and increases with the increasing magnitude. Distance measures introduced for capturing saturation effects should be computed based on the dimensions of the fault rupture area. To determine the geometry of the ruptured area, empirical magnitude scaling relations such as those proposed by Wells and Coppersmith (1994) may be used in the computational framework of seismic hazard analysis (SHA). They formulated the rupture model parameters including the ruptured length, the ruptured width, and the ruptured area based on the moment magnitude. The aleatory uncertainties associated with these parameters are important source of variability and may significantly affect the final result of seismic hazard studies. We performed SHA for some earthquake scenarios to evaluate the sensitivity of various distance metrics to the uncertainties of fault rupture model parameters. Results show a better performance of the effective source to site distance in the near field region compared to distance metrics based on the extended source.

Upper Bounds of Sensitivities in Seismic Hazard Analysis

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It is common practice to define future seismic demands using probabilistic seismic hazard analysis (PSHA). Often it is not obvious, how PSHA responds to changes in its input parameters. In addition, PSHA relies on many uncertain inputs. Sensitivity analysis (SA) is concerned with the assessment and quantification of how changes in the model inputs affect the model response and how input uncertainties influence the distribution of the model response. Recently developed derivative-based global sensitivity measures can combine the advantages of Automatic Differentiation (AD) based adjoint methods with efficient sampling strategies facilitating quantitative global sensitivity analysis (GSA) for complex models.

In this work, we propose and implement exactly this combination. It allows an upper bounding of the sensitivities involved in PSHA globally and, therefore, an identification of non-influential and most important uncertain inputs. To the best of our knowledge it is the first time derivative-based GSA measures are combined with AD in practice. An illustrative example is shown for the suggested derivative-based GSA of a PSHA which uses stochastic ground-motion simulations.

Mean Seismic Hazard and Uncertainty Analysis Based on the UCERF3 Geologic Slip Rate Uncertainty Model for California

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The Uniform California Earthquake Rupture Forecast version 3 (UCERF3) model (Field *et al.*, 2014) considers epistemic uncertainty in fault slip rate via the inclusion of multiple rate models based on geologic and/or geodetic data. However, these slip rates are commonly clustered about their mean value and do not reflect the broader distribution of possible rates and associated probabilities. Here, we consider both a double-truncated 2-sigma Gaussian and a boxcar distribution of slip rates and use a Monte Carlo simulation to sample the entire range for California fault slip rates. We compute the seismic hazard following the methodology and logic tree branch weights applied to the 2014 national seismic hazard model (NSHM) for the western US region (Petersen *et al.*, 2014; 2015). We find a significant increase in the mean probabilistic ground motion over 1000 Monte Carlo samples of slip rate for a fixed annual probability in comparison with that calculated using only the mean or preferred slip rates in California. The difference in the mean probabilistic peak ground motion corresponding to a 2% in 50 year probability is less than 1% on average over all of California for both the Gaussian and boxcar probability distributions, but may reach about 18% in areas near faults compared with that calculated using the mean or preferred slip rates. The average uncertainties in 1-sigma peak ground motion level are 5.5% and 7.3% of the mean with the relative maximum uncertainties of 53% and 63% for the Gaussian and boxcar pdf, respectively.

Comparing Seismic Hazard Calculated with the 2014 USGS NSHM at Select Sites in the US at Different Periods and Site Classes

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The 2014 update of the USGS National Seismic Hazard Model (NSHM) included maps of ground motions with 2% and 10% probabilities of exceedance in 50 years, derived from hazard curves for peak ground acceleration (PGA), and 0.2 and 1.0 second spectral accelerations (SA) for NEHRP site class boundary B/C. With the fall 2016 release of the new USGS Java-based computer codes (nshmp-haz), revised maps were produced, which include additional periods and site classes. For both the central and eastern US (CEUS) and western US (WUS), additional maps for 0.1, 0.3, 0.5, and 2.0 second SA were produced. The WUS additionally includes maps for 0.75, 3.0, 4.0, and 5.0 second SA. The use of region-specific suites of weighted ground motion models (GMMs) used in the 2014 USGS NSHM precludes the calculation of ground motions for a uniform set of periods and additional site classes over the entire US. In the CEUS, hazard curves were calculated and a map was produced for NEHRP site class A. In the WUS, the calculation of ground motion is based on Vs30 or site class, so hazard curves were calculated and maps were produced for NEHRP site classes B, C, C/D, D, and D/E. Previous sensitivity analyses of the 2014 NSHM GMMs showed that some GMMs gave unrealistic results at specific periods and site classes. In these rare instances, the GMM in question was removed from the hazard calculation for all periods and site classes and its weight was redistributed to the remaining GMMs. We present hazard curves, uniform hazard response spectra (UHRS), and deaggregations for select sites in the CEUS and WUS at these additional periods and site classes, and compare the results with the 2008 USGS NSHM. The additional period and site class hazard curves and maps will be published on the USGS website and will also be submitted to the Building Seismic Safety Council (BSSC) for consideration in the development of the next-generation of multi-period seismic design value maps as part of Project '17.

Seismic Hazard, Risk, and Design for South America

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We calculate the seismic hazard, risk, and design criteria across South America using the latest data, models, and methods to support public officials, scientists, and engineers in earthquake risk mitigation efforts. The updated continental scale seismic hazard models are based on a new seismicity catalog, updated seismicity rate models, reevaluation of earthquake magnitudes, revision of fault geometry and rate parameters, and modification of ground motion models. The resulting probabilistic seismic hazard maps show peak ground acceleration, Modified Mercalli Intensity, and spectral accelerations at 0.2 s and 1 s periods for 2%, 10%, and 50% probabilities of exceedance in 50 years. Ground shaking soil amplification at each site is calculated by considering a reference soil with Vs30 of 760 m/s that is applied in modern building codes or by applying site specific factors based on shear wave velocities determined through a topographic proxy technique. We use these hazard models in conjunction with the PAGER model to calculate risk. Risk is computed by incorporating the soil amplified hazard, PAGER fragility/vulnerability equations, and LandScan 2012 estimates of population exposure. We also calculate building design values using the guidelines established in the National Earthquake Hazards Reduction Program building code provisions. The resulting hazard and associated economic and societal risk is high along the northern and western coasts of South America reaching damaging levels of ground shaking in Chile, western Argentina, western Bolivia, Peru, Ecuador, Colombia, Venezuela, and in localized areas distributed across the rest of the continent where historical earthquakes have occurred. Constructing buildings and other structures to account for strong shaking in these regions of high hazard and risk should mitigate losses and reduce casualties from effects of future earthquakes.

Recent Advances in Very Broadband Seismology
Poster Session · Thursday 20 April ·

A New Range of Direct Bury Instruments, from Very Weak to Strong Motion Sensors

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The endeavor to make every type of seismometer, weak to strong motion, reliable and economically deployable in any terrestrial environment continues with the availability of three new sensors and seismic systems including the Cascadia with over 200dB of dynamic range. Until recently there were probably 100 pier type broadband sensors for every observatory type pier, not the types of deployments geoscientists are needing to advance science and monitoring capability. The new Horizon broadband sensor will work both in a direct burial application or as a robust pier instrument. Boreholes are recognized as the quieter environments for the lowest noise observatory class instruments and the new T360 based instruments can now be deployed in direct burial environments which is unprecedented by removing the logistical limitations of previous systems. The experiences of facilities in large deployments of broadband seismometers in continental scale rolling arrays proves the utility of packaging new sensors in corrosion resistant casings and designing in the robustness needed to work reliably in temporary deployments. Integrating digitizers and other sensors decreases deployment complexity, decreases acquisition and deployment costs, increases reliability and utility. We'll discuss the informed evolution of broadband pier instruments into the modern integrated field tools that enable economic densification of monitoring arrays along with supporting new ways to approach geoscience research in a field environment.

New Instrumantation for Measuring Acceleration, Pressure, and Temperature (APT) with Wide Dynamic Range and Bandwidth

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We present a new tool that facilitates the study of inter-related geodetic, geodynamic, seismic, and oceanographic phenomena. It incorporates a temperature compensated tri-axial accelerometer developed by Quartz Seismic Sensors, Inc., a pressure sensor built by Paroscientific Inc., and a low-power, high-precision frequency counter built by RBR, Ltd. The sensors are housed in a 7 cm o.d. titanium pressure case designed for use to full ocean depths (withstands more than 20 km of water pressure). Sampling intervals are programmable from 0.08 s to 1 hr; standard memory can store up to 130 million samples; total power consumption is roughly 115 mW when operating continuously and proportionately lower when operating intermittently (*e.g.*, 2 mW average at 1 sample per min). Serial and USB communications protocols allow a variety of autonomous and cable-connection options. Measurement precision of the order of 10-8 of full scale (*e.g.*, pressure equivalent to 4000 m water depth, acceleration = ± 3 g) allows observations of pressure and acceleration variations of 0.4 Pa and 0.3 µm s-2. Long-term variations in vertical acceleration are sensitive to displacement through the gravity gradient down to a level of roughly 2 cm, and variations in horizontal acceleration are sensitive to tilt down to a level of 0.03 µrad. With the large dynamic ranges, high sensitivities and broad bandwidth (6 Hz to DC), ground motion associated with microseisms, strong and weak seismic ground motion, tidal loading, and slow and rapid geodynamic deformation—all normally studied using disparate instruments—can be observed with a single tool. Installation in the marine environment is accomplished by pushing the tool roughly 1 m vertically below the seafloor with a submersible or remotely operated vehicle, with no profile remaining above the seafloor to cause current-induced noise. The weight of the tool is designed to match the sediment it displace

Early Results from the Borehole Very Broad Band Seismometer Development Program

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In 2013, the USGS issued a Request for Information on the state of existing or planned Very Broad Band (VBB or 360s – 50Hz) instrumentation suitable for operation in programs such as the Global Seismographic Network (GSN). A Request for Proposals was issued in 2014. A Contract was awarded to Kinemetrics, Inc., heading a team including Streckeisen, GmbH for development of a prototype VBB Borehole Sensor. A prototype sensor was delivered in 2015, followed by delivery of 3 pre-production sensors in 2016. Tools and methods for evaluation were developed to facilitate testing of the new sensors, including a controlled test site with 3 adjacent boreholes in the Albuquerque Seismological Laboratory (ASL) tunnel to facilitate coherence analysis and evaluate methods of mechanical coupling of the sensors to the borehole environment. A miniature vibratory compactor tool was developed to accelerate mechanical settling of borehole installation. A small, highly portable drill was employed to enable rapid installation of the new sensors in shallow boreholes in pier installations or other appropriate setting as a possible improvement over surface instrumentation. A shallow borehole was installed through the pier at GSN station TUC (Tucson, Arizona). Results will be presented for the TUC deployment and tests of the new sensors in deep boreholes at ASL. Further work will be discussed.

Co-Located Broadband Ground Motion Similarity During Moderate Shaking from 100 to 400 s Period

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During large earthquakes, co-located seismic sensors (when well calibrated) should see similar ground motions. Deviations between the sensors indicate that our ability to estimate ground motions with high fidelity could be compromised, or that we do not completely account for all of the variables in the data that we record. We look at variations between co-located sensors for events of M>6.5 from 2010 through 2015 using data from the IRIS/USGS (network code IU) component of the Global Seismographic Network (GSN) which has approximately 80 stations. Most of these stations are composed of a very broadband primary sensor (STS-1 or KS-54000; corner period of 360 s) as well as a secondary broadband sensor (STS-2 or T-240; corner period of 120 s or 240 s, respectively). Recent studies have shown that at low noise levels, such as in the vault at the Albuquerque Seismological Laboratory (ASL), coherence between even very closely spaced sensors drops off drastically at long periods. Noise levels at GSN sites can be highly variable and can also vary between co-located sensors, but by examination of moderate shaking from large earthquakes, we observe and analyze ground motions well above GSN station noise models.

Verification Testing of Trillium 360—A New Seismometer for Global Seismology

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Test results for Trillium 360 show this seismometer can resolve the Peterson New Low Noise Model down to 300 seconds period. This has been confirmed at multiple sites: Pinon Flat (California), Albuquerque Seismological Laboratory (New Mexico) and Nanometrics (Ottawa, Canada).

The Pinon Flat deployment captured the March 2, 2016 M_w=7.9 Indonesian event and showed a response coherent with reference sensors including an STS-1 at periods down to 0.0015 Hz. At frequencies below 0.0015 Hz the reference sensors showed a noncoherent spurious response, *i.e.* noise in the presence of signal, whereas the Trillium 360 was relatively unaffected.

Magnetic sensitivity has been measured to be ~0.01 m/s^2/T in two independent tests at ASL and Nanometrics. Temperature sensitivity is ~3*10^-4 m/s^2/T. This combination of low sensitivity to both magnetic field and temperature is achieved through magnetic shielding which resolves the side effect of magnetic sensitivity in temperature-compensated ferromagnetic spring alloys.

The T360 seismometer components are sufficiently miniaturized for deployment in a borehole. This enables low-noise performance even in an urban environment with thick sediments (at Nanometrics, Ottawa) since the seismometer can be emplaced in bedrock below surface sediments and away from surface noise.

