University of California, Berkeley

Berkeley Seismology Lab

2016-2017

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Welcome to the 2016-17 report from the UC Berkeley Seismology Lab. This year, we decided to try a new format and also to share this update with a much wider group of colleagues, alumni and friends. Let us know what you think—please email comments to me at rallen@berkeley.edu.

The Seismology Lab has a long history of working at the interface of fundamental and applied earthquake science. It is such a pleasure for me to walk into McCone Hall each morning to hear about the research conducted by our students, staff and faculty, and to see the ongoing instrument preparation of our field team. Each week, BSL staff work on expanding the geophysical networks that collect the critical data researchers need to study the Earth and the impacts of its dynamic processes on our society. I believe it is this synergy that leads to our graduate program being ranked #1 in seismology and geophysics by the US News and World Report.

Growing up in the UK, I did not have to worry about earthquakes. I focused on studying the structure and dynamics of the Earth and plate tectonic processes. As my career drew me ever further west, it was impossible not to engage with the critical challenges that earthquakes pose. The Berkeley Seismology Lab is unique in how it sustains the full spectrum of these research efforts. In these pages, you can read about the link between rainfall, drought and earthquake occurrence in California, about Berkeley's new global seismic network that harnesses over 250,000 smartphones around the world, about the structure of Cascadia and what it might tell us about plate tectonic forces, and about how unused fiber-optic cables could be turned into a seismic sensing network across the US, and beneath the oceans.

The ongoing effort to build a public earthquake early warning system — ShakeAlert — for California, Oregon, and Washington has also advanced over the last year and you will see this throughout this report. In February 2016, the White House hosted an earthquake resilience summit to promote the project and I had the privilege of speaking at this summit. Later in the year, State Senator Jerry Hill introduced legislation to further the effort in California and Governor Jerry Brown proposed a $10 million contribution to build the necessary infrastructure. This comes in addition to the $8.2 million Congress allocated to the project earlier in the year. Along with colleagues at the US Geological Survey, Caltech, and the Universities of Oregon and Washington, we are now rapidly expanding our capabilities to install new sensors and to speed the roll-out of the public warning system. I want to take this opportunity to thank our staff for their enthusiastic response to these new opportunities.

For all that the Berkeley Seismology Lab has to offer, I will always be deeply grateful to Barbara Romanowicz, who was the director for 20 years before me, and built the lab into the vibrant community that we enjoy today. Barbara formally retired from the university this last summer; however, I have not seen any change in her level of engagement with our students and community. While we celebrate her contributions at the time of her retirement, we look forward to the many that are still to come.

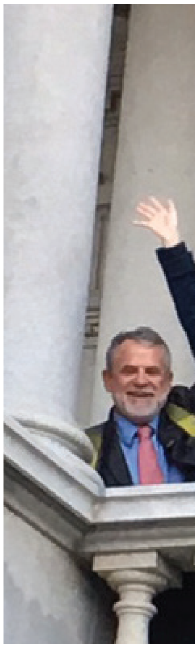
Finally, I invite you to visit our new website: earthquakes.berkeley.edu where you can learn more about our activities and find real-time maps of earthquakes. Our annual Lawson Lecture is a great opportunity to hear outstanding speakers talking about relevant earthquake topics each year. Also, our weekly BSL seminar is open to all. For those of you interested in supporting and enhancing the research experience of our graduate students, I encourage you to contribute to our student fund (http://earthquakes.berkeley.edu/seismo.support.html) which provides travel and research support directly to students.

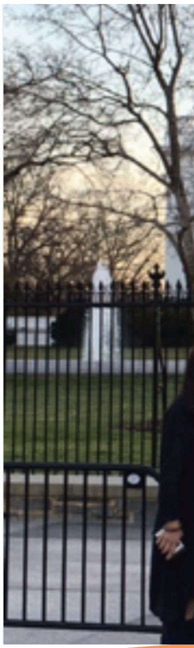
Thank you for your interest in the Berkeley Seismology Lab. Let us know what you think of the report, and let us know what you are up to. Next year, we hope to include alumni updates as well.

Best wishes,

Richard Allen
Director, Berkeley Seismology Lab
Professor and Chair, Dept. of Earth and Planetary Sciences

BSL AT THE WHITE HOUSE





BERKELEY SEISMOLOGY LAB WAS INVITED TO THE WHITE HOUSE EARTHQUAKE RESILIENCE SUMMIT

As part of a delegation representing the ShakeAlert Earthquake Early Warning project, the BSL was invited to the White House Earthquake Resilience Summit on February 2, 2016. The Earthquake Resiliency Summit was an opportunity to bring together stakeholders to discuss the state of earthquake early warning systems as well as to announce that Congress had appropriated $8.2M in the fiscal year budget to ShakeAlert. John Holdren, senior science advisor to then President Obama, opened the summit and was followed by Secretary of the Interior, Sally Jewell. Dr. Holdren and Sec. Jewell explained the value of earthquake early warning to the United States. BSL Director Richard Allen outlined the status of the ShakeAlert early warning system during a panel titled "The Promise of Earthquake Early Warning". BSL partner Bay Area Rapid Transit was represented by Director John McPartland, who discussed the necessity of earthquake early warning to train systems both in terms of protecting passengers and physical assets, and he went on to discuss the large role that a fully functioning train system could play in the overall post-recovery effort. U.S. Senator Jeff Merkley and U.S. Representatives Peter DeFazio, Adam Schiff and Derek Kilmer from the states of Oregon, California, and Washington, respectively, all spoke of their desire to see public warnings funded and implemented. The panel closed with Prof. John Vidale (U. Washington) laying out the implementation plan for how this large public safety infrastructure project was going to be launched. Finally, Robert Kirshner from the Gordon and Betty Moore Foundation announced new commitments to the project on behalf of various federal, state and private entities, including an additional $3.6M from the Moore Foundation itself. This important meeting of scientists, legislators, and other stakeholders provided a wonderful platform to communicate the possibilities that the early warning system brings to resiliency efforts to the West Coast of the United States.

