01. Far-field ground-motion model for the North Australian Craton

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The Australian territory is just over 400 km from an active convergent plate margin with the collision of the Sunda-Banda Arc with the Precambrian and Palaeozoic Australian continental crust. Seismic energy from earthquakes in the northern Australian plate margin region are channelled efficiently through the low-attenuation North Australian Craton (NAC), with moderate-sized (MW 5.0+) earthquakes in the Banda Sea commonly felt in northern Australia. A far-field GMM has been developed for use in seismic hazard studies for sites located within the NAC. The model is applicable for hypocentral distances of approximately 500-1,500 km and magnitudes up to MW 8.0. A strong hypocentral depth dependence is observed in empirical data, with earthquakes occurring at depths of 100-200 km demonstrating larger amplitudes for short-period ground motions than shallower events. The depth dependence of ground motion diminishes with longer spectral periods, suggesting that the relatively larger ground motions for deeper-earthquake hypocenters may be due to more compact ruptures producing higher stress drops at depth. Compared with the mean Next Generation Attenuation-East GMM developed for the central and eastern United States (which is applicable for a similar distance range), the NAC GMM demonstrates significantly higher short-period ground motion for Banda Sea events, transitioning to lower relative accelerations for longer-period ground motions.

02. Empirical Site Response Model using Earthquake HVSR: from using only its Peak Frequency to using the Whole Curve

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We will present the evolution in the use of the horizontal-to-vertical spectral ratio of earthquakes (eHVSR): (a) using only its peak frequency; (b) using the how curve after simple correction; and (c) using the whole curve as a vector-valued predictor variable in a machine learning-based site response model. We compare and test the performance of each of the above approaches at 145 sites using the site-to-site variability as a benchmark. Results show that the site-specific eHVSR curve from weak motions is a very effective predictor of site responses in the whole frequency range 0.1-20 Hz, and its inclusion in the machine model as a vector-valued explanatory variable can lead to a significant reduction in the site-to-site variability.

03. Earthquake source parameter inversion in the western Quebec Seismic Zone

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The western Quebec Seismic Zone (WQSZ) is an active seismic area in eastern Canada that encloses the Ottawa Valley from Montreal to Temiscaming and from Cornwall up along the Laurentian Mountains, posing moderate seismic hazard to large cities including Montreal and Ottawa. Earthquakes in the WQSZ are mainly distributed along NW-SE elongated trends sub-parallel the Ottawa and Saint Lawrence Rivers. However, several recent earthquakes, including M3.1 in 2016, M3.7 in 2020, and M3.9 in 2021 with felt reports in Montreal, are not located within the well-documented Ottawa-Bonnechere Graben fault zone structure, suggesting that other active fault zones may be responsible for the shaking in/near the metropolitan area. In this study, we first use the Multi-station Matched Filter (MMF) signal processing method to enhance the seismicity catalog by detecting new events of similar waveforms to those from the Natural Resources Canada catalog since 2010. Next, we perform seismicity relocation to get more accurate relative hypocenters that allow us to better identify possible fault structures. We further calculate event source parameters, including focal mechanism solution and stress drop estimates (spectra and event-pair spectra ratio fitting). In particular, the FMSs can be used to corroborate fault orientations highlighted from the seismicity relocation, which are critical input for Montreal seismic hazard models. We will also compare our WQSZ stress drop estimates to results from other intraplate seismic zones, such as Charlevoix (Quebec), for a broad context of fault strength and geological conditions in eastern Canada.

04. Assessment of the Earthquake Point-Source Integrated Code Algorithm for Earthquake Early Warning in Eastern Canada using Historical Earthquakes

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In Eastern Canada, ~30 earthquakes >Mw3.0 are located each year, 25 of which are reported to be felt. This rate implies future damaging earthquakes are probable, and an Earthquake Early Warning (EEW) system would be a useful risk-reduction tool. To assess the performance of the Earthquake Point-Source Integrated Code (EPIC) algorithm used by the United States Geological Survey ShakeAlert system for EEW, eight earthquakes in Eastern Canada recorded by the Canadian National Seismograph Network were processed. As EPIC was developed for the geological characteristics of western North America, testing is necessary to determine its efficacy in Eastern Canada.

Historical earthquakes were examined based on magnitude, location, and waveform data availability. Ideally, an earthquake should include at least four stations within 50 km of its epicenter, be located in an area where EEW stations are to be deployed and have a magnitude >Mw3.5. Eight earthquakes (3.4 < Mw < 5.0), four in both the Western Quebec and the Charlevoix Seismic Zones, were selected from the NRCan earthquake database based on these criteria. Network geometry of the recording stations is likely sparser and less balanced than the intended EEW network. A playback of the waveform data through EPIC resulted in solutions for seven of the eight earthquakes. The quality of the solutions was assessed by their deviation in location, origin time, and magnitude from the catalog solution. The initial solutions from EPIC were acceptable, with overall assessment scores of >87%.

For each earthquake, the quality of the EPIC solutions progressively decreases as more distant stations get added and EPIC locations and magnitudes deviate from the catalog solution. For example, the 2005, M4.7 Riviere-du-Loup earthquake had an initial assessment score of 91%, but a final score of 68%. Despite the decrease in quality for the final solutions, the positive results for the initial solutions suggest that EPIC could be useful for EEW in Eastern Canada, but adjustments will be necessary to get stable higher-quality solutions and more accurate magnitude estimates.

05. Characteristics of Nonlinear Site Response from Borehole Strong-Motion Recordings

Z. Wang (University of Kentucky, zmwang@uky.edu) and S. Carpenter (University of Kentucky)

Site response is caused by the increase of shear-wave velocity with depth, gradually or intermittently, at a site and measured by the soil-to-rock spectral ratio in seismology and ratio of response spectra in earthquake engineering. Site response can also be measured by the borehole Fourier and response transfer functions. Furthermore, site response is nonlinear, because the near-surface soils and rocks are highly nonlinear. We explored the characteristics of nonlinear site response utilizing strong motions with peak ground acceleration greater than 0.10g recorded at surface by 11 borehole arrays in California and Japan. These arrays were chosen because they have multiple strong-motion recordings with peak ground accelerations ranging from less than 0.05g (weak motion) to greater than 0.15g (strong motion). We calculated empirical borehole Fourier and response transfer functions for different ground-motion levels and determined the corresponding fundamental site frequencies and their associated amplifications at these sites. We also performed horizontal-to-vertical ratio analysis for the different ground-motion levels. We performed the spectral analyses on the S-wave part of the waveforms, except for the one from the 2011 Tohoku earthquake, for which we windowed around the peak ground acceleration. Our results show that both the Fourier and the response borehole transfer functions demonstrate nonlinear response characteristics: the fundamental site frequency decreases with increasing surface peak ground acceleration. Similarly, the fundamental site frequency decreases with increasing peak ground acceleration on the HVSR curves. We also observed that the magnitudes of the spectral ratios at the peak frequencies do not decrease or increase consistently with increasing peak ground acceleration.

06. Site conditions and potential earthquake shaking in southwestern Ontario

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The 2018 Nuttli magnitude 4.1 Amherstburg, Ontario earthquake resulted in 684 reports of shaking intensity submitted online to Natural Resources Canada. The earthquake primarily caused low shaking intensities, 81% of responses correspond to a Modified Mercalli Intensity (MMI) II level. We performed an earthquake site characterization campaign to assess variability in local site conditions and their potential impact to shaking intensities in the Amherstburg area. We targeted five locations for detailed site characterization, performing active- and passive-source surface wave array recordings to obtain Rayleigh wave dispersion curves and microtremor horizontal-to-vertical spectral ratios (MHVSRs) for joint inversion and determination of the site's shear-wave velocity (Vs) depth profile. For regional coverage, only MHVSRs are obtained at an additional 75 locations. We find that there is little variability in site conditions across Windsor, exhibiting a consistent 2 Hz site frequency (consistent resonator depth) and seismic site class D (average Vs of the upper 30 m (Vs30) of 240 to 298 m/s). In Amherstburg, there is greater variability in soil thickness (site frequencies of 4-17 Hz) and thus site classes B to C (Vs30 of 909 to 444 m/s). These local trends in site frequency (total soil thickness) are consistent with the Ontario Geological Survey's drift thickness map but are not apparent from the relatively consistent reported MMI II shaking intensities. We then compile our 11 total Vs depth profiles in the area with other available invasive data to derive an average Vs depth profile for post-glacial soils in southwestern Ontario. We demonstrate that our average Vs profile, better predicts site frequency for the known drift thickness compared to using average Vs profiles for post-glacial soils in Ottawa and Montreal.

