01 Frequency-Difference Back-projection of Earthquakes

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Back-projection has proven useful to image large earthquake rupture processes. It utilizes array techniques to estimate the spatial and temporal evolution of earthquake rupture over time, and can help us identify interesting earthquake phenomena like supershear rupture. However, the method does not directly solve an inverse problem and has difficulty in quantifying epistemic uncertainties, which can be caused by seismic array configurations, structural heterogeneities in the Earth's crust, unknown seismic phases, and variations in the focal mechanism. These uncertainties may cause erroneous interpretations of earthquake physics, which is particularly challenging to distinguish for complex earthquake rupture processes.

In this study, we develop and apply a new frequency-difference back-projection method to image earthquake rupture processes. The method is developed from a frequency-difference beamforming approach, which was originally designed to locate acoustic sources. Frequency-difference beamforming utilizes frequencies below the bandwidth of the signal, which are less affected by multipathing and structural inhomogeneities. This method can potentially allow us to locate sources more accurately even in the presence of strong scattering, albeit with lower resolution. We will first verify robustness of the method through both synthetic simulations and analysis of M6 earthquakes. We will then apply the method to the 2015 M7.8 Nepal earthquake to unveil its early rupture evolution. Our research aims to address how Nepal earthquake rupture evolved during the first 20s and overcame a geometric fault barrier, which is challenging to resolve because of the difficulties in imaging early rupture propagation process using other kinds of back-projection approaches.

02 Earthquake response analysis on soil-structure interaction of multi-storey R.C building under different soil conditions

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The aim of this study is to investigate the seismic response of a structure under different soil conditions when subjected to earthquake-induced vibration. For this purpose, 6-story reinforced concrete building is selected for this study and a two dimensional (2D) finite element model was developed with Mohr-Coulomb failure criterion under plane-strain conditions using PLAXIS FEM package. Viscous artificial boundaries, simulating the process of wave transmission along the truncated interface of the semi-infinite space, are adopted in the non-linear finite element formulation in the time domain. The local soil conditions and the characteristics of input excitations are important parameters for the numerical simulation in this research. The analysis was performed for four different cases: Fixed base without considering soil structure interaction (SSI), flexible base by considering SSI in hard (dense) soil condition and flexible base by considering SSI in soft soil condition. Kobe (Japan, 1995) earthquake is defined as input motion for dynamic load. All analyses are compared for outcomes such as storey displacements and accelerations. Through the conducted analyses, it appeared that various deformation types can occur due to the earthquake for different types of soil and deformations change depends on the local soil types. Therefore, precautions should be determined according to local soil conditions. The analysis demonstrated that for different conditions delimitation, distribution of travel and the fundamental frequency for each soil type change according to its mechanical properties. According to the obtained results, It was found that SSI can affect the seismic performance of building in terms of seismic force demands and deformations.

03 Selection of Ground Motion Models for Probabilistic Seismic Hazard Analysis in Iran

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Ground motion models (GMMs) are an essential component of probabilistic seismic hazard analysis (PSHA), in which their validity is basically dependent on the sufficiency of the data. In the current practice of PSHA, the different estimates of the ground motions predicted by different empirical GMMs are attributed to the epistemic uncertainty. The epistemic uncertainties arise from the lack of knowledge, which is reflected in imperfect models and can be handled by data-driven selection methods, which reduce subjectivity and guide the selection process in a quantitative way. In this study, we apply three data-driven selection methods, the log-likelihood (LLH), the Euclidean distance-based ranking (EDR), and the deviance information criterion (DIC), to objectively evaluate the predictive capability of ten GMMs developed from Iranian and worldwide datasets against a new and independent Iranian strong-motion dataset. The independent dataset that used in this study contains 201 records from 29 recent events with moment magnitudes $4.5<M_w<7.3$ with distances up to 275 km. The results of this study show that the prior sigma of the GMMs acts as the key measure used by the LLH and EDR methods in the ranking against the dataset. In some cases, this leads to the resulting model bias being ignored. In contrast, the DIC method is free from such ambiguity as it uses the posterior sigma through the Bayesian statistics as the basis for the ranking. Thus, the DIC method offers a clear advantage of partially removing the ergodic assumption from the GMM selection process and allows a more objective representation of the expected ground motion at a specific site when the ground motion recordings are homogeneously distributed in terms of magnitudes and distances.

04 Application of Support Vector Machine for Classification of Induced and Tectonic Earthquakes in Central and Eastern United States

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The number of induced earthquake cases in Central and Eastern United States is growing since 2009. The substantial increase in seismicity rate has been linked to the appearance of the number of wastewater disposal wells, especially in Texas, Arkansas, and Oklahoma. The sequence of earthquakes is associated with oil and gas production. Induced and natural tectonic events potentially are similar, and a large number of seismic events in the suspected areas make challenges for identifying man-made seismic events. In this study, we considered three large comprehensive datasets for applying the method to classify induced earthquakes from natural tectonic events. For this purpose, we use a support vector machine (SVM) as one of the most efficient machine learning algorithms. The SVM is based on the risk minimization principle that minimizes an upper bound on the expected risk. This allows the SVM to achieve an optimum network structure by balancing between the complexity of the approximating function and the complexity of the approximation of the data used. In this study, the dataset that we used includes the NGA-East tectonic natural, Induced earthquakes, and a comprehensive test dataset which contains the earthquake events with moment magnitude range between 3 to 5.8, depths up to 15 km and distances up to 200 km. The accuracy of the classification approach is obtained with a k-fold cross-validation procedure. Since the classification result is binary, a receiver operating characteristic curve is shown to illustrate the diagnostic ability of a binary classifier. The results of this study will demonstrate the feasibility and effectiveness of the SVM to classify the induced earthquakes from natural tectonic events in Central and Eastern United States.

05 A Misplaced 19th Century Earthquake in Oklahoma

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An earlier study (Hough and Page, 2015) suggested that most significant 20th century earthquake activity in present-day Oklahoma was associated with early wastewater injection, a practice that dates back to the mid-20th century. The study also concluded that the largest tectonic earthquake in present-day Oklahoma State was the event that occurred on 22 October 1882. With sparse and fragmentary archival accounts, previous published locations for the 1882 event have bounced across three states: Arkansas, Texas, and Oklahoma. The conventionally accepted location is in eastern Oklahoma near Fort Gibson. Accordingly, the event has been known in recent times as the Fort Gibson earthquake, although the U.S. Geological Survey catalog location, specified only to whole degrees in latitude and longitude, is nearly 200 km S-SE of Fort Gibson (34.0°N, 96.0°W). Hough and Page (2015) found a previously unknown account of the earthquake describing relatively severe effects in southeastern Oklahoma: fallen chimneys and a "general overturning of things". Their preferred location places the event towards the northern edge of the Ouachita fold and thrust belt (OFTB), at the time part of the Choctaw Nation, with an estimated magnitude of 4.8. Reviewing the seismic catalog, we find two other M~4 earthquakes near the Choctaw and Ross Creek thrust faults, the frontal faults of the OFTB in Oklahoma and Arkansas, respectively. Although instrumental seismicity is relatively low, the example of the Meers fault indicates that large late Holocene earthquakes can occur in the region in areas with low present-day and historical seismicity. We propose that the 1882 earthquake should be renamed the Choctaw Nation earthquake, with the magnitude and location determined by Hough and Page (2015). We also suggest that further work may be useful to consider the OFTB as a potential source zone.

06 Examining Earthquakes and Blasts in Georgia-South Carolina Seismic Zone, 2012-2014

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The Southeastern United States has a rich tectonic history resulting in complex regional structures including multiple stages of Appalachian orogenesis, continental rifting, and magmatism associated with the Central Atlantic Magmatic Province. In addition to these potential tectonic controls on the region's seismicity, streams and reservoirs have also been associated with earthquakes in the region. In 2012-2014, the addition of seismic stations from the US Transportable Array and the SESAME (Southeastern Suture of the Appalachian Margin Experiment) Array provides an opportunity to better characterize seismicity in the Georgia-South Carolina region. We developed a catalog of >1000 events from March 2012 to May 2014 and performed double-difference event relocations using arrival picks. We tested multiple approaches to discriminate between the blasts and earthquakes on the basis of event location, timing, and waveform properties. Many events were identifiable as either earthquakes or blasts based on the time at which an event occurred or an event's proximity to a dense cluster of other daytime events. We use these events to train an artificial neural network to discriminate between earthquakes versus blasts based on the frequency content of P and S arrivals and the P/S spectral amplitude ratio. Based on this analysis, ~10% of the events in the catalog were classified as earthquakes. Most of the earthquakes southeast of the Eastern Tennessee Seismic Zone are located in the Carolina Terrane, particularly where the Carolina Terrane intersects major rivers or reservoirs. One particularly prominent region of seismicity along the Savannah River near Thurmond Lake corresponds with an ~15-inch rise in water levels in 2013. A seismic swarm in April 2013 was followed by increased levels of ambient seismicity preceding the nearby MW 4.1 earthquake in 2014. These results suggest that seismicity is localized through a complex interaction between the pre-existing structural fabric, reservoirs, and rivers.

07 Mantle structure and dynamics at the Eastern North American passive margin inferred from anisotropic S-wave tomography

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The eastern North American passive margin (ENAM) is the ultimate result of the rifting of North America from Africa and Europe during the breakup of Pangea. As part of the ENAM Community Seismic Experiment designed to target this GeoPRISMS focus site, a 2014-2015 deployment of ocean-bottom seismometers (OBS) off the coast of ENAM extends broadband seismic coverage from the Transportable Array across the ocean-continental transition of a rifted passive margin. Shear wave splitting results in the area, which indicate seismic anisotropy and 'by proxy' mantle dynamics, show several perplexing patterns. For instance, neither margin parallel offshore fast azimuths nor null splitting on the continental coast obviously accord with margin-perpendicular continental extension or the current motion of the North American plate. Shear wave splitting offers no depth constraint on anisotropy, and the mantle has not been imaged in detail across the ocean-continent transition using these OBSs. Here we present results from a joint velocity-anisotropy inversion of ENAM that crosses the shoreline.

Using teleseismic travel times and shear wave splitting delay times measured with 1.5 years of OBS data and 5 years of Transportable Array data, we conduct joint isotropic/anisotropic S- and SKS-wave tomography. Results suggest multiple layers of anisotropy which could indicate depth varying mantle flow. Further, the joint inversion allows us to address the trade-off between anisotropy and velocity, improving our isotropic models. Our velocity results show several anomalies which have previously been interpreted as lithospheric foundering, the Farallon slab, and post-rift magmatic structure. We add anisotropic constraints to these observations. The model presented here, in conjunction with an ongoing joint surface and body wave velocity inversion and anisotropic surface wave analysis, will together flesh out the structure and dynamics of the crust and mantle across the ocean-continent transition of ENAM.

08 Rapid fluid injection into a low permeability laboratory fault promotes seismic swarms

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Fluid injection, from activities such wastewater disposal, hydraulic stimulation, or enhanced geothermal systems, decreases effective normal stress on faults and promotes slip. Earthquake nucleation models suggest the slip at low effective normal stress will be stable and aseismic, contrary to observed increases in seismicity that are often attributed to fluid injection. We conducted laboratory experiments using a biaxial loading apparatus that demonstrate how an increase in fluid pressure can induce "stick-slip" events along a preexisting saw-cut fault in a poly(methyl methacrylate) (PMMA) sample. We compared slip events generated by externally squeezing the sample (shear-triggered) to those due to direct fluid injection (fluid-triggered) and studied the effects of injection rate and stress levels. Shear-triggered slip events began on a localized nucleation patch and slip smoothly accelerated from slow and aseismic to fast and seismic. Fluid-triggered slip events initiated far more abruptly and were associated with swarms of tiny foreshocks. These foreshocks were able to bypass the smooth nucleation process and jump-start a mainshock resulting in an abrupt initiation. Analysis of these foreshocks indicates that the injection of fluid into a low permeability fault promotes heterogeneous stress and strength which can cause many events to initiate, some of which grow large. We conclude that while a reduction in effective normal stress stabilizes fault slip, rapid fluid injection into a low permeability fault increases multi-scale stress/strength heterogeneities which can initiate small seismic events that have the potential to grow rapidly, even into low stress regions.