Figure 1 (clockwise from top left) Paul Bodin (U Washington), Jennifer Strauss (BSL), Douglas Given (USGS), Michelle Moskowitz (UC Berkeley), Thomas Heaton (Caltech), Doug Toomey (U Oregon), and Richard Allen (BSL) overlooking the balcony. Allen and John Holdren, senior science advisor to President Obama, at the summit. Allen, Strauss, and Nancy Koch (Gordon and Betty Moore Foundation) at the summit. Moskowitz, Given, Heaton, Allen, Toomey, and Strauss in front of the White House.

RESEARCH GLIMPSES


William Hawley

William Hawley (PhD student) uses ocean bottom seismometers off the coast of the Pacific Northwest to study the subducting Juan de Fuca plate. The large array of seismometers on the ocean floor allows a seismologist like Hawley to study, for the first time, an oceanic tectonic plate in detail. Plate tectonics are a simple, but fundamental concept that unifies the Earth sciences, but the degree to which flow in the mantle drives the motion of tectonic plates remains a topic of debate. Hawley hopes that detailed observations of fast-moving oceanic plates will provide new insights into this decades-old problem. (Refer to Figure A)


Christopher Johnson

Christopher Johnson (PhD student) focuses on earthquake triggering; induced seismicity; seasonal loading and interseismic deformation using seismic data, geodetic data, and modeling tools. Johnson's goals are to measure stress changes in the crust, explore seismicity rate variations and migration patterns, and model crustal deformation in order to characterize the evolving state of stress on faults and the migration of fluids in the crust. Recent work characterizing the relationship between surface loading cycles and modulated seismicity provides a natural experiment to quantify crustal properties and further our knowledge of the state of stress in the lithosphere.


Michael Manga

Michael Manga (Professor) studies two aspects of induced seismicity. First: how does geological setting influence when and where earthquakes occur? Second: how do induced earthquakes cause changes in groundwater and surface water?


Avinash Nayak

Avinash Nayak (PhD student) works with Professor Douglas Dreger to investigate the source mechanisms of an exotic seismic sequence associated with the collapse of a brine cavern and formation of a sinkhole at the Napoleonville salt dome, Louisiana. They established a framework for automated detection, location, and moment tensor inversion of these events by incorporating wave propagation effects in a realistic 3D seismic medium. This medium contains a high velocity salt dome surrounded, and overlain, by low velocity sediments. Nayak also works with Dr. Taka'aki Taira on a rigorous analysis of the empirical Green's tensors estimated from ambient noise cross-correlations at the Geysers geothermal field, Northern California.

Alex Robson

Alex Robson (PhD student) pursues a new stochastic approach to understanding Earth's 1D elastic structure. He augments existing normal mode catalogues and uses a Markov chain Monte Carlo regime to produce a probabilistic model for the Earth, starting with the inner core.

Christine Ruhl

Christine Ruhl (postdoc) generated a catalog of rupture simulations for California in order to test the Geodetic Alarm System (G-larmS), the GNSS-based earthquake early warning algorithm developed in collaboration between the BSL and New Mexico Tech. Because G-larmS is rarely exercised by large earthquakes, simulations are crucial for assessing its performance. The catalog includes synthetic displacement waveforms for over 1,000 GPS stations across the western US for 4,050 ruptures built with realistic fault geometries in California. Ruhl is now using this catalog to test and develop G-larmS.

Kathryn Materna

Kathryn Materna (PhD student) studies the distribution of aseismic creep at the Mendocino Triple Junction using characteristically repeating earthquakes (CREs). These small earthquakes (magnitude 2-3) constrain the location and time-dependent creep history of faults that slip aseismically. Using this new dataset, Materna finds a narrow region of previously-unreported aseismic creep between Cape Mendocino and Punta Gorda. Furthermore, Materna interprets this region of creep to represent slip between the Pacific and Juan de Fuca plates. This region provides a unique opportunity to study an oceanic transform fault close to land and to probe the geologically youngest parts of the San Andreas fault system. (Refer to Figure B)

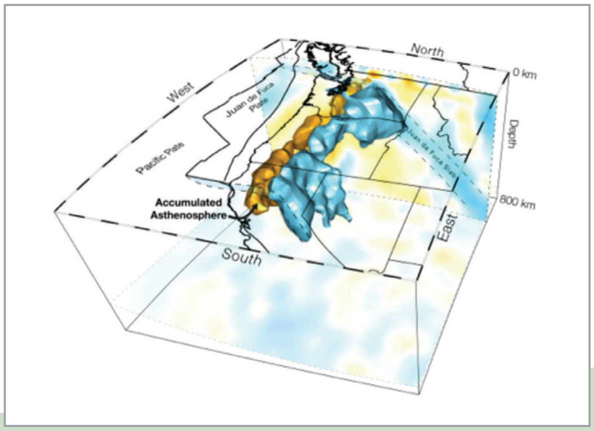


Figure A 3D rendering of the CASC16-P tomographic model. The blue indicates the subducting Juan de Fuca slab, where seismic waves travel more quickly than average. The orange, a region where seismic waves travel more slowly than average, has been interpreted as the accumulation of asthenospheric material. This weak material is not easily dragged down into the mantle with the subducting plate, and therefore it accumulates under the bend in the subducting plate.

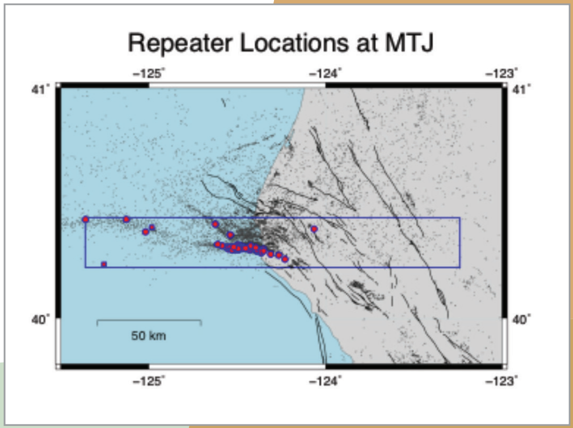


Figure B This figure shows the locations of characteristically repeating earthquakes detected at the Mendocino Triple Junction (magenta dots). Background seismicity is shown as black dots. Materna infers that the narrow region with most of the characteristically repeating earthquakes is aseismically creeping at a significant fraction of its total slip rate.