Event Based Seismic Station and Network Quality Analysis for Temporary Deployments

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Often seismic station data quality is defined by metrics such as data completeness or background seismic noise levels in specific frequency bands. However, for temporary networks such as aftershock deployments or induced seismicity monitoring, many times the most critical metric is how well the station performed when recording particular events of interest. This type of feedback can be used for real-time network maintenance and to help make decisions about which stations may need to be moved or are redundant. We employ several event-based metrics to assess station and network performance including determining signal-to-noise ratios and relative recorded amplitude for local events. We also use regional and teleseismic events to determine relative station orientation and relative amplitude response between each of the deployed stations. At times, a complete catalog of local seismic events may not exist, such as in an aftershock deployment where hundreds to thousands of small earthquakes may be happening but catalog generation efforts cannot keep up. To overcome this we use an envelope of the average energy recorded by the network to identify events of interest. We find that the log amplitude of events identified using this technique scales linearly with local earthquake magnitudes indicating that this approach can be used to determine seismicity rates and detection thresholds for small events (m<2.0) even with an incomplete local earthquake catalog. Rapid determination of these parameters can help guide station maintenance and has the potential to give new insight into future temporary deployment strategies.

Detection of Low Magnitude Intermediate Depth Earthquakes from Bucaramanga Nest Across Dense Surface Seismic Array

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Intermediate-depth earthquakes (50-300km deep) are relatively poorly understood when compared to their deep and shallow earthquake counterparts. The most studied and active intermediate-depth earthquakes are located in the Bucaramanga Nest in Colombia. This active seismic patch (4 x 4 x 8km) is known to exhibit both spatially and temporally repeated earthquakes that are recorded and observed on the Colombian Seismic Network (RSNC). Although this sparsely distributed receiver network across Colombia is utilized mainly for relocation purposes, and is limited in producing only earthquake catalogs complete up to M2.0 and greater.

The objective of our research is to push the detection threshold down to include lower magnitude earthquakes (M<2.0) occurring from the intermediate-depth Bucaramanga earthquake nest utilizing a dense surface seismic array that was deployed a few hundred kilometers north of the earthquake nest. The array is about 70km^2 with over 4500 single component (z-direction) receivers, spaced 100m apart, and was left recording continuously for 4 days.

By utilizing the close geophone spacing, we try to detect new smaller-magnitude earthquakes (M<2) across the 4-day recording period using the larger magnitude detected earthquakes from the RSNC catalog observed during the same time period of the recording surface array as reference earthquakes and cross-correlate each reference earthquake's waveform with the whole surface array recording time series.

Our Preliminary results suggest that the dense surface array is capable of detecting additional lower magnitude earthquakes absent from the RSNC catalog. One of the biggest challenges is related to poor S/N ratio across parts of the dense array and complicates the waveform-based detection. Proper signal processing is necessary to do prior to waveform-based cross-correlation detection and will be investigated in future work.

Mitigation of P-Wave Reverberations in Teleseismic Earthquake Signals Observed with Floating-Platform Seismographs

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A 34-station broadband array was installed across the approximately 1000 km wide Ross Ice Shelf (RIS) in late 2014 in a two-year deployment. The data will be utilized for passive imaging of crustal and upper mantle velocity structures of the portion of West Antarctic Rift System located beneath RIS. However, the floating ice shelf platform presents significant and unusual challenges to the use of teleseismic body wave arrivals for imaging: (1) The water layer decouples steeply-incident direct S-waves and P-to-S conversions originating in the lithosphere; and (2) Strong impedance contrasts at the ice-water and water-sediment interfaces result in large amplitude P and S reverberations. We test the efficacy of different algorthims for removing the effects of the ice and water layers and also discuss prospects for incorporating reverberations as a control parameter in crustal inversions.

Portable Array Deployment in the Zevulun Valley (Haifa Bay), Israel—Ground Motions and Amplifications

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The Zevulun Valley (ZV), northern Israel, underlies the densely populated metropolitan of Haifa. Also a major infrastructure (*e.g.* port) and industrial (*e.g.* petrochemistry) hub. The ZV is located in close proximity to active tectonic borders: the Dead Sea transform (50 km to the east) and the Cyprus/Lebanon Collison zone (up to 180 km to the north). The Israeli seismic network is deployed mainly on hard rock sites and does not cover the ZV. Although being a seismically vulnerable and strategically critical region, earthquake ground motion records in the ZV are not available.

The geological structure of ZV is complex, comprised of two grabens bounded by east-west striking normal faults divided by a horst. At its southern-end the ZV is bounded by the active Carmel fault. At the surface, the Kurkar Gr. (Vs ~ 200 m/s) covers the entire valley, tens of meters thick atop the grabens and thinner above the horst, it contains clayey and sandy soils, sand dunes and conglomerates. Beneath this layer the grabens are filled with soft chalks and limestones of the Saqiye Gr., Avdat Gr., and the Mount Scopus Gr. The top of the Judea Gr., a significant seismic reflector (Vs ~ 2000 m/s), closes the structure from below with a maximum depth of 2000 m at the southern graben and 400 m at the northern graben.

Here we report the results of a 16 months long (08/14–12/15) monitoring campaign using a small portable array of broadband seismometers, deployed both on rock and basin fill. During the deployment of the array more than 80 magnitude M 2 to M 5.5 regional earthquakes and numerous M > 5 global earthquakes were recorded with an acceptable S/N ratio. We study ground motion amplifications of selected earthquakes using both single-station horizontal over vertical spectral ratio and site-to-reference spectral ratio. We find significant ground motion amplification in the Zevulun basin, up to a factor of 8 at in the shallow part of the basin and up to a factor of 4 in the deeper parts.

Recent Moderate Oklahoma Earthquakes: Widely Felt and Often Damaging

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Vs30 from Multi-Method Site Characterization Approach at Seismograph Locations in the Fairview, Oklahoma Region

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To better constrain ground motion models for induced seismicity in the Oklahoma region, we acquired active- and passive-source seismic data for time-averaged shear wave velocity to 30 m depth (Vs30) at 13 seismograph locations near Fairview, Oklahoma. Each seismograph had recorded at least one M4+ earthquake within 20 km hypocentral distance. We collected active-source P- and SH-wave body and surface wave data on 72-sensor linear arrays, with collocated 4.5 Hz vertical and single-component horizontal sensors. The sensors were spaced at 1.5 m with off-end source locations, using a 4.5 kg sledgehammer source, for each dataset. In addition, we collected linear-array passive refraction microtremor (ReMi) data with vertical sensors. The active source data were analyzed for P- and SH-wave refraction traveltimes and Rayleigh- and Love-wave phase velocity dispersion. The resulting observations were then modeled in a nonlinear least-squares joint inversion to obtain a best-fit one-dimensional shear wave velocity-versus-depth profile for each site. The ReMi passive-source data were independently forward-modeled for comparison. At many of the sites the preferred joint inverse model did not optimally fit each of the Love, Rayleigh and SH traveltime datasets; therefore, two of the three sets were typically fit preferentially. Taken as a whole, we estimate five sites to be NEHRP class D while the remaining eight are class C. Site amplification estimates were next calculated from 1D SH transfer functions (program "nrattle"). The active-source models suggest amplifications up to 7 within the 2-7 Hz frequency band relative to modeled bedrock depth and Vs at a given site. The ReMi models tend to be less variable in Vs30 but also indicate amplification in the 3-6 Hz range. Horizontal-to-vertical spectral ratios from the seismograph data are also amplified in the 2-10 Hz range. The Vs30 values and site classes are broadly comparable with estimates from other data sources in this area.

Brune Stress Parameter Estimates For The 2016 Mw5.8 Pawnee And Other Oklahoma Earthquakes

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I have estimated Brune (single-corner) stress parameters for several Oklahoma earthquakes, including the 2016 M_w5.8 Pawnee earthquake. My approach is to estimate corner frequency from the peak of the tangential component of the velocity Fourier spectrum using recordings about 50 km or less from the epicenter, when possible. Because Brune stress parameter is for body waves, care has been taken to avoid contaminating spectral peaks from leaky-mode surface-waves, nearby-building interactions, and soil resonances. For shallow earthquakes, leaky-mode surface-waves have been observed overlapping P and S waves, including in Oklahoma. So spectral shape fitting has been avoided in this study. Brune stress parameter for an earthquake is estimated from the corner frequency and seismic moment (from moment magnitude). Oklahoma earthquakes (potentially induced) tend to be shallow (less than 10 km and usually ~5 km or less). In general, Brune stress parameter for the M_w5.8 Pawnee and other Oklahoma mainshocks ranges between 15 and 20 MPa, while aftershocks and smaller magnitude earthquake stress parameters fall in the 1 to 10 MPa range. These values are typical for the south central US potentially induced and natural earthquakes. Other eastern North America regions have natural earthquake stress parameters above 15 MPa, but shallow natural earthquakes can have values in the 2 to 12 MPa range similar to potentially induced earthquakes. Comparisons with the CEUS estimates using spectral shape fitting approaches of Yenier and Atkinson (2015) and Boyd *et al.* (2017) demonstrate that leaky-mode surface waves and site resonances can bias corner frequency estimates, which affects stress parameter values and interpretations.

Regional Moment Tensor Inversion—Creation of a Defensible Velocity Model for Inversion

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We have undertaken the task of determining regional moment tensors for M > 3.5 earthquake in the continental US and Canada (excluding California). Our catalog of over 1400 solutions is dominated by recent activity in Oklahoma due to induced earthquakes. This catalog is a resource for other studies on stress directions and high frequency ground motion scaling. Since most of these earthquakes are shallow, and since earthquake depth determined by arrival times is a poorly defined parameter unless there are observations at stations within a few source depths, full waveform modeling through moment tensor inversion offers an independent depth estimate if the local velocity model used can be defended. This emphasis on depth is important for induced earthquakes when the question is whether the events occurred in the basement or in the overlying sedimentary section. We present case studies for source areas in Oklahoma, Texas and Kansas that highlight the combined use of short period dispersion tomography, receiver functions and known geology to define velocity models that can be used to test the moment tensor depths obtained using generic regional models.

MyShake: Smartphone-Based Detection and Analysis of Oklahoma Earthquakes

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MyShake is a global smartphone seismic network that harnesses the power of crowdsourcing (myshake.berkeley.edu). It uses the accelerometer data from phones to detect earthquake-like motion, and then uploads triggers and waveform data to a server for aggregation of the results. Since the public release in Feb 2016, more than 220,000 android-phone owners have installed the app, and the global network has recorded more than 450 earthquakes by Jan 2017.

In Oklahoma, there are about 200 active users each day providing enough data for the network to detect earthquakes and for us to perform analysis of the events. MyShake has recorded waveform data for M2.6 to M5.8 earthquakes in the state. For the September 3, 2016, M5.8 earthquake 14 phones detected the event and we can use the waveforms to determine event characteristics. MyShake data can provide estimations of location, magnitude, stress drop and so on. For other earthquakes in Oklahoma, MyShake is providing an extra dataset for the earthquakes in Oklahoma.

MyShake is still a rapidly expanding network that has the ability to grow by thousands of stations/phones in a matter of hours as public interest increases. These initial results suggest that the data will be useful for a variety of scientific studies of induced seismicity phenomena in Oklahoma as well as having the potential to provide earthquake early warning in the future.

Poroelastic Properties of the Arbuckle Group in Oklahoma Derived from Well Fluid Level Response to the Mw5.8 Pawnee and Mw5.0 Cushing Earthquakes

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The Arbuckle Group (Arbuckle) is a basal sedimentary unit that is the primary target for salt water disposal (SWD) in Oklahoma. Thus, the reservoir characteristics of the Arbuckle, including how the poroelastic properties change laterally and over time are of significant interest. We report observations of fluid level changes in two monitoring wells in response to the 3 September 2016 M_w5.8 Pawnee and the 7 November 2016 M_w5.0 Cushing earthquakes. We investigate the relationship between the fluid level change at the wells and static strain resulting from these events. We predict the fluid level response by estimating static strains from a set of earthquake source parameters and spatiotemporal poroelastic properties of the Arbuckle in the neighborhood of the monitoring wells. Results suggest that both the direction of the fluid level step and the amplitude can be predicted from the computed volumetric strain change and a reasonable set of poroelastic parameters. Modeling results indicate that poroelastic parameters differ at the time of the Pawnee and Cushing earthquakes, with a moderately higher Skempton's coefficient required to fit the response to the Cushing earthquake. This may indicate that shaking from the Pawnee earthquake resulted in physical alteration of the Arbuckle at distances up to ~50km away.

Understanding the Roles of Fluid and Faulting in Earthquake Sequences Using Data from Central Oklahoma

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The Prague, Oklahoma, earthquake sequence that occurred in November 2011 produced three earthquakes with magnitudes M_w 5.0, 5.6, and 4.9. The sequence occurred along the Wilzetta fault system and delineates a nearly vertical fault that trends to the NE. Immediately southeast of the Prague sequence, there is another cluster that lacks any M4 events. Double-difference relocation with a 3D model and waveform cross-correlation reveals clear fault trends in the southeast cluster, which consists of three sub-parallel fault trends. Analysis of the spatial-temporal evolution of the Prague sequence (after declustering) and the southeast cluster shows clear diffusivity from the location of the first events, suggesting the involvement of fluid. To better understand the occurrence of large magnitude events, we conduct further detailed seismological analysis in this area, and seek to compare the two clusters in terms of the seismicity, source parameters and relationship to injection history.