09 The 2018 Update of the U.S. National Seismic Hazard Model: Ground Motion Models in the Central and Eastern U.S.

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The U.S. Geological Survey (USGS) National Seismic Hazard Model (NSHM) is the scientific foundation of seismic design regulations in the United States and is regularly updated to consider the best available science and data. The 2018 update of the conterminous U.S. NSHM includes significant changes to the underlying ground motion models (GMMs), motivated to enable the new multi-period response spectra (MPRS) requirements of seismic design regulations. To enable the new MPRS calculations, the USGS GMM selection criteria are updated to extend the applicability range of GMMs to 22 spectral periods and 8 site classes compared to the previous 3 periods and 1 reference site class. As a result, in the central and eastern United States (CEUS), the 2018 NSHM update incorporates 31 new GMMs for hard-rock site conditions as compared to the previous 2014 NSHM update with 9 GMMs. These 31 GMMs include 17 models from the Next Generation Attenuation relationships for central and eastern North America (NGA-East) with a total weight of two-thirds, and 14 traditionally developed “seed” GMMs with a total weight of one-third. The two suites of GMMs are used to better represent epistemic uncertainty (modeling uncertainty). New aleatory variability (natural uncertainty) and site-effect models specific to the CEUS are applied to all CEUS GMMs. The updated GMM medians, aleatory variability, epistemic uncertainty, and site-effect models will be compared to their counterparts used in prior NSHMs. For large magnitude events, the median ground motion generally increases at mid to long distances but decreases at very short distances; aleatory variability does not change significantly, but epistemic uncertainty increases substantially. This results in a broad ring of increased ground motions around the New Madrid seismic zone compared to the 2014 NSHM.

10 New Site Correction Factors and Design Response Spectrum: Their Applications in the Central United States

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Currently, the time-weighted average of shear-wave velocity for the top 30 m of soils and rock, Vs30, is the key parameter used to account for ground-motion site response (i.e., modification of ground motion by the near-surface soft sediments in terms of peak amplitude, frequency content, and duration) in engineering design and other applications in the United States. Vs30 has been found to be an inappropriate parameter, however, particularly for the central and eastern United States, because Vs30 does not correlate with site response. Site response is physically determined by the shear-wave velocity structure and associated parameters, such as density, damping, and nonlinearity, and uniquely quantified by two parameters: the fundamental (i.e., base mode) site period (Tf) and corresponding peak amplification (A0) at a site. We have developed new site correction factors based on Tf and A0 and the response spectral characteristics of incident rock motion. We estimated Tf and A0 from empirical and theoretical methods including surface-to-bedrock borehole spectral ratios, horizontal-to-vertical spectral ratios (HVSR) of earthquake S-waves, and 1-D site-response analyses at six sites in the central United States. We also applied new correction factors to develop design response spectra with three synthetic incident rock motions at these sites. The preliminary results demonstrate that the design response spectra developed using the new site correction factors can better capture site response.

11 Can Proxies Adequately Approximate Site Resonance?

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Numerous proxies have been proposed and used to account for site response, i.e., modification of ground-motion by near-surface, low velocity materials in terms of spectral content, amplitude, and duration. Some proxies are based on portions of a site's velocity profile including the time-average shear-wave velocity from the surface to a particular depth or the depth to a particular velocity. Others are based on the surface geology or thickness of unlithified sediments over bedrock. Empirical and theoretical studies have shown that site response can be quantified by the fundamental and peak site frequencies, f0 and fpeak, and the corresponding amplifications, A0 and Apeak, respectively. We estimated fundamental- and peak-response parameters from empirical and theoretical 1-D site responses at selected U.S. vertical seismic arrays, in Kentucky, California, and Alaska, and in Japan and at seismic stations in the thick sediments of the upper Mississippi Embayment (central U.S.) where velocity profiles to bedrock are available. We then compared the fundamental and peak site frequencies and the corresponding amplifications with those proxies. Our results show that the fundamental site period and peak amplification do not simultaneously correlate with velocity- or thickness-based proxies. For example, in the upper Mississippi Embayment where unlithified are up to ~1km thick, although f0 correlates strongly with depth to bedrock, A0 does not. Further, there is no correlation between fpeak and Apeak and sediment thickness. Likewise, the average S-wave velocity in the upper 30 m does not correlate with f0. Our results suggest that a single proxy cannot capture site response and reliably predicting linear site response relies on site-specific characterizations.

12 Fractal Dimension Analysis of Southern California from 1989 to 2019

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Power-law scaling relationships concerning earthquake frequency-magnitude distribution and fractal geometry of spatial seismicity patterns may provide clues to the earthquake rupture process. Past studies on the fractal characteristics of seismic phenomena have observed spatial differences in clustering and b-value in relation to fractal dimension value. In this study, an investigation of temporospatial seismicity patterns in southern California for the years 1989 to 2019 is conducted with an emphasis on seismicity near and within the San Andreas fault system and eastern California shear zone. In particular, capacity and correlation dimension values of earthquake hypocenters listed in the Southern California Earthquake Data Center catalogue are calculated for each year for magnitudes greater than or equal to 1.5 and length scales between 0.1 to 100 km. Preliminary results suggest a bimodal distribution in effective length scales, negative correlation between b values and correlation dimension values, and high correlation dimension values for years that include earthquakes with magnitudes approaching or exceeding 7.0. These observations may suggest applications of fractal seismology in delineating different earthquake types, in addition to identifying patterns for earthquake forecasts.

13 Existence of a low-viscosity layer beneath the 660-km discontinuity based on the orphan slabs imaged beneath East Asia

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It is debated whether full mantle convection or layered convection dominates the mass and heat exchange between the upper and lower mantle through the transition zone. Previous work indicates that the different modes of mass exchange through the subducting slab are controlled by the slab rigidity and variations in mantle viscosity. However, this relationship is complicated by the unresolved radial viscosity structure of the mantle. The latest geodynamic modelling shows slab orphaning (breakoff) across the 660-km discontinuity determined by the slab rigidity, and more importantly, the presence of a low-viscosity layer right beneath the transition zone. Due to the lack of data coverage and less accurate seismic tomography method, only the orphan slabs long after the breakoff have been imaged in the deep lower mantle. However, our new seismic model of East Asia (EARA2020), based on an unprecedented seismic data set and an advanced full waveform inversion, for the first time clearly captures the ongoing orphaning of the subducted pacific slab right below the 660 km depth. This seismic observations of orphan slabs at the top of the lower mantle definitively confirms the presence of a low viscosity layer underlying the 660-km discontinuity at the top of the lower mantle.

14 On the Unphysical Nature of the Brune Source Model

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The earthquake source model of Brune (JGR, 1970) is widely used to extract source parameters from earthquake waveforms and as the source spectrum in ground motion models. Its popularity notwithstanding, the Brune source model is fundamentally unphysical. The Brune source spectral shape is based on a source time function (STF) that is infinite in duration, something that is counter to the observations of displacements on real faults. If the source corner period is much shorter than the STF duration, then the source amplitude spectrum proposed by Brune (1970) is probably a good approximation to the real earthquake amplitude spectrum. However, if the STF duration is shorter than the source corner period, then the amplitude spectrum of the Brune source becomes distorted. If an earthquake STF has multiple peaks, a common observation even for relatively small earthquakes, scalloping of the amplitude spectrum can make the corner frequency difficulty to determine accurately. Savage (BSSA, 1966) proposed a kinematic model that predicts the STF of an expanding circular rupture, the same rupture shape as for the Brune source model. Amplitude spectra of the Savage STF are very different from the amplitude spectra of the Brune source model, and in many cases the amplitude spectra of the Savage source model show no clear corner frequency at all. These considerations indicate that source parameters that are determined by fitting a Brune (1970) spectral shape to observed earthquake amplitude spectra should be assigned a high level of uncertainty. The Brune source model may be appropriate when applied to very small earthquakes but is a poor source model for large, complex earthquake ruptures.

15 Matched Filter Detection of Seismicity in the Eastern Tennessee Seismic Zone around the Mw 4.4 December 2018 Decatur, Tn Earthquake

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Small to moderate-size earthquakes have occurred along the Eastern Tennessee Seismic Zone (ETSZ) for decades, resulting in the second highest seismicity rate in Central and Eastern US (CEUS) following the New Madrid Seismic Zone. The current seismicity forms a roughly 250-km long diffuse zone from northeastern Alabama to southwestern Virginia, without clear lineation of fault structures. The largest present-day earthquakes are about M~4.6, however causes of seismicity in the ETSZ remain unclear. The recent December 2018 Mw 4.4 earthquake near Decatur, Tn provides an opportunity to study one of the largest events in this region. We use a matched filter technique to detect earthquakes not previously catalogued. We apply a bandpass filter of 2-16 Hz to over 900 catalogued templates spanning over 15 years (January 2005 to May 2020), within 150 km of the center of seismicity. These templates are then used to detect missing events within 4 weeks before to 4 weeks after the mainshock, during which time several new events are detected. Cross-correlation based arrival time refinements are calculated to relocate the events. We use two relocation algorithms, XCORLOC and HYPODD, to comparatively relocate detected events. Relocated hypocenters are examined in an effort to resolve fault structures and orientations related to this earthquake. We also calculate the magnitudes of new events using principle-component fitting between templates and newly detected events.

16 A local earthquake tomography study using aftershocks of the 2011 Mineral earthquake, Central Virginia Seismic Zone, Virginia, USA

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A detailed tomography study is conducted using the local earthquake tomography inversion technique to understand the geological structure of the upper crust and its relationship to aftershock earthquake activity following the 2011 Mineral, Virginia, earthquake. This study helps explain the seismicity distribution in the central Virginia seismic zone. The inversion used a total of 5125 arrivals (2465 P-wave and 2660 S-wave arrivals) from 324 aftershocks recorded at 12 stations. These stations and aftershocks are located within ~15 km of the 2011 mainshock epicenter. The inversion volume is small (22 x 20 x 16 km, with a block size of 1 x 1 x 1 km) that covers several kilometers around the mainshock and main aftershock cluster area. The inversion used a halfspace with Vp=5.96 km/s and Vs=3.53 km/s as the initial velocity model that is based on previous studies. Good resolution is obtained in the central portion of the inversion volume within 1 ~ 5 km depth. The majority of the aftershocks located at or below 2 km are associated with a zone of negative Vp anomalies, positive Vs anomalies, and Vp/Vs ratios as low as 1.54. This zone trends NE and dips to the SE. We attribute the velocity anomalies to the presence of highly quartz-rich rocks based on laboratory measurements of Vp and Vs. We suggest that the rocks originated as sandstones in Paleozoic time along the passive margin of Laurentia and were later incorporated into the Chopawamsic formation during island arc collision in the Taconic orogeny.

17 The potential for an Earthquake Early Warning System in eastern Canada

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Eastern North America has a history of moderate earthquakes affecting a wide area due to the low attenuation of its competent bedrock. For example, the 2010 Val-de-Bois Mw 5.0 earthquake was felt more than a thousand kilometers away. With the advancement of real time acquisition and processing of seismological data, Earthquake Early Warning Systems (EEWS) have been proven capable of providing a warning for some affected regions before the strong shaking occurs. Canada is developing a national EEWS with the intention of covering several areas including eastern Canada. It is shown that such a system would be capable of producing meaningful warnings for cities in this region. A preliminary layout of an EEWS network is tested with a synthetic earthquake catalog, which was created to represent 10,000 years of seismicity based on the 2015 Canadian national seismic hazard model. The test identifies the usefulness of an EEWS in eastern Canada by estimating the warning rates at large cities such as Montreal, Ottawa and Toronto, and the amount of warning time based on specific seismic sources.

18 Coherence as a Measure of Body-Wave Signal to Noise Ratio in the Northeastern United States and Southeastern Canada

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Determination of the source parameters of a local earthquake from full seismic waveforms requires seismograms with clear body-wave signals from an earthquake source. Coherence of the earthquake body-wave seismograms recorded at two different receivers can be used to estimate the SNR of the body-wave energy radiated by the source. In this study, the coherence of earthquake body waves recorded in the Northeastern United States and Southeastern Canada (NEUSSEC) is measured as a function of frequency, interstation distance, ambient SNR and seismic phase, and then used as an estimate of body-wave SNR. Seismograms from the TA, NE, N4, CN, IU and US arrays were used to measure coherence between stations with a mean separation of 70 km. Seismograms from the Acton Littleton Seismic Array (ALSA) were used to measure coherence at 5 km mean station separation. Coherence is measured at frequencies between 0.8-10 Hz for Pn and Sn phases from NEUSSEC earthquakes with magnitudes (M) between 2 and 4.7 at distances between 180-1800 km as well as at frequencies between 0.05-5 Hz for the first arrivals of P and S waves from earthquakes >M6 at distances >2500 km. The teleseismic P waves display values of coherence greater than 0.9 out to interstation distances of 1600 km at frequencies <0.8 Hz, but as frequency increases, the interstation distance at which coherence falls below 0.9 decreases. Teleseismic S and regional Pn and Sn waves display coherence values around 0.5, suggesting they are dominated by noise, likely in the form of converted and reflected or refracted P waves and in the form of a greater ambient SNR. The variations in coherence for different seismic phases within this region can be used to quantify the presence of scattered seismic energy and ambient noise in the different frequency bands and interstation distances.