SEASONAL SURFACE LOADING MODULATES CALIFORNIA SEISMICITY

Christopher W. Johnson and Roland Bürgmann

In California, seasonal crustal stress variations result from all of the following: hydrospheric surface loads (groundwater, surface water, snow), pore pressure fluctuations, Earth and ocean tides, and temperature gradients. Many of these processes follow an annual periodic cycle and even deform the crust. Data from the Bay Area Regional Deformation and the Plate Boundary Observatory, the latter using continuous global positioning system (GPS), provide real-time measurements that allow detailed spatiotemporal characterization of the crustal deformation throughout California. Annual vertical and horizontal displacement amplitudes of GPS stations in the Sierra Nevada and California Coast Ranges produced by seasonal changes in water storage are on the order of 1-5 mm and 0.5-2 mm, respectively. Water loss due to drought conditions in recent years resulted in longer-term uplift of areas surrounding the Central Valley at rates of up to ~5 mm/yr. In contrast, stations in the Central Valley and other young sedimentary basins rise and fall with the groundwater level in the aquifer below due to the poroelastic response to changes in water head. Incorporating the GPS derived surface displacements into water storage models allows the development of time-series which details the surface loading cycles (Figure 1). These cycles, in turn, provide the framework for a in-depth investigation of the seasonal stress changes felt by active fault structures throughout the region.

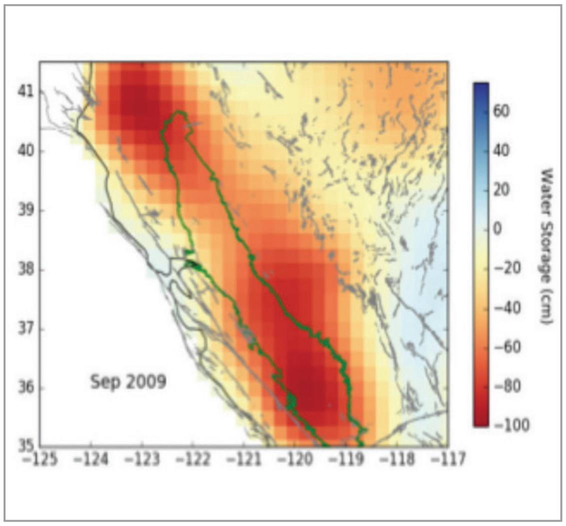


Figure 1 Snapshot of the inferred annual water storage relative to January 2006 shown for the late summer in 2009 and derived from the vertical displacements observed with the GPS network. The gray lines are the U.S. Geological Survey mapped fault traces and the green line defines the Central Valley. The melting snow pack throughout the year results in a net water storage deficit. The changes in surface loads deform the crust and result in seasonal stress changes on active faults in the region.

A number of studies suggest that seismicity correlating with seasonal forcing and periodicities in earthquake occurrence may represent a seismic response to seasonally varying stress conditions due to changes in surface loads. Other studies have suggested that micro-earthquakes in California follow an annual and semiannual cycle and even posit that factors such as annual temperature, atmospheric pressure, or hydrologic changes may strain the lithosphere and modulate earthquake rates. To explore the influence of seasonal loads on the central San Andreas Fault (SAF) and surrounding faults we model deformation at seismogenic depths for each of these structures using the time-series of surface water storage. The deformation is resolved as a shear and normal stress for the appropriate fault geometry and reported as the Coulomb failure stress which incorporated a coefficient of friction on the fault interface. The results indicate a peak-to-peak annual Coulomb stress change of ~1-2 kPa for the different faults in this region (Figure 2). To estimate the stress change at the time and location of each recorded earthquake requires additional knowledge of the failure planes at the time of rupture. We extend this analysis to include the earthquake focal mechanism geometry for all events between 2006-2015 and find positive stress changes occurring at the time of failure for many of the earthquakes (Figure 2).

Our study investigated additional sources of surface loading and stress in California, and our observations indicate that the hydrological cycle is the largest source of regional transient deformation recorded with the GPS network. We explore the phase and amplitude information of the periodic stress cycle with respect to the seismicity. The analysis finds a positive correlation with seasonal loading cycles and seismicity suggesting a 1-5kPa stress change is capable of modulating earthquakes. The results provide new insight to the fault mechanical properties and support the notion that earthquake populations are modulated at periods of natural hydrological loading cycles.

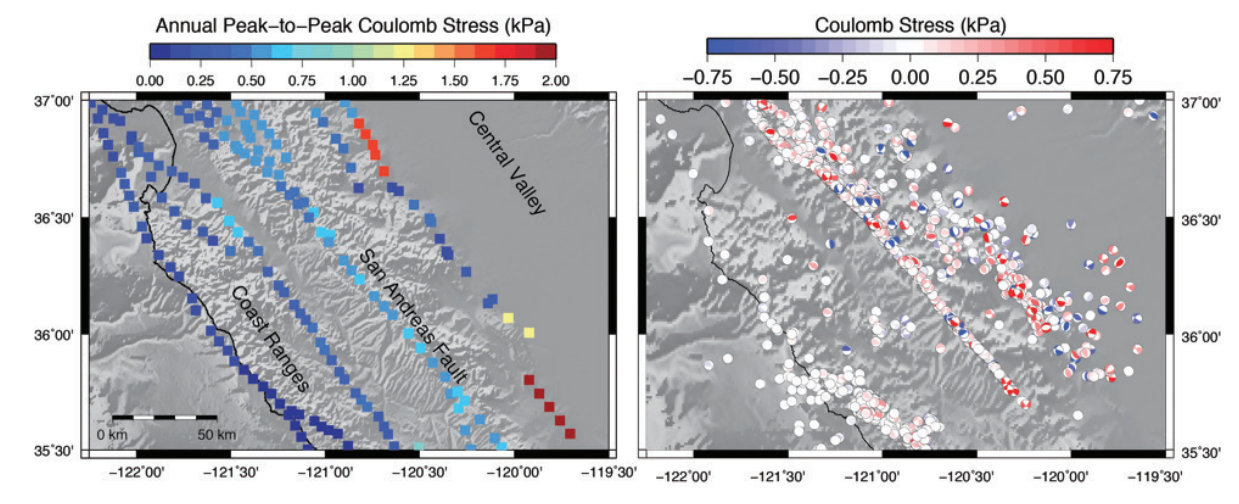


Figure 2 Seasonal Coulomb stress changes resolved on the through-going fault geometry (left) and the focal mechanism orientation (right) from the deformation caused by the annual hydrological load cycle. The stress resolved on the large-scale regional faults is the average annual peak-to-peak stress change experienced for that particular geometry. When investigating individual events the focal geometry is utilized to constrain the failure plane and compute the stress change at the time of failure. The panel on the right shows the Coulomb stress from hydrological loading on the favored fault plane of all 2006-2015 focal mechanisms at the time of rupture. The results indicate many earthquakes are occurring during periods of hydrological load conditions that favor slip (mechanisms in shades of red).