07. Fault Orientation and Relocated Seismicity Associated with the December 12, 2018 Mw 4.4 Decatur, Tennessee Earthquake Sequence

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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. However, the underlying driving force of seismicity in the ETSZ remains unclear. The recent December 2018 Mw 4.4 earthquake near Decatur, Tennessee provides a unique opportunity to study one of the largest events in this region. We use a matched filter technique to detect microearthquakes around the Mw4.4 mainshock not previously catalogued. We create templates from 967 catalogued templates spanning over 15 years (January 2005 to May 2020) in the ETSZ. These templates are used to detect missing events 4 weeks before to 4 weeks after the mainshock, resulting in 167 newly detected events. We calculate the magnitudes of new events using principle-component fitting between templates and newly detected events. Two relocation algorithms, XCORLOC and HYPODD, are used comparatively to relocate detected events. Relocated hypocenters are examined to resolve the fault structure ruptured during the mainshock. We construct focal mechanism solutions for earthquakes around the mainshock using HASHpy, and refine the focal mechanism and depth solution of the mainshock using the Cut and Paste (CAP) method. The mainshock appears to have occurred at a shallower depth than typical seismicity in the ETSZ, along a N/NW trending strike-slip fault. This is consistent with the relocated aftershock location and one of the nodal planes of the mainshock. Due to its unusual shallow depth and timing, we argue that the nearby Watts Bar Reservoir may have triggered the mainshock due to delayed unloading of the reservoir. Declustered background seismicity also shows increasing rate within 25 km of the reservoir following loading and unloading of the reservoir, indicating that the Decatur mainshock may be a case of reservoir induced seismicity.

08. Investigating the Use of the HVSR Method to Measure Fundamental Frequencies of an Earth Embankment Dam

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The purpose of this investigation into the use of geophysical methods to assess the stability of earth embankment levees and dams is to identify locations of weaknesses that may result in future failures of such structures. Exploring geophysical methods for this purpose is desirable because many of these methods are efficient, noninvasive, and inexpensive. The method that we investigate is the application of horizontal-to-vertical spectral ratios of ambient seismic noise, commonly referred to as H/V spectral ratios or HVSR, to record fundamental frequencies (f0) of measurement sites. The HVSR method was first proposed by Nakamura (1989), and its application for assessing earth embankment structural integrities has since been suggested by others (i.e., Neroni et al., 2018). In order to assess the effectiveness of the HVSR method for recording ambient seismic noise atop earth embankments and to investigate the causes of shifts in fundamental frequencies, a series of measurements along the earth embankment dam of the Chestnut Hill, MA reservoir was performed. Repeated measurements have been performed for the purpose of 1) evaluating the ability of the equipment and HVSR method to record fundamental frequency peaks and produce spectral curves 2) investigate the repeatability of measurements at sites with prominent frequency peaks and 3) monitor shifts in fundamental frequencies over time with changes in reservoir depth and with the seasons. This presentation will explore the results of the reservoir measurements thus far (repeated measurements are still being made) through HVSR curves, data plots, and other figures. The observations made from these measurements will be applied when using the HVSR method to assess the structural integrities of other earth embankment levees and dams in the future.

09. Seismic and Liquefaction Hazard Maps for Five Western Tennessee Counties

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A five-year seismic and liquefaction hazard mapping project for five western Tennessee counties began in 2017 under a Disaster Resilience Competition grant from the U.S. Department of Housing and Urban Development to the State of Tennessee. The project supports natural hazard mitigation efforts in Lake, Dyer, Lauderdale, Tipton, and Madison counties. The updated county seismic hazard maps for Lake County in northwestern most Tennessee were completed in early 2018. Similar maps for Dyer County were completed in 2019. Maps for Lauderdale County were completed in early 2020, for Tipton County in early 2021, and for Madison County are being completed in late 2021. Additional geological, geotechnical, and geophysical information has been gathered in all five counties to improve the base northern Mississippi Embayment hazard maps of Dhar and Cramer (2017). Information gathered includes additional geological and geotechnical subsurface exploration logs, water table level data collection, new measurements of shallow and deep shear-wave velocity (Vs) profiles, and the compilation of existing Vs profiles in and around the counties. Improvements have been made in the 3D geological model, water table model, the geotechnical liquefaction probability curves, and the Vs correlation with lithology model for these counties. The resulting improved soil response amplification distributions on a 0.5 km grid were combined with the 2014 U.S. Geological Survey seismic hazard model (Petersen et al., 2014) earthquake sources and attenuation models to add the effect of local geology for Lake, Dyer, Lauderdale, Tipton, and Madison Counties. The resulting products will be similar to the Memphis and Shelby County urban seismic hazard maps recently updated by Cramer et al. (2018). Generally, the effect of local geology is to reduce seismic hazard at short periods and increase it at long periods. Liquefaction hazard is high only in the alluvial lowlands, but not in the loess covered uplands.

10. The Milwaukee, Wisconsin, Earthquake 6 May 1947

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The State of Wisconsin is not known for earthquake activity. Furthermore, while some modern earthquake catalogs include a spattering of small events in Wisconsin, prior investigations have shown that many types of events, such as explosions and cryoseisms, have made their way into earthquake catalogs in this region. It is therefore an interesting question: was the earthquake touted by some as the "largest known earthquake in Wisconsin" in fact an earthquake? I summarize available information about the earthquake that was felt in eastern Wisconsin at 15:27 local time on 6 May 1947. As what appears to be the largest historical earthquake in the State of Wisconsin, it is of public interest, its modest size notwithstanding. I conclude that no useful instrumental records of this event exist, due in part to a teleseismic event that occurred approximately 3 minutes later, generating surface waves that were recorded on early long-period instruments in the region. Instrumental data may exist for this event, but have not been found. Available macroseismic data does support the conclusion that the event was indeed an earthquake. Comparing the felt area with information from recent earthquakes in the region, I estimate an intensity magnitude of 3.8 for the event, with a subjectively estimated uncertainty range 3.5-4.1. Relatively strong effects, including reports of broken dishes in Milwaukee, and shaking described as short but especially sharp, suggest that the event may have been among the sprinkling of shallow earthquakes now known to occur in the upper Great Lakes region. These events, small and few as they may be, potentially provide insights into the processes that control seismogenesis in low strain-rate regions. One intriguing hypothesis (Yao et al., SRL, 2021) is that shallow earthquakes might be triggered by lake-level changes in the nearby Great Lakes.

11. Predicted Ground Motions From Magnitude 7 & 7.3 Summerville, South Carolina Earthquakes and Building Damage in Charleston During the August 31, 1886 Earthquake

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We have re-examined building damage in Charleston, South Carolina using predicted earthquake ground motions from large earthquakes at the epicenter of the August 31, 1886 event. A previous study (Robinson and Talwani, 1983) noted very little difference in brick building damage with respect to geologic site conditions during the 1886 earthquake. Here we use georectified 1884 Sanborn Fire Insurance maps and a building damage report keyed to these maps to locate and assess damage of residential and commercial brick structures. We used a previously developed damage scale (Miner, 2014) to assign a damage state (0 = no damage up to 4 = partial collapse) for each of the building's 4 walls. Of the 606 structures examined so far, 455 (75%) have at least minor damage and 110 (18%) major damage. For each structure we use predicted ground motions (PGA, 0.3 sec SA and 1.0 sec SA) from magnitude 7 and 7.3 strike-slip earthquakes propagated through a 3-D VS model of Atlantic Coastal sediments plus a more detailed VS model of the top 30 meters (Cramer et al., 2020). Ground motions are evaluated on a 100 m x 100 m grid. Our primary result is that ground motions vary very little in our study area, i.e., 4-8% for the M7 earthquake and 2-6% for the M7.3 earthquake. There are weak trends in ground motion as a function of damage intensity, but they are different for the M7 and M7.3 scenarios. For the M7 event PGA increases but 0.3/1.0 sec SA decrease with increasing building damage. For the M7.3 event 0.3 sec SA increases but PSA/1.0 sec SA decrease with increasing building damage. Thus it appears the nonlinear behavior of the entire Atlantic Coastal sedimentary structure outweighed local near surface site effects during the damaging strong ground motion in 1886.

12. A brand new seismic network at Querétaro state, Central Mexico

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Mexico is a large country with different tectonic environments, high and variable seismicity rates. Even though the number of seismic stations has increased in the last 10 years, it is necessary to improve its density and space distribution. We present two brand new seismic networks in central Mexico, where the seismicity rates are still unknown. In 2010 we installed the first VBB station in Querétaro, recently moved to Tequisquiapan city. During 2021 we installed nine stations, two intermediate period and seven short period. They have an average distance of about 50 km. This network will enable a better seismic monitoring at the Sierra Madre Oriental and the Mesa Central. The epicenters confirm former locations obtained by temporal networks. On the other hand, since 2019 we have installed more than 20 accelerographs at Queretaro city. This network has well recorded the ambient seismic noise and the ground motion produced by the local and regional earthquakes. After the beginning of the COVID outbreak, we carried out a detailed survey of Querétaro ambient seismic noise, the correlations show a similar worldwide behavior. Now a days, we are expanding this network to other towns to improve the regional coverage. Recently, both networks recorded two episodes occurred on September 2021, which were widely felt in the region. The first one was a far and shallow earthquake (Mw7) occurred close to the Acapulco turistic harbor. The second one was a seismic swarm occurred towards the north of Guanajuato state ($3.5 < M < 4.6$). These networks will enable a systematic monitoring of local intraplate seismicity, to study the kinematic and dynamic characteristics of the active structures, to define the regional velocity structure, to characterize the seismogenic sources, and to obtain seismic zonation maps.