19 Uncertainty in seismic hazard in southeastern Canada

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Seismic hazard estimates in stable continental regions such as southeastern Canada are uncertain due to the lack of earthquake rate data and of recorded strong ground motions. In standard probabilistic seismic hazard analysis, this lack of knowledge is typically expressed by the use of a logic tree that attempts to quantify the (epistemic) uncertainty through the implementation of alternative hypotheses. Despite this, a single representative statistical value, such as the mean or median, is frequently the only parameter reported or required for engineering practice. This presentation will discuss how epistemic uncertainty is included within the 6th Generation Seismic Hazard Model of Canada for southeastern Canada and how the spread in hazard varies for two important Canadian localities, Montreal and Toronto. For the two cities examined, a lognormal distribution was able to reproduce the spread in hazard values remarkably well and the epistemic uncertainty in median hazard was estimated to be roughly a factor of two at short periods, with Toronto slightly higher due to greater uncertainty in the rates of nearby low-seismicity sources.

20 Crustal unloading as a source of induced seismicity in Plainfield, Connecticut in 2015

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On January 12, 2015, a magnitude 3.1 mainshock occurred in Plainfield, Connecticut near Wauregan Tilcon Quarry, causing modified Mercalli II-IV intensities. Shortly after the event, a team from Weston Observatory installed portable seismographs in the epicentral area. The portable array detected hundreds of small earthquakes from around the quarry, with 26 events that were accurately located. P-wave first motion directions obtained from readings of the mainshock suggest a thrusting focal mechanism on a NNE-SSW trending fault. In this research, we collect 113 gravity measurements in the proximity of the quarry to verify and correct fault geometry proposed by historic aeromagnetic and geologic mapping. Interpretations of the computed Simple Bouguer anomaly are consistent with historic mapping, with a few exceptions. The gravity survey further constrains a NNE-SSW trending fault that dips west underneath the quarry, inferred to be the Lake Char-Honey Hill fault, and reduces ambiguity in the position of an undefined ESE-WNW trending fault, which appears to be on strike to intersect the quarry. A 3D boundary element program (3D~Def) is then used to simulate quarry-induced stress changes on these faults in order to analyze the possibility of inducing seismicity through crustal unloading in the region. Quarry operations resulted in the removal of mass from the crust, which decreases lithostatic load. In a setting confined by a maximum horizontal compressional stress, decreasing the lithostatic load, or minimum principal stress (σ_3), shifts a Mohr-Coulomb diagram toward failure. The boundary element model shows that following the excavation of materials at the quarry, the largest Coulomb stress changes occur on the west dipping Lake Char-Honey Hill fault. In agreement with past studies, the results suggest that quarrying operations can trigger seismic activity in specific settings with an ideal stress regime, fault orientations, and rock characteristics. In order to mitigate the risk for future earthquakes related to quarrying operations, these factors must be considered before operations begin.

21 High-resolution airborne magnetic and seismic reflection data image basement faults in the Charleston, South Carolina seismic zone

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The Charleston seismic zone is home to modern seismicity mostly M<3.0 and a historical M7.0 earthquake that did severe damage to the city of Charleston, SC and surrounding area in 1886. Locations of faults that are capable of a large earthquake and are favorably oriented in the modern stress field remain debated. These interpretations are based on shallow wells, sparse reflection seismic profiles, diffuse seismicity, and 1950's-1970's-era aeromagnetic data. Surface mapping of faults is especially challenging because the crystalline basement, where most seismicity occurs, is buried beneath 500-1000 m of Cretaceous and Cenozoic sediment. In 2019 the USGS contracted a high-resolution airborne magnetic and radiometric survey over the seismic zone (a 90 km x 134 km area) to better image basement structures. Such structures are likely to be associated with either Mesozoic rifting and opening of the Atlantic Ocean, or Paleozoic orogenic events. The magnetic data and derivative maps reveal numerous lineaments (linear anomalies and anomaly gradients). These include ESE-striking lineaments that are at most 30 km long and parallel or sub-parallel to the inferred edge of the Georgia rift basin. These lineaments terminate along a linear, NE-striking trend that is over 50 km long and parallel to mapped Paleozoic structures farther inland. Comparisons to reprocessed legacy seismic reflection profiles collected by Virginia Tech, the Consortium for Continental Reflection profiling (COCORP) program, and the U.S. Geological Survey suggest that both the ESE and NE-striking magnetic features are caused by faults with vertical displacements within the crystalline basement. In many areas, these basement displacements correspond to faults or folds in the overlying younger sediments, suggesting deformation has continued after the opening of the Atlantic Ocean. The NE-striking magnetic lineaments, interpreted as inherited Paleozoic structures, are greatest in length and thus suggest possible candidates for larger earthquakes within the region.

22 Investigation of the correlation between kappa and soil nonlinearity

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Soil nonlinear behavior is often triggered at soft sites subjected to strong ground motions. However, previous studies on kappa, which is a commonly used high-frequency attenuation parameter, have mainly focused on the linear-elastic regime associated with small shear strains. Large deformations induced by strong ground motion lead to an increase of material damping ratio, which has been observed in dynamic laboratory testing of soils. High-frequency waves with short wavelengths should experience multiple cycles of shearing within soil layer, allowing them to experience more attenuation than low-frequency waves. Hence, in this study, the high-frequency parameter kappa is hypothesized to be influenced by large shear strains and soil nonlinearity. Twenty stations from the Japanese Kiban-Kyoshin network (KiK-net) database are used to study the connection between nonlinear site response and kappa. We found that soil nonlinearity can affect estimates of kappa, but this influence is station-dependent. Observed complicated local site conditions and site-specific response also demonstrate the limitations of using a single site parameter, such as Vs30 (the time-averaged shear wave velocity for the top 30 m), to describe the correlation between soil nonlinearity and kappa estimates.

23 Preliminary Seismic Analyses of Quarry Blasts in NW Miami, Florida

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Quarry blasting is conducted in NW Miami to mine aggregate for the construction industry. The upper layer of limestone is mined using ripple blasting with charges of about 50,000 lbs of explosives. We installed a network of 6 seismic stations in July 2019 and to date have recorded 480 blasts. The instruments are four Raspberry Shake 3-component seismometers and two Raspberry Shake vertical seismometers plus infrasound sensors. The network aperture is about 10 km. The blasts occur in at least six different mines. Blasting is done between the hours of 8 a.m. and 4 p.m. local time Monday through Friday. Many of the blasts are felt by local residents as both seismic shaking and airwaves that are heard as well as causing air-coupled shaking. The seismic waves are high-frequency (8-10 Hz) P waves in the initial phases and low-frequency (1-3 Hz) Rayleigh waves dominating the later parts of the seismograms. S waves are observed in some cases, presumably as a result of the ripple blasting. The largest blasts have magnitudes of M~3 although logA0 values are not well known. Cultural noise is high in Miami, but there are no natural sources of seismicity nearby, so the blast signals stand out clearly. The velocity structure is poorly known. The top layer is overburden (muck) about 2 m thick. The mined unit is the Miami limestone directly under the muck. It is about 30 m thick and has a Vp of about 2.7 km/sec. The underlying unit (> 30 m) has Vp>3 km/s. Head waves are observed for some events at distances as close as 3 km. Efforts are under way to evaluate amplitude as a function of distance for several different wave types. This will help establish wave propagation and attenuation properties of the carbonate rocks of the Florida Peninsula.

24 Fiber Optics for Environmental SEnsEing (FORESEE) array in Eastern US

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We describe the Fiber-Optic foR Environmental SEnsEing (FORESEE) project at Pennsylvania State University, the first continuous monitoring distributed acoustic sensing (DAS) array in the Eastern US. This array is made up of nearly 5 km of pre-existing dark telecommunications fiber underneath the Pennsylvania State University Campus. The campus sits in the Allegheny Mountain region of the US, and our aim is to understand urban hydrology and detection of geohazards (particularly karst features). Here we detail the FORESEE experiment setup, fiber calibration, and observations of natural events and anthropogenic activities in the first year. We calibrate the DAS measurement using M8.0 Peru earthquake data by a nearby seismometer and active-source geophone data. The observation of the S-wave reversal-polarity in the zigzag array is explained by the directionality of S-wave using the plane wave simulation. We observe a wide variety of seismic sources: natural events (earthquakes and thunderstorms), mining blasts, vehicles, music concerts, and walking steps. We observe clear recordings of ground motions due to thunder not observed on previous dark fiber arrays. These thunderquake signals could be an important source of broadband energy for seismic imaging in an area with little earthquake seismicity. Further, we show preliminary results towards near-surface imaging with ambient noise interferometry, which requires careful preprocessing in the presence of anthropogenic noise, which builds further evidence that dark fiber can be a useful tool for seismology in cities.

25 Crustal structure variations of the Eastern North American Margin controlled by its antecedent subduction history

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Using 64,000 km of seismic reflection data tied to 40 wells and published geological and geophysical data, we quantified along-strike variations in the distribution of rift structures, magmatism, crustal thickness, and early post-rift sediments from Cape Hatteras to the Canadian border. This area consists of three segments: Baltimore Canyon trough (BCT), Long Island Platform, and Georges Bank Basin (GBB). BCT is narrow (80-120 km), has few rift basins, and consists of thin crust overlaid by a thick volcanic succession along its hinge line. In contrast, GBB is wide (~200 km), has many syn-rift structures, and contains seaward dipping reflectors located ~200 km seaward of the hinge line. Early post-rift subsidence at GBB coincided with ~20-25 km-thick continental crust suggesting "uniform" thinning of the lithosphere under the pre-magmatic rift. Models for the formation of volcanic margins do not explain the wide structure of GBB. We distinguish between pre-magmatic (before ~195 Ma) and magma-assisted modes of rifting. The variant styles of crustal deformation coincide with pre-rift crustal terrane distribution that we interpret to have controlled the pre-magmatic response of the lithosphere to extension. These terranes were accreted to the ENAM margin during a late Paleozoic convergence to form an asymmetric lithospheric structure with rheological variability. In BCT, strong rheology, associated with the Avalon terrane having an oceanic island-arc affinity resisted necking of the cold lithosphere, whereas the weaker crustal composition of the Meguma terrane in GBB (and Nova Scotia) with passive margin affinity promoted wide pre-magmatic necking. During the magma-assisted phase of the rift, steep geothermal gradients overwhelmed compositional controls on the rheology and facilitated regional strain localization. At BCT, the localized crustal thinning coupled with intense magmatism acted on a crust unthinned by the pre-magmatic rifting. In contrast, at GBB, magma-assisted rifting was superimposed on an already thinned and extended crust.

26 Foreshock and aftershocks sequence of the M5.1 Sparta Earthquake in North Carolina

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On August 9, 2020, a Mw5.1 earthquake occurred near Sparta, North Carolina. This earthquake ruptured the uppermost crust of a stable continental region of the North American Plate, which has been quiet since the M5.2 1916 Great Smoky Mountain earthquake. The mainshock was preceded by several ~M2 foreshocks within the last 24 hours, and was followed by many aftershocks occurring at very shallow depths. This sequence provides a unique opportunity for better understanding the local fault structures as well as the source processes of intraplate tectonic regimes. In this study we combine a deep learning earthquake phase picker - EQTransformer and matched filter detection to create a more complete earthquake catalog for this sequence. During the time period of August 6 and September 3, the deep learning picker was able to identify 90 new events that were not listed in the standard USGS catalog. These new events were then being combined with events listed in the standard catalog to form a pool of 283 earthquake waveform templates for matched-filter detection. The matched-filter detections were made by first performing moving window cross-correlation of the template waveforms with daily continuous data, and then identifying the times where high coefficients are present. In order to avoid biases at individual stations, we stack and take the average of the cross-correlation functions of each channel available. Detections are then declared at the times when the coefficients are higher than 9 times median absolute deviation (MAD). Through the matched-filter procedure, we were able to detect 9 times more small earthquakes. Our next step is to relocate these newly detected events with waveform cross-correlations, and then use them to illuminate subsurface fault structures and spatio-temporal evolutions of seismicity in this sequence.

27 High-resolution earthquake locations for the Sparta aftershock sequence

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Following the historic M5.1 event near Sparta, NC on August 9, 2020, we installed 4 stations equipped with a Wildlife Acoustics recording system, sampling at 4000 samples/s. The 4.5 Hz geophones and the acoustic infrasound sensors recorded dozens of events in the early aftershock sequence, from Sunday, August 9, through Thursday August 13. This deployment overlapped briefly with the U. Memphis/CERI array, augmenting the 5 stations and, thus, providing additional constraints on earthquake location and velocity structure. We recorded approximately 100 events after the main shock and before the U. Memphis/CERI started recording data on Tuesday, several of which were located. The event time series shows about 5 events per hour for the first 20 hours following the M5.1 main shock; after 20 hours, the rate drops off considerably. These events are too small to be registered at broader networks where stations are tens to 100's of km distant. In addition, a recorded production blast in a quarry located within 5 km from the main shock offered further data for reconstruction of a detailed 1-D velocity model. The augmented array and new seismic velocity data provide critical constraints for earthquake locations at a local scale in this poorly characterized region.