BSL AWARDS AND PROGRAMS

YOUNG SCIENTIST PRIZE

In 2016, the government of Japan awarded Taka'aki "Taka" Taira the Young Scientists' Prize. The award is bestowed by the Japanese Ministry of Education, Culture, Sports, Science and Technology which grants this commendation for science and technology on individuals under the age of 40 whose research exhibits uniqueness, highly advanced ability, and exceptional merit.

Taira has been a member of the Berkeley Seismology Lab since 2014 and currently holds the title of associate researcher. Taira has broad expertise in earthquake signals; high-frequency seismic signals; geodetic and seismic observations; and source study and sensor characterization. Many of Taira's key publications in peer-reviewed journals analyze repeating earthquakes. Overall, Taira has proven himself to be a highly valuable member of the BSL as he strives to enhance the quality of BSL data.

Taka Taira

CHARLES F. RICHTER EARLY CAREER AWARD

Diego Melgar Moctezuma, assistant geodetic researcher, was awarded the 2016 Charles F. Richter Early Career Award. The Richter Award honors an outstanding scientist's efforts to the goals of the Seismological Society of America in the early stage of his or her career. Already, Melgar has made significant contributions to the research areas of earthquake rupture, earthquake early warning, and tsunami modeling. Taking a keen interest in public outreach Melgar has also spoken on the significance and science of seismology to audiences in La Jolla, Berkeley and Marin County, California.

Diego Melgar

Melgar analyzes the source of earthquakes in order to improve seismologists' understanding of the physics of earthquake rupture. He contributes to the ShakeAlert earthquake early warning system in the West Coast by maintaining a 32 station real-time GPS network. Melgar is also developing rapid and efficient tsunami warning systems. In terms of publishing, Melgar has 27 articles in top-tier, peer-reviewed journals under his belt.

Before being appointed to his current researcher position, Melgar received his undergraduate degree at the National Autonomous University of Mexico (UNAM); his doctoral degree at the Scripps Institution of Oceanography, UC San Diego; and most recently completed a postdoc at UC Berkeley.

EXCHANGE PROGRAM

Clothilde Venereau is participating in an exchange program as a visiting undergraduate student at UC Berkeley. Originally from France, Venereau is studying at Imperial College in London where she is currently enrolled as a junior majoring in Geophysics. She became fascinated with seismology in her second year at Imperial College after taking a "Global Seismology" class. Venereau loves the fact that seismology can be applied to fundamental and diverse scientific questions such as the structure of the earth and geohazard management. Venereau decided to spend the year abroad at UC Berkeley because it was always her dream to study in California. In addition, Clothilde came to UC Berkeley to take advantage of the plethora of classes and to pursue in-depth research at the Berkeley Seismology Lab. Her all-time favorite geological place is the French Alps, but she has fallen in love with the geological wonderlands of Yosemite and the Grand Canyon here in the states. In conclusion, Venereau's time at UC Berkeley and at the BSL, more specifically, has been a busy year but probably the best and most exciting time of her life.

Clothilde Venereau

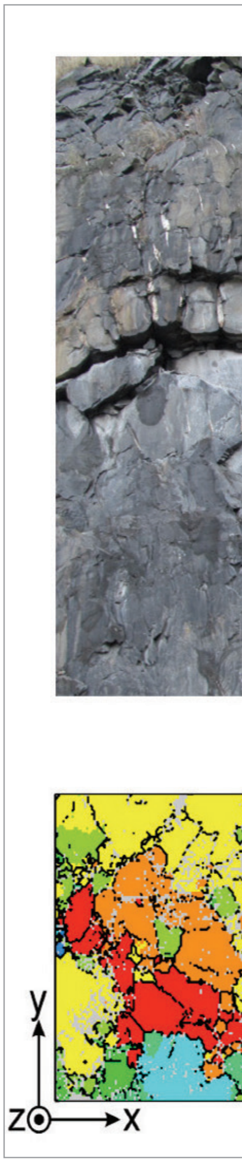
PALEOSTRESS AND EARTHQUAKES

Rudolph Wenk

In rocks that have been subjected to stress, such as in lateral faults or thrust faults, some of this stress is preserved by microscopic distortion in the crystal lattice of component minerals. This “paleostress” can now be recorded with X-ray diffraction patterns. The Laue microdiffraction beamline at the Advanced Light Source (ALS) of Lawrence Berkeley National Laboratory is providing entirely new possibilities. A synchrotron X-ray beam is focused to a 1 micron spot on the sample surface (Fig. 1). With colleagues at ALS, our graduate students and I have investigated samples of cataclasite from the SAFOD (San Andreas Fault Observatory at Depth) drill core at a depth of 2.7 km, where the drillhole intersects the fault. Lattice distortion of quartz in SAFOD samples corresponds to stresses of about 200 MPa which is over five times the resolution of the method and similar to stresses observed in quartz subjected to meteorite impact such as Vredefort (South Africa), represented in histograms of Figure 2. This is much higher than bulk rock strengths of fault gouge and was probably produced during a seismic event. These observations made headlines at ALS (http://newscenter.lbl.gov/2015/03/03/new-level-earthquake-understanding/), DOE, and even local newspapers. It establishes that minerals in rocks inherit information about stresses during deformation and can indeed be used as paleopiezometers, calling for systematic investigations of stress levels along fault zones.

These investigations were about paleostress magnitudes. More recently we started using the same methods to investigate stress directions and apply them to quartz from the original boudinage locality in Bastogne, Belgium. Boudinage is a well-known feature in metamorphic rocks where stiff layers segregate into blocks like a string of sausages (Fig. 3a). While boudinage in high grade metamorphism is generally attributed to extension, there have been suggestions that at the original boudinage locality it formed by compression and this is exactly what micro-X-ray diffraction confirmed: the compressional axes maintained in quartz are parallel to the boudinage layer (Fig. 3b,c).