13. On the Applicability of using Horizontal-to-Vertical Spectral Ratios of Ambient Seismic Noise to Assess the Stability of Earth Embankment Dams and Levees

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The purpose of this project is to investigate the use of geophysical methods to assess the stability of earth embankment levees and dams, with the goal of identifying locations of weaknesses that may result in future failures of these structures. The method that we are investigating is the use of horizontal-to-vertical spectral ratios of ambient seismic noise (usually called HVSR) for assessing the stability of earth embankment levees and dams. We use modeling based on the programs NRattle and HVINV to assess the conditions where the H/V spectral ratio method might be able to resolve changes in the subsurface material strength or erosion of subsurface materials. We use a typical velocity-depth profile of an earth embankment levee from Texas and then compute how much change can be expected in the frequency of the fundamental resonance peak in the H/V spectral ratio due to a change in subsurface seismic velocities. The modeling shows that the HVSR method is more sensitive to subsurface S-wave velocity decreases than velocity increases and to layers in the deeper part of the earth embankment structure than to those near the top of the structure. Furthermore, a decrease in the S-wave velocity of about 20% is sufficient to cause a resolvable decrease in the frequency of the peak of the fundamental resonance. It is concluded that the HVSR method should work well at identifying subsurface conditions that may pose a hazard to earth embankment levees and dams.

14. Leveraging machine learning algorithms to efficiently identify events in eastern Kentucky

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The Kentucky Seismic and Strong-Motion Network monitors natural and man-made events in and around Kentucky. Using a network of temporary and permanent stations and other regional stations, we detected and associated seismic events in and around eastern Kentucky using the carlstatrig/carlsubtrig routines in the Earthworm software package. Random noise events and blasts throughout the region resulted in a large number of false and undesirable triggers. To reduce analyst review time, we reprocessed the dataset through the machine-learning-based algorithms General Phase Detection and PhaseLink for arrival detection and association, respectively. We used default parameters for General Phase Detection. Associated parameters were optimized to capture all events in two months of an analyst-developed earthquake catalog, including the smallest-magnitude events that had been located within the study region. We discovered that the key parameters for reducing the most false detections, yet capturing all manually identified earthquakes in the study area, were the minimum probability threshold (0.555), number of picks needed to nucleate an association (9), and number of picks to validate a detection (10). Using our preferred parameters, we processed 55,609 Earthworm triggers from September 2018 through June 2021; this eliminated 98.5 percent of the initial trigger dataset. Of the 794 associated events, 152 were noise triggers and 649 were real seismic events. Based on the distribution of event types from manually classified triggers during an earlier phase of analysis of these networks' recordings, we estimate that ~28,000 of the initial triggers may have been caused by mine blasts. Thus, as much as 98% of the blast recordings were automatically removed. Our results show that the GPD and Phaselink algorithms together can dramatically reduce an analyst's effort to identify local earthquake triggers in a noisy dataset and in a region that experiences frequent mine blasts.

15. The 4 August 2020 Beirut Chemical Explosion

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On August 4, 2020, a massive explosion occurred in the city of Beirut, Lebanon. This accident was reported to be caused by the deflagration of 2,750 tons of ammonium nitrate stocked at the port district of Beirut (Guglielmi, 2020). Based on regional data recorded both on- and off-shore stations, we investigated the properties of the explosion as well as 6 nearby earthquakes between July 2018 and August 2020. Both body- and surface- wave magnitudes were calculated based on Lg and Rayleigh waves for these events. The magnitudes for the Beirut explosion are mb(Lg) = 3.17 ± 0.52 and Ms = 1.46 ± 0.29, respectively. Considering the explosion was caused by chemicals stored above the ground surface, the conventional magnitude-yield empirical relations for buried source would greatly underestimate its yield. Therefore, we chose another fitting curve based on the size of the crater produced by explosive charges above the ground surface (Ambrosini et al., 2002). The diameter of crater size is about 100 m. The yield was estimated to be 1,22 kt TNT if the burst height is 1.0 m. The P/S spectral amplitude ratios, including Pg/Lg, Pn/Lg and Pn/Sn, were calculated and effectively discriminated the Beirut explosion from nearby natural earthquakes. Besides, we investigated the variations of the spectral amplitude ratios from different sources including, (a) the open-pit explosion including the Beirut explosion and Xiangshui explosion, (b) six underground nuclear explosions in North Korean, and (c) natural earthquakes. Results shows that the P/S spectral amplitude ratios can also effectively discriminate the open-pit explosion with the underground nuclear explosion. This research was supported by the National Key Research and Development Program of China (2017YFC0601206) and the National Natural Science Foundation of China (41974061, 41974054, 41630210, and 41674060).

16. Movement towards Broadband nodal instrumentation

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Broadband seismometers have traditionally used an analogue force-feedback design to increase the linearity and dynamic range of the sensor. However, a drawback of this design has been the large masses required to improve noise performance which inherently has made broadband seismometers cumbersome. In addition, traditional seismometers have also required the sensor to be accurately levelled so that the sensor components are aligned with the field of motion.
Over the last 5 years, Güralp Systems have developed a new sensor technology that makes use of a digital feedback loop that ensures constant performance regardless of the angle of tilt. This novel sensor technology has implications in a range of research areas, including ocean bottom, borehole and near surface seismology.

The integrated digital feedback system allows for the sensor's long period corner to be adjusted remotely, allowing users to effectively have multiple sensor types in a single package. This feature in particular makes Güralp's next generation sensors incredibly versatile tools, especially for operators with limited resources. The integration of the Minimus digitizer allows for users to intelligently select crucial operating features to reduce the power consumption of the systems significantly, reducing the power requirements for remote deployments.
These features of the sensor can be seen as a first step towards nodal broadband systems that someday may be able to be deployed in large-n arrays to provide excellent low frequency seismic data, especially in harsh conditions where traditional seismometers are difficult to transport and deploy due to their weight. Future development of this sensor technology will look to further reduce the form factor of the sensors as well combining data acquisition and power modules to provide a truly nodal broadband seismometer.

17. Novel Autonomous and Cabled OBS Solutions for Offshore Seismic Research

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Despite the fact that 70% of Earth is covered by water, seismologists have historically focused on terrestrial research, mainly due to the logistical and financial challenges presented by offshore research.

Güralp has accomplished technological advancements which allow the seismology community to easily monitor offshore seismicity, improving offshore data resolution. This is due to systems such as the Aquarius autonomous ocean bottom seismometer (OBS) and world-leading engineering advancements in Science Monitoring and Reliable Telecommunications (SMART) cables.

Aquarius can be deployed autonomously on the sea floor for up to 18 months. The sensor works at any angle without using a gimbal system, and wirelessly transmits data to the surface through an acoustic modem. These features allow researchers to monitor and transmit data without offshore cabling, thereby reducing the logistical challenge associated with offshore OBS deployments. Optional surface communications can be permanent (buoy-mounted), semi-permanent (wave-glider) or on demand (ship-of-opportunity or dedicated voyage).

Cabled solutions are also still important however, as they give users access to high-resolution data in real-time via a data cable linked to an onshore data centre. As an example, Güralp's Orcus cabled OBS provides these features as a complete underwater seismic station with observatory grade seismometer and strong-motion accelerometer in a single package.

SMART show great potential for improving cabled observatory deployment in the future. Combining several applications into one system, including seismic monitoring and telecommunications, large scale monitoring networks can be created by combining efforts from several industries into one project. As a practical example, GSL is developing a demonstration SMART Cable system to monitor volcanic and seismic activity offshore in the Ionian Sea. This will be the first practical demonstration of this technology and there are plans for additional projects in the future.