Our current dataset consists of 6450 earthquakes in the Prague area, including events obtained through subspace detection, which significantly increased the number of events at shallower depths. We have currently obtained stress drop value for 518 events in this sequence using a stacking-based empirical Green's function (EGF) analysis. We are currently conducting finer scale analysis to investigate the stability of the stacking analysis, and comparing results with individual-event pair analysis. For the southeast cluster, we are also analyzing source parameter variations, but only with individual pair methods, as it lacks the large number of events for stacking analysis.

Combing the seismicity statistics, source parameter analysis for each separate cluster and injection well records, we will try to understand if there are any manifestations of fluid flow propagation from earthquake parameters, and if there is any correlation between fault mechanics and the occurrence of events M>5.

Seismotectonics

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Seismic Evidence for Splays of the Eureka Peak Fault beneath Yucca Valley, California

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In April 2015, we acquired high-resolution P- and S-wave seismic data along a 3.1-km-long, E-W-trending profile in Yucca Valley, California. Our seismic survey was designed to locate possible sub-parallel faults of the Eureka Peak Fault, which trends ~NW-SE near the western end of our profile. The Eureka Peak Fault is a potential hazard to the Yucca Valley region, as it appears to have experienced surface ruptures associated with both the 23 April 1992 M 6.1 Joshua Tree earthquake and the 28 June 1992 M 7.3 Landers earthquake. We simultaneously acquired P- and S-wave data using explosive sources spaced every 100 m, along with higher resolution P-wave data from seisgun sources spaced every 5 m. Each shot was co-located with and recorded by 634 P-wave geophones (40-Hz) spaced 5 m apart and 250 S-wave geophones (4.5-Hz) spaced 10 meters apart. We developed P-wave tomographic velocity models and reflection images that show at least one significant fault about 2.3 km NE of the Eureka Peak Fault. This fault may potentially pose a hazard and affect groundwater flow in the area.

From Slab to Peak: A Summary of Recent Seismic Advancements to Understanding Llaima Volcano, Chile

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Llaima Volcano in Chile is one of the largest and most active volcanoes in the southern Andes, with over 50 eruptions since the 1600s. After years of persistent degassing, Llaima most recently erupted in a series of violent Strombolian eruptions in 2008-2009. This period had few precursory signals, which highlights the need to obtain accurate magma storage information. While petrologic advancements have been made in understanding magma degassing and crystallization trends, a comprehensive geophysical study has yet to be completed. From January 2015 to March 2015, twenty-four broadband seismic stations were operated continuously on an approximately 30 km by 20 km area surrounding Llaima volcano as part of a UNC Chapel Hill, MIT, and Boise State University collaboration. We bring together recent results from 2-D travel time, ambient seismic noise tomography, and receiver function studies to present a geophysical model of Llaima's internal geometry. Arrival time perturbations from regional and teleseismic events were used to identify a low velocity anomaly at least 10km in diameter beneath the volcano edifice. Ambient noise tomography was used to estimate group velocity dispersion between receiver pairs in the array. Initial results reveal two low velocity zones beneath the volcano: one below the summit and a second eastward of the summit. Receiver function H-k stacking and common conversion point (CCP) stacking were conducted to obtain a crustal thickness estimate of 42 km and to examine crustal discontinuities. A seismic phase converter was discovered at approximately 12 km depth to the southeast of Llaima, which we interpret to be the top of a body of partial melt. By combining these complementary results, we present a new geophysical model of Llaima Volcano that is consistent with available petrologic data.

A New Method for Statistical Assessment of Shear Wave Splitting Measurements

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Shear wave splitting, which measures the effects of elastic anisotropy, has proven to be an excellent technique for constraining the strain history of the lithosphere. However, the two most commonly used methods for measuring shear wave splitting both suffer from limitations. The widely-used Silver and Chan [1991] method is not easily adaptable to complex anisotropic scenarios without significant assumptions, and has been shown to underestimate uncertainties [*e.g.* Walsh *et al.*, 2013]. The cross-convolution method by Menke and Levin [2003] can analyze more complex anisotropy, but there is no clear way to assess uncertainties. Without true uncertainties, one cannot conduct formal hypothesis testing. Moreover, in an Earth with complex lithospheric and asthenospheric strain histories, having a method to correctly combine multiple observations to improve resolution of layered structure is essential. We propose a statistical augmentation to the cross-convolution approach. In our method, correlation structures of the noise are accounted for to create a log-likelihood surface of the splitting parameters that provides the statistical context for formal hypothesis testing of anisotropy. The method has been benchmarked using synthetics along with data from the Pasadena, California seismic station (PAS) and the results have been sensible and consistent with previous studies [*e.g.* Liu *et al.*, 1995]. The current method has been developed for a single-layer approach, but the path is clear for analyses of anisotropy for multiple and dipping layer models.

The Future of Past Earthquakes

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A Late Cenozoic Kinematic Model for Fault Motion within the Greater Cascadia Subduction System

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Relatively low fault slip rates have complicated efforts to characterize seismic hazards associated with the diffuse subduction boundary between North America and offshore oceanic plates in the Pacific Northwest 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—all 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 scope of 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 Ma to present, with only minor reorganization 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 across the central 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, and substantial oroclinal bending of the Crescent Formation basement surrounding the Olympic Peninsula.

This quantitative reconstruction provides an integrated framework with which to investigate the motions of various Pacific Northwest 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 Pacific Northwest region.

Increased Late Quaternary Slip Rates in the Southern Lower Rhine Graben, Central Europe

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Low-strain regions are characterized by long earthquake recurrence intervals (10^4-10^6 yr). In these regions, it is often difficult to find Quaternary markers suitable for documenting fault slip histories. The Lower Rhine Graben (LRG) in the border region of Germany, Netherlands, and Belgium provides a unique opportunity to evaluate the steadiness of Quaternary slip rates using the basal contact (2.29 Ma) and surface (700 ka) of the regionally extensive Hauptterrasse (main terrace) deposited by the Rhine and Maas Rivers. These markers are vertically offset by a distributed network of northwest-trending, slow-slipping (<0.1 mm/yr) normal faults. In this investigation, we construct Quaternary slip histories for the southern LRG faults using vertical offset measurements for the surface of the Hauptterrasse made from light detection and ranging (LiDAR)-derived terrain models. We synthesize these surface offset measurements with previous vertical offset constraints for the basal contact of the terrace using 91 collocated displacement sites. We find that >80% of the sites record an apparent increase in slip rate for the more recent interval from 700 ka to present, which corresponds to a period of increased regional uplift and volcanism. The average amount of slip rate increase is ~87%. However, the basal contacts may be non-correlative, resulting from erosion of the footwall surface below the Hauptterrase in the early Quaternary. In this case, the apparent displacement is smaller than the total vertical offset since the start of the Quaternary, leading to an apparent increase in slip rate. Prior work focused on seismic characterization of LRG faults has preferentially relied on the average fault slip rate constrained using the base of the main terrace. We suggest that average fault slip rates calculated using the 700 ka terrace surface are subject to fewer uncertainties and sample a time interval that is more relevant for seismic hazard analysis.

A New Slip Rate for the West Tahoe Fault and the Age of Glacial Deposits Using Cosmogenic 10Be Near Lake Tahoe, California

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The West Tahoe Fault is the 45 km long, primary range-bounding fault of the Sierra Nevada at the latitude of Lake Tahoe, California. It is a N-NW striking, east dipping normal fault that has a pronounced terrestrial Holocene scarp extending from near Meyers, CA to Emerald Bay, where it continues offshore along the western margin of the lake until it approaches Tahoe City. The West Tahoe Fault displaces late Pleistocene moraines and glacial deposits along much of its extent. Terrestrial Cosmogenic Nuclide (TCN) surface exposure ages of sixteen boulders were collected from faulted moraines at Cascade Lake. The eight ages from the last-glacial Tioga moraine range from 13.8 to 23.7 ka, and seven of these ages average 21.6 ± 2.8 ka, similar to the age of Tioga moraines elsewhere in the Sierra Nevada. The eight ages from the penultimate Tahoe moraine are distributed and scattered from 14.5 to 120.8 ka. We treat the oldest measured boulder of 120.8 ka as the minimum age of deposition for the older Tahoe moraine based on the assumption that morainal boulders contain little cosmogenic inheritance and scatter is largely the result of weathering processes. Vertical separation produced by fault displacement is measured from lidar to be 32 ± 8 m of vertical offset across the Tioga moraine and 59 ± 10 m of vertical offset across the Tahoe moraine. Dividing these ages (21.6 and 120.8 ka) by these vertical separation measurements, gives average vertical separation rates of 1.5 ± 0.6 mm/yr since Tioga time, and 0.5 ± 0.1 mm/yr since Tahoe time. It is reasonable to assume that the fault dips 60° as does the neighboring Genoa fault (with a similar strike and length), and this dip allows for an average slip rate of the West Tahoe Fault of 1.7 ± 0.7 mm/yr since Tioga time and 0.6 ± 0.1 mm/yr since Tahoe time. This almost threefold increase in slip rate may be real or is possibly an artifact of the younger moraine being draped over a preexisting scarp.

Quaternary Active Tectonic Deformation of the Transgressive Surface Offshore Ventura, CA, Constrained by New Geophysical Data

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The Transverse Ranges are a thrust-and-fold belt that accommodates the contraction resulting from a regional restraining bend in the San Andreas fault. The E-W trending Ventura basin, which is filled by more than 5 km of Pleistocene sediment, is shortening at about 10 mm/yr as inferred from geodetic data. Although the geological structure is fairly well known in the onshore areas of the basin, there is still discussion about how the different onshore thrust and folds continue in the offshore, and the deep relationship between the main faults. New high-resolution seismic data (chirp) was acquired in the area, that when combined with existing geophysical information, allows for a better understanding of the current activity of geological structures in the offshore. The dense seismic dataset allows us to identify different latest Quaternary seismostratigraphic units and horizons, with the most regionally recognized being a transgressive surface (LGTS) associated to the Last Glacial maximum and subsequent sea level rise. This surface is cut across and deformed by a series of E-W regional folds that produce elongated and parallel highs and depressions, and some emergent faults. Below the LGTS there is Early to Late Pleistocene units that are deformed by high amplitude regional folds and some local faulting. Above the LGTS we have identified progradational and agradational units that are related to global sea level rise, and which show less deformation (folding and faulting) than the lower units and horizons. Based on our analysis of the entire dataset, we have mapped the late Quaternary active structures in the offshore Ventura basin, which leads us to propose a new deep structural geological model of the basin. In addition, a preliminary interpretation of some specific fold growth sequences has allowed us to identify different tectonic deformation events (*e.g.* earthquakes) and, thus, their deformation history may be determined.

A 200 Ka Paleoseismic Record of Earthquake-Triggered Slumps and Soft Sediment Deformation in the Dead Sea Basin

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Extensive exposures of spectacular slump sheets in lake deposits within the Dead Sea Basin are interpreted as seismites related to the activity of the plate-bounding Dead Sea Fault. The late-Pleistocene Lisan Formation and subsequent Dead Sea deposits comprise alternating aragonite laminae precipitated from the hypersaline lake and detrital laminae of fine clastic material that was washed into the lake during winter floods. The detritus-aragonite ratio in the layers affects their style of deformation, where ductile folding preferentially occurs in detritus-rich strata and brittle faulting is more common in aragonite-rich strata. We interpret the large variety of folds and thrusts as showing evolutionary sequences that reached different stages of development. Individual slump sheets appear to consist of multiple coeval second-order flow cells, each includes normal faults and pinched strata as well as folds and thrusts. The cells interact with neighbouring cells during translation of the slump. We interpret slumps with alternating systematic reversals in fold vergence up through the sequence that are truncated at the top and capped with upward-finning breccia, as the result of earthquake-triggered seiches.

We conclude that the slump sheets were triggered by earthquakes, facilitated by detrital-rich horizons, and controlled by the palaeoslope orientation. The stable stratification, asymmetry of the folds that evolved from open moderate folds through billow-like asymmetric folds, coherent vortices, and finally turbulent chaotic structures, are explained by the Kelvin-Helmhotz shear instability as the governing mechanism. The Dead Sea Deep Drill Core extends the paleoseismic record back to about 200 ka, one of the longest continuous records in the world.

Paleoseismic Interpretation of Past Earthquakes Validated by Long Historical Records Argue for Large Scale Regional or Fault Interaction

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Analysis of paleoseismic records in regions of long historical accounts of earthquakes provides an independent test of the paleoseismic data. In this study, we test the 2000-year record of paleoseismic events from the North Anatolian fault (NAF) in Turkey and the Dead Sea Transform fault (DST) in the Levant against the historical record of destruction from large earthquakes. Taken by itself, the age uncertainties associated with paleoseismic data along the NAF allow for multiple interpretations, including random distribution of earthquakes through time. The historical data resolve a more systematic and potentially interpretable pattern. Historical data also confirm that the paleoseismic data are reliable in the sense of identifying important events and not being cluttered with other disturbances not related to earthquakes. There is a virtual one-to-one correlation between paleoseismic events and historical earthquakes, validating the nearly twenty paleoseismic studies that have been conducted on the NAF plate boundary. As further confirmation, 3D trenching at some sites demonstrates that interpreted events produced meters of displacement. Similarly, 2D and 3D paleoseismic data from the DST, although sparser, are confirmed by the long historical record of damaging earthquakes. With the temporal resolution of historical EQ ages, both data sets argue for temporal sequences of large earthquakes followed by periods of one to several hundred years of quiescence. This pattern is similar to the current situation in California where there is a nearly 100 year open interval for large earthquakes on the main plate boundary faults. We favor an explanation of long gaps that involves large scale regional fault or lithospheric interaction, and in which event triggering is only partially explained by Coulomb stress interactions.