28 Disentangling Anthropomorphic Noise Sources During the COVID-19 Virus Lockdowns: Examples from the Washington DC and Boston Areas

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The COVID-19 global slowdown in human activity resulted in a decrease in high-frequency seismic noise at many sites around the world (Lecocq et al., 2020; L20). Approximately 40% of the L20 stations were Raspberry Shakes (RSs). These RSs are often installed in urban and suburban sites, subject to more anthropomorphic noise than traditional quiet observatory sites. The time-varying noise levels before and during the lockdowns presents an opportunity to investigate specific noise sources.

Vertical component seismograms from these RS sites (beginning 01/01/20) were filtered in the 4-20 Hz band, and envelopes were calculated for different sub-bands of that range. These sites have overall patterns of post-lockdown decrease after mid-March, but the patterns vary due to local sources. For the DC site (RAC22), daytime noise levels before the lockdown were ~0.4 µm/s with peaks of 0.5 µm/s during rush hours. After the shutdown, weekday levels decreased to ~0.2 µm/, a decrease of ~50%. For the Boston area, we analyzed two RSs at Boston College (RA2DE and R57EC) to attempt to untangle very local (within ~200 m) vs global effects. Noise levels for these two sites are much higher than for the DC site, ranging from as great as ~10 µm/s before lockdown to as low as ~1 µm/s after lockdown. RA2DE is in an athletics center, and R57EC is in a classroom building. RA2DE is closer to Boston commuting activity than R57EC.

We compare this seismic noise with independent measures of human activity, the Apple Mobility Index (AMI) and the Citymapper Mobility Index (CMI). These measures show ~90% decrease after lockdowns and more recent recovery to pre-pandemic levels. The broad trends of the noise generally correlates with the AMI and CMI data, but that pattern is mixed with noise from sources near the RSs (e.g., people walking, and vehicles).

29 Why do continental normal fault earthquakes have smaller maximum magnitudes?

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Continental normal fault earthquakes have been reported to have smaller maximum magnitudes (Mmax) than continental earthquakes with other fault geometries. This difference has significant implications for understanding seismic hazards of extensional regions. Here, we examine how Mmax varies with fault geometry in continental regions using the Global Centroid Moment Tensor (GCMT) catalog. We explore whether the lower normal fault magnitudes are an artifact of the relatively short earthquake catalog, and - if not - potential physical reasons for the smaller magnitudes.

We find that the largest continental normal fault earthquakes are ~ Mw 7 while other fault geometries can reach ~ Mw 8. Furthermore, the magnitude-frequency distribution of continental normal fault earthquakes has a higher b-value and lower corner magnitude than the other fault geometries. We find that if significantly larger continental normal fault earthquakes could occur, the GCMT catalog is long enough to capture them. Therefore, the observation that continental normal fault earthquakes have smaller Mmax appears to be true and not simply due to our classification criteria or relatively short catalog lengths. We also find that normal faults are long enough to host larger earthquakes, so fault length is likely not the primary factor limiting Mmax.

In contrast, oceanic normal fault earthquakes do not exhibit lower Mmax or significantly different magnitude distributions relative to other fault geometries. The larger oceanic normal fault earthquakes occur between the trench and outer rise, due to plate bending. Bending produces a different stress field than pure extension and appears to allow for larger normal fault earthquakes. Because such bending environments do not occur in regions of continental extension, such earthquakes do not arise. Hence although both pure extension and bending lead to normal fault earthquakes, only bending produces the stress conditions necessary to produce very large normal fault earthquakes.

30 The May 15, 2020 M 6.5 Monte Cristo Range Earthquake

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On May 15, 2020, a magnitude 6.5 earthquake occurred near Tonopah, Nevada in the Monte Cristo mountains. The earthquake was widely felt through Nevada, eastern California and parts of Utah, although no fatalities were recorded. The focal mechanism solution and the distribution of abundant aftershocks suggest that the earthquake occurred on an east-northeast trending, steeply-dipping fault with left lateral slip. The largest aftershock with a magnitude of 5.1 happened a few minutes after the main shock. In this study, we used ascending and descending pairs of Sentinel1-A Synthetic Aperture Radar (SAR) data acquired before and after the earthquake to calculate the satellite line of sight (LOS) surface displacement associated with the main event and its immediate aftershocks. LOS deformation reached 40 cm. The LOS displacement data were inverted to model the fault displacements at depth based on the formulation of Okada (1992). We will present the results of a series of simple models, comparing estimates of strike, dip and surface displacement with other available data. Preliminary results indicate broad agreement with the seismic data, with maximum fault displacement at depth equal to 1.5 to 2 meters.

31 Seismicity Detection at the Slowly Deforming Iberia using Deep Learning

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Iberia is a slowly deforming region (SDR) in Southwest Europe, with tectonic deformation rates ≤1 mm/yr, except in the Betics near the boundary between Nubia and Eurasia plates. Seismic behavior of SDRs remains an open question due to the low tectonic loading rates, complex fault systems and episodic and migrating seismic activity that complicate the understanding of earthquake cycle and hazard assessment. As in other SDRs, seismic activity in Iberia is characterized by frequent low-magnitude earthquakes at shallow depths (<30 km) with infrequent moderate to high magnitude earthquakes. Dense temporary seismic networks, such as the IberArray and WILAS networks, were deployed in the region from 2007 to 2014. The data collected during these deployments hold untapped information that can improve the seismic catalog and help gain insights on the tectonic processes of SDRs.

In this study we trained a convolutional neural network-based phase-identification classifier (Zhu et al., 2019) using data from permanent seismic networks in the region. We built a dataset of waveforms of events with manually picked P and S phases, thus ensuring a balanced dataset, cutting 25 s windows around the phase arrival. We only used events with station-source distances smaller than 400 km. We added noise windows right before and after the P and S-windows, respectively, creating a 144390 waveforms dataset (70% training, 15% validation and 15% testing). Before reading the three component waveforms for training we randomly cut a 20s window and applied a soft-clipping function. We achieved an overall best model with 96.30% training and 96.05% validation accuracies and achieved 95.81% accuracy on the test dataset. We used our model to pick phases at the permanent and the temporary networks that will be associated to build a new local earthquake catalog in this region. Additional performance metrics and results will be presented at the meeting.

32 Site Response Study in the New York Metropolitan Area with an Investigation of the Magnitude 3.1 New Jersey Earthquake of September 2020

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The magnitude 3.1 Freehold, New Jersey earthquake on September 9th, 2020 caused weak to light shaking (II-IV on the MMI scale) from the epicenter out to New York City and the surrounding metropolitan area. The USGS reported a Peak Ground Acceleration of app. 5% g about 5-10km from the epicenter, and app. 0.2% g as far as uptown Manhattan.

The surficial and bedrock geology of New York City is exceedingly varied in a compact region, which makes constraining the exact effects of small to moderate local earthquakes difficult. Site effects caused by soil amplification from small to moderate-sized earthquakes are a major risk in this region. Seismic wave amplifications caused by low velocity and density glacial soils underlain by hard, competent bedrock are documented in the New York City area (Field et al., 1990; Nikolaou & Edinger, 2001; Stephenson et al., 2009). The effects from this high impedance contrast at the soil-bedrock interface leave much of New York City, specifically unreinforced, older masonry buildings, vulnerable to soil amplification caused by a small to moderate-sized earthquake, similar to Boston, MA (Baise et al., 2016).

We utilize the Horizontal-to-Vertical Spectral Ratio (HVSR) of ambient noise to obtain the soil layer's fundamental frequency at numerous accelerometer stations in the New York metropolitan area. Additionally, we analyze HVSR of the New Jersey earthquake to validate the soil resonance and pick out its variations from the ambient HVSR. Using 1D numerical modeling of an SH1D half-space, we estimate the expected amplifications at these sites given known geological data, and compare these to the observed response. We combine these data with prior studies in the region to show spatial trends in site response, and to reaffirm the need for additional soil amplification studies due to the high cost and density of vulnerable assets in the area.

33 Seismic and Chemical Signature of the Continental Accretion of the Eastern North American Margin

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The continental accretional history of the eastern margin of the North American continent has been mainly mapped by its fold and thrust seen near the surface, together with a glimpse of the deep structure along certain transects where seismic profiles are available. However, its complete image along this ancient tectonic boundary has yet to be fully understood. In this presentation, we provide a seismological view of the crustal architecture beneath the eastern margin extending from the northern Appalachian to the Gulf of Mexico through a comprehensive set of seismic images built from the Earthscope/USArray data. These images include ambient-noise and earthquake based shear velocity (Vs) structure of the crust and uppermost mantle, crustal thickness constrained by the receiver functions, as well as the newly measured Poisson's ratio for the crystalline crust. After being corrected for temperature and pressure, these high-resolution seismic properties are then translated into the chemical composition of the crust, producing a 3 dimensional model of the silica content across the eastern margin with associated uncertainties. The resulting model reveals a chemical boundary in the deep crust which transitions the mafic Precambrian basement to the more felsic accreted terranes of the Piedmont and Coastal Plain. Notably, this chemical boundary does not simply follow the basement-cored uplift along the blue ridge belt, but varies along strike significantly from north to south. We conclude that these new seismic-derived compositional images provide insights into the complex history of the early accretion of the continent.

34 Evolution of seismic hazard estimates in Eastern Canada

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A key output of seismological research is seismic hazard estimates that improve societal resistance to earthquakes. True hazard values are unknown and estimates often change with time. A simple model for possible change suggests that some countries start high and in successive hazard estimates approach the target ("true") value from above, but most countries start low and approach the value from below. In either case the hazard estimate seldom moves monotonically towards the target level, but oscillates above and below the trend. Since 1953, Natural Resources Canada (and its predecessors) has been responsible for six generations of seismic hazard maps for Canada. These have formed the basis for the seismic design provisions of the National Building Code of Canada. I present a 65-year history of 5% damped spectral acceleration at 0.2 s mean-hazard estimates for the 2%/50yr probability level for Montreal, Toronto and other eastern cities. Site Class C was used for the comparison. The earlier short-period hazard estimates were adjusted to be equivalent to Sa(0.2) at the 2%/50yr probability level by using ratios of results from Canada's 4th Generation model. Hazard estimated for Montreal has increased reasonably steadily at about 0.6% per year. Changes from generation to generation appear large, but Montreal's previous estimates fall within the 16th-84th percentile uncertainty range of the 6th Generation model estimates. In a statistical sense, the underlying median changes are not different. However, these changes still need to be adopted into the building code, because small changes in median or mean hazard can lead to large changes in expected building collapse rates due to the shape and overlap of the fragility and seismic hazard distributions.

35 Coulomb Static Stress Transfer during Pohang, Korea Enhanced Geothermal System Injection-Induced Seismicity

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Between January 2016 and September 2017, two injection wells were hydraulically stimulated at the Pohang, Korea Enhanced Geothermal Systems (EGS) site. Five stimulations were spatiotemporally correlated to seismicity including a magnitude (M) 3.2 and M 5.5 event, two months after the last stimulation. The M 5.5 event caused damage and injuries in the city of Pohang and shut down the EGS operation. Investigation concluded that the seismicity was induced by injection of fluids during the hydraulic stimulations.

In this study, multiple mechanisms for the triggering of induced seismicity were investigated. Pore pressure modeling and Coulomb static stress modeling were used to determine a causal mechanism for the mainshock. Fifty-nine relocated earthquakes with M > 0.3 were used in the Coulomb static stress transfer modeling. Cumulative stress changes at the location of the M 3.2 foreshock and the M 5.5 mainshock were determined as well as stress change at each earthquake location directly before the individual events occurred.

We found that a majority of events occurred in areas with positive Coulomb static stress change. The modeling also indicated that close to half of the events occurred in areas of Coulomb stress change > 0.01 MPa. Prior to the individual event, static stress change at the location of the M 3.2 foreshock ranged from 0.02 to 0.04 MPa and at the location of the M 5.5 mainshock ranged from 0.13 to 0.15 MPa. Stress change caused by earthquake interactions at the foreshock location were comparable to the pore pressure change. Stress change at the location of the mainshock, however, was higher than the pore pressure change. We conclude that earthquake interactions play a significant role in the triggering of induced seismicity.

36 A Surprising Dam Failure Caused by the August 31, 1886, Charleston, South Carolina Earthquake: Why Did Langley Dam Fail?