18. The Rome Trough: A Seismically Quiescent Intraplate Rift

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The Rome Trough, a northeast-trending graben system extending from eastern Kentucky across West Virginia and Pennsylvania into southern New York, is part of a larger, failed, intraplate rift system. Although the trough is heavily faulted, the historical earthquake catalog shows a dearth of seismicity. The possibility of inducing earthquakes by potential new hydrocarbon production of the Rogersville Shale deep in the trough motivated a project to characterize background seismicity. We operated a temporary network of eight to 14 broadband seismic stations in the Rome Trough of eastern Kentucky from mid-2015 through June 2021. Using both traditional and machine-learning-based algorithms, we developed a catalog of 236 earthquakes within ~250 km of the network centroid from the continuous waveform data. Consistent with the historical seismicity patterns, very few-15-earthquakes occurred in the crust beneath the trough, and most of them were near the edge: only six earthquakes occurred more than 10 km from the trough's boundary faults. A likely explanation for the seismic quiescence beneath the trough is that most faults are not optimally oriented for slip in the contemporary stress regime. To investigate this possibility, we refined and updated the basement fault maps in and around the Rome Trough and compiled new regional stress data and that available in the World Stress Map database. Interpolated SHmax orientations from 27 data points within or near the trough boundaries yield an average σ_1 azimuth of 57°. Geologic materials under confining pressure tend to shear at ±30° from the σ_1 direction. Therefore, faults in this strike-slip regime trending near either 27° or 87° azimuth would be preferentially oriented for slip. However, because the Rome Trough border faults and the vast majority of internal faults trend between azimuths of 45° and 70°, they are not likely to slip in the current regional stress field.

19. Using Machine Learning for Surface-Wave Quality Control

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Surface waves carry valuable information about both subsurface structure and earthquake characteristics. Due to background noise or other factors, a significant portion of recorded surface-wave seismograms may not be suitable for further analysis. To avoid inclusion of noisy signals, reliable surface-wave-related investigations usually incorporate a labor-intensive and tedious quality control process. With an ever-increasing volume of available surface waves, this quality control process can become a bottleneck for seismological study. Researchers often exclude otherwise useable data to reduce analysis time to a manageable level. Because of complexities such as radiation patterns and signal dispersion, the performance of traditional automatic algorithms for surface-wave quality control trails far behind human analysts. To improve the efficiency and accuracy of automated approaches, we explored five different machine learning (ML) algorithms for the quality control of surface waves including logistic regression, support vector machines, k-nearest neighbors, random forests (RF), and artificial neural networks (ANN). We trained the ML models using human-assigned quality labels compiled from several earthquake relocation studies that analyzed nearly 400,000 waveforms. The ANN and RF models exhibited higher test accuracy (92%) than other algorithms. Using seismic data never seen by the ML models, the best ML models matched human performance but required only 0.5% of processing time once trained. Our analyses demonstrate that the two best-performing ML algorithms can complete the quality control screening task efficiently and accurately without human intervention. The trained ML models can help facilitate detailed waveform analysis and reducing outliers in surface-wave-related measurements.

20. Improved Microearthquake Monitoring in the Source Zone of the 1886 M 7 South Carolina Earthquake

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Since late May 2021, we began deploying a USGS NEHRP-funded network of L22 3-component short period seismometers in the Middleton Place-Summerville Seismic Zone (MPSSZ); i.e., the presumed source area of the August 31, 1886 M~7 South Carolina earthquake. The objective of this ~2-year deployment is to better define fault sources associated with modern microseismicty and shed light upon the fault that ruptured during the large 1886 earthquake. As of September 4, 2021, this network has expanded to 19 stations, complementing the 4 permanent stations in the MPSSZ operated by the University of South Carolina and the US Geological Survey. Data from the open station, WSCT, is currently being streamed in real-time to the Center for Earthquake Research and Information and from there to the Incorporated Research Institutions for Seismology Data Management Center (IRIS DMC, network code YH). Data from WSCT has already proven valuable in improving the detection level of microearthquakes in the MPSSZ. Five events with magnitudes 1.1-2.0 were located by the five-station real-time network (WSCT plus the 4 permanent stations) in July and August 2021; preliminary analysis of data recovered from the other stations suggest an additional ~10 events may be locatable. We have also found evidence for clusters of closely located events; e.g., M 1.1 and 1.3 earthquakes plus a smaller event (M~0.9) on July 21-22, 2021 have nearly identical waveforms, suggesting a similar source location and orientation. Our next step is to apply both machine-learning and template matching techniques to detect/locate microseismic events recorded by our dense network, and use them to better illuminate subsurface faults in this region.

21. First Microseismic Event Detections in Tompkins County, New York in Preparation for Geothermal Installation

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In order to help achieve carbon neutrality goals, Cornell University is planning to dig an exploratory borehole in early 2022 to study the possibility of using deep direct use geothermal to heat its Ithaca, NY campus. To effectively explore the availability of geothermal resources and the feasibility of extraction, an accurate understanding of regional geologic features and seismicity is required. However, available national and regional seismic networks do not have sufficient sensitivity to record any microseismicity over the last decades in Tompkins County, NY, where Ithaca is located. In preparation for drilling, two seismic networks were installed to study the background seismicity of Tompkins County. The first network, CorNET16, operated from 2015-2016 with 12 seismometers and recorded about 30 events in Tompkins County, all outside the network. The second network, CorNET21, has been in operation since 2019 with 15 seismometers including surface and borehole instruments over a larger aperture based on preliminary assessment of events located by CorNET16. Preliminary analysis indicates 360 seismic events in Tompkins County between August 2019 and August 2021 not recorded on national or regional networks. Most events are related to construction, but there are some natural microearthquakes actively being studied. About 70 of the larger events are considered well-located after manual review. Events as small as Mw -2.5 associated with repeated dropping of a 10-ton weight from 15 meters during construction at the Cornell campus have been detected. Preliminary error analyses of the CorNET21 network reveal probable location uncertainties of approximately 500 meters horizontally and on the order of a kilometer in depth, and efforts to decrease uncertainty are ongoing. We are currently comparing coda magnitudes to moment magnitudes for the events. Continued operation of a local network is recommended to detect seismic activity missed by regional and national networks.

22. Evidence for complex faulting at the northern edge of the Basin and Range province from relocation and moment tensor analysis of the 2020 Stanley, Idaho earthquake sequence

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The Mw6.5 2020 Stanley, Idaho earthquake was the largest earthquake to occur in the Intermountain West region since 1983. It occurred just north of the mapped Sawtooth Fault. The Sawtooth Fault is the westernmost range-bounding normal fault of the northern Basin and Range region and shows evidence for Holocene surface rupture. The Stanley earthquake, however, has a left-lateral strike slip mechanism and ruptured on a northerly-trending hidden fault. No surface ruptures have been reported from the remote epicentral region. A lack of a geomorphic expression suggests the causative fault is immature and has limited cumulative slip. We used data from a temporary seismic network installed by Boise State and from permanent regional seismic stations to relocate the mainshock and ~1,400 aftershocks and to determine moment tensors for ~150 events. The mainshock nucleated at the base of the seismogenic crust and based on first day aftershock locations and aftershock strike-slip mechanisms propagated upwards and bilaterally along a ~30-km-long, steeply westward-dipping transform fault. The rupture likely stopped near the northern end of the Sawtooth Fault. There, aftershocks are widely distributed and have strike-slip and normal faulting mechanisms with varying orientations indicating activity on several, distinct faults. The complexity possibly reflects accommodation of stress concentrations at the southern tip of the rupture where deformation transitions from strike-slip to normal faulting resulting in distributed deformation involving several faults. Some aftershocks may have occurred on the northernmost Sawtooth Fault, which likely was brought closer to failure by the Stanley earthquake.

23. B-VALUE AND FRACTAL DIMENSION STUDY OF SOUTHERN CALIFORNIA SEISMICITY FROM 1982 TO 2020

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Power-law scaling relationships concerning earthquake frequency-magnitude distribution and fractal geometry of spatial seismicity patterns may provide applications to earthquake forecasting and earthquake hazard studies. Past studies on the fractal characteristics of seismic phenomena have observed spatial and temporal differences in earthquake clustering and b-value in relation to fractal dimension value. Earlier results suggested either coseismic or postseismic changes in temporal b-value and correlation dimension (D2) associated with large earthquakes, including the M7.3 Landers, M6.7 Northridge, M7.1 Hector Mine, M7.2 El Mayor-Cucapah, and M7.1 Ridgecrest. In this study, an investigation of spatiotemporal seismicity patterns in southern California for the years 1982 to 2020 is conducted with an emphasis on seismicity near and within the San Andreas fault system and eastern California shear zone. In particular, b-values and D2-values of earthquake hypocenters listed in the Southern California Earthquake Data Center catalogue are calculated for each year for magnitudes between 1.5 and 4.5 and length scales between 1 to 10 km. In general, results show a background b-value of approximately 1.0 and D2-value of 0.8; relatively low b-values and relatively high D2-values occur within a radius less than 100 km of large earthquakes. The perturbations in b-values are coseismic, whereas the perturbations in D2-values are coseismic and postseismic, potentially reflecting a difference in aftershock sequences for large earthquakes. Preseismic changes in b-values and D2-values were not detected. The ability for D2-values to delineate both the temporal and spatial extent of aftershock sequences for large earthquakes may prove to have an application in earthquake hazard studies.