Century-Long Paleo-Seismic Hiatus in California and New Zealand

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Dates of paleoseismic events at 32 sites on 13 California faults, compiled for the third Uniform California Earthquake Rupture Forecast (UCERF3), revealed a puzzling feature: no events after 1918. Corrected for multiple-site ruptures, the total reported paleo-event rate for the whole record is about 0.04 per year. A century-long hiatus is extremely unlikely (about 1%) for a Poisson process at the average rate, and even less probable for an ensemble of quasi-period processes as reported in the UCERF3 reports.

Paleoseismic data for New Zealand, as summarized by Nicol *et al.* in 2016, show a similar feature. The most recent primary rupture at any of the 27 sites occurred before 1900. The average rate of events there is about 0.03 per year; The probability of a century or longer hiatus there is about 3% assuming that the faults are independent and the whole ensemble behaves as a Poisson process.

Possible explanations for the anomalous hiatuses include (1) extreme luck, (2) unexplained regional fault interaction, or (3) significant over-estimation of the paleo-seismic event rate.

Explanation (1) can be rejected with 99% and 97% confidence, respectively, if California and New Zealand are considered separately. The probability that both would experience quiescence during the same century is about 0.0003.

Explanation (2) is not supported by any evidence in the pre-1916 paleoseismic history nor in any theoretical models yet reported.

Explanation (3) could explain the data if non-seismic paleo-events were counted before the instrumental seismic era, but not afterwards.

Variations in Surface Fault Rupture Recurrence and Seismic Moment Release in the San Francisco Bay Region During the Past Four Centuries

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The paleoseismic history of the ensemble of faults that defines the Pacific-North American plate boundary in the San Francisco Bay Region (SFBR) provides, together with historical seismicity, an earthquake catalog to evaluate rates of surface faulting and seismic moment release from about 1600 AD to the present. With these data we define five intervals: 1) 1600-1689 and 2) 1690-1776 are paleoseismic; 3) 1777-1905, 4) 1906, and 5) 1907-2016 are historical /instrumental. For the paleoseismic intervals 11 ruptures on ten fault sections are modeled as 7 (minimum), 11 (maximum) and 9 (preferred) sources (single and multi-fault) with estimated M_w ranging from 6.5 to 7.8 The number of surface ruptures for each interval is: 1) 3; 2) 6; 3) 3 (1838 San Andreas, 1868 Hayward, 1890 San Andreas; 4) 1 (1906 San Andreas); 5) 2 (1983 Greenville, 2014 West Napa). Based only on surface faulting estimates the sum of the mean moment (10^E dyn·cm) and moment release rate (10^E dyn·cm/yr) for each interval are, respectively: 1) 4.7^{26}, 5.28^{24}; 2) 2.34^{27}, 2.72^{27}; 3) 5.87^{26}, 4.59^{24}; 4) 3.82^{27}; 5) 1.97^{25}, 1.79^{23}. SFBR moment release rates for the entire 1600-present interval are 1.75×10^{25} dyn·cm/yr from surface faulting and 2.21×10^{25} dyn·cm/yr with seismicity included. 1690-1776 stands out as a regional cluster followed by infrequent surface faulting until 1906. Similarly, only two minor surface ruptures have occurred since 1906. This analysis shows that large amounts of moment release can be distributed across the SFBR's major faults during a relatively short interval or can occur in a single great event like 1906. Both styles result in subsequent century-long reductions in rates of surface faulting. How post-1906 quiescence will end is uncertain but it is perhaps more likely to follow the paleoseismic pattern than to repeat 1906.

Earthquake Forecast For The Wasatch Front Region by the Working Group on Utah Earthquake Probabilities: Final Results

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In the first comprehensive study of its kind outside of California, the Working Group on Utah Earthquake Probabilities (WGUEP) has assessed the likelihood of large earthquakes in the Wasatch Front region. The WGUEP forecast includes the probability of one or more earthquakes of a specified magnitude range in the region in the next 30, 50, and 100 years. Both time-dependent and time-independent models were used to characterize the probabilities for the central segments of the Wasatch fault zone and the Great Salt Lake fault zone. Only time-independent probability estimates were made for the other 45 faults and fault segments and background earthquakes within the Wasatch Front.

There is a 43% probability that the Wasatch Front region will experience at least one moment magnitude (M) 6.75 or greater earthquake in the next 50 years. This total probability for the entire region is based on new geologic information on the timing and location of large prehistoric earthquakes on known faults in the region. For example, the WGUEP's review of paleoseismic investigations of the Wasatch fault zone indicates that at least 22 large prehistoric earthquakes have ruptured parts of this fault between Brigham City and Nephi in the past 6000 years. The probability of at least one M 6.75 or greater earthquake on the Wasatch fault zone is 18% in the next 50 years and 6% on the Oquirrh-Great Salt Lake fault zone. The probability of one or more M 6.75 or greater earthquakes on the other 45 faults or fault sections is 25% in the next 50 years.

There is a 57% probability of one or more M 6.0 or greater earthquakes in the region in the next 50 years. This total probability is based on the probability of M 6.0 or greater earthquakes on known faults and a reevaluation of the size of historical earthquakes that have occurred since the settlement of the region. There is a 14% probability of a M 6.0 or greater background earthquake occurring in the next 50 years.

Constraining the Potential for Early Repeats and Clustering Using Historical and Paleoseimological Data

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Paleoseismological data are routinely analyzed for each fault in isolation (except to infer the lateral extent of the ruptures). The resulting recurrence models are incorporated in hazard and risk models.

From a risk perspective, though, the regional behavior is highly relevant. The potential for both early repeats and spatio-temporal clustering need to be assessed.

We developed four different frameworks to model clustering in time or in space from historical or paleoseimology data.

0. For single ruptures, we use geomorphology and trench data to infer the combination of models best reflecting the datasets (Fitzenz and Nyst, 2015).

1. For pairs of faults, we developed a Bayesian method to test if individual faults or the system they form have an intrinsic clock. In other words, should the recurrence model be constrained using the two event catalogs combined, or separately.

2. Zooming out of a given segment to study interevent times can help characterize the potential for early repeats on the segment as well as in the region. Combinations of early repeats and an overall quasi periodic behavior is found to be well modeled by a combination of BPT and Weibull for the segments of the subduction zone in Mexico.

3. For those cases where nearby segments have failed within a short amount of time in the past (*e.g.*, New Madrid, Nankai), adapting the framework 1 to add correlation of interevent times between the segments is not sufficient to ensure clustering. The absolute times of the events need to be taken into account in the generative model.

Evaluating the Relationship Between the Entiat Earthquake Cluster and the 1872 Chelan Earthquake, Central Washington State

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A 700 km^2 rectangular seismicity cluster near Entiat, Washington, is a prolific source of seismicity east of the Cascade arc, producing mainly thrust focal mechanisms. The M6.5 to M7 1872 Chelan earthquake was one of the largest historic earthquakes in Washington. Its epicenter lies within the cluster, but the cluster's constant rate of seismicity (17 events/year) between 1981 and 2006 suggests that it is not an aftershock sequence related to the 1872 earthquake, for which a decreasing seismicity rate would be expected. During this interval, the modified Omori's law (using constants determined for California) predicts 4 to 5 M≥3 aftershocks of the 1872 earthquake whereas 21 M≥3 cluster earthquakes were observed. Based on this finding, as well as the constant seismicity rate, focal mechanisms, and the orientation of microseismicity, we suggest that the cluster accommodates ongoing clockwise rotation of the Pacific Northwest via thrust faulting. The cluster is bounded to the southeast by the Spencer Canyon fault scarp identified in LiDAR imagery. Paleoseismic investigation indicates that this scarp formed in the late 1800s from SE-directed thrusting on a NW-dipping plane. Bakun *et al.* (2002) estimated a magnitude range between 6.5 and 7.0 for the 1872 Chelan earthquake using reported seismic intensities. Maximum fault displacement versus magnitude relationships for thrust faults indicate that the observed 1 to 2 m high fault scarp would be expected for a magnitude 6.5 to 6.7 earthquake, at the lower end of the estimated magnitude range for the 1872 event. Magnitude-area relationships indicate that the 700 km^2 area of the Entiat cluster is consistent with a magnitude 6.8 earthquake source. To help clarify fault geometries within the cluster, we present preliminary results from a 2016 deployment by the Washington Department of Natural Resources of 12 temporary 3-component seismic stations above it.

Resolving 1906 Meihsan M7.1, Taiwan, Earthquake Using Historical Waveforms: Blind Thrust Faulting Mechanism with Observed Strike-Slip Surface Rupture

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The 1906 Meishan earthquake (M7.1) was one of the largest damaging earthquakes in Taiwan in the early 20th century. Historical literatures and recent studies showed that the 1906 Meishan earthquake was related to the Meishan Fault and had a right-lateral faulting mechanism striking in east-west direction. With the historical Omori records at station Taipei, Taichung and Tainan, we carried out a waveform simulation of the 1906 Meishan earthquake for understanding source rupture properties of the 1906 Meishan earthquake and the yielding predicting ground-motion in the region. A two-step waveform simulation based on SGT (strain Green's tensor) is carried out for this attempt. In the first step, possible fault models of the 1906 Meishan earthquake from geological survey and recent studies are compiled for simulation. As the preliminary results, with an east-west strike faulting mechanism as Meishan fault, the synthetic waveforms and intensity maps were not well explained. We, thus, further carried out a grid-search in focal mechanism by fitting first-motion and shear-wave polarities of historical records and synthetics to evaluate possible focal mechanism. By comparing the simulated intensity distribution maps with the historical records, the 1906 Meishan earthquake is suggested to be associated with a north-south striking thrust faulting mechanism. This might indicate that the rupture of the Meishan fault is a transfer fault between two thrust faulting systems in the western coastal plain of Taiwan. The fault systems in the western part of Taiwan might be primarily dominated by the north-south striking thrust faults even though an east-west striking surface rupture with a strike-slip mechanism was found after the Meishan earthquake. This result brought a hint on the importance of understanding the tectonic fault systems, rather than single fault for future task on seismic hazard assessment.

The Future of the Past and Present Earthquake of Padangpanjang on June 28, 1926, West Sumatera, Indonesia

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Seismicity of Sumatera Island Indonesia, consist of three seismic source zones are West Sumatera Subduction seismic source, Sumatera Active Fault seismic source and North Sumatera Back Arc Thrusting seismic source.

The area along the Sumatera Active Fault seismic source zone is an earthquake prone region in Sumatera Island. Solok, Padangpanjang and Bukittinggi cities traverse by this seismic source zone and divided into seismic source of Suliti fault segment, seismic source of Sumani fault segment and seismic source of Sianok fault segment, where is the past (1822, 1926 and 1943 earthquakes), the present (2004, 205 and 2007 earthquakes) and the possibility of the future earthquakes (?) located.

Based on the geological deformations and damaging areas distribution during the past and the present earthquake and the existing trace of the Sumatera active fault segments in between Solok, Padangpanjang and Bukittinggi, can be predicted the area of the future earthquake with the magnitude 6.5 M_w will be located in the seismic source of Sianok fault segment (55 Km length).

In order to mitigate the impact of future seismic hazard, the ground shaking seismic hazard micro zonation map and potential seismic risk assessment and its mitigation programs should be done to the cities which is located in and around this region.

Keywords: Sumatera active fault seismic source zone.

Neotectonic and Seismicity Assessment of the 1961 Kara Kore Earthquake in the Marginal Grabens of the Afar Rift (Ethiopia)

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On the outer edge of the Afar rift, the marginal grabens are major tectonic elements that formed in the early stages of continental rifting and demonstrate present-day activity. Of societal relevance, the marginal grabens represent a significant earthquake hazard owing to proximity to population centers in the Ethiopian Highlands. In May of 1961, a large earthquake (M 6.6) occurred in the Kara Kore area, less than 300 km from the nation's capital, Addis Ababa. This is the largest recorded earthquake in the marginal grabens, and produced a surface rupture of 12-15 km long. This study assesses the 1961 earthquake in terms of its rupture and fault kinematics. Earthquake statistics were calculated from a modern seismicity catalog. In the field, recent faulting is observed in bedrock and alluvial fault scarps. Recent exposure along bedrock scarps is likely associated with the 1961 rupture and suggests 50-60 cm of displacement. This is consistent with the moment magnitude displacement scaling relations. Fault plane solutions demonstrate primarily normal faulting in the marginal grabens. A fault scarp in alluvium was surveyed using differential GPS. The scarp profile depicts 1.1-1.3 m of throw, which suggest it is composite displacement of the 1961 earthquake and the prior event. This could imply that the 1961 Kara Kore earthquake is a typical size event and reflects the overall fault kinematics and, hence, represents the continual increment of growth of the marginal grabens.