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The failure of Langley Dam, located near Aiken, South Carolina, is one of the more noteworthy and surprising far field (epicentral distance ~ 176 km) effects of the M7.0, August 31, 1886 Charleston, SC earthquake. Langley Dam, a relatively small earthen mill dam, was constructed on Horse Creek circa the Civil War. Almost immediately after the earthquake shaking ceased, Langley Dam failed and the discharged water damaged two railways, which caused two separate train derailments. Two of the fatalities attributed to the Charleston earthquake were from crewmembers on the two trains. We integrated historical accounts of the dam failure with recently completed geotechnical investigations and site response modelling to explain the surprising failure of Langley Dam. Henry W. Grady, who was managing editor of the Atlanta Constitution newspaper, wrote an important historical account of the Langley Dam failure. Mr. Grady left Atlanta for Charleston within hours of the main shock. His detailed trip accounts provide a unique perspective on the aftermath of the Charleston earthquake. In particular, his description of the post-failure condition of Langley Dam is critical in understanding how the dam failed. Our analysis indicates that the foundation conditions and geologic setting of Langley Dam, and the materials and methods used to construct the dam played key roles in its failure. Recognition of the geologic conditions that contributed to the failure of Langley Dam has implications for seismic design of modern structures in similar settings in Georgia and South Carolina.

37 High resolution P- and S- wave tomography from combined geophone and DAS sensing at the DFDP-2 Borehole, Alpine Fault, New Zealand

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A series of high-spatial resolution zero-offset and walk-away VSP (Vertical Seismic Profile) surveys were carried out in the cased DFDP-2 borehole in order to better image the Alpine Fault and to obtain in situ measures of wave speeds. The survey was conducted within the Whataroa Valley, that was originally glacially scoured and now consists of a variety of high-energy fluvial deposits contained within the fault-related metamorphic schists and mylonites. The upper 245 m of the borehole are through the sediments with metamorphic rocks encountered below this depth. The survey incorporated both wall-locking geophones at close vertical spacings as small as 1-m to depths of 394 m simultaneously recorded with a cemented digital acoustic sensing (DAS) cable along the entire 893m of the deviated borehole. The offset records show direct P and S arrivals, the latter interpretation confirmed by eigenanalysis of the 3-component geophone data and enhanced by a polarization filter. These two arrivals are interpreted as direct P-wave and S-wave produced at the lithological boundary between sedimentary rock and the beneath bedrock. All the transit times for P- and S-wave are manually picked and then used in a wavepath eikonal traveltime (WET) type inversion to obtain both high-resolution 2D P- and S- wave velocity tomograms at a number of azimuths extending from borehole. The WET inversion is based on a finite frequency assumption using wavepath with a certain width instead of typical ray tracing. Interpretation of the tomogram panels are complicated by the geometry of the valley. Wave speeds in the fluvial deposits range from 1132.5 m/s to 2057.9 m/s. The wavespeeds in the metamorphic rock mass, under the assumption of isotropy, only reach as high as 4024.4 m/s and 2836.0 m/s for P and S waves, respectively.

38 Initial Observations of the M=5.1 Sparta, NC Earthquake of August 9, 2020

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The M5.1 Sparta earthquake was strongly felt locally, with light to moderate damage (intensity VI), and lightly felt in Cincinnati Ohio and Wilmington NC. The NCGS observed potential surface rupture along a ~1.1km trend with azimuth ~106°. A source radius of ~1 km is compatible with a stress drop of 22 MPa estimated for this event. The M5.1 was preceded by 8 foreshocks (1.8 <= md <= 2.6) over ~24 hours and followed by more than 184 locatable aftershocks (-0.8 <= md <= 2.9) into September. A first motion reverse-slip focal mechanism was determined for the main shock with strike, dip and rake of 109+-3, 59+-3 and 31+-4. The strike, dip and rake are consistent with the observed surface deformation. The depth estimate (7.8km) of the main shock was poorly constrained because the closest station was 50 km distant. Therefore, CERI deployed 4 real-time stations in the local area. A subset of aftershocks has been relocated using only the 4 temporary stations and using a program (HYPOELLIPSE) that allows depths above sea level. These aftershocks show a significant scatter in map view and linear trends are not pronounced. In cross-section, the hypocenters occur largely between the earth's surface and 3km below sea level. This is reasonable evidence that the main-shock fault is also shallow and contained within the aftershock distribution. The distribution has a cone shape in cross-section, wide at the top and narrowing towards depth, encompassing the potential surface rupture features in map view. An InSAR interferogram (produced using ascending ESA Sentinel-1A pre-earthquake scene from August 8 and post-seismic scene Sentinel-1b from August 14, 2020) shows fringes and unwrapped phase in the epicentral area indicating uplift southwest of the NCGS surface rupture trend. A CORS GPS station in Sparta also exhibits co-seismic offset and provides Hi-rate GPS seismograms.

39 Characterization of swarm and aftershock behavior in Puerto Rico

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The recent Puerto Rico earthquake sequence has drawn attention as the seismicity rate in this area is unprecedented. The sequence began on Dec 28, caused a 6.4 magnitude earthquake on Jan 7, and remains active. This sequence has fit the nominal definition of an earthquake swarm (sustained high seismicity rate without a clear triggering mainshock, an abrupt beginning, and a lack of adherence to Bath's Law) while also having several mainshock-aftershock sequences embedded within it. In an effort to place this sequence in the context of the previous seismicity in Puerto Rico, we investigated the existence of swarms recorded by the Puerto Rico Seismic Network since 1987 by identifying sequences of increased seismicity rate when compared to the background rate. The distinction of aftershocks from swarms was based on the existence of an initial event that was at least 0.5 magnitudes higher than the other events and evidence for Omori decay. However, when we examined the relationship between the number of events in a sequence versus the maximum magnitude, we did not observe the expected separation between the two sequence types. This separation did emerge when we divided the study area into geographic regions, indicating that a higher magnitude of completeness in the northern offshore regions create artificially lower numbers per sequence. Focusing on sequences over the last five years, we observe better magnitude of completeness in all regions and a clearer separation of swarm and aftershock behavior. Detailed characterization of the swarm and aftershock patterns for the Puerto Rico region will be a critical input for improved aftershock and swarm forecasts that are becoming a key component of hazard mitigation.

40 Tracking anthropogenic seismic noise variations during the COVID-19 pandemic using fiber optic sensors

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World-wide quieting of seismic noise has been observed by seismometers due to COVID-19 lockdown measures. Detailed study of anthropogenic seismic noise variations in a city scale could provide a means to investigate the COVID-19 impact on human activities, evaluate the effectiveness of these measures, and finally provide feedback to adjust the measure in urban areas. While sparse distribution of seismometers in a city-scale area to characterize noise lack of spatiotemporal resolution, considering complex anthropogenic noise sources in spatiotemporal domains, distributed acoustic sensing (DAS) could provide high spatiotemporal resolution seismic data in cities, by converting existing optic fibers to dense sensor arrays with low-cost and low-maintenance.

Here we report anthropogenic noise monitoring results during COVID-19 pandemic from the 4-km-long DAS array in the city of State College, PA. We observe a wild drop of seismic noise level across the array after the stay-at-home (lockdown) order was issued on March 18th 2020 in PA. And the seismic noise gradually increased back after lifting the restrictions on business and individual mobility on May 1st 2020. Temporally, anthropogenic noises including footstep, traffic and industrial construction in the 1-50 Hz are reduced significantly up to 50% and then increased. Spatially, DAS can capture the noise variation in the city block scale. Noises in "rural" area, main campus and western campus are dominated by environmental noise, traffic noise and human-generated noise, respectively. During lockdown, noises in rural areas remain relatively stable but high-frequency traffic noise (>10 Hz) on main campus and low-frequency noise (<10 Hz) in western campus reduced significantly. Our results that correlate well with independent mobility data suggest that DAS can serve as an innovative approach to monitor the dynamics of COVID-19 lockdown measures with high spatiotemporal resolution in future cities.

41 Site classification to verify "hard" rock at 25 seismograph stations in Eastern Canada

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The time-averaged shear-wave velocity (Vs) of the upper 30 m (Vs30) is the only seismic site parameter in the National Building Code of Canada (NBCC) to classify rock sites. It is typically assumed that seismograph stations in Eastern Canada are placed on hard rock (i.e. Vs30 > 1500 m/s or site class A). This study tests the application of non-invasive seismic techniques at Eastern Canada stations and verifies the hard rock site class assumption. A multi-method approach using active and passive seismic methods was applied. Active-source techniques were the most successful, velocity measurements were almost always obtained. Passive-source techniques were often less successful, but measured rock velocity. Rayleigh wave dispersion estimates were acquired for 16 stations and inverted for the Vs depth profile using two methods. Bayesian inversion provided quantitative uncertainty of the station Vs30 while a neighborhood algorithm provided the lowest misfit Vs30. Of the 16 stations, we determine 5 stations correspond entirely to NBCC site class A, 9 stations span site classes A and B (1500 m/s boundary), and 2 stations are softer than the hard rock assumption. Stations on younger Paleozoic rocks are observed to have a lower Vs30 compared to older Precambrian rocks, as expected. Station amplification functions are also obtained using microtremor and earthquake horizontal-to-vertical spectral ratios.

42 Pushing the limit of single station: source characterization for two small earthquakes in Dartmouth, Nova Scotia, Canada

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A pair of small earthquakes (M 2.4~2.6, Earthquakes Canada) hit the city of Dartmouth, Nova Scotia, Canada in early March 2020. The two events are recorded by three seismic stations within 200 km, but only one station is close enough (HAL, < 10 km) to offer high-quality broadband signals. In this study, we explore their source parameters using the nearest station through waveform modelling. A nearby quarry blast (MN 2.0) with known GPS coordinates is adopted as a reference for regional velocity model building and location calibration. We first build a half-space velocity model by estimating the P-S travel time difference of the blast and determine the near-surface velocity through full-waveform modelling (i.e., comparing a set of synthetic waveforms with the observed blast). The velocity model is then used to evaluate the pair of earthquakes, where waveform fitting and Rg/S amplitude ratios suggest shallower depths (~0.7 km) than reported (2 km, Earthquakes Canada). The epicenters of these two earthquakes are situated in a recently constructed commercial development. Lastly, single station template matching finds no similar earthquakes near the hypocenters of the two events in the past decade and only three aftershocks in the following four months. Taking advantage of a ground truth blast and waveform modelling, our study demonstrates the potential to construct a detailed regional velocity model and determine accurate earthquake source parameters in regions where only a single station is available.

43 Revisiting classical hard-rock kappa values from CENA

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κ_0 is the principal site parameter controlling high frequencies (>5 Hz) at short distances. Current uncertainty in hard-rock κ_0 is large, affecting seismic risk of critical infrastructures. Considering classical reference rock κ_0 values from literature (0.005-0.006 s) for hypothetical rock outcrops, analytical studies suggest large increases in response spectra above 10 Hz for hard-rock sites in Central-Eastern North America (CENA) compared to soft-rock sites in Western North America (WNA). Yet observed ground motions from CENA do not show this large increase (Ktenidou and Abrahamson, 2016), resulting in analytical and empirical amplification factors for CENA differing by factors of 2.5-4.0 in the frequency range 20-40 Hz. To start to understand the cause for the large difference, we revisit the data used in the 1990s (EPRI, 1995) and compare the empirically-derived κ_0 values with the classical values currently used for hard-rock sites. We couple the original broadband estimation methods (κRESP) with current band-limited approaches (κAS, κDS). For the latter we introduce a new tool, the moving window, to detect frequency dependence of the estimated κ_0. For some sites, the bandlimited κ_0 estimates depend strongly on the choice of frequency band, and maximizing the selected bandwidth can decrease the uncertainty and bring estimates closer to the broadband estimates. The sensitivity to frequency is partly due to high-frequency resonances from shallow impedance contrasts, which can yield highly variable, non-positive apparent κ values. These low values, reflecting the net effect of damping and amplification, may eventually control ground motion scaling if used to derive rock correction factors. Overall, we find that the classical reference rock κ_0 values used in literature are lower than our hard-rock κ_0 estimates, which only partly accounts for the discrepancies between empirical and analytical scaling factors observed in Ktenidou and Abrahamson (2016). The remaining difference may reflect amplification effects not accurately modeled in the current approach.

44 Tuning of automatic picking algorithms for detection of local and regional earthquakes in Canada

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Four decades have passed since Allen (1978) proposed an automatic arrival detection system based on the ratio of the short-term and long-term averages (STA/LTA). There is, as yet, no general procedure for optimally configuring these pickers, and this is a particularly challenging task for large heterogeneous seismograph networks like the Canadian National Seismograph Network. We are developing a procedure for selecting the optimal filter for STA/LTA picking at each station. We focus on small local and regional events, specifically events detected at between three and six stations, in hopes of enhancing the network's ability to detect these earthquakes. We consider several metrics to measure the similarity between sets of automatic and manual analyst picks, as we seek to minimize both false positive ("fake") and false negative ("missed") picks. The optimal centre frequency and bandwidth of the STA/LTA pre-filter vary from station to station. At each station, we compare this filter to the expected signal-to-noise ratio as a function of frequency, computed as the ratio between modelled Brune spectra and measured ambient background noise. The representative magnitude and distance for the modelled spectra are selected from the same subset of events, where the station in question is between the third and sixth closest. By understanding the determinants of the optimal choices, the hope is that an optimal automatic picker setup can be approximated for brand new stations, prior to the laborious manual cataloguing of arrivals.