This opens a whole new field in structural geology and tectonics: use microdiffraction at the micron scale to map stress and strain directions during tectonic deformation. Lately, we have applied our method to the exfoliation of Sierra Nevada granite focusing on an extraordinary site at Twain Harte where amazing exfoliation has been observed (https://www.youtube.com/watch?v=MWhmoW1PzwU) and is closely recorded by seismologists. Microfocus X-ray diffraction recods extensional stresses perpendicular to the granite surface. The X-ray results have been confirmed by neutron diffraction on bulk granite samples.



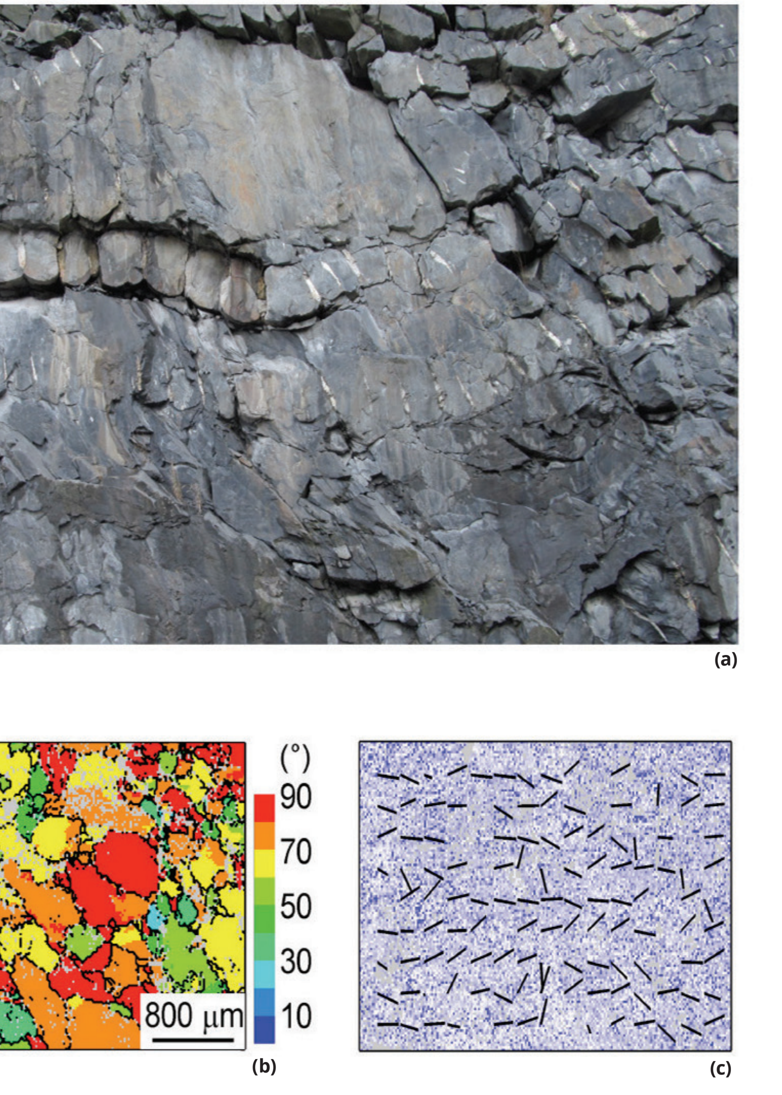


Figure 3 Boudinage from Bastogne (Belgian Ardennes). (a) Outcrop with a string of blocks resembling a chain of sausages, separated by quartz veins. (Width 2m). (b) Micro XRD scan over quartz vein. Colors indicate crystal orientation. (c) Corresponding map of the short axis of the strain tensor projected on the XY plane. Note that most of the compressional axes are parallel to the boudinage plane.

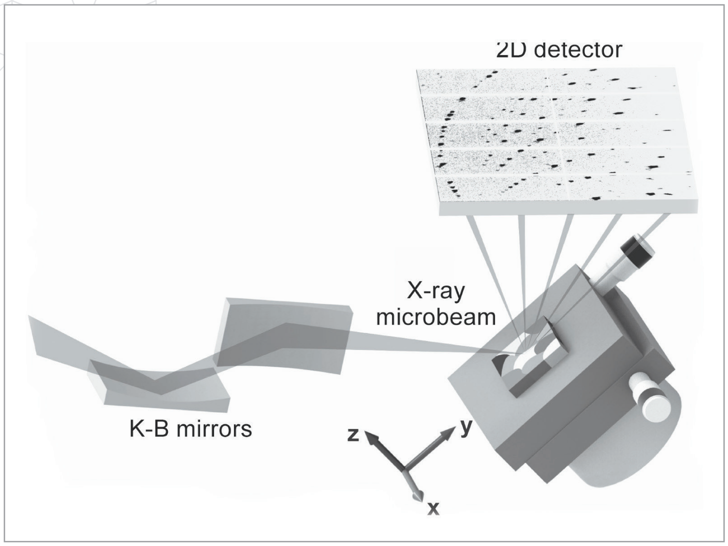


Figure 1 Geometry of X-ray Laue microdiffraction at beamline 12.3.2. of the Advanced Photon Source. An X-ray beam is focused on the sample surface and a Laue diffraction pattern is recorded by a 2D detector. The whole surface of the sample is scanned in 1 micron steps.

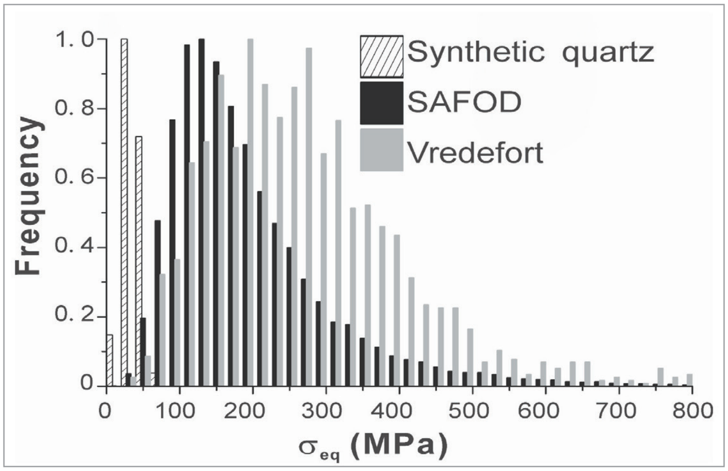


Figure 2 Histograms of preserved in lattice stress in quartz from synthetic quartz (used to establish experimental resolution), SAFOD cataclasite and quartz from the Vredefort meteorite impact site.