Luminescence Dating for Paleoseismic Reconstructions: A Practical Guide to New Technology, Applications and Sampling Methods

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Luminescence dating methods provide an age estimate for the last time sediment was exposed to sunlight and can provide improved dating resolution in the commonly coarse-grained alluvial/colluvial settings associated with paleoseismic studies. While radiocarbon dating requires the presence of organic material, luminescence techniques are able to date the abundant sands and silts that comprise most faulted deposits. Moreover, luminescence ages are directly reported as calendar years (at 1- or 2-sigma standard error) and do not need to be calibrated, which reduces the resolution of most radiocarbon ages, particularly those dating to the last 1ka. Carefully collected and appropriately analyzed luminescence ages also have the benefit of dating the actual timing of sediment deposition, where radiocarbon dating can have significant built-in lags due to incorporation of soil carbon or redisposition of the dated material. Despite its benefits, luminescence dating can also have challenges in fault proximal and fluvial settings due to incomplete solar exposure prior to deposition. For these reasons, it is very important that sediments selected for dating are carefully targeted to include facies most likely to have been bleached (reset) prior to deposition. In many cases, it is advised that the sediments are dated using single-grain dating techniques to allow isolation of the population of grains that were reset prior to deposition for age calculation. Other problems related to the source-sediment mineralogy may also arise in some settings, and it is recommended that researchers consult with a luminescence specialist prior to sampling.

Fault Zone Landforms and Paleoseismology

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Interactions between surface processes and earthquake deformation produce distinctive landscapes. Information such as fault zone geometry, deformation rate and localization, paleoseismic site context, paleoearthquake offset, and possibly paleoearthquake correlation may be inferred from fault zone landforms. Technological developments in geochronology and high resolution topography (HRT; > 1 sample / sq. m.) have advanced our ability to extract usable paleoseismic information. From HRT data, we can measure sensitive landscape elements (gully heads, channel margins, etc.) at the appropriate fine scale of individual earthquake offsets. Along with this sharpened view of topographic indicators of fault behavior come interpretive challenges that are the subject of this review. There is a tension between the ability to remotely, synoptically, and systematically examine the topography of fault zones and infer paleoearthquake offset distributions and the relatively expensive, local, and possibly subsurface field-based reconstruction of particular offset features. While experts might agree on the aleatory uncertainty in landform reconstruction, they may encounter significant epistemic challenges: What does the feature indicate about a paleo earthquake? In addition to the relative rates of feature formation vs. tectonic offset, the fidelity of deformed markers also depends on understanding the driving forces behind geomorphic modifications. Enhancing our ability to confidently extract information from these landscapes comes from additional validation efforts, development and integration of keystone field sites with more synoptic datasets, exploitation of regionally correlative weather events and climate variations, and elaboration of heuristic surface process models. These surface process models include nonlinear diffusion, episodic incision and channel back fill, and earthquake offset enabling an exploration of the paleoseismic sensitivity of fault zone landforms.

High Resolution DTM Reveals Tectonic Signal of the Dead Sea Fault at the Ateret Archaeological Site

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Previous work has shown that repeated earthquakes have left their traces on archaeological structures on the Tel Ateret, which is located on the Jordan Gorge Fault, a segment of the Dead Sea Fault. The structures range from the Hellenistic to the Ottoman period and at least four earthquake displacements have been documented. At the right bank of the Jordan River, south of Ateret, the remains of several flour mills are preserved. A recent high resolution DTM based on combined airborne and terrestrial laser scans covers 200x500 m, including the ruins of the Crusader castle on the hill. The raw scan was split into 2 m wide east-west trending stripes and all vegetation and recent structures were manually deleted resulting in DTM with 5 cm spatial resolution. The traces of three water channels parallel to the Jordan River are traceable in the model. Two of the channels show left lateral horizontal displacements up to 1.6 m at the intersection of the fault that was previously described on the basis of offset archaeological remains of Ateret. A positive slope of the water channels at their southern end might indicate a vertical component of the deformation or block rotation. Dating of the age of the channels is pending.

Constraining the Holocene Extent of the Meers Fault, Oklahoma Using High-Resolution Topography and Paleoseismic Trenching

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The ~55 km-long Meers fault (Oklahoma) is one of few seismogenic structures with Holocene surface expression in the stable continental region. The ~37 km-long southeastern portion is interpreted to be Holocene-active. The ~18 km-long northwestern portion is considered to be Quaternary-active (pre-Holocene); however, its subdued geomorphic expression and anthropogenic modifications obscure the length and style of Holocene deformation. We reevaluate surface expression and earthquake timing of the northwestern portion of the Meers fault to improve fault characterization, earthquake rupture models, and seismic hazard evaluations based on fault length. Airborne lidar (0.5–2 m-resolution), historical aerial photos, and balloon-based photogrammetric (Structure from Motion) topography (0.25–0.5 m-resolution) were collected and analyzed to characterize the fault scarp and local geomorphology. In the northwest, complex surface deformation includes fault splays, monoclinal warping, and a minor change in fault strike that contributes to its subtle surface expression. The fault is expressed by linear escarpments, incised channels on the upthrown side of the scarp, and closed depressions on the downthrown side. We further examined the northwestern scarp in a paleoseismic excavation where weathered Permian Hennessey Shale and a ~1–2 m-thick veneer of Holocene alluvial deposits have been deformed during three surface-folding earthquakes. In an adjacent stream exposure these units are faulted near the surface. Accelerated mass spectrometry (AMS) dating of detrital charcoal and optically stimulated luminescence (OSL) dating of sandy alluvial beds indicate two earthquakes occurred since 6 ka and one event prior to 6 ka. This analysis lengthens the Holocene extent of the Meers fault by ~6 km, to 43 km, and extends the paleoseismic record of the Meers fault to 6 ka. These data will improve fault-rupture and earthquake recurrence models used for seismic hazard analysis.

Evidence for Prehistoric Earthquakes on the Southern Fairweather Fault in Trenches across the 1958 Surface Rupture, Glacier Bay National Park, Alaska

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The Fairweather Fault in southeast Alaska accommodates ~46 mm/yr of dextral slip (>90% of relative Pacific–North America Plate motion) where the Yakutat terrane collides obliquely with North America. In 1958, the Fairweather Fault ruptured over 260 km from near Cross Sound northward toward Yakutat Bay during the M 7.8 Lituya Bay earthquake. We acquired lidar along parts of the 1958 fault rupture not covered by water or ice to aid fault mapping and identify sites that might record prehistoric earthquakes. We selected a site at the north end of Crillon Lake where post-1958 earthquake surveys measured ~6.5 m dextral and >1 m vertical offsets, but coarse sediment and shallow groundwater prevented trenching across uphill-facing scarps here. West of the primary fault scarp, we discovered a second scarp with 1 m dextral and 0.5 m vertical offsets; tilted and fallen trees along the scarp imply slip in 1958.

Lidar-derived terrain models helped select a second trench site, 3 km southeast of the Crillon Lake site, where an alluvial fan filled a closed depression present in 1958 photos. On the west, the fan is bounded by a fault scarp along the base of a ridge of sandy and gravelly till; the 1958 rupture shattered the ridge. Fan deposits abutting the ridge consist of 0.5–3.3 m of laminated fine sand and silt that bury a possibly pre-earthquake soil. Trenches across the scarp provide evidence for past earthquakes. Trench A exposed tilted deposits of till and fan alluvium, and fault zones and fissures that terminate within successively younger deposits. The faulted strata and fissures provide evidence for at least three earthquakes, likely including 1958. Trench D exposed till, scarp-derived colluvial wedges, and tilted organic-rich layers that provide evidence for three earthquakes. Massive till in trench D obscures faulting, but stratigraphic relationships suggest an oblique-reverse sense of motion. Ongoing 14C analyses will anchor estimates of earthquake timing.

Paleoseismic Results from Excavations across the Surface Rupture Associated with the 2014 South Napa Earthquake

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We excavated eight trenches across the two most significant fault ruptures associated with the 24 August 2014 M6.0 South Napa earthquake. The trench site, chosen because the two rupture traces traverse Quaternary sediments associated with a flight of fluvial terraces above Redwood Creek, is near the northern termination of mapped surface faulting. At this location, Fault trace A (the principal rupture trace) and Fault trace C (the largest of the secondary ruptures) are approximately 100 meters apart. Fault slip in 2014 was minor at this location on both fault traces: about 5 cm of right-lateral displacement on Fault A and 3 cm on Fault C. Trenches 1 through 6, excavated on the lower, younger terraces, exposed no faulting in the underlying interbedded fluvial sand, silt and gravel deposits. Trenches 7 and 8, sited on the higher, older terrace, exposed shear zones that juxtapose bedrock (most likely rocks of the Late Cretaceous Great Valley Sequence) against fluvial gravel that we estimate is Pleistocene in age based on the geomorphic position of the terrace. Radiocarbon analyses of charcoal samples collected from sediments exposed in trenches 1 through 6 suggest there has been no significant surface rupture on either fault in more than approximately 6000 years. These results suggest that no large surface rupture has occurred on either of these two faults in the late Holocene at this location, and establish that the 2014 surface rupture is too small to be preserved in the stratigraphic record at this site. This result indicates that while earlier earthquakes roughly the same size as the 2014 event could have occurred during the late Holocene and were not recorded in the stratigraphic section, it is unlikely that any late Holocene earthquakes involving large offset have occurred at this location on these faults.

Testing the Shorter and Variable Recurrence Interval Hypothesis along the Cholame Section of the San Andreas Fault

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The Cholame section of the San Andreas Fault records the interactions between the semi-creeping Parkfield section to the NW and the locked Carrizo section to the SE. Although offset reconstructions exist for this ~75 km reach, rupture behavior is poorly characterized, placing significant limitations on evaluating seismic hazard. We present new paleoseismic results from 3 trenches at the site, which is located 20 km SE of Hwy 46.

Fault zone stratigraphy consists of alternating finely bedded sand, silt, and gravel strata interlayered with bioturbated soil horizons. Evidence for 6 surface rupture events are recorded in the stratigraphy of the site, with evidence for ground shaking deformation after the 1857 Ft. Tejon earthquake. Strata display vertical offsets ranging from 60 cm near the base of the exposure to 12 cm near the most recent earthquake (MRE) horizon, with small colluvial wedges and sag deposits within the ~6 m wide fault zone expressed as small horst and graben structures. E6, E5 and MRE are well supported by evidence of abrupt up-sequence decreases in vertical separation, capped fissure fills, and buried colluvial wedges. The E2, E3 and E4 event horizons are less certain, supported by abrupt upward decreases in vertical separation and the presence of ponded "sag" deposits in the fault zone. The MRE horizon, which overlies a burn horizon, extends 6 m across the main fault zone, and consists of a silty clay sag deposit capped by very fine, bedded sand and coarse gravel.

This site contains abundant detrital charcoal in many of the units and burn horizons at or near event horizons providing great potential for bracketing ages of these paleoearthquakes. Four preliminary dates indicate that all six inferred events occurred between 1100 A.D. and 1857. If the MRE is indeed the 1857 event, there is significant potential to correlate this earthquake sequence with the high quality rupture records at Bidart and Frazier Mountain (70 and 180 km SE, respectively).

Investigating the History of Large Wasatch Fault Earthquakes along the Fort Canyon Fault at the Traverse Ridge Paleoseismic Site

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The Fort Canyon fault (FCF) trends east-west across Traverse Ridge, linking the Salt Lake City and Provo segments of the Wasatch fault, which dips directly beneath the densely-populated Salt Lake-Provo metropolitan area. Understanding the history of surface-rupturing earthquakes on the FCF is important because the extent to which segment boundary faults influence the propagation of large normal-faulting earthquakes is a significant source of uncertainty in seismic hazard assessments. To address this issue, we conducted a paleoseismic investigation at the Traverse Ridge site (40.492°, -111.805°). Two trenches were excavated across parallel traces of the FCF. The north trench exposed a fault zone with Tertiary volcanic rock in the footwall and three scarp-derived colluvial wedges. The south trench exposed a fault zone with Tertiary alluvial fan units in the footwall and one distinct colluvial wedge overlying a massive deposit of fault-derived colluvium in the hanging wall. Three of these colluvial wedges have dark soil A-horizons preserved within them and are found beneath steep scarps that are similar to those along adjacent parts of the fault with established Holocene records of rupture. Thus, we infer that 2-3 earthquakes have ruptured through this site during the Holocene. Colluvial wedge heights, ranging from 0.5-1 m, provide a lower limit for vertical displacement in these events. Given this displacement minimum, and considering empirical relationships among rupture parameters and magnitude, we infer that these events were greater than M 6.5. Forthcoming radiocarbon age results will be used to constrain the timing of earthquakes at this site and compare the FCF earthquake chronology to records for the Salt Lake City and Provo segments. This will enable us to assess whether recent ruptures on the FCF were (1) spill-overs from earthquakes on an adjacent segment, (2) floating ruptures centered on the segment boundary, or (3) larger multisegment ruptures.