45 An Interpretation of Ground Motions, Intensities, and Stress-Drop for the M5.1 Sparta, North Carolina, Earthquake

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Observed ground motions, intensities, and mainshock stress-drop can provide important insights into the earthquake setting both geophysically and geologically, particularly from a seismic hazard view point. The observed mainshock Brune stress drop of 22 +6/-4 MPa is consistent with published regional stress-drops for the eastern US and is consistent with the level of shaking and damage associated with the Sparta earthquake, indicating what can be expected in future earthquakes in the region. Intensity observations provide a means of estimating ground motions in the epicentral region where no instrumentation is available. The observed intensity 7 in the Sparta area suggests peak ground accelerations of 0.2-0.4 g and peak ground velocities of 6-8 cm/s using an updated Ground Motion vs. Intensity Correlation Equation for Central and Eastern North America. These estimates provide engineering guidance for mitigation of future earthquake shaking and are consistent with observed damage in and around Sparta. The regional intensity pattern from the Sparta earthquake reinforces observations from the 2011 M5.7 Mineral, VA earthquake of differences in shaking attenuation along and across regional structure. From the Sparta earthquake intensities, we see more shaking attenuation to the W and NW and less shaking attenuation to the E, even before reaching the Atlantic Coastal Plain. Ground motion observations indicate an azimuthal dependence similar to the intensity pattern of shaking. A factor of 6 decrease in ground motions to the W and NW relative to those to the E develops between 50 and 100 km from the epicenter and appears consistent out to 900 km. This increased seismic attenuation suggests a higher attenuating region associated with the Valley and Ridge sedimentary rocks between the Blue Ridge crystalline rocks in which the Sparta earthquake occurred and the rocks of the Cumberland Plateau. Beyond ~100 km, crustal attenuation is similar in all directions.

46 Earthquake depth and local velocity estimation using crustal reverberations and phase correlation for Cushing Fault zone

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There has been a significant rise in induced seismicity largely attributed to wastewater injection in Oklahoma. The induced earthquakes have reactivated several fault zones which had remained dormant in the past. One such location is the Cushing Fault zone in northern Oklahoma which has observed several > 4 Mw earthquakes in the past few years. In order to understand earthquake triggering mechanisms with respect to the local fluid injection activities, we require precise earthquake depth locations. Due to the absence of accurate velocity models in the region and sparse station coverage, earthquake depth estimations suffer from significant errors.

We use reverberations within the sedimentary layer observed for earthquakes clustered within the Cushing Fault zone to constrain the depths for these earthquakes using regional stations. We first use cross-correlation to group events with similar waveforms at different stations and use a "multiple-detector" to search for stations with crustal reverberations and obtain stacked waveforms from similar event groups. Then, we perform forward waveform modeling using F-K algorithm based on a 1-D velocity function and regional basement depth model. By evaluating the misfits between the modelled and observed waveforms, we refine earthquake depths, basement depths and shallow velocity model. The delay times between reverberations are sensitive to the shallow velocity structure, while the relative amplitude is sensitive to the basement depth. The forward modeling allows us to narrow the earthquake depth location at a much shallower basement depth than previously estimated.

Using a dense nodal array deployed in 2019 covering the Cushing Fault zone, we find phase conversions at the basement interface. With forward travel time modeling, we are able to identify the converted phase as S-P conversions at the basement. We further model these phase conversions using F-K algorithm to constrain the local velocity model in the study area.

47 Synergy of inherited structures and modern processes in the Eastern Tennessee Seismic Zone

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As with most intraplate seismic zones, the cause of high earthquake rates in Eastern Tennessee (ETSZ) is unknown. Here, we begin by cataloging aspects of the ETSZ that differ from other parts of the central/eastern United States (CEUS) and then explore links between these anomalies and seismicity. During Proterozoic shear, a releasing bend in the southern ETSZ created heavily fractured crust atop the subsequent lithospheric suture. There, the receiver function Moho is faint or absent, and the ETSZ as a whole features low-velocity, conductive middle/lower crust and the lowest-density lower crust in the CEUS. Buoyancy overcompensates topography, manifest in highly negative isostatic residual gravity. Some tomograms suggest lower lithospheric removal and resultant upwelling along the suture. Miocene drainage reorganization triggered a rapid pulse of erosion now sweeping through the ETSZ. Most critically, focal mechanisms and stress inversions document oblique extension that is unique in eastern North America. We create a 3D model of lithospheric density and finite-element model of associated stress, then solve for the tectonic stress that, -when summed therewith-, best reproduces stress directions and faulting styles across the CEUS. Stress due to buoyant lower crust overwhelms regional tectonic compression, accounts for the anomalous extension, and elevates net stress, focusing strain. We propose a unified explanation for these phenomena. Mantle-derived fluids (from any of several periods of subduction) preferentially flux along the inherited lithospheric-scale fractures and then the pervasive crustal fault system. Hydration-induced retrogression of garnet-bearing lower crust to less dense assemblages produces conductive, slow, buoyant lower crust. Increased buoyancy excites uplift, erosion, and further rebound, increasing flexural tension and relieving confining stress on faults. In this conception, the synergy of features and process responsible for seismicity is unique to the ETSZ, such that future seismicity may remain largely confined to the same region.

48 Soil amplification in glaciated terrain: using ambient noise, local event and shear wave velocity data to compare surficial geologic units in New England

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New England's surficial geologic environment is predominantly a product of glaciation: it is blanketed by till, lined with moraines, dotted with drumlins and filled with glacially derived clays. These surficial features, overlying high shear wave velocity crust yield a structure with a large impedance contrast at the soil-bedrock interface, a setting prone to site amplification. Being a region of high population and economic vitality, the study of the possible hazards to New England's infrastructure and population is essential. In this study, we examine ambient and earthquake signals recorded in four glacially derived surficial geologic units: 1) glacial lakes, specifically Lake Hitchcock, 2) till-filled topographic depressions, predominantly in the lakes region in northern Maine, 3) river basins, particularly the upper Connecticut River north of Lake Hitchcock and 4) the marine clay deposits of the Presumpscot formation and the Boston Blue Clay. We use ambient noise and earthquake signals recorded on these units to estimate soil fundamental frequency, shear wave velocity, depth, impedance contrast at the soil-bedrock interface and damping. We then compare the results, presenting their spatial variability within each of the four features and between different features. We show that these four geologic subunits are all prone to site response at frequencies of engineering interest but that they differ in the character of their signals and in their spatial distribution.

49 Seismic Observations of Four Thunderstorms Using an Underground Fiber-Optic Array

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Thunderstorms are known to generate acoustic/electromagnetic waves which interact with the ground surface to cause measurable ground vibration. Recordings of these seismic signals can be used to study the movement and lightning activity within thunderstorms, as well as leading to a better understanding of atmosphere-lithosphere coupling and a potentially good source of seismic waves for subsurface imaging.

Distributed acoustic sensing (DAS) is an ideal tool for thunderstorm studies as it is highly sensitive and allows for constant monitoring and dense sampling in a large, low impact array. In this study, we use the Penn State FORESEE array in State College, PA, to expand on preliminary work by Zhu and Stensrud (2019) and present substantial thunderstorm data from four dates ranging from May to September 2019. The full waveform and frequency content of the signal shows recognizable features of thunderquakes and is easily comparable to equivalent seismometer data. We use a time-domain grid search and modified Geiger's method to obtain the back azimuth and slowness of the waves, and to pinpoint source locations where the thunderstorms interact with the ground surface. Correlated with the time of the recorded signal, this data allows reconstruction of thunderstorm movement, as well as offering some subsurface velocity information.

50 Coseismic and long-term changes of site response on liquefiable sites: a case study of Onahama Port Array in Japan

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The 2011 M_w 9.0 Tohoku Earthquake generated widespread strong shaking and liquefaction along the east coast of Japan. A vertical array located at Onahama Port, near Iwaki City in Fukushima Prefecture, observed sand boils and strong ground motion as large as 1.8 g. In this study, we systematically analyze coseismic and long-term changes of soil properties of liquefiable dense sands in the shallow crust from sixteen years before to nine years after the Tohoku main shock using seismic data recorded by the Japanese Port and Airport Research Institute. We used sliding window spectral ratios computed from pairs of surface and borehole ground motion records to track the temporal changes of site response at Onahama Port Array. Our results show the resonant frequency gradually drop and then recover following a logarithmic trend during strong motions. The resonant frequency drops by about 70% at PGA time of the Tohoku mainshock while increase by about 30% at a short period near PGA occurrence. This short-life increase of resonance frequency is due to high-frequency acceleration spikes related to dilatant nature and pore water effects of dense sands. We also observe two stages of resonant frequency recovery after a sharp drop of resonance frequency during the Tohoku main shock. The first stage is a rapid recovery to 80% of pre-Tohoku level within about one hundred seconds after the PGA time of Tohoku mainshock, and the second stage is a slow recovery of about four hours. A periodic change of resonance frequency is observed, which implies the effect of seasonal changes of ground water table on site response of shallow soil sites.

51 Unique Earthquakes in Oklahoma and The Associated Ground Motion Duration

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The number of induced earthquakes associated with wastewater disposal in Oklahoma have reduced year after year for the last four years. However, the number of earthquakes associated hydraulic fracturing activities in the state increased concurrent with the decrease wastewater-disposal linked events. During that period, we have observed an increase in pairs of earthquakes that occur closely both in space and time. Some of the events occur with such a short difference in origin time that the ground motion elongates the event duration at a single site. We classify local earthquakes in Oklahoma as single, twin, or multi-phased events based on the P and S phase pair. By defining the ground motion duration on the basis of the Arias intensity and determining the duration using Husid plots, we describe twin events as two single events with identifiable body wave phases whose significant duration overlap occur in close proximity in both time and space, and multi-phased events as earthquakes with multiple phases due to crustal reverberations. We identify at least 21 twin pairs and over 85 multi-phased earthquakes in the last year since June 2019. A comparative analysis of the significant duration shows an increasing duration with epicentral distance for the three sets of earthquakes but at a higher rate for the twins, multi-phased events and then singles in that order.

Occurrence of the earthquakes with the characteristics we describe also coincide with an inflation in the intensity of reported felt ground motions in the SCOOP and STACK area, relative to the magnitude of the source event. We thus examine whether the relationship between the ground motion duration influences the felt intensity of a particular event, as reported in the "Did You Feel It" (DYFI) program. We will present updated research that has implications for better understanding felt ground motions of earthquakes induced by hydraulic fracturing.

52 A Geophysical Technique for Studying the Sedimentary Structure of a Paleoliquefaction Site in the New Madrid Seismic Zone

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Geophysical surveys along with ditch exposures are used to understand how the distribution of sedimentary deposits influences the formation of liquefaction features. The study site is adjacent to the Pemiscot Bayou near Blytheville, AR, an area where earthquake-induced liquefaction features formed during the 1811-12 New Madrid earthquakes and at least two prehistoric earthquakes. On satellite imagery, apparent sand blows appear to occur along an abandoned channel. The sand blows and related sand dikes were confirmed in the ditch exposures. ER tomography data were collected along two parallel profiles using a dipole-dipole array. The resulting data provide information about the subsurface to a depth of approximately 15 m. Data from these surveys confirm that the liquefaction features formed along the margins of an abandoned channel of the Pemiscot Bayou. The resistivity low in the central upper portion of the profile is interpreted as an abandoned channel deposit composed of fine-grained sediment that filled an abandoned course of the Pemiscot Bayou. The resistivity values increase with depth, representing a transition to coarser-grained sediment in the base of the abandoned channel. Higher resistivity values along the base of the profile are likely to be braided stream deposits. Adjacent to the abandoned channel deposit, a low-resistivity layer is underlain by a medium-resistivity layer followed by a high-resistivity layer. This sequence is interpreted as fine-grained backswamp and levee deposits underlain by point bar and braided stream deposits. The finer-grained deposits likely acted as an aquitard and allowed fluid pressure to increase in coarse-grained deposits below during ground shaking, resulting in liquefaction, upward flow of sediment-entrained water, and formation of a water-interlayer below the aquitard. Further, inclined contacts between finer-grained deposits and coarser-grained deposits may have guided the flow of the escaping fluids, influencing the emplacement of sand dikes and formation of sand blows.