24. The 'Kappa Project': hard-rock attenuation at sites in Canada and France

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We summarize the results of a collaborative project dedicated to kappa (the high-frequency site attenuation factor), which has just been completed. A number of rock and hard-rock sites were selected, namely 7 in Quebec and 8 in mainland France. One of the key aims of the project was to focus on characterized stations, as some of our earlier attempts showed that site amplification may likely bias kappa estimation, even at rock sites where it has been considered minimal. Previous work on kappa has considered generic linear-elastic crustal amplification, but not site-specific transfer functions derived from in-situ Vs measurements. The latter is done for the first time in this project. A suite of methods is applied, including broadband inversions solving for source, path and site parameters, and band-limited approaches targeted at the site. Our results show that the ability to correct for the site amplification due to shallow velocity contrasts and gradients improved the robustness of site attenuation estimates; however, the variability in the results also showcased another aspect: kappa most likely also includes components from the deeper geological structure, which are not accounted for through typical (geophysical) shallow site characterization. The effect of deeper regional structure is in line with existing conceptual models proposed in the past by the group, but is more challenging to quantify. It can help explain and refine uncertainty found in kappa estimates when combining sites with similar near-surface but different deeper characteristics.

25. A Measured Quake: The 2020 MLg 3.1 in Marlboro, New Jersey, Serving to Understand and Remove the Instrument Response

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Many in Princeton, New Jersey, and neighboring communities felt a jolt in the middle of the night of September 9th 2020. The next morning the cause was clear: a magnitude 3.1 earthquake had struck Marlboro, NJ, some 31.4 km away. What, precisely, was the measured effect of the Marlboro earthquake, in physical units, across a range of frequencies, and recorded by instruments of very different makes (broadband seismometer, accelerometer, Raspberry Shake)? To better understand earthquakes as a hazard and to better understand the interior structure of the Earth, we need displacement, velocity, or acceleration measured across the Earth's surface. A routine step in an observational seismology workflow is the removal of the instrument response, from the digital counts reported by a seismometer to the physical units of ground motion. The seismometer is a linear time-invariant system, its output record a convolution of ground motion with a transfer function that gain-scales and phase-shifts the incoming input signal. Numerous software packages are widely used to accomplish the necessary deconvolution of the instrument's transfer function. In this presentation, we take a step back to fully explore the choices made during this routine step, and explain the reasons for making them. In addition, we introduce open-source routines in Python and MATLAB as part of our rflexa package, which identically reproduce the results of the Seismic Analysis Code, a ubiquitous and trusted reference. The entire workflow is illustrated on data recorded by seismic instruments of a variety of types on Princeton University campus in Princeton, New Jersey, of the September 9th 2020 magnitude 3.1 earthquake in Marlboro, New Jersey.

26. Potential Surficial Evidence of Low-rate Deformation in the Eastern Tennessee Seismic Zone?

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The ~400-km-long Eastern Tennessee Seismic Zone (ETSZ) is the second most seismically active region east of the Rocky Mountains. Much of the seismicity occurs below the Paleozoic fold-and-thrust belt within the Mesoproterozoic basement, at depths of 5-20 km, and earthquake magnitudes during the instrumental record have been low (Mw,â§4.8). The deep seismicity, combined with humid climate, rapid erosion, and anthropogenic landscape modification, has complicated the search for records of faulting and related surface deformation. Paleoseismic trenches have identified deformation suggestive of Quaternary faulting in the southeastern ETSZ, but clear Quaternary surface faulting or tectonic surface deformation has not yet been identified elsewhere. To that end, we interrogated the landscape at different spatial scales. First, we evaluated morphotectonic and channel metrics, such as channel sinuosity and steepness, relief, and catchment-scale hypsometry on 30-m and 10-m gridded elevation data. Additionally, we mapped topographic lineaments on 1-m lidar data. Finally, we integrated our observations with previous bedrock and limited Quaternary surficial mapping. At a regional scale, most morphotectonic and channel metrics have a strong lithologic control. Within smaller regions of similar lithology, we observe landscape metrics like channel sinuosity and catchment-scale hypsometry that spatially correlate with lineaments newly mapped in this study and previously mapped east-west Cenozoic faults. These previously mapped faults generally have left-lateral senses of motion, are optimally oriented to slip in the current stress field, and match kinematics derived from focal mechanisms of recent earthquakes. We propose that strike-slip or oblique-slip faulting at depth propagates upward through the Paleozoic overburden and may be manifested as subtle distributed deformation on broadly east-west-oriented, 10- to 25-km-wide fault zones at the surface. Although evidence for a discrete, single fault trace that offsets Quaternary deposits remains elusive, we suggest that alignments of the lineaments could be characterized as broad fault zones with continued study.

27. The Intriguing Variety of Things We Record with Our Raspberry Shakes: Citizen Scientists, Educators, and Research Scientists Collaborating to Monitor Our Active Planet

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When we first (four years ago) became aware of the availability of the low-cost Raspberry Shake (RS) seismograph, we were intrigued about how well it would record earthquakes; intrigued enough to buy some of them and see what they might record. As each of us installed and ran our RSs (and Raspberry ‚ÄúBooms‚Äù for infrasound), we formed this group of professional and citizen seismologists (within the larger, global RS community) working together to discern what these small, affordable RSs might record. The results were surprising and intriguing. We discovered that there was more interesting seismology recorded by these $400 instruments than we imagined possible. Three surprises, in particular, were: 1. Yes, these little high-frequency geophones, integrated with some clever software on a Raspberry Pi computer, do record long-enough period signals for recording earthquakes, 2. Signal coherence between nearby stations allows for advanced signal processing, and 3. These RSs record a lot of other interesting seismic events, such as storms, snow plows, wind turbines, street traffic, aircraft, construction sites, thunder, washing machines, and more.

Here we show some of the many seismic events we have recorded on our RSs. Many more examples are on various social media platforms, research publications by many scientists, meeting posters and presentations, blogs, and online newsletters. See, for example, twitter.com/Weston_Quakes and twitter.com/KristiFinkTXESP, where we are able to efficiently reach a wide and diverse audience, bring science to people, and people to science. We found that RSs are surprisingly good for recording local and regional earthquakes and also record some large, distant earthquakes better than we expected. Plus, we are intrigued by the many other types of seismic sources recorded by our RSs that we are just beginning to explore. This experience highlights opportunities for citizen scientists, educators, and research scientists collaborating to monitor our active planet.

28. Seismic Evidence for an Intermediate Phase during the Olivine-Wadsleyite Transformation within the Subducting Pacific Slab in Kuril

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At the top of the mantle transition zone, olivine (α) transforms to wadsleyite (β) at about 410 km depth under equilibrium conditions, i.e., a pressure around 14 GPa and a temperature of about 1350 °C. The subsequent wave speed increase upon the α-β phase transition led to the discovery of the "410-km discontinuity" as a global feature thanks to seismology. In contrast, lower temperatures (< 1000°C) within the slab inhibit diffusive processes, thus diffusionless transformations might occur, such as the transition from α-olivine to ω-olivine (ε*-phase), i.e. new high-pressure polymorphy recently discovered in heavily shocked wadsleyite and ringwoodite meteorites.

Our seismic waveform inversion results of the triplicated P wave datasets (in the Kuril subduction zone) show drastic variations of P-wave velocity inside the slab: a zone of extremely low wave speed (wave speed reduction < -20%) is located between 383 and 415 km depth, close to the cold core of the slab. These observations indicate that a layer of destabilized olivine exists within the cold slab, which highlights the transient (meta)stability of theε*-phase, under substantial shear stress. Nonetheless, any phase transformation at relatively low temperatures necessarily induces long-lived grain-size reduction, which is also known to reduce P wave velocities. Whichever the transformation, we propose that the extremely low wave speed zone corresponds to a layer of partially transformed material, possibly consisting of a mixture of α, ω, and β-olivines.

29. Soil Amplification in Glaciated Terrain: Geology and geomorphology based f0 model of New England

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Near surface site characterization is essential for earthquake hazard assessment and ground motion prediction. Currently, the earthquake engineering community uses Vs30 as the primary proxy for site amplification in design spectra development. This value, though useful, doesn't capture all information necessary for a complete understanding of a site's information like depth to the impedance contrast and shear wave velocity of layers deeper than 30 meters. In recent years, f0, the site fundamental frequency, has become popular due to its low cost and easy calculation using the HVSR technique. In addition to its attractive economic attributes, f0 is useful because it contains information on both shear wave velocity and depth. We therefore argue that f0 is a worthwhile parameter to measure at a site and worthy of further study. In this research, we build a model of f0 in the New England region using two predictors: geology and geomorphology. To develop the database, we compiled around 1000 f0 measurements in the region and collected 380 more to expand our coverage into unsampled geologies. We then developed a digital elevation model of New England by mosaicking relevant DEM data sets from the SRTM 1-arc second global model. From this model, we calculated slope, curvature, topographic roughness index, and compound topographic index and using the National Hydrography Dataset, we developed a distance to nearest waterbody raster. For the last database development step, we collected the New England state surficial geologic datasets, reduced the number of units in each map, and unified the maps across borders. With these datasets in one model, we intersected the f0 values with each layer. Using this final table, we performed uni and multivariate regressions and found the optimal model for predicting f0 in New England.