Theoretical and Methodological Innovations for 3D/4D Seismic Imaging of Near-surface, Crustal, and Global Scales

Poster Session · Thursday 20 April ·

Construction of Coherent Fréchet Kernels for Full-3D Tomography

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Full-3D waveform tomography is becoming a popular method for imaging Earth structure on local to global scales. It combines numerical simulations of wave propagation in heterogeneous media with adjoint techniques to construct seismogram sensitivity (Fréchet) kernels with respect to model parameters. The performance of this method is strongly determined by data resolution, which depends on the ability to identify coherent seismic phases, measure their phase and amplitude spectra, and model the effects of interference from other signals. For seismograms computed for a 1D Earth model, the decomposition into standard seismic phases is relatively straightforward (*e.g.*, through the numerical synthesis of discrete traveling modes or generalized rays), but these classical techniques are of limited utility for structures with strong 3D heterogeneity. We present a new technique for systematically separating seismic phases using time-frequency spectra computed by the S-transform, which is based on Gaussian wavelets. We decompose the seismogram by iterative waveform stripping and calculate the Fréchet kernels for each waveform in this catalog using first-order Born theory. These individual kernels are often poorly localized in the spatial domain and show high-wavenumber variations off the main wavepath. We therefore recombine subsets of waveforms into well-organized seismic phases through a procedure that optimizes the localization of the waveform in the time domain and the Fréchet kernel in the spatial domain. This algorithm allows us to identify phases of interest even in the coda of the seismogram, increasing the structural information that can be derived from a single seismogram. We show examples of the seismogram decomposition and tomographic kernels computed using synthetic and real data from earthquakes in Central California.

High Resolution Shear-Wave Velocity Structure of Greenland from Earthquake and Ambient Noise Surface Wave Tomography

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We present a high resolution seismic tomography model of Greenland's lithosphere from the analysis of fundamental mode Rayleigh-wave group velocity dispersion measurements. Regional and teleseismic events recorded by the GLISN seismic networks over the last 20 years were used. In order to better constrain the crustal structure of Greenland, we also collected and processed several years of ambient noise data. We developed a new group velocity correction method to alleviate the limitations of the sparse Greenland station network and the relatively few local events. The global dispersion model GDM52 from Ekström [2011] was used to calculate group delays from the earthquake to the boundaries of our study area. An iterative reweighted generalized least-square approach was used to invert for the group velocity maps. A Markov chain Monte Carlo technique was then applied to invert for a 3D shear wave velocity model of Greenland up to a depth of 200 km and estimate the uncertainties in the model. Our method results in a shear wave velocity model of Greenland's lithosphere that is consistent with previous studies but of higher resolution and we show that in regions with limited stations and local seismicity, we can rely on global models to construct relatively large local data sets that can provide some important constraints on regional structures. We expect the results of the ambient noise tomography to cross-validate the earthquake tomography results and give us a better estimate of the spatial extent and amplitude of a low velocity zone that we resolve between central-eastern and northeastern Greenland and that correlates well with a previously measured high geothermal heat flux. A refined regional model of Greenland's lithospheric structure should eventually help better understand how underlying geological and geophysical processes may impact the dynamics of the ice sheet and influence its potential contribution to future sea level changes.

Ambient Noise Tomography of Azerbaijan

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The Caucasus-Caspian region exhibits large seismic velocity variations due to its complex geologic and tectonic setting. The Arabian-Eurasian collision led to complex lithospheric structures of diffused deformation and deep sedimentary basins. As a result of northwestward movement of Anatolian plate, Lesser and Greater Caucasus mountains are formed. A comprehensive lithospheric model is crucial in understanding the complex tectonic and geologic setting of the Caucasus-Caspian region and essential in mapping the regional wave propagation, therefore improving regional earthquake hypocenter locations and source parameterization. To develop a 3D velocity model we use three years of continuous broadband seismic recordings from the Azerbaijan Seismic Network, consisting of 35 stations, and perform ambient noise cross correlation to obtain fundamental Rayleigh wave group and phase velocity dispersions. Initial results show slower group and phase velocities in the basin and faster velocities in the Greater and Lesser Caucasus, consistent with the geologic structure. The resulting dispersion curves are used to invert for Rayleigh wave group velocity maps. Additional constraints on Moho thickness from receiver functions will be included when available.

Reverberant S-Waves on a Floating Ice Shelf: Temporal Monitoring of the Ross Ice Shelf Using Ambient Noise Cross-Correlations

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The advent of global climate change has prompted increased study of Earth's polar regions, where these effects impact heavily. We make use of a unique multiyear broadband seismic deployment on the Ross Ice Shelf (RIS), Antarctica, to construct ambient noise cross-correlation functions across 33 stations spanning the entire shelf. Spectral signatures in the correlation functions show the presence of low frequency (presumably ocean gravity wave-generated) vertically dominant reverberations, as well as higher frequency horizontally polarized reverberations. The lower frequency signals are most strongly present during the austral summer, when the Ross Sea polynya adjacent to the ice front is present, whereas the higher frequency signatures, appearing as a series of 4-10 Hz modes, are dominant during the austral winter. The onset of these higher frequency modes is well matched by sea ice mapping, in that the higher modes are coincidental with the closing of the polynya. These higher modes, interpreted as trapped SH modes resulting from the coupling of the sea ice/ocean with the RIS, shows smooth seasonal dependence in frequency content, reducing in frequency during the Antarctic winter, thus suggesting that the seismic response is sensitive to seasonal changes in the RIS. We use a combination of forward modeling and analytical solutions to model these reverberations and consider possible associated temporal changes in the physical parameters of the RIS.

P and S Body Wave Tomography of the West Antarctic Rift System: Evidence for Cenozoic Rifting?

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Imaging the upper mantle of West Antarctica can provide valuable constraints to its deep structure, the source of subglacial volcanism and the age of rifting in the West Antarctic Rift System (WARS). The WARS extends across West Antarctica and is identified as a topographic low beneath the ice, with the deepest area along the Bentley Subglacial Trench. Seismic data from broadband seismometers that are part of the Polenet Network are used to obtain improved images of the upper mantle. The data comes from 34 backbone stations, 13 temporary broadband stations deployed across the WARS from the Whitmore Mountains to Marie Byrd Land from January 2010 to January 2012, and 10 stations deployed above the Byrd Subglacial Basin from January 2015 to the present. Using multi channel cross correlation of P and S body waves from teleseismic earthquakes, travel time residuals have been obtained for 477 events. VanDecar's linear inversion method has been used with the travel time residuals to develop a model of relative P and S wave velocity variations in the upper mantle. Our preliminary P-wave model shows a low velocity anomaly in the upper mantle beneath Marie Byrd Land and faster wave speeds across much of the WARS, consistent with previously published tomographic models of West Antarctica.

Internal Structure of the San Jacinto Fault Zone at Dry Wash from Data Recorded by a Dense Linear Array

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We analyze seismograms recorded in the San Jacinto Fault Zone, at Dry Wash (DW), southeast of the trifurcation area, by a dense linear array with 12 stations separated by ~30-40 m and ~400 m in aperture crossing the fault (SW to NE). Data of events recorded in 2014-2015 are used to search for changes in early P waveform across the array and fault zone head and trapped waves. Delay times between phases generated by teleseismic and local earthquakes are utilized to estimate velocity variations across the array. For teleseismic events, we pick the peak of the early P waveform to obtain the relative travel time. For local events, we use automatic P picks for each source-receiver pair to calculate relative slowness, the ratio of each station pick to the array-wide average pick with proper correction for the effect of wave propagation. The results for both data sets indicate that P waves travel faster beneath the SW than the NE of the array. Combined with clear changes in early P waveform observed consistently in the middle of the array, the main seismogenic fault is inferred to be located at the center of the array. Potential trapped waves following both P and S body waves are identified. These trapped waves are observed clearly only at a few stations on the SW part of the array where the relative slowness is larger. Updated results will be presented in the meeting.

Internal Structure of the San Jacinto Fault Zone in The Trifurcation Area Southeast of Anza, California, from Data of Dense Seismic Arrays

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We analyze two-year data from a linear array composed of six 3-component sensors separated by about 25 m (SGB array), and one-month data from 1108 vertical geophones in ~650 m x 650 m box configuration with instrument spacing 10-30 m (dense array). Both arrays straddle the Clark branch of the San Jacinto fault zone southeast of Anza, California. The examined data include recordings from >10000 local events and several teleseismic events. Automatic picking algorithms and visual inspection are used to identify P and S body waves, along with fault zone head and trapped waves. The locations of the seismogenic fault and main damage zone are found by examining waveform changes in both along-strike and fault-normal directions. The inferred location of the seismogenic fault agrees well with one mapped surface trace of the Clark branch, while the main damage zone is associated with a second mapped surface trace. The delay times from teleseismic events and analysis of P arrival times of local events indicate a local reversal of the velocity contrast across the fault, with slower velocities NE of the fault related to the fault damage zone. A portion of the damage zone generates P trapped waves based on visual examination and automatic detection. Waveforms recorded by several fault-normal lines of the dense array are stacked to improve the ability to detect fault zone head and S trapped waves. S trapped waves detected in the SGB array are inverted for trapping structure properties. Updated results will be presented in the meeting.

High-Resolution Body Wave Tomography of the Ross Sea Embayment, Antarctica

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The West Antarctic Rift System (WARS) remains the least understood continental rift system on the planet. The WARS is largely composed of the Ross Sea Embayment, which is overlain by the Ross Ice Shelf between Marie Byrd Land and the Transantarctic Mountains. Active volcanism on Ross Island continues to challenge our understanding of the seismically quiescent rift system. Previous regional-scale body wave tomographic investigations have identified areas of low seismic wave speed to about 200 km depth beneath Ross Island. However, the extent of the low velocity structure in the WARS remains unknown due to insufficient resolution of upper mantle structure under the Ross Sea Embayment away from Ross Island. For this investigation, we utilize teleseismic P waves recorded on the recently deployed RIS/DRIS network, which consists of 33 seismometers deployed across the Ross Ice Shelf, along with data from nearby POLENET and TAMSEIS stations. Relative P wave travel time residuals were obtained from 560 events using a multichannel cross correlation method, and have been inverted to obtain a preliminary model of the upper mantle. Initial results suggest that the low wave speed structure under Ross Island extends roughly halfway across the Ross Sea Embayment. A final model will be used to help understand the chronology of extension in the WARS, mechanisms of uplift for the Transantarctic Mountains, among other open questions.

Three-Dimensional Vp/Vs Tomography with Body and Surface Wave Data

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Models of Vp/Vs play a very important role in geological interpretation given the direct relations to lithology, partial melting, water or gas saturation, cracks and porosity. However, it is difficult to obtain a reliable Vp/Vs model by simply dividing Vp by Vs models due to the different resolvability of different data sets in seismic tomography. Here we propose a new method to obtain a Vp/Vs model by jointly inverting body and surface wave data. The method takes advantage of the complementary strength of both data sets, with body waves provide better constraints for Vp values at deeper sections, while surface wave data better resolve Vs and Vp values at shallower depth. This makes it possible to increase the reliability of Vp/Vs model from simply dividing Vp by Vs model. Synthetic tests show the Vp/Vs model is better resolved from joint inversion compared to separate inversions using only body or surface wave data or deriving separately Vp and Vs models. The method is applied to the Southern California Plate Boundary Region, which has been well studied and both Vp and Vs models are available. The results are comparable to Vp and Vs models in terms of anomalies and consistent with local geological structures. We also compare the 3D Vp/Vs model with average Vp/Vs model in this region from receiver functions.

Basin-Wide Vp, Vs, Vp/Vs, and Poisson's Ratios of the Napa Valley, California

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In September 2016, we acquired two active-source seismic profiles along and across the Napa Valley, an ~20-km-long, NW-SE-oriented profile along the valley and an ~ 15-km-long, NE-SW-oriented profile across the valley, crossing the West Napa Fault Zone (WNFZ). The two seismic profiles were centered on and intersected in downtown Napa. Seismic sources were generated by 34 buried explosions (~ 1-km spacing), and the data were recorded using 666 vertical- and horizontal-component seismographs (~ 100-m spacing). Using data from the cross-basin profile, we developed tomographic Vp (1.6 -~6.0 km/s) and Vs (0.6-3.5 km/s) models and corresponding Vp/Vs and Poisson's ratio models of the upper 4 km beneath the Valley. Our models show a low-velocity (Vp and Vs) basin that is deepest between the WNFZ and the Napa River, bounded by high-velocity volcanic rocks. Volcanic rocks (Vs = 1.5 km/s at the surface) appear to be about 0.6 km depth beneath the central basin, suggesting relatively shallow basins sediments. Below about 2 km depth, the WNFZ marks a transition from relatively high-velocity (Vs > 3 km/s; Vp > 5 km/s) rocks to the east and relatively low-velocity (Vs ~ 2 km/s; Vp ~ 4 km/s) rocks to the west. Vp/Vs ratios range from 3.4 in the near-surface of the central basin to about 1.7 below 1.5 km depth. The highest Vp/Vs ratios occur in the upper 500 m at three locations: beneath the WNFZ, beneath a mapped fault at the Napa River, and beneath Highway 29 (a possible zone of faulting). These three zones also coincide with clusters of red- and yellow-tagged buildings caused by the 24 August 2014 M_w 6.0 South Napa earthquake. Poisson's ratio varies from about 0.45 at the surface to about 0.2 at depths >2 km beneath the central basin. The WNFZ forms a prominent boundary between high Vs and Vp (low Vp/Vs and Poisson's ratios) to the east and relatively low Vs and Vp (high Vp/Vs and Poisson' ratios) to the west, suggesting it is a major crustal fault.