SEISMIC DATA FROM SMARTPHONES

MYSHAKE: BUILDING A GLOBAL SMARTPHONE SEISMIC NETWORK

Qingkai Kong, Richard Allen, Louis Schreier

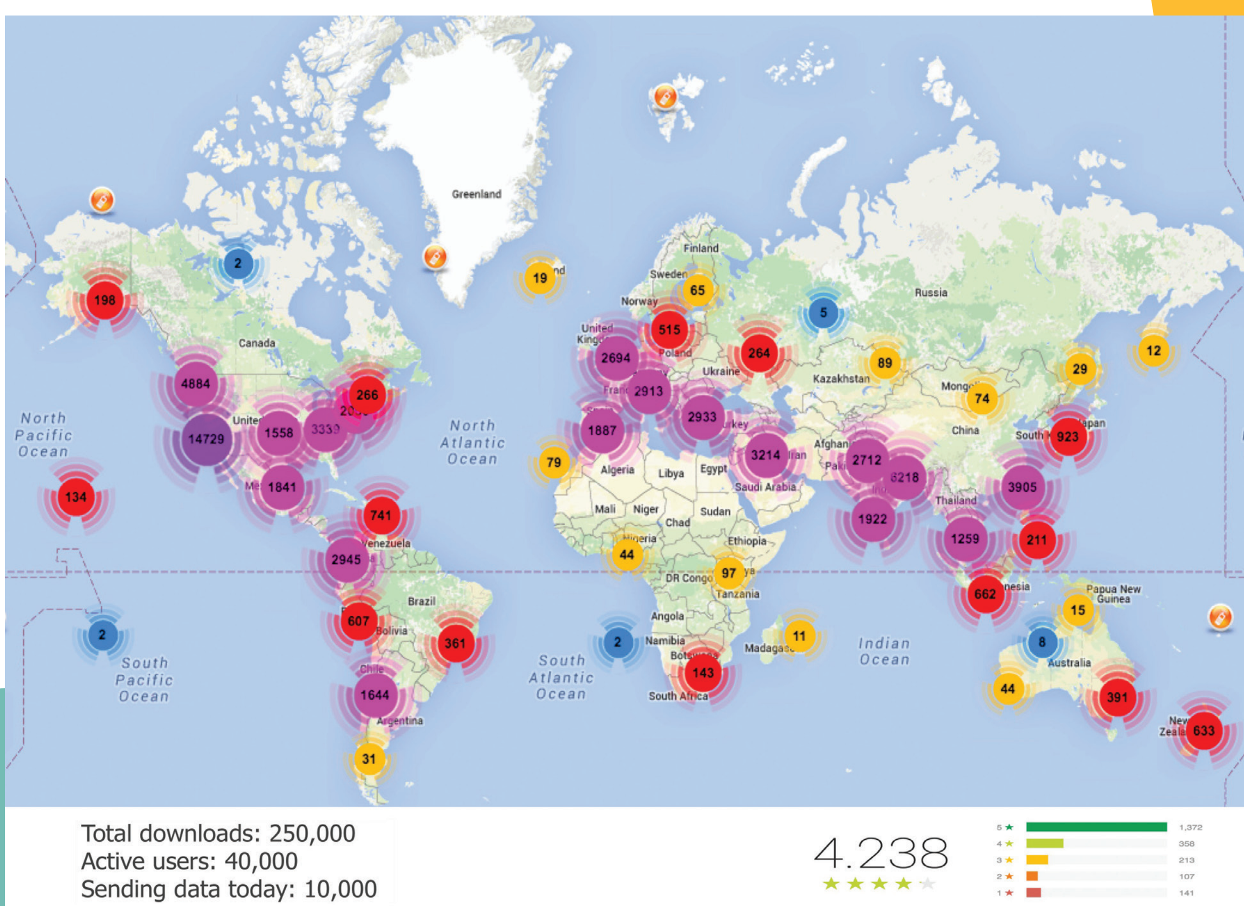
Every now and then, large earthquakes shake our nerves. Often, we wonder is there a way for us to increase the density of earthquake monitoring instruments at a fast and low-cost rate so that we can better monitor these devastating earthquakes. The answer is: YES! We are working on it— MyShake, a smartphone application developed by the Berkeley Seismological Laboratory and Deutsche Telekom Silicon Valley Innovation Center, is now approaching this goal by turning users' smartphones into portable seismometers. To turn your smartphone into a seismometer, just simply download the application, and run it in the background of your Android phone (for installation see http://myshake.berkeley.edu). After the application is installed, the accelerometer, which already is used to detect the change of the orientation of the phone, or your gesture when you play games on the phone, will monitor the movement of the phone. A smart algorithm running will decide if the motion of the phone is due to an earthquake or human activities. When the algorithm detects earthquake-like motion, it will send a message to our data center as well as a 5 min time history of the movement (this 5 min data will be sent when the phone is connected to power and to WiFi).

Data from this smartphone seismic network can be used in many ways to understand earthquakes better and to provide earthquake early warning alerts to the public. The basic principle of an earthquake early warning system is to detect an earthquake as it begins and send information about the inevitable shaking to people before the shaking arrives. These systems take advantage of the fact that electronic signals travel faster than seismic waves (speed of light vs speed of sound in rocks). Using a dense network of phones near the epicenter, we can detect the earthquake quickly and send out the alert to other users away from the epicenter. The amount of warning a user would get depends on how far the user is from the epicenter and the speed at which the system can send the message.

The more phones there are near the epicenter, the faster the detection would be and the larger the warning time. The data recorded by MyShake can also provide a detailed map of shaking intensities with a higher resolution than from traditional seismic stations, since we could have data from phones on each city block, rather than the more regional scale of current networks. This kind of information can be used to better tailor post-earthquake evaluation.