30. Assessment of Non-Geoscientist's Understanding of Real-Time Earthquake Information Products

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Public engagement through outreach is a key mechanism for learning about science and to communicate societal impacts of government-funded science. However, outreach effectiveness could be limited if approaches are not evidenced-based. Partnerships with cognitive scientists who study fundamental learning processes suggests helping people to learn how and why earthquakes happen would improve understanding of earthquake hazards and reasons for preparedness. We recently developed a seismology-cognitive science partnership that demonstrated non-geoscientists do not have improved understanding of basic seismology concepts after viewing Ground Motion Visualizations despite being widely used for outreach. In this study, we sought to evaluate understanding by non-geoscientists of widely viewed USGS realtime products ShakeMap and PAGER. Based on discussions with USGS staff, we constructed 13 free response questions probing understand of these products and included the Graph Literacy Scale (GLS) for comparison. Through Zoom interviews of 100 participants, we found poor performance (28% correct) on the PAGER and ShakeMap questions despite good performance (76% correct) on the GLS. When coding the free responses, we identified an average of 13 misconceptions per participant. Five misconceptions were observed in over half of the participants, including how the reports are constructed and used in realtime, that the reports are estimations not observations, and difficulty interpreting probabilities. The performance and misconceptions led us to develop a revised PAGER with scatter plots to visualize fatality and damage probabilities among other simplifications. We used a multiple-choice survey to assess understanding using the original and new visualizations in random order with another 100 participants. We found significant improvement: Participants scored 49% correct when seeing the revised visualization first, compared to 36% when seeing the original visualization first. Our findings suggest these realtime products are poorly understood by non-geoscientists, but efforts to adjust these products can improve their effectiveness when disseminating earthquake information to non-geoscientists.

31. A Geospatial Model for Predicting Site Response Complexity

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Seismic waves can be modified due to local geology and topography. These so-called site response can significantly influence ground motions and subsequent damage patterns. One-dimensional site response models vertically incident SH waves propagating through the laterally constant soil layers (referred to as SH1D) and is widely used in site-specific site response and ground motion prediction. However, many studies have demonstrated the limitations of 1D site-response analyses. The term “site response complexity” (SRC) refers to the degree of discrepancy between the observed empirical transfer function (ETF) and theoretical site response (TTF) computed with SH1D. We present a geospatial approach to estimate site response complexity using globally or regionally available geospatial proxies and statistical methods. A dataset consisting of 114 KiK-net vertical seismometer arrays is compiled. The site response complexity is calibrated according to Thompson et al. (2012)’s taxonomy that relies on two parameters, r (Pearson’s correlation coefficient between ETF and TTF) and σ_i (inter-event variability of ETF). We examine 18 geospatial proxies associated with site stiffness, topography, basin, and saturation conditions. Multinomial logistical regression is used to classify the site response complexity, and linear regression models are developed to predict the r and σ_i, separately. A hybrid feature selection procedure integrating correlation-based feature filter and the exhaustive wrapper is implemented to select the best feature subset. The AICc and Wald statistics are used to guide the model selection. We recommend two SRC classification models. The best model uses $\ln(V_{S30})$, $elevation^{0.5}$, $TRI^{0.5}$, and $Z1.5^{0.5}$, and achieves training and testing accuracy of 0.61 and 0.55, respectively. The alternate model uses $\ln(V_{S30})$, $elevation^{0.5}$, $TRI^{0.5}$, and $thickness^{0.5}$, and has training and testing accuracy of 0.65 and 0.55, respectively. The AICc of the best model and alternate model are 197.2 and 208.7, respectively. We use the best model to generate a SRC classification map for Japan. We conclude that these models could provide first-order approximations of the site response complexity.

32. Change in seismic velocity during laboratory triaxial stick-slip experiments

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Seismic velocity changes resulting from crack opening and closure within fault damage zones may be indicative of stress state and proximity to failure. However, such velocity changes are commonly extremely small and thus hard to resolve in the natural system at high temporal and spatial resolution. Here, we analyze subtle changes in seismic velocities in triaxial laboratory compression tests on pre-faulted samples. We use both direct phase picks and the coda part of the waveform which samples a broader region within the highly-scattering fault damage zones. Using this property of the coda wave, we measured high-resolution seismic velocity changes during the laboratory experiments. We used homogenous Westerly granite samples with a precut fault at an angle of 30º to the loading axis. Coda Wave Interferometry (CWI) is applied to waveforms of active laboratory source pulses that were generated and recorded by an array of 8 pairs of piezoceramic transducers. The sample was subjected to confining pressure increase from 2 to 120 MPa, followed by axial load and stick-slip. The results demonstrate that the coda waves are sensitive to the change in seismic velocities that were not sensed by the direct phase arrivals. When comparing consecutive waveforms, lag times were observed to be non-uniform and increased as we progress towards the coda portion of the seismic wave. The coda part shows that the velocity change is highly-correlated with the applied confining stress and it samples a broader volume of the medium that is more sensitive to bulk confining pressure increase. The use of CWI in laboratory experiments may help quantify other frictional and fracture processes associated with labquakes.

33. Seismological studies of the 2019 M5.1 Sparta Earthquake sequence, North Carolina

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On August 9, 2020, a Mw5.1 earthquake ruptured the uppermost Crust near the town of Sparta, North Carolina. This earthquake ruptured the shallow crust of a stable continental region which has been quiet since the M5.2 1916 Great Smoky Mountain earthquake. Following the mainshock 5 temporary seismic stations were also deployed in the area. Together with state-of-the-art earthquake detection and relocation techniques, this sequence provides an opportunity to better understand the local fault structures and the source processes of intraplate earthquakes.
Here we combine a deep learning earthquake phase picker (EQTransformer) and a matched filter technique to compile a more complete earthquake catalog for the sequence. We perform detections for the period of August 1 to November 18, 2020. We first detect P and S waves and associate them using EQTransformer. We then combine the resulting earthquake catalog with the USGS catalog to build a template catalog with a total of 498 events. We search for additional earthquakes using a matched filter technique by cross-correlating the waveforms of the templates with daily continuous waveforms. using cross-correlation derived differential-travel times, we relocate the detected events to obtain a final catalog of 896 earthquakes. With the relocated catalog we identify a major lineament of aftershocks that propagate to NW of the mainshock epicenter and a smaller parallel cluster can be identified to the NE. The aftershock area extends to 8 km depth around the mainshock epicenter and becomes shallower to the NW. We also identify 10 foreshocks in the 2 days before the mainshock. Then, we use the generalized cut-and-paste (gCAP) method to determine the focal mechanism of the mainshock with the local waveform data. The Green,Äôs functions are calculated with the CUS velocity model. The inversion results show that the mainshock is a thrust event with some strike-slip component, with a moment magnitude of 5.13. The two double-couple nodal planes are 349º/69º/116º and 115º/32º/41º for an optimal centroid depth of 1.3km. The percentage of the non-DC components is about 12%, which might imply that the mainshock ruptured along with complex fault geometries. Updated results will be presented at the meeting.

34. Polarization based S-wave pre-selection for interferometry and near-surface Vp/Vs ratio estimation

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Ambient noise recorded at surface stations is dominated by surface waves, thereby making body wave retrieval by interferometric methods difficult. Although dense and regular receiver arrays offer the advantage of using offset-based processing methods to identify body waves, such arrays are usually not available due to financial and logistical constraints. Here, we propose a single station polarization-based methodology to preselect S-waves for interferometric processing. The selection metric combines instantaneous frequency, RMS amplitude and polarization incidence to identify steeply incident S-waves from ambient noise data. The methodology is validated using a 3-component dataset recorded at the Wellington oilfield (Kansas, US) by 15 short-period receivers. Single station interferometry (autocorrelation; AC) of the S-wave dataset reveals shallow (< 1 km) reflectivity structure that is also corroborated by well log data. Synthetic data analysis shows that S-to-P conversion in the near surface can lead to pitfalls in the interpretation of the shallow reflectivity structure derived from horizontal component AC. To avoid misinterpretation, we only consider the AC response after 0.6 s for S-wave reflectivity. Lastly, we estimate the near surface Vp/Vs ratio using the P-wave reflectivity from a previous interferometric study done on the same dataset. Our results suggest that polarization-based S-wave selection can enhance passive reflectivity imaging for sparse and irregular arrays. The methodology can potentially be useful for time-lapse Vp/Vs monitoring of fluid injections or extractions in reservoirs.