53 Towards Quantitative Seismic Hazard Assessment from Interseismic Locking Models

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Interseismic locking models derived from geodetic data indicate future earthquake potentials. However, ruptures starting from different hypocenters in a locked region may develop into earthquakes with completely different final magnitudes, making it difficult to assess seismic hazard from locking models. Here, we examine ground motion predictions in dynamic rupture models derived from locking models in Nicoya. By considering models with different hypocenter locations, we generate predictions for ground shaking intensity measures (IMs), including peak ground displacement (PGD), peak ground velocity (PGV), and peak ground acceleartion (PGA). IM predictions derived from Feng's locking model (Feng et al., 2012) are well consistent with near-field observations during the 2012 Nicoya Mw 7.6 earthquake in low frequency (< 0.5Hz for PGV and < 0.25Hz for PGA). Our results demonstrate the feasibility of ground motion prediction from interseismic locking models, which is a critical step towards quantitative seismic hazard assessment from interseismic locking models.

54 Limited and Localized Magmatism in the Central Atlantic Magmatic Province

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Magmatism during the emplacement of large igneous provinces is thought to have profound impacts on the tectonic and climatic evolution of Earth. Here, we focus on the Central Atlantic Magmatic Province (CAMP), described as the most aerially extensive magmatic event in Earth's history. Many questions remain, however, about its origin, volume, and distribution. Despite many observations of CAMP magmatism near the Earth's surface, few constraints exist on CAMP intrusions at depth. Here we present detailed constraints on crustal and upper mantle structure and sedimentary thickness from wide-angle seismic data from Lines 1 and 2 of the SUGAR (SUwanee suture and GA Rift) experiment, which cross the western and eastern South Georgia basin, a Triassic rift basin that formed shortly before CAMP. On Line 1, high crustal P-wave velocities of >7.2 km/s are localized beneath the area with the thickest sediments and most concentrated crustal thinning, which we interpret to represent mafic intrusions into the crust. In contrast, most of the crust beneath Line 2 has lower P-wave velocities < 7.0 km/s and lower average VP/VS, consistent with an intermediate composition and limited mafic intrusions. The localization of magmatism where synrift sedimentary fill is thickest and the crust is thinnest suggests that lithospheric thinning influenced the locus and volume of magmatism. These results suggest that magmatism in the South Georgia Rift is caused by syn-rift decompression melting of a warm, enriched mantle. The limited distribution of lower crustal intrusions implies modest total CAMP volumes of 85,000 to 169,000 km^3 beneath the South Georgia Rift, consistent with moderately elevated mantle potential temperatures (<1500 C).

55 Exploring the python package, easyQuake, a turnkey machine-learning driven earthquake identifier and locator tool

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We developed a Python package, easyQuake, that consists of a flexible set of tools for detecting and locating earthquakes from FDSN-collected or field-collected seismograms. The package leverages a machine-learning driven phase picker, coupled with an associator, to produce a Quake Markup Language (QuakeML) style catalog complete with magnitudes and P-wave polarity determinations. We describe how nightly computations on day-long seismograms identify lower-magnitude candidate events that were otherwise missed due to cultural noise and how those events are incorporated into the Oklahoma Geological Survey (OGS) statewide network upon analyst manual review. We discuss applications for the package, including earthquake detection for regional networks and microseismicity studies in arbitrary user-defined regions. Because the fundamentals of the package are scale invariant, it has wide application to seismological earthquake analysis from regional to local arrays, and has great potential for identifying early aftershocks that are otherwise missed. The package is fast and reliable; the computations are relatively efficient across a range of hardware and we have encountered very few (~1%) false positive event detections for the Oklahoma case study. The utility and novelty of the package is the turnkey earthquake analysis with QuakeML file output, which can be dropped directly into existing real-time earthquake analysis systems. We have designed the functions to be quite modular so that a user could replace the provided picker or associator with one of their choosing. The Python package is open-source, available through Github (https://github.com/jakewalter/easyQuake), and development continues. We will discuss the package, demonstrate current applications with case studies, and discuss improvements/further development.

56 Source characteristics of the 2020 Mw 7.4 Oaxaca, Mexico earthquake estimated from GPS, InSAR and teleseismic waveforms

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On 23 June 2020, a Mw 7.4 earthquake struck near Oaxaca, Mexico, which provided a unique opportunity to understand the seismogenic tectonics of the Mexican subduction zone. In this study, near-field coseismic deformation caused by the event was retrieved from global positioning system (GPS) observations and interferometric synthetic aperture radar (InSAR) measurements. Given static geodetic measurements, high-rate GPS waveforms and teleseismic waveforms, the fault geometry and rupture process for the 2020 Oaxaca earthquake were robustly determined by a nonlinear joint inversion. The main slip was located ~17.5 km-depth above the hypocenter, with a peak slip of 2.4 m. The total released seismic moment was 1.39 x 10^20 N m, corresponding to Mw 7.36. The rupture process lasted 30 s, while the dominant rupture occurred during the first 18 s. The mainshock rupture mostly occurred along the strike, covering a size of ~55 km (along strike) x ~35 km (along dip) and totally overlapping with the 1965 Mw 7.5 rupture, which indicates that this event was a repeat event following that in 1965. Interseismic stress distribution and fluid percolation under the slab are two potential reasons for the unidirectional slip pattern for the 2020 Oaxaca earthquake.

57 Cellular Seismology Analysis of the Pacific Northwest

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Cellular Seismology (CS) is applied to earthquakes in the Pacific Northwest (PNW) to investigate the extent to which past PNW earthquakes delineate zones where future earthquakes are likely to occur. Earthquake catalogs are divided into two categories based on the timing of the earthquakes: older for the “before” (Pre-CAT) category, and more recent for the “after” (Post-CAT) category. The Pre-CAT is used to construct circles around the earthquakes such that the area the circles take up covers a given percentage of the map area. The Post-CAT is analyzed to test whether the later occurring earthquakes were located within the Pre-CAT circles (i.e., “hits”). We evaluate how the percentage of hits (%hits) varies for sub-regions of the study area.

CS analysis was applied to a PNW earthquake catalog (1900 to 2020, M>2.5). The Pre- and Post-CATs were organized to cover different sub-regions and time periods depending upon research questions being addressed. Specifically, we explored CS results to address questions regarding the entire PNW region, areas surrounding PNW crustal faults, and areas surrounding “Episodic Tremor and Slip” activity (ETS). We also investigated variation in hypocenter depth to explore CS variation for different depth ranges associated with the subduction process in this region. For the entire PNW region, the %hits for results so far ranged from 76% to 98% for different sampling of the Pre- and Post-CATs, consistent with the range of %hits from previous CS studies in plate boundary environments worldwide. For an ETS zone, within which there are shallow crustal faults, we find very high values of %hits: 96% to 98%. Preliminary results for the depth analysis did not show any obvious differences for very shallow (<5 km) earthquakes compared with deeper earthquakes. These preliminary results motivate more in-depth analysis of how CS varies for different sub-regions within the PNW.

58 A Review of Hydraulic Fracturing-Induced Seismicity

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Hydraulic fracturing (HF) due to fluid injected under high pressure is now commonly used for extracting petroleum resources from impermeable host rocks. This technique has been transformative for the hydrocarbon industry, unlocking otherwise stranded resources; however, environmental concerns make HF controversial. One concern is HF-induced seismicity, since fluids driven under high pressure also have the potential to reactivate faults. Controversy has inevitably followed these HF-induced earthquakes, with economic and human losses from ground shaking at one extreme and moratoriums on resource development at the other. This presentation will review the state of knowledge of HF induced seismicity (Schultz et al., Rev. Geophy., 2020).

We will first provide essential background information on HF along with an overview of published induced earthquake cases to date. Expanding on this, we will synthesize the common themes and interpret the origin of these commonalities, which include recurrent earthquake swarms, proximity to well bore, rapid response to stimulation, and a paucity of reported cases. Next, we will discuss the unanswered questions that naturally arise from these commonalities, leading to potential research themes: consistent recognition of cases, proposed triggering mechanisms, geologically susceptible conditions, identification of operational controls, effective mitigation efforts, and science-informed regulatory management. Finally, we will conclude that HF-induced seismicity provides a unique opportunity to better understand and manage earthquake rupture processes, and that understanding HF-induced earthquakes is important to avoid extreme reactions in either direction.

59 Analysis of microseismicity during hydraulic fracture: application of spatial temporal magnitude calibration

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It is well known that hydraulic fracturing generates microseismicity at the source rock during hydrocarbon production. Detailed knowledge of in situ fracture size and orientation will assist in obtaining optimal levels of production which may be achieved through the analysis of the microseismic source parameters such as magnitude. Precise magnitude estimation in microseismic events is a useful asset in the analysis of the fracture system and its growth which can provide information to aid in hydraulic fracturing diagnostics as well as design. A detailed analysis of microseismicity source parameter is performed to a legacy dataset of four hydraulic fracture treatments of Cotton Valley formation in 1997 at the Carthage gas field of East Texas. From our analysis we show event clustering based on spatial temporal waveform similarity. Furthermore, we analyze the waveform energy within each stage and recalibrate the given magnitude value to each cataloged waveform. Magnitude calibration shows improvement on the distribution of events amplitude ratios and relative magnitudes. We first show our corrected magnitude for all events and compare the results after applying our magnitude calibration for each cluster.

60 Structure and dynamics of the Central Appalachian lithosphere: Results from the MAGIC array

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The passive continental margin of the eastern United States has undergone two complete cycles of supercontinental assembly and breakup over the past ~1.3 Ga. Multiple episodes of orogenesis, rifting, and post-rift evolution have resulted in the surface geology and topography visible today; however, it is poorly known how the crust and mantle lithosphere have responded to these tectonic forces over time, and whether and how the geological units preserved at the surface relate to deeper structures. The MAGIC geophysical experiment deployed a linear array of 28 broadband seismometers across the Central Appalachians, with coverage from the Atlantic Coastal Plain in Virginia across the present-day Appalachian Mountains to western Ohio. This talk will present two major results from the MAGIC deployment: evidence for the preservation (over approximately one billion years) of a deformation front associated with the Grenville Orogeny in the mid-crust, and evidence for the relatively recent (Eocene) removal of mantle lithosphere beneath the Appalachian Mountains. In the first case, images of crustal structure derived from P-to-S receiver function analysis show evidence for a prominent negative velocity gradient in the mid-crust beneath Ohio and West Virginia. This converter dips gently to the east and projects to the surface near the assumed location of the Grenville Front in western Ohio. In the second case, multiple types of observations (including body wave travel time analysis, P wave attenuation measurements, S-to-P receiver function imaging of lithospheric structure, and a model of electrical conductivity derived from a companion magnetotelluric deployment) argue for locally thin lithosphere beneath the Central Appalachian mountains. The region affected by lithospheric removal corresponds to the location of unusually young (Eocene) volcanic rocks at the surface, suggesting a lithospheric loss event approximately 50 million years ago. Results from MAGIC therefore yield evidence both for the preservation of features in the crust (in this case, associated with the Proterozoic Grenville Orogeny) over long periods of Earth history, and for the relatively recent modification of lithospheric structure at a passive continental margin.

61 Toward Understanding Anomalously Low Aftershock Productivity

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Understanding aftershock seismicity is important for seismic hazard assessment and for understanding earthquake stress changes and triggering. Analyses of global and regional catalogs of seismicity have confirmed that descriptive statistics such as Omori's Law, the Gutenberg-Richter distribution, and Bath's Law seem to hold across diverse tectonic settings. By investigating the productivity of aftershock sequences in intraplate regions with few tectonic events and long interevent times, we assess the applicability of common earthquake statistics to these low seismicity regions, compared to areas of induced and plate boundary seismicity. We document multiple mainshocks with anomalously low productivity and lower than anticipated maximum magnitude aftershocks that substantially deviate from Bath's Law. These include the M4.2 earthquake that occurred in 2017 outside Dover, DE, and the M4.2 earthquake that occurred in 2015 in south-central Michigan. We discuss the viability of hypotheses to explain the low aftershock productivity, including mainshock alignment with the regional stress tensor, fault complexity and orientation, as well as pore fluid diffusion.

62 Relationship between earthquake b-values and differential stress in the Charlevoix and Western Quebec seismic zones, eastern Canada

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The Charlevoix and Western Quebec seismic zones (CSZ and WQSZ) are the two most active seismic zones near population centers in eastern Canada. The paucity of stress measurements at depth impact the adequacy of current seismic hazard assessments. Several studies suggest that stronger fault segments exhibit higher differential stress (σ_D) and lower b-values, whereas weaker segments exhibit lower σ_D and higher b-values. In this study, we investigate the relationship between b-value and σ_D in the CSZ and the WQSZ and its potential as a stress meter proxy.