The MyShake application was released to the public on Feb 12th, 2016 and has been downloaded more than 250,000 times within one year. Within a very short amount of time, MyShake has spread to six continents with consumer smartphones, especially in regions where earthquake hazards are high. On a typical day, there are about 10,000 active MyShake users around the globe monitoring the occurrence of earthquakes. Over 500 earthquakes were recorded by at least one MyShake user since its launch on Feb 1st 2017. The MyShake seismic network recorded earthquakes with magnitude ranging from M2.5 to M7.8, with the deepest earthquake recorded so far in Japan with a depth of 350 km. Many recorded earthquakes are from California, Oklahoma, Alaska, and Hawaii in the U. S., and Chile, Ecuador, Italy, Morocco, Nepal, Japan, Taiwan, and others (see http://myshake.berkeley.edu). For smaller earthquakes, around M2.5, the recordings typically come from phones nearest the epicenter (within 5 km). But for a M5.0 earthquake, we can see the recordings from large distances, even around 200 km.

The MyShake global smartphone seismic network is still in its infancy. There are many challenges to address before it will issue accurate earthquake early warnings or apply to broad scientific applications. But the potential of this network is already clear. If you have any comments or suggestions, please contact us.



BSL RESEARCH AFFILIATES

MYSHAKE GLOBAL SEISMIC NETWORK AT MOBILE WORLD CONGRESS

On February 12, 2016, MyShake debuted on the Google Play store (see earlier in this report). To our wonderful surprise, the number of downloads kept climbing over that first weekend to greatly exceed our expectations. Very soon after the release, some of the team presented the app at the Mobile World Congress in Barcelona, Spain. Over 100,000 attendees were at this conference learning about the newest innovations in mobile devices. This allowed MyShake to extend its reach to a very different audience than most seismology applications are afforded. We continue to support our global seismic network, for which tens of thousands of citizen scientists on almost every continent provide data through their smartphones. The app is available on the Google Play store at: MyShake or on Twitter @MyShakeApp. Join the global seismic network.

EARTHQUAKE RESEARCH AFFILIATES PROGRAM

The BSL would like to extend our thanks to our Earthquake Research Affiliates: **Bay Area Rapid Transit, Pacific Gas & Electric** and **Deutsche Telekom Silicon Valley Innovation Center.**

Their support and commitment to furthering seismological research and connecting it to real-world applications is of great value to the lab. Many projects like our MyEEW app are only possible through the partnerships we have with our ERA members. MyEEW is a fully featured application that delivers ShakeAlert early warning alerts to people's cell phones. The app was well received at the White House summit and is in use by project scientists and our ERA partners. It is not yet available to the public.

This year, our annual ERA meeting included some journey mapping exercises between the ERA members, the ShakeAlert Joint Committee for Communication, Education, and Outreach, EEW beta testers, and other interested external parties. The experiences of the participants were recorded and are now being analyzed to inform policy and practical choices for messaging, thresholds, and other key portions of the communication effort.

Figure 3 MyEEW app made possible through the support of ERA members. This app delivers Shake-Alert warnings to smartphones.

Figure 2 Jennifer Strauss (External Relations Officer, Berkeley Seismology Lab) and Louis Schreier (VP of theDeutsche Telekom Silicon Valley Innovation Center) at the DT booth at Mobile World Congress Barcelona, Spain.

FIBER OPTIC SEISMOLOGY

Nate Lindsey, Shan Dou, and Jonathan Ajo-Franklin

Earthquake wavefields encode massive amounts of information on fault rupture, subsurface rock and soil properties, and near surface site response. Unfortunately, these datasets are aliased by even the densest seismic arrays. One explanation for this shortcoming is the three-point compromise between the experimental aperture, resolution, and cost. Recent advances in fiber optic Distributed Acoustics Sensing (DAS) enable measurement of the dynamic strain field acting on a small length of fiber optic cable (e.g., 10 meters). DAS uses laser interferometry to transform standard telecommunications fibers into ultra-dense seismic arrays (1 sensing site per linear meter) with precision that rivals sensitive broadband instruments.

Researchers at Lawrence Berkeley National Laboratory (LBNL) and UC Berkeley are leveraging DAS to answer questions in near surface hydrology, earthquake rupture process, permafrost thaw, site response, as well as monitoring challenges in CO2 sequestration and geothermal energy.

Last summer in Alaska, Shan Dou (BSL PhD, ’15; LBNL postdoc) and Nate Lindsey (BSL PhD student) recorded over 50 TB of continuous seismic data with a ~4000 linear-meter fiber optic DAS array, which was centered atop a permafrost controlled-thaw experiment. They hoped to study the thaw process and its critical role in arctic infrastructure hazard (Figure 1). Dou and Lindsey are part of a broad team that includes researchers at LBNL, UC Berkeley, the Army Corps of Engineers, Sandia National Laboratory, and Stanford University; they are funded by the U.S. Department of Defense to build advanced subsurface monitoring systems into the next generation of arctic installations, or “smart infrastructure” for cold climates.

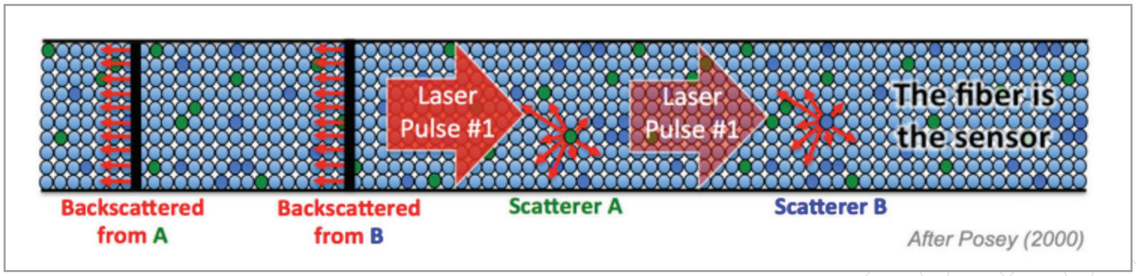


Figure 1 Concept illustration of Distributed Acoustic Sensing (DAS).