The 2016 East Bay Seismic Investigation: Seismic Tomography Imaging across the Hayward Fault Zone near San Leandro, California

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The Hayward Fault (HF) is a major seismic hazard within the eastern San Francisco Bay area. One of the main faults of the Hayward Fault zone (HFZ), the Quaternary-active Chabot Fault (CF), parallels the active trace of the HFZ ~2 km to the east. Previous studies have shown that the HF and CF bound the San Leandro block, a massive, 25-km-long Jurassic gabbro unit, the western edge of which hosts the majority of seismicity along the central HFZ. Piercing-point evidence suggests that the CF has accommodated ~15% of total slip along the HFZ, and fault mechanics suggest the sub-parallel CF is oriented favorably to slip in the current regional stress field. If the 2014 M_w 6.0 South Napa earthquake is an indicator, subsidiary faults such as the CF, Miller Creek, Ashland thrust, and other HFZ faults should be re-evaluated as potential hazards. To better understand these potential hazards, we conducted the 2016 East Bay Seismic Investigation, a NEHRP-funded collaborative effort between the USGS and CSUEB. We used active sources, with 16 explosive shots spaced at ~1-km intervals along a NE-striking (~055°), 15-km-long seismic line centered on the HFZ. Vertical- and horizontal-component sensors were spaced at 100-m intervals along the entire profile, with single-component (vertical) sensors spaced at 20-m intervals across mapped or suspected fault traces. We used off-line shots (5-6 km) along known fault traces of the HFZ to generate guided waves that were recorded along the recording array. From the data, we developed Vp and Vs seismic tomography models and corresponding Vp/Vs and Poisson's ratio models. We also developed shallow-depth, 2-D, Vs models using the multichannel analysis of surface waves (MASW) method on Rayleigh and Love waves. Our ultimate goals are to use these and other data to develop 3D models of the HFZ, determine the connectivity of faults within the HFZ, and better understand the overall seismic hazards of the East Bay.

Southcentral Mexico 3D Velocity Model

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We present an integrated 3D Velocity Model of the Southcentral region of Mexico, including results from adjoint wavefield inversions, geotechnical information, and receiver functions. Our initial model was built by gathering previous tomographic studies. Fréchet kernels for the adjoint tomography were computed using the octree-based finite element numerical solutions of the 3D elastodynamic wave equation (Tu *et al.*, 2006). We made more than 2,000,000 misfit observations for different phases on records of 77 ($4.5<M_w<5.5$) earthquakes recorded from 2005 to 2015 at 240 three-component stations. Additionally, we considered observations from more than 250 Green's Functions constructed from earthquake-record cross-correlations between pairs of stations. Shallow S-wave profiles, derived from geotechnical studies, for several urban regions (*e.g.* Mexico City, Guadalajara, and Oaxaca) were carefully embedded in the regional model. The Moho and subduction slab were derived using previously calculated receiver functions and the updated model.

We used synthetic seismograms for the 2014 M_w 7.3 Papanoa earthquake to test the model at frequencies below 1Hz. Using two goodness-of-fit criteria (Olsen and Mayhew, 2010; Anderson, 2004) and approximately 100 records, we conclude that the model has an overall "good" performance.

Active Lesser Himalayan Duplex: Constraints from Velocity Structure and Regional Waveform Inversion

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In the Himalaya intense microseismicity zone at mid crustal ramp along the Main Himalayan Thrust results due to the convergence between Indian and Tibetan plate. In order to understand the role of crustal structures in genesis of earthquake kinematics we in combination study the 1D and 3D velocity structure along with earthquake moment tensors in the region of the Garhwal-Kumaun Himalaya. The updated hypocentral parameters reveal that most of the seismicity is constrained within 20 km depth. The inversion of 3243 P and 3088 S phases shows the crust above the mid crustal ramp is typically characterized by low Vp and low Vp/Vs anomaly, whereas below it the anomaly both in Vp and Vp/Vs is high. The seismicity clusters are strictly confined either along very low Vp/Vs values or follow the trace where very low and very high Vp/Vs anomaly intersects, and tends to avoid the zone with high Vp/Vs ratios. A multistep moment tensor inversion of 11 moderate earthquakes with M_w between 4.0 and 5.0, through modeling of full waveforms and amplitude spectra at regional distances reveals the presence of dominant thrust fault kinematics persisting along the Himalayan belt. At this shallow depth, the low as well as high angle thrust faulting is the dominating mechanism. The centroid depths for these moderate earthquakes are shallow between 1 and 12 km also confirmed by additionally modeling P phase beams at seismic arrays at teleseismic distances. The updated seismicity, constrained source mechanism and depth, and tomography results indicate typical setting of duplexes above the mid crustal ramp where slip is also confirmed along out-of-sequence thrusting. The low Vp/Vs anomaly above the mid crustal ramp indicates a highly fractured fluid filled zone than the surrounding crust, indicating high activity and intense deformation in the Lesser Himalayan Duplex system, supporting the notion of critical taper wedge theory in the Himalaya.

Eikonal Tomography of the Southern California Plate Boundary Region

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We use eikonal tomography to derive directionally-dependent phase velocities of surface waves for the plate boundary region in southern CA sensitive to the approximate depth range 1-20 km. Seismic noise data recorded by 346 stations in the area provide a spatial coverage with ~5-25 km typical station spacing and period range of 1-20 s. Noise cross-correlations are calculated for vertical component data recorded in year 2014. Rayleigh wave group and phase travel times between 2 and 13 sec period are derived for each station pair using frequency-time analysis. For each common station, all available phase travel time measurements with sufficient signal to noise ratio and envelope peak amplitude are used to construct a travel time map for a virtual source at the common station location. By solving the eikonal equation, both phase velocity and propagation direction are evaluated at each location for each virtual source. Isotropic phase velocities and 2- psi azimuthal anisotropy and their uncertainties are determined statistically using measurements from different virtual sources. Following the method of Barmin *et al.* (2001), group velocities are also inverted using all the group travel times that pass quality criteria. The obtained group and phase dispersions of Rayleigh waves are then inverted on a 6 x 6 km2 grid for local 1D piecewise shear wave velocity structures using the procedure of Herrmann (2013). The results agree well with previous observations of Zigone *et al.* (2015) in the overlapping area. Clear velocity contrasts and low velocity zones are seen for the San Andreas, San Jacinto, Elsinore and Garlock faults. We also find 2-psi azimuthal anisotropy with fast directions parallel to geometrically-simple fault sections. Details and updated results will be presented in the meeting.

Frequency Dependence of Attenuation in the Crust beneath Southern California

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At higher frequencies, anelastic attenuation becomes more important, and the elastic scattering depends on unresolved small-scale heterogeneities, giving rise to a complex apparent attenuation structure that depends on both position and frequency. We place constraints on the structure in the band 1-10 Hz through the analysis of earthquake waveforms recorded by the Southern California Seismic Network (SCSN). We localize signals in frequency and time using wavelet transforms, and we account for source structure and geometrical spreading by referencing the spectral amplitudes to values computed from 1D synthetic seismograms. The data indicate that the apparent attenuation is frequency dependent with a logarithmic derivative $\gamma = d\ln Q/d\ln f$ that ranges from ~0.3 for $1 < f < 6$ Hz and ~0.6 for $6 < f < 10$ Hz. The quality factor for *S* waves (Q_S) is consistent with the scaling $Q_S \sim 50V_S$ used in southern California ground motion simulations at frequency less than 1 Hz. Across the 1-10 Hz band and at all crustal depths, the apparent quality factor for *P* waves (Q_P) is less than the apparent quality factor for *S* waves (Q_S), probably due to strong scattering effects. Inversions of the amplitude data account for frequency-dependent variations in the source spectrum and site effects. The source spectra show an average roll-off rate *n* of about 2.5 for both *P* and *S* waves. The station residuals reflect the attenuation and scattering structure near the surface, and they show stronger apparent attenuation in the Los Angeles basin and weaker apparent attenuation in the Peninsular Ranges and Mojave. We explore 3D heterogeneity in attenuation structure using ray-theoretic tomographic inversions.

Receiver Function Analysis of Geologic Structures in the Southeastern United States

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The southeastern United States is dominated by accreted terranes produced by two complete Wilson cycles. During collision events of the second cycle, island arcs and sedimentary packages were accreted onto the Grenville age basement rock, and created a thin-skinned flat-ramp geometry that transported thrust sheets westward. These thrust sheets ultimately flatten at depth into a basal detachment fault. The Grenville aged basement and the Alleghanian aged decollement have been imaged with seismic reflection profiles from the Consortium for Continental Reflection Profiling (COCORP), the Appalachian Ultradeep Core Hole (ADCOH) study, and in reprocessed industry profiles. The reflection profiles suggest the presence of Grenville basement structures below the decollement. The decollement is located at 4-6 km depth beneath the Blue Ridge province, and reaches a maximum depth of ~12 km to the east within the sedimentary sequence. The eastern limit of the detachment is unknown, as is the geologic structure beneath the decollement. The depth and structure of the Mohorovicic discontinuity throughout this region is also poorly understood. We calculate receiver functions for 134 USArray Transportable Array seismic stations using teleseismic events with a waterlevel deconvolution in the frequency domain and a high Gaussian value (a = 5-8) to recover frequencies of 2-3 Hz. This results in improved resolution of the crustal structures. The receiver function solutions are used to create multiple profiles across the Alleghanian decollement, which are then correlated with reflection profiles. The primary targets are structure on the decollement surface and the structural fabric of associated sedimentary rocks, as well as the geologic structure of the Grenville aged basement rocks.

Toppled and Rotated Objects in Recent, Historic, and Prehistoric Earthquakes

Poster Session · Thursday 20 April ·

Rectangular Blocks vs Polygonal Walls in Archaeoseismology

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Collapsed or deformed walls in ancient structures constitute important evidence in archaeoseismology, where damage is interpreted in terms of earthquake ground motion. A large variety of wall types have been developed during the millennia in different cultural backgrounds. Often walls with polygonal-shaped building blocks are regarded as more earthquake-resistant than a wall consisting of rectangular elements and, as is sometimes speculated, that the irregular wall types were intentionally developed for that purpose. We use simply structured discrete element models of four walls with different block geometries, perfect rectangular, an Inka-type structure and two polygonal designs, to test their dynamic behavior. In addition to an analytic calculation of ground motion, we use measured strong motion signals as boundary conditions for the 3D wall models with varying height to width ratios. At peak ground accelerations between 1.0 and 9.0 m/s^2 and major frequencies of 0.5 to 3 Hz, numeric experiments with the horizontally applied analytic ground motions result in clear differences in the resistance of the four wall types with the rectangular block wall being most vulnerable. For more complex measured 3D motions the Inka-type wall proves more stable than the rectangular block wall; however, height to width ratio still has equally strong influence on the stability. Internal deformation of non-collapsed walls shows some correlation with the parameters of the driving motion. For simple impulsive ground motions, a peak ground displacement threshold exists between toppling and remaining upright for all four models but peak acceleration cannot be reliably back calculated.

Understanding and Modeling Ground Motions and Seismic Hazard from Induced Earthquakes

Poster Session · Thursday 20 April ·

Comparison of the USGS 2016 and 2017 One-Year Seismic Hazard Forecasts for the CEUS with a Focus on Oklahoma

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The U.S. Geological Survey (USGS) 2016 one-year seismic hazard forecast for the Central and Eastern United States (CEUS) was developed because the USGS 2014 update of the National Seismic Hazard Model purposefully excluded a large number of induced earthquakes. Creating a new forecast model took a community effort, including: (1) a workshop in 2014 to discuss the potential methods and models, (2) a preliminary suite of sensitivity models published in 2015 to solicit feedback, and (3) help from State geological surveys and local experts to define the areas of induced seismicity. These efforts led to the March 2016 release of the one-year forecast that includes natural and induced earthquakes. In early 2017, the USGS will release an updated one-year forecast. Two notable earthquakes occurred in Oklahoma during 2016 (near Fairview [M5.1] and Pawnee [M5.8]). These earthquakes generated Modified Mercalli Intensities in the range of VII (Fairview) and VIII (Pawnee) and they occurred in the highest hazard areas of the 2016 forecast, illustrating the merits of the model.

This study presents a comparison of the probabilistic ground motions from the USGS 2016 and 2017 forecasts, with a focus on Oklahoma and Kansas. Oklahoma and Kansas produced the highest seismic hazard in the 2016 forecast. The overall rate of earthquakes in this area has decreased from the year 2015 to 2016. This decrease, however, is less dramatic in the declustered catalog, which is the basis for the one-year forecast, and the resulting effects on seismic hazard are less than would be predicted from the full catalog's rate change alone. Considering the first 6 months of seismicity in 2016, seismicity has generally increased in the east and decreased in the western part of Oklahoma. We present the sensitivity of the 2017 forecast to rate changes, indicate how the changing spatial pattern of seismicity has affected the forecast and present the effects of modeling changes (*e.g.*, ground motion model weights.