We use a Gaussian mixture model (GMM) to divide earthquakes epicenters ($M_N \geq$-1.0, 1985/01-2020/05) into areal clusters and compute the b-value for each cluster. The b-values in the CSZ range from 0.62 to 0.92, slightly higher within the meteorite impact zone than those outside. b-values are in the range of 0.65 to 1.14 in WQSZ, typical of natural tectonic seismicity. We calculate the focal mechanisms (FMs) of 159 M 1.3+ earthquakes reported in the CSZ and augment our solutions with FMs from previous studies. Stress ratios (R) and orientations are inverted for each GMM cluster as defined above. We find that the stress ratios range from 0.17 to 0.38 and 0.34 to 0.64 in the CSZ and the WQSZ, respectively.

The b-values linearly decrease with R in both seismic zones. Hence, we infer that b-value inversely correlate with σ_D in both intraplate seismic zones, which suggests that b-value could serve as a proxy stress meter. Future studies with enhanced seismicity catalog with high-precision locations could be useful for mapping the spatial variation of crustal strength within such intraplate seismic zones.

63 Global anthropogenic seismic noise quieting due to COVID-19 pandemic lockdown measures

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Human activities causes high-frequency vibrations that propagate into the ground as seismic waves. "Lockdown" measures were enforced all around the world to mitigate the coronavirus disease 2019 (COVID-19) pandemic. The widespread changes in human activities had a direct impact on the environment, for example with the reduction of air pollution or audible noise. It also led to a months-long reduction in seismic noise. The 2020 seismic noise quiet period is the longest and most prominent global anthropogenic seismic noise reduction on record. The reduction is strongest at surface seismometers in highly populated areas, but this seismic quiescence extends for many kilometers radially and hundreds of meters in depth. This period provides an opportunity to detect subtle signals from subsurface seismic sources that would have been concealed in noisier times and to benchmark sources of anthropogenic noise. A strong correlation between seismic noise and independent measurements of human mobility suggests that seismology provides an absolute, real-time estimate of human activities. The initial lockdown rules were usually immediate and strictest in the beginning. Then, the lifting of the rules was more progressive. This could allow for studying and separating different noise sources. In this communication, we will also shortly present the community behind this study, the tools and ways we used to coordinate the analyses and to write of the article.

64 Sedimentary and crustal structure of California and Nevada from joint inversion of multiple passive seismic datasets

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Although the California and Nevada region has been the subject of numerous tomographic studies, there is still a lack of a 3-D velocity model that can accurately describe both the shallow sedimentary structures with depths less than 8 km and the deeper crystalline crustal structures. With the outstanding station coverage in California and Nevada, we build a new 3-D shear wave speed model by jointly inverting Rayleigh wave phase velocity, Rayleigh wave ellipticity, and teleseismic P waveforms. The Great Valley forearc basin, the most significant basin system in this study region, is imaged as an asymmetric syncline with a steeply dipping west flank and a gently dipping east flank. Under the Coastal Range, we resolve the Franciscan complex as a low-velocity zone with shear wave speed less than 3.6 km/s extending throughout the upper-middle crust. The Franciscan Complex shows up in the images as a wedge-shaped structure underlying the west limb of the Great Valley. In the southern part of the central Basin and Range, we resolve a thick crust with an averaged thickness of 38.6 km, much thicker than its southern and northern neighborhoods with an averaged thickness of only 33.3 km. Furthermore, our model reveals a region with thicker crust largely overlapping with the main volcanic field, with an ignimbrite flare-up during mid-Tertiary. Our new seismic images indicate (1) the uplift of the west limbs of the Great Valley and the eastward shifting of depositional center caused by the wedging of the Franciscan Complex, due to the compressional force generated by the slab subduction, and (2) magmatic intrusion contributing to the growth and thickening of the continental crust of North America in the central Basin and Range.

65 The magma plumbing systems beneath the magma-poor rifts of the East Africa

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The East African Rift (EAR) is an active continental rift zone, including the magma-poor western branch and the magma-rich eastern branch. Although it is known that the melt plays an essential role in initiating rifting in the magma-rich rifts, the mechanism initiating the magma-poor rifts is still under debate. To better image the melt distribution in the crust and the uppermost mantle beneath the western branch of the EAR, this study extracts Rayleigh wave phase velocity dispersions from both two-station and three-station ambient noise interferometry. The measurements involve seismic recordings from 232 broadband stations of 17 networks deployed between 1994 and 2019. The phase-velocity maps in the period range of 5~41 seconds indicate low-velocity anomalies along the rift axis of the western branch in the crust, and beneath the west flank of the Malawi Rift, including the Rungwe Volcanic Province, in the crust and the uppermost mantle. These low-velocity anomalies imply potential melt existence. The further inversion of the joint datasets will provide a high-resolution shear wave speed model beneath the Tanzanian Craton and the Malawi Rift to elucidate the mechanism initiating the magma-poor rifting of the EAR and the evolution of the Tanzanian Craton.

66 An updated East Asia Radially Anisotropic Model (EARA2020) of the crust and the upper mantle based on full waveform inversion

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The nature of deep earthquakes with depths greater than 70 km is enigmatic because brittle failure at this high-temperature and high-pressure regime should be inhibited. Three main hypotheses have been proposed to explain what causes deep earthquakes within the subducted slabs, dehydration embrittlement, phase transformational faulting, and thermal runaway instability. However, the existing seismological constraints can't yet definitively distinguish between these hypotheses, because the fine 3-D slab structures are not well constrained. To better image the slabs in the Western Pacific subduction zones, this study employs a full waveform inversion (FWI) that minimizes waveform shape misfit between the synthetics and the observations from a large dataset, with 142 earthquakes recorded by about 2,000 broadband stations in East Asia. A 3-D initial model that combines two previous FWI models in East Asia (i.e., FWEA18 and EARA2014) is iteratively updated. Our FWI minimizes the misfit measured from both body waves (8~40 s) and surface waves (30~120 s). Compared to the previous models, the new FWI model (EARA2020) after 20 iterations shows much stronger wave speed perturbations within the imaged slabs. The high wave speed anomalies indicating subducted slabs reach a maximum of 8% for Vp and 13% for Vs. Our new model EARA2020 provides one of the best imaged 3-D slab morphology in East Asia. It will be further interpreted to map the spatial variations of slab deformation and stress accumulation, as well as their relationships with deep earthquake distribution.

67 Fine Structures of the 410-km Discontinuity and the Slab in the Kuril Subduction Zone

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Using triplicated P waves, we applied the genetic algorithm to invert for the topography of the 410-km discontinuity near the Kuril slab. Our results show azimuthal variations of the 410-km discontinuities topography, the amount of uplift of the 410-km increases from 5-10 km in the north to 15-20 km in the central region. However, the 410-km discontinuity in the south is complicated by a large volume of slab penetration. Meanwhile, the best fitting model for the southern region reveals not only a slab upper interface with a 3-5% P wave speed increase, but also an extremely low wave speed zone with 10% speed reduction. This low wave speed zone is located near the 410-km discontinuity with a width of ~20 km. This observation indicates the possible existence of a metastable olivine wedge which can explain the genesis of deep-focus earthquakes.

68 Evaluation of a Novel Application of Earthquake HVSR in Site-Specific Amplification Estimation

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Ground response analyses (GRA) model the vertical propagations of SH waves through flat-layered media (1DSH) and are widely carried out to evaluate local site effects in practice. Horizontal-to-vertical spectral ratio (HVSR) technique is a cost-effective approach to extract certain site-specific information, e.g., site fundamental frequency (f0), but HVSR values cannot be directly used to approximate the levels of S-wave amplifications. Motivated by the work of Kawase et al. (2019), we propose a procedure to correct earthquake HVSR amplitudes for direct amplification estimations. The empirical correction compensates HVSR by generic vertical amplification spectra categorized by the vertical fundamental frequency (f0v) via k-means clustering. In this investigation, we evaluate the effectiveness of the corrected HVSR in approximating observed linear amplifications in comparison with 1DSH modellings. We select a total of 90 KiK-net (Kiban Kyoshin network) surface-downhole sites which are found to have no velocity contrasts below their boreholes and thus of which surface-to-borehole spectral ratios (SBSRs) can be taken as their empirical transfer functions (ETFs). 1DSH-based theoretical transfer functions (TTFs) are computed in the linear domain considering uncertainties in VS profiles through randomizations. Five goodness-of-fit metrics are adopted to gauge the closeness between observed (ETF) and predicted (i.e., TTF and corrected HVSR) amplifications in both amplitude and spectral shape over frequencies from f0 to 25 Hz. We find that the empirical correction to HVSR is highly effective and achieves a ‘good match’ in both spectral shape and amplitude at the majority of the 90 KiK-net sites, as opposed to less than one-third for the 1DSH modelling. In addition, the empirical correction does not require a velocity model, which GRAs require, and thus has great potentials in seismic hazard assessments.

69 An Open-Source Site Database of Strong-Motion Stations in Japan: K-NET and KiK-net (v1.0.0)

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We will present an open-source site database for a total number of 1742 earthquake recording sites in the K-NET (Kyoshin network) and KiK-net (Kiban Kyoshin network) networks in Japan. This database contains site characterization parameters directly derived from available velocity profiles, including average wave velocities, bedrock depths, and velocity contrast. Meanwhile, it also consists of parameters obtained from earthquake horizontal-to-vertical spectral ratio (HVSR), e.g., peak frequency, amplitude, width and prominence. In addition, the site database also comprises topographic and geological proxies inferred from regional models or maps. Each parameter is derived in a consistent manner for all sites. This site database can benefit the application of machine learning techniques in studies on site amplification. Besides, it can facilitate, for instances, the search of the optimal site parameter(s) for the prediction of site amplification, the development and testing of ground-motion prediction models or methodologies, as well as investigations on regional variability in site response. All resources (the site database, earthquake HVSR data at all sites and the MATLAB script for peak identification) can be freely accessed online.

70 Green's function analysis to study wavefield distribution in ambient vibration recordings

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We examine the contribution of different wave types in the ambient vibration wavefield at six sites in Windsor, Ontario, Canada. For each site, two seismometers were deployed, one acts as a pseudo source and the other as a receiver. The main assumptions are that uniform energy is coming from all azimuths and the ambient vibrations are uncorrelated in time and space. Microtremor horizontal to vertical spectral ratios showed that three sites are suspected of 'normal' surface wave conditions, contrary to the other three sites suspected of 'contamination' by body waves. We calculate three Green's functions per site by cross-correlating the vertical component recording at the pseudo source with the vertical, transverse, and radial recordings at the receiver. These Green's functions are calculated over three frequency bandwidths: low frequency (0.1-1 Hz) below the site fundamental frequency (f0), middle frequency (1-5.5 Hz) spanning f0 and 2f0, and high frequency (5.5-64 Hz). We visualize the Green's functions as cross (particle motion) plots to analyse energy partitioning between pseudo source and receiver. Cross-plots at the low frequency bandwidth indicate the dominance of body waves. Middle frequency band plots show that for three sites most of the energy is in vertical direction with some energy transformed into the radial direction; for the other three sites, significant vertical component energy is transformed into the transverse direction. This indicates that the first three sites are dominated by Rayleigh waves and the later ones may have Love or body waves contributing to the recorded wavefield. Cross-plots at the high frequency band show that the wavefield is dominated by surface waves with elliptical motions.

71 Detecting the earliest aftershock following moderate-size earthquakes in Eastern US

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Earthquakes are generally followed by many aftershocks with their rates decay with time since the mainshocks, known as the Omori's law. While new techniques such as template matching or deep learning have been developed in the past decades to detect missing earthquakes from the continuous waveforms, it is still relatively challenging to identify aftershocks in the first few or tens of seconds due to masking of the mainshock coda waves. Here we use multiple techniques to examine the near-field recordings during several recent moderate-size earthquakes in Eastern US (e.g., the 2014 M4.1 Edgefield, South Carolina, the 2018 M4.4 Decatur, Tennessee, and the 2020 M5.1 Sparta, North Carolina earthquakes). We choose these events, mainly because they are not followed by many aftershocks as listed in the existing USGS catalogs. Hence, it is reasonable to assume that the probability of missing any aftershocks immediately following these mainshocks is relatively small. We use a combination of high-pass-filter and template matching methods to scan the first few hundred seconds following these mainshocks. So far, we have identified one aftershock about ~223 s following the M5.1 Sparta mainshock with an estimated magnitude of 3, as well as a few smaller events following the other mainshocks. Our next step is to relocate these missing early aftershocks with respect to the mainshocks and other aftershocks to better understand their spatio-temporal relationship. In addition, we plan to generate synthetic aftershock catalogs and waveforms based on the aftershock activity at later times to test our algorithm's ability to detect aftershocks that are completely buried in the mainshock coda. Updated results will be presented at the meeting. The results are also useful to verify Zhuang et al. (2017)'s statistical method for replenishing missing earthquakes.