35. Magnitude Recalculation Using Relative Magnitudes for the 2011 Prague, Oklahoma Induced Earthquake Sequence

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Accurate calculations of earthquake magnitude are necessary prerequisites for statistical measures of earthquake hazard. However, calculating these magnitudes is not always a straightforward process, especially when the earthquakes are small or occur in a region that experiences gaps in seismic and/or geologic data. Furthermore, certain magnitude scales are preferred for different ranges of earthquake size which leads to catalogs with more than one magnitude type that do not always merge together correctly.

In an effort to improve the quality of magnitude estimates for induced earthquakes and attempt to 'bridge the gap' between different magnitude types, we use a modified version of Cleveland and Ammon's [2015] relative magnitudes from cross correlation method to recalculate magnitudes for events recorded during and after the 2011 Prague, Oklahoma earthquake sequence. This method uses a principal component analysis to determine the amplitude ratio between waveform pairs with high cross-correlation. Then, these interlinked amplitude ratios are inverted for the relative magnitudes. To expand the Cleveland and Ammon method to a larger dataset where we assume unknown magnitudes, we choose to incorporate a separate catalog of precisely calculated moment magnitudes and a constant term to stabilize the least squares inversion. We also compare these recalculated magnitudes to the previously cataloged local and moment magnitudes.

Preliminary results show that many of these newly recalculated relative magnitudes are lower than previously cataloged, especially for small earthquakes. These differences in magnitude modify the magnitude-frequency distribution resulting in a lower b-value for the same population of events, which can be an important consideration for hazard estimates of induced earthquakes in central Oklahoma. Further work will include processing more data from other nearby TA stations to expand the number of magnitude recalculations and refine the current magnitude estimates.

36. Empirical relationship between different source-to-site distances

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To determine the seismic hazard of an area, it is essential to predict the ground motion observed at the site accurately. Ground motion prediction equations (GMPE) generally determine the intensity of ground motion observed in an area based on the distance from the ruptured surface to the site such as Joyner-Boore distance (RJB) and Rupture distance (RRUP). However, Probabilistic Seismic Hazard Analysis (PSHA) utilizes point-source based distances like Epicentral distance (REPI) and Hypo-central distance (RHYP), where the fault geometry may not be known. We develop empirical relationships between various distances to help convert from one distance to another and avoid conducting computationally intensive tasks such as computing finite-fault based distances for different fault geometry of a virtual rupture plane for each point source and vice versa. The empirical equations provide the relation between two distance metrics (RJB and RRUP, RJB and REPI, etc.) based on the magnitude of the earthquake and the dip angle of the fault. A method to determine the variability due to the conversion between distance metrics have also been discussed. We compare the results with previous equations developed by various researchers and found a good fit. The equations developed in this paper can be directly applied in PSHA and is independent of the GMPEs used for seismic hazard calculations.

37. Some features of earthquake swarms

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We report results of a study of earthquake swarms in several tectonic environments. We studied durations. Volcanic swarms using local data have a mean duration of 5.5 days. For volcanic teleseismic data this increases to 9.6 days. This suggests that short swarms of small events are not seen teleseismically. For swarms on megathrusts, the mean duration is 11.5 days. When examining the magnitude difference between the largest and 2nd largest events, we note a gap at 0.7 M units. The samples are large (67 to 174 events), so this appears to be a robust result. We tested background seismicity rates before and after swarms. We used data on 174 megathrust swarms from Holtkamp and Brudzinski (2011), and examined periods of 3 months before swarm onsets and 3 months after swarm ends. We used circles with radius 30 km for M5 and 40 km for M6 largest events, centered on the swarm geographic centers. The results show that there are generally more events after swarms than before, suggesting that either swarms have ‚Äúaftershocks‚Äù or the ends are not well defined. To identify swarms in a MAR catalog, we selected events <20 km and <3 days of each other. This returned 758 sequences of two or more events. We plotted log10(cumulative number swarms) versus log10(number events/swarm) and observed a power law. Virtually all published swarms have >6 events. Choosing only those with >6 events gives a sample of 77 swarms, good for comparison with similar samples for other areas. However, the fact that the power law extends down to 2 events has several consequences. First, it implies (via self-similarity) there is no difference in process between 2, 3, 4 or any other number of events as a lower limit. Thus, the choice of what to call a swarm may be arbitrary.

38. Induced seismicity spikes during abrupt changes in injection and production rates in geothermal reservoirs

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Fluid injection in deep geothermal reservoirs can result in fluid pressure changes that are sufficiently high to induce seismicity. There are, however, some examples of seismic activity during a decrease in injection rates. Here, we analyze the strong seismic response due to abrupt maintenance shutdowns in the Blue Mountain geothermal reservoir in Nevada. We use continuous seismic monitoring data recorded by a local array of 8 stations from 2016 to 2020 for seismicity analysis. We identify episodes of coherent seismic energy excitation across the array using a network-detection algorithm and determine accurate phase-arrivals using an AIC picker applied to trimmed single-channel waveforms. The picks satisfying appropriate signal-to-noise ratios (SNR) were used for locating events with NonLinLoc and subsequent local magnitude calculation. The results show that seismicity is clustered around the geothermal reservoir with focal depths shallower than 1.5 km and magnitudes smaller than 2.5 The most striking observation is that seismicity rates spike during the operation shutdowns. Interestingly, seismic activity decreases as geothermal operations resume and reaches the background seismicity rate within a week. The sudden seismicity rate increase after shutdown may be a result of the unclamping of pre-stressed faults due to the release of poroelastic stress.

39. Lessons and preliminary data analysis of the first DAS experiment in Oklahoma

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Distributed acoustic sensing (DAS) is an emerging technology that converts existing fiber into densely spaced seismic channels. Previous studies have demonstrated high-resolution imaging of the wavefield. During summer 2021, we installed a Silixa interrogator at northwestern Oklahoma State University with collaboration from Oklahoma OneNet. We used a 50-km long Eastern segment and a 66-km long Western segment along a state highway. The wavefield is dominated by traffic signal at 5 Hz and above. Tap test signals are clearly identified when filtered below 5 Hz. Two earthquakes in the OGS catalog are identified through preliminary analysis. One earthquake is located within proximity (< 2 km) to the western segment and is recorded across the entire array. The other earthquake is located a bit further array and is only recorded along a shorter segment. In this presentation, we describe preliminary analysis of data recorded during the deployment, and lessons learned from the challenges encountered during the experiment.

40. A Workflow of Phase Picking for DAS

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Recent studies have demonstrated that Distributed Acoustic Sensing (DAS) is a promising means to monitor earthquakes with high resolution. Phase picking is a fundamental step to fully exploit the DAS's potential for earthquake monitoring. Current phase pickers, conventional or machine learning based, are designed with standalone seismometers in mind. However, DAS has a very different nature from conventional standalone seismometers, because of its unprecedented density and large data volume. Moreover, DAS recordings have only a single along-fiber component and are often contaminated by heavy traffic noise, making phase picking more difficult. Here we design a workflow to perform phase-picking in DAS. This workflow includes traffic noise reduction with FK filtering, short-term-average/long-term-average ratio (STA/LTA) to obtain initial picks, random sample consensus (RANSAC) to ensure pick consistency across the array, and finally neighbor-channel waveform cross-correlation to optimize P and S picking. This study aims to find reliable and generalizable methodologies to obtain accurate phase picks for DAS arrays.

41. Enhancing earthquake depth estimates using dense nodal arrays for the Cushing Fault Zone

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The significant rise in the seismicity in Oklahoma due to wastewater injection has reactivated several dormant fault zones in the region. The Cushing Fault Zone in central Oklahoma is one such location that has hosted several Mw>4 earthquakes. It is important to understand the hazards associated with the earthquakes in Cushing as the city hosts one of the largest oil storage facilities. Accurate earthquake location is a key parameter to understand seismic hazard and injection-induced earthquake triggering mechanism. Several earthquake relocation algorithms reduce the errors in lateral earthquake locations, but earthquake depth remains a challenge due to lack of accurate velocity model and tradeoffs during inversion. In 2019, we deployed a dense network of 130 5Hz 3-component Fairfield nodes covering the Cushing Fault Zone. High-resolution waveform observations revealed converted phases for three events that occurred within the Cushing fault zone. To model these phase conversions, we picked P and S arrivals on the 130 nodes and use Velest algorithm to simultaneously invert for earthquake location and a 1D local velocity model. Then, we perform forward travel time modeling to evaluate the effects of basement depth, earthquake depth, and velocity changes on the different phase arrivals. The forward modeling suggests that these converted phases are S-to-P conversion at the basement interface. We further compute synthetic seismograms using F-K algorithm to model the converted phase. We perform waveform cross-correlation to constrain the basement depth using delay times between S and S-P phases. We use delay times between both P and S, and P and S-P phases to constrain earthquake depths. The earthquake locations are better constrained by the new velocity model, and depth estimates are enhanced by the delay times from the converted phase.