Access to "Did You Feel It?" Data for Induced Earthquake Studies

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The significant rise in seismicity rates in Oklahoma and Kansas (OK–KS) in the last decade has led to an increased interest in studying induced earthquakes. Although additional instruments have been deployed in the region, there are still relatively few recordings at the distances (<20 km) and magnitudes (M4+) most relevant to earthquake hazard. In contrast, the USGS Did You Feel It? (DYFI) system has collected more than 200,000 observations during this period with 22,000+ observations at distances less than 20 km. This dataset has already been used to study the unique characteristics of induced earthquakes, to evaluate the extent of felt area, shaking, and damage, to compare intensity and ground motion metrics, and as constraints for ShakeMaps used by utilities, insurers, and other affected parties. To facilitate continued use, we have produced a catalog of DYFI intensity observations associated with OK–KS events from 2001 onwards. We provide (anonymized) individual responses to the DYFI questionnaire, compute individual user intensities, and aggregate event-associated intensities in 1-km and 10-km boxes. We anticipate that this DYFI catalog will be particularly useful in conjunction with instrumental recordings of induced earthquakes to improve macroseismic intensity prediction equations (IPEs) and equations for converting between macroseismic intensity and instrumental measures. To this end, we have collated the DYFI dataset with the induced earthquake catalog and ground-motion data collection of Rennolet *et al.* (2016). We have also provided tools for users to replicate, filter, and update the dataset via the USGS GeoJSON feeds. The dataset and associated tools are available on the USGS GitHub repository. For GIS users, the induced earthquake DYFI dataset can be reviewed or accessed via the USGS Earthquake Hazards Program's GIS web services.

The Contribution of Uncertainty in Magnitude and Location to Near-Distance Variability in Ground Motions for Potentially-Induced Earthquakes in Oklahoma

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An important issue in ground motion and hazard analysis for induced earthquakes is the variability of ground-motion amplitudes (referred to as sigma) at close distances (<10 km). We investigate the contributions of errors in magnitude and location to sigma, at <10km, using ground-motion recordings from 55 induced earthquakes in Oklahoma with moment magnitudes between 3.0-4.1. We optimize the location and magnitude of events with respect to a selected ground-motion prediction equation (GMPE) that has zero-bias on average. We define the ground-motion center (the GMC) as the location and magnitude that results in the lowest standard deviation (sigma) with respect to the GMPE. An iterative grid search technique is used to find each event's GMC, alternating between searching for the optimum epicenter of the GMPE and then searching for the optimum moment magnitude; the best location and magnitude is that which minimizes the residuals (averaged over response spectra at 0.5, 1, 3.3, 10 Hz, peak ground acceleration and peak ground velocity). For observations within 10 km, the value of sigma is very sensitive to location, and slightly sensitive to magnitude. Location error impacts the intra-event component of sigma, whereas the magnitude impacts the inter-event component of sigma. Before optimizing the location and magnitude of the events, the total sigma (averaged over the selected frequencies) is 0.28 log10 units, whereas the corresponding sigma value based on the GMC locations and magnitudes is 0.23 log10 units. The results indicate that about 0.05 log10 units of sigma could be attributable to typical errors in location and magnitude, for events in Oklahoma recorded at <10 km.

Scaling Rotational and Translational Ground Motion Parameters from Induced Seismic Events

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The areas of intensive mining can be used as seismological test fields, to study strong ground motion effects. It is so because the magnitudes of induced mining seismic events may exceed 4 with return period of 3-5 years and the seismic events triggered at the nearby faults resemble shallow, natural earthquakes. Recently rotational ground motion filed is an emerging subject of seismology (see *e.g.* BSSA 2009, vol.99, special issue). However he key remaining problem is to acquire and analyze respective STRONG MOTION rotational records.

The purpose of the presentation for the SSA Meeting is to report recent results of a program of collecting rotational ground motion records at the Polish region of the Upper Silesian Coal Basin. The early results of recording 51 mining events with magnitudes from 1.7 to 2.7 and the strongest MM intensity IV (horizontal PGV up to 2cm/s) and with maximum rotational accelerations up to 2.53 degs/s^2 were already reported in the January/February issue of SRL vol.88(1).

The program of recording rotational ground motions at the "Piast-Ziemowit" mine site is being continued. Thus the purpose of the presentation for the SSA 2017 Meeting will be to report updated results of extensive analyses of the rotational ground motion effects and source parameters such as magnitude, seismic moment and seismic energy. In addition, spectral characteristics of selected 6 DOF records (3 translations and 3 rotations) will be presented in detail and analyzed. Some proposals for empirical formulas of a various rotational and translational ground motion parameters recorded in epicentral area as functions of magnitude and seismic moment are planned to be presented.

So far it was observed that the distributions of the rotational ground motions with time are similar to the respective translational time history records, while their Fourier spectra are clearly shifted to higher frequencies. The latter effect is predicted by earlier theoretical studies.

Empirical Ground Motion Characterization of Induced Seismicity in Alberta and Oklahoma

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Over the last decade instances of induced seismic activity resulting from waste water injection and hydraulic fracture treatments have increased significantly both in rate and maximum magnitude of observed events. Evaluation of the induced-seismicity hazard requires development of appropriate ground-motion prediction equations (GMPEs). We use a generalized inversion to solve for regional source, attenuation and site parameters in order to define region-specific GMPEs from induced ground motion observations in Alberta and Oklahoma following the method of Atkinson *et al.* (2015 BSSA). The Alberta database is compiled from over 200 small to moderate seismic events (M 1 to 4.2) recorded at ~ 50 regional stations (distances from 30 to 500 km). We use over 13,000 small to moderate seismic events (M 1 to 5.8) recorded at ~ 1600 seismic stations (distances from 1 to 750 km) in Oklahoma. Magnitude scaling, regional anelastic attenuation terms and geometric spreading functions are removed from observed ground motions, which are then inverted for stress parameter and site amplification. Resolving these parameters allows for the derivation of regionally-calibrated GMPEs that can be used to compare ground motion observations between waste water injection (Oklahoma) and hydraulic fracture induced events (Alberta), and further compare observations for induced events with ground motions from natural sources (California, NGAWest2) -all within a common framework. The derived GMPEs have applications for the evaluation of hazards from induced seismicity and can be used to track amplitudes across the regions in real time, which is useful for ground-motion-based alerting systems and traffic light protocols.

Processed Ground-Motion Records for Induced Earthquakes for Use in Engineering Applications

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We compile and process an electronic database of ground motions recorded on accelerometers and broadband seismographic instruments for induced earthquakes of **M** ≥ 4 at distances <50 km in central and eastern North America. Most of the data are from Oklahoma, with some records from Alberta. Our focus is on the subset of available records that are of most interest for engineering analyses aimed at evaluation of the potential hazards from induced events. We considered all records to 50 km for events of **M** ≥ 4.5. For events of **M**4 to 4.5, we select records at close distance (<15 km), having good signal strength (PGA >~3%g), in order to allow high-quality time histories to be obtained. The selected records are windowed, filtered and instrument-corrected to compile a set of records having acceptable acceleration, velocity and displacement time histories. The records and their response spectra are provided as electronic files. We note that the record set is not suitable as a response spectra database for development of ground-motion prediction equations, because for **M**<4.5 the record selection is biased to records with higher amplitudes. Rather, the intended use of the records is as seed records, which can be readily scaled in the time domain to approximately represent induced-event target scenarios.

Verification and Validation of Earthquake Occurrence and Hazard Forecasts

Poster Session · Thursday 20 April ·

USGS Research toward Validation of the 2016 Earthquake Hazard Forecast

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The significant increase in seismicity in the central and eastern United States (CEUS) since 2009, thought to be due to anthropogenic causes, has motivated updates of the National Seismic Hazard Maps (NSHM) to deal with the high rates of moderate-magnitude earthquakes. Seismic hazard was significantly elevated in a "one-year seismic hazard forecast" for which calculated ground motions have a 1% probability of exceedance. A positive attribute of this change is the opportunity for meaningful comparison of the model with ground motions recorded in 2016. In addition, the abundance of new instrumental ground motion observations and felt reports provide an opportunity to test the sensitivity of model parameters (ground motion models (GMMs), source models). The best example of recorded ground motions is from an earthquake on the November 6, 2016 M5 near Cushing, Oklahoma where 5 stations are within 10 km of the epicenter.

We find that the ability of the 2016 hazard model to predict observed ground motions is dependent upon the region and metric used. For example, we find that model calculations agree well with the ground motions that were recorded from >M4 earthquakes in 2016. If, however, the test includes all earthquakes down to M3.5, the 1-year model under-predicts the 2016 ground motion observations. In addition, earthquake hazard can change with changes in wastewater injection rates and location. These complexities makes hazard model testing difficult however, given the uncertainty in GMMs and hazard curves we find that the 1-year model effectively forecasted the ground motions experienced in some regions (central Oklahoma, Raton Basin) during 2016. In other regions (Dallas, Arkansas, Charleston) the hazard forecast over-predicted 2016 ground shaking. Results from these studies allow us to select appropriate metrics for evaluation of earthquake hazard model and improve earthquake hazard model parameter selection that will contribute to accurate future forecasts.

A Comparison between the Forecast by the United States National Seismic Hazard Maps with Recent Ground Motion Records

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Verifying a seismic hazard model using observations collected after the model has been made (*i.e.*, prospective data) is a true test of the predictive power of the model. We compared the predicted rate of ground motion exceedance by four versions of the USGS national seismic hazard map (NSHMP 1996, 2002, 2008, 2014) with the actual observed rate during 2000-2013. The data were prospective to the two earlier versions of NSHMP. We used two sets of somewhat independent data, namely 1) the USGS "Did You Feel It?" (DYFI) intensity reports, 2) instrumental ground motion records extracted from ShakeMap stations. Although both are observed data, they come in different degrees of accuracy. We separately verified the suitability of the two datasets.

Our result indicates that for California, the predicted and observed PGA hazards are very comparable. The result for spectral acceleration (at 1 second) was different; the model appeared to be conservative. The instrumental and macroseismic datasets gave consistent results, implying robustness. This consistency also encourages the use of DYFI data for hazard verification in the Central and Eastern US (CEUS), where instrumental records are lacking. The result for the CEUS shows that the observed hazard is largely consistent with the predicted one.

We studied also the effect of the data quantity to the usefulness of the test, in terms of the statistical power. This provides an estimate on how much a hazard model is empirically verifiable. The usefulness of DYFI data in hazard model verification provides a prospect of testing models in poorly instrumented regions.

Recent Achievements of the Collaboratory for the Study of Earthquake Predictability

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The Collaboratory for the Study of Earthquake Predictability (CSEP) supports a global program to conduct prospective earthquake forecasting experiments. CSEP testing centers are now operational in California, New Zealand, Japan, China, and Europe with 442 models under evaluation. The California testing center, started by SCEC o Sept 1, 2007, currently hosts 30-minute, 1-day, 3-month, 1-year and 5-year forecasts, both alarm-based and probabilistic, for California, the Western Pacific, and worldwide. Our tests are now based on the hypocentral locations and magnitudes of cataloged earthquakes, but we plan to test focal mechanisms and finite rupture forecasts as well. We have increased computational efficiency for high-resolution global experiments, such as the evaluation of the Global Earthquake Activity Rate (GEAR) model, introduced Bayesian ensemble models, and implemented support for non-Poissonian simulation-based forecasts models. We are developing formats and procedures to evaluate externally hosted forecasts and predictions. CSEP supports the USGS program in operational earthquake forecasting and a DHS project to register and test external forecast procedures from experts outside seismology. We found that earthquakes as small as magnitude 2.5 provide important information on subsequent earthquakes larger than magnitude 5. A retrospective experiment for the 2010-2012 Canterbury earthquake sequence showed that some physics-based and hybrid models outperform catalog-based (*e.g.*, ETAS) models. To expand the CSEP procedures to other parts of the model chain of seismic hazard analysis, we tested intensity-prediction equations for Italy and ground-motion prediction equations for Japan. These tests were complemented by tests of the various seismic hazard models for the US. Current CSEP development activities include testing of simulation-based forecasts and finite-rupture forecasts.

Updates of the ISC-GEM Global Instrumental Earthquake Catalogue: Status after Three Years of the Extension Project

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After a 27-month project co-funded by the GEM Foundation, the first release of the ISC-GEM Global Instrumental Earthquake Catalogue (1900-2009) (www.isc.ac.uk/iscgem/index.php) was released in January 2013 (Storchak *et al.*, SRL 2013). One of the main objectives of this project is to reassess the homogeneity (to the largest extent possible over time) of the earthquake parameters (especially location and magnitude) and list them along with formal uncertainties as a special product for seismic hazard and Earth's seismicity studies.

Due to time and resource limitations, the first release of the ISC-GEM catalogue (1900-2009) included earthquakes selected according to the following time-variable cut-off magnitudes: Ms=7.5 before 1918; Ms=6.25 during 1918-1963; and Ms=5.5 from 1964 onwards. Because of the importance of having a reliable seismic input for seismic hazard studies, funding from USGS, NSF, GEM and a few commercial companies in the US, UK and Japan allowed us to start working on the extension of the ISC-GEM catalogue both for earthquakes that occurred after 2009 and historical earthquakes listed in the International Seismological Summary (ISS), which fell below the original ISC-GEM cut-off magnitude of 6.25 before 1964. This extension is part of a four-year project that aims at adding as many earthquakes as possible that occurred between 1904 and 1959. In this contribution we present the updated ISC-GEM catalogue at the end of the third year extension program, which includes over 2000 more earthquakes during 2010-2013 and thousands more between 1920 and 1963 as compared to the first release. Further catalogue extension between 1904 and 1919 is currently under way. The extension of the ISC-GEM catalogue will also be helpful for regional seismic hazard studies as the ISC-GEM catalogue can be used as basis for cross-checking location and magnitude of those earthquakes listed both in the ISC-GEM global catalogue and in regional catalogues.

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