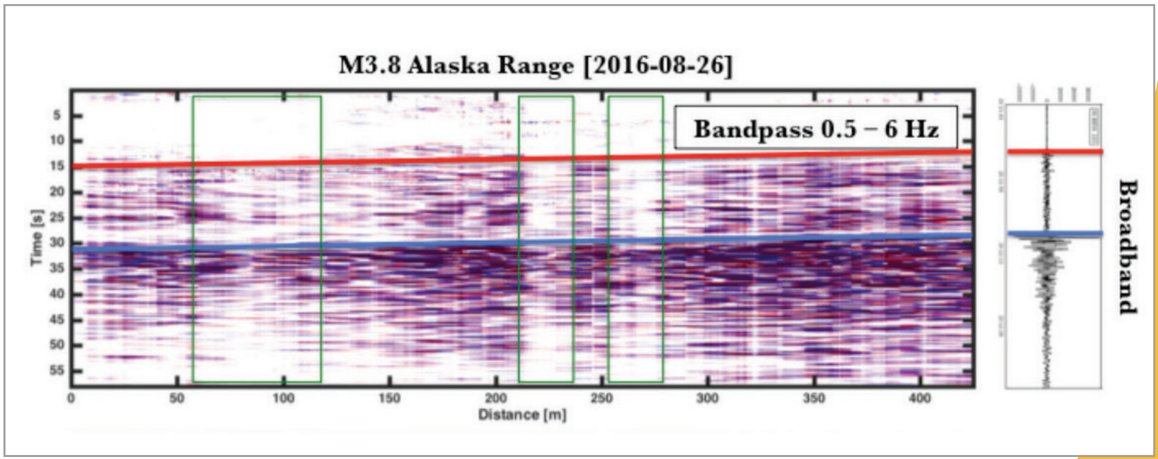


Figure 2 One minute recorded using 450m-long fiber optic cable buried along a road at 50cm in Fairbanks, Alaska.

While the primary aim of the permafrost warming fiber array was to use ambient noise to retrieve time-dependent thaw behavior as the subsurface was heated, the team also recorded several earthquakes from local, regional and teleseismic distances (Figure 2).

The potential to leverage pre-existing telecomm networks in urban and offshore areas represents a force multiplier for the seismic community. Consider the present call to develop offshore seismometer observatories, which provide the highest quality data from a single seafloor position. DAS provides the ideal dovetail -- millions of kilometers of low-cost offshore fiber capacity already buried beneath our oceans to expand ocean-bottom seismic apertures and enable array methodology from coast to trench.

This research is supported by the US Department of Defense through the Resource Conservation section of the Strategic Environmental Research and Development Program (SERDP) as grant RC-2437 (PI's J. Ajo-Franklin & A. Wagner). Nate Lindsey is supported through the National Science Foundation Graduate Research Fellowship Program.

To learn more about the permafrost warming experiment project please visit: https://www.facebook.com/serdpFiberPermafrost/

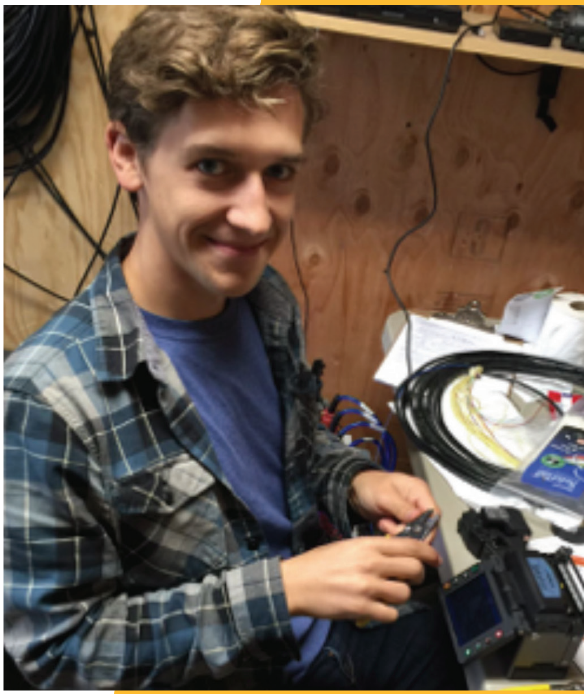


Figure 3 Nate Lindsey making an arc fusion splice.

BSL NETWORK ACTIVITIES

The BSL began collecting seismic data in April 1887, when seismographs were installed on campus at Student Observatory Hill and at the Astronomical Observatory being constructed on Mt. Hamilton. Since that time, providing earthquake information to government institutions and the general public, and making high quality data available to researchers have been high priorities for the operations team. Over time, we have transitioned through many generations of instrumentation, and our data are now used by researchers around the globe.

By the mid-1990s, the BSL's network of stations was converted to high-dynamic range digital broadband seismometers and co-located accelerometers. At a subset of the sites, data from real-time continuously-operating geodetic receivers were installed. Beginning from a very sparse network of three digital broadband stations distributed throughout Northern California in the 1880s, the BSL now operates 77 geophysical stations. Forty-five of them have broadband and strong motion sensors, at 33 there are continuously transmitted and recorded geodetic receivers, and at 28 there are boreholes with some combination of downhole geophones, accelerometers and broadband seismometers (see map).

HIGHLIGHTS FROM 2016

Tremorscope: The installation phase of the Tremorscope project, funded by the Moore Foundation, was finally completed in August 2016, with the deployment of downhole digital broadband seismometer/accelerometer packages at the stations TCAS, TSCS, and TRAY (See inset on map). Data from these stations and the initial four surface stations (TSCN, THIS, TRAM and TCHL) now support earthquake monitoring and improve the station coverage for the study of tectonic tremor. Recently, the BSL began continuous monitoring of the speed of earthquake waves in the Parkfield region. Changes in this parameter are associated with large earthquakes in the region, but may also be caused by other environmental factors such as extensive rainfall.

Oroville Dam: When the Oroville Dam was constructed in the 1960s, the phenomenon of seismicity induced by filling the reservoir behind a dam was already known. Thus, a seismic station was included to the north of the dam during construction. In June 1975, almost 6 years after the reservoir was first filled to capacity, moderate earthquakes started to occur south of Lake Oroville. The shocks culminated on August 1, 1975, in a magnitude 5.7 quake, which was felt across large parts of Northern California. In the following