42. Continental Divide: Precise delineation of the CEUS/WUS ground motion boundary in the Rocky Mountain region

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There are profound differences in crustal seismic attenuation and perhaps earthquake source parameters, – chief among them stress drop, – between the central and eastern United States (CEUS) and the western US (WUS). Implementation of ergodic ground motion models in the USGS National Seismic Hazard Model (NSHM) requires a defined boundary between the two regions, yet studies specifically designed to delineate the border are lacking; the current boundary is chiefly based on historical seismicity rates and geophysical proxies.
It envelops the Rio Grande Rift and southern Colorado Rockies in WUS before doubling back south and west to follow the Wasatch Front northward, which places the Colorado Plateau, northern Colorado Rockies, and Wyoming Craton in CEUS ground motion territory. Crustal (Lg) attenuation tomography is first used to assess the validity of this outline, and the Colorado Rockies are indeed separated from the Basin and Range by an arm of low attenuation that extends south from the Wyoming Craton through the Colorado Plateau interior. Tomograms, however, depict high attenuation throughout the Colorado Rockies, ending at the southern edge of the Wyoming Craton. Single-event and repeating-event amplitude vs. distance transects are then used to refine this boundary beyond tomographic resolution. Separately, empirical Green's functions are being developed to constrain stress drops for comparison of earthquakes in this nebulous Rocky Mountain region with sequences in the Basin and Range and with CEUS events. The combined spatial patterns of earthquake source parameters and crustal attenuation will help shape the boundary used in the 2023 NSHM.

43. A Retrospective, Machine-learning Assisted Analysis of Seismic Sequence Migrations in Jones, Oklahoma and Delineating Fault Structures

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We investigate fault geometries in central Oklahoma during the initiation of seismicity starting in 2010. To conduct this retrospective analysis, we utilize a Python package, easyQuake, that was recently developed by the Oklahoma Geological Survey, to augment their earthquake monitoring via pickers that are trained on millions of seismograms with neural network deep learning. The easyQuake software was used to investigate earthquake nucleation in the Jones, Oklahoma region as well as increase the catalog completeness and accuracy, by analyzing seismic data collected from 2009 to 2015. An early case study for large volume (~1 Mbbl/mo) wastewater injection inducing earthquakes at greater than 10 km distances (Keranen et al., 2014) was located near Jones, which is why it is the area of interest for this project. easyQuake outputs a catalog in QuakeML format, of which the associated metadata, such as pick times, can be read into the hypoDD format. We relocate the catalog with hypoDD to explore cluster and fault geometries, as well as earthquake sequence migration. With the hypoDD results, we utilize machine-learning techniques packaged in the Python machine-learning library scikit-learn for spatial clustering (e.g. DBSCAN) followed by linear regression (e.g. RANSAC) of those clusters to identify suspected fault segments. We identified 18 potential instances of seismically active segments in the Jones area and plan to expand the analysis to examine a wider range of the state‚Äôs fault segments and more current seismic sequences. The intent of this additional examination is to further investigate spatio-temporal patterns of ongoing clustered fault segments from the earlier catalog through the present. This type of work improves our understanding of the seismic hazard as it increases the database of known fault segments throughout the broader region.

44. Modern CENA aftershock sequences are smallish, a little lazy, and persistent

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Data from 157 central and eastern North America (CENA) earthquake sequences (1974-2021; mainshocks Mwe 3.5-5.84) are used in the largest known study, by a factor of ~13, of the statistical, spatial, and temporal characteristics of intraplate aftershock behavior. Background earthquake rate density and magnitude of completeness (i.e., #eventsM>=Mc km-2 yr-1) are determined for each cluster. Gutenberg-Richter and Omori parameters are determined, such that Rate(time)=10a+b(Mmain-Mc) time-p. The b-value hovers unremarkably near 1.0. CENA sequences may be initially an order of magnitude less productive, averaging 'a'=-2.78, to California's -1.80. Omori decay is much slower for CENA aftershocks than the California sequences used for nearly all declustering algorithms: The latter decay with a median value of time^-1.06, but CENA sequences fall of as time^-0.71 (median) to -0.58 (mean). A slant-stacked catalog of all 157 sequences similarly dies out as time^-0.77. Next, the post-mainshock rate density is calculated on a grid in epicentral distance and time for each cluster, and its already-determined background rate density subtracted to map aftershock rate density. Using their respective b-value and Mc, clusters can be rescaled and stacked to show where, when, and how many CENA aftershocks occur. Few aftershocks occur beyond 25 km from the epicenter, but rates do not return to pre-mainshock levels for a few months (Mmain 3.5-4.0, 128 days) to a few years (1583 days, Mmain 5.0-5.84). These empirical durations are about four times as long as in the current USGS declustering algorithm (from Gardner and Knopoff, 1974). CENA-specific declustering parameters could greatly impact hazard: Much of the region is devoid of known fault sources, so the declustered historical/instrumental hazard catalog is the sole meaningful source for decadal peak ground motions and thus controls hazard levels. CENA Earthquake Early Warning efforts could also benefit from region-specific Omori decay parameters.

45. Triggering of moderate-size earthquakes in Central-Eastern United States by External Stress Perturbations

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Recent studies have shown that microearthquakes and deep tectonic tremor along major plate boundary faults can be triggered/modulated by external stress perturbations. These include pore fluid variations and aseismic slip, dynamic stresses from large regional and distant earthquakes, solid earth tides, as well as annual hydrological loading cycles. However, it is still not clear whether similar triggering/modulating processes are linked to earthquakes occurring at intraplate regions and how they relate to the earthquake cycle. An improved understanding of such triggering behavior can help us better decipher the physical processes of earthquake nucleation and driving forces of intraplate seismicity. In this study, we systematically examine how external stress perturbations affect the occurrence of several moderate-size earthquakes in Central-Eastern United States, such as the 2014 M4.1 Edgefield, South Carolina, the 2018 M4.4 Decatur, Tennessee, and the 2020 M5.1 Sparta, North Carolina earthquakes. In each case, we compute tidal strains at the hypocenters and stresses resolved on the local fault planes, and compare with the timings of the mainshock and the seismicity before and after each mainshock. We also identify distant earthquakes that have produced more than 1KPa dynamic stresses at each mainshock, and explore their triggering relationship with local seismicity. Finally, if the event is close to large-volume of water bodies such as natural lakes or reservoirs, we compare timings of local mainshocks with water levels to explore their triggering relationship. We hope that our systematic examination can shed new insights on the triggering mechanism of intraplate seismicity. Updated results will be presented at the meeting.

46. Towards an Understanding of Seismogenesis and Seismic Hazard in Eastern North America: Progress and Challenges

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As the understanding of earthquake processes, seismotectonics, and seismic hazard in active plate boundary zones such as California continues to move forward, investigations of earthquakes and their effects in Central and Eastern North America (CENA) have long been hampered by fundamental data limitations. Decades of painstaking work have yielded important observational results, including recurrence rate estimates for the New Madrid Seismic Zone (NMSZ) (e.g. Tuttle et al., 2002), identification of persistent zones of deformation within and beyond the NMSZ (e.g., Guo et al., 2014), and better constraints on strain rates (e.g., Craig et al., 2014), as well as a number of hypotheses regarding seismogenesis (e.g. Costain, 1987; Anderson, 1986; Grollimund and Zoback, 2000; Ghosh et al. 2018). Ghosh et al. (2018) concluded that large-scale tectonic stresses and first-order lithospheric strength variations can account for intraplate CENA seismicity. Even now, however, more than a half century since the development of plate tectonics theory provided a framework to explain interplate earthquakes, the processes that control seismogenesis in intraplate regions remain enigmatic. What controls the spatial and temporal distribution of CENA seismicity, both natural and induced? Is strain release localized, or distributed in both space and time? How do the stress drops of CENA events compare to those of interplate earthquakes, and what causes the differences? In recent years, high-resolution seismic methods and large-N data-collection have been used to record and analyze aftershocks and induced seismicity in CENA (e.g., Davenport et al., 2015; Daniel et al., 2020; Cochran et al., 2020). Although low rates of natural seismicity pose a challenge even for these approaches, the advent of large-N experiments and methodologies, including distributed DAS sensors and machine learning, provide an opportunity to push down detection thresholds and location errors to improve understanding of seismogenesis in low strain-rate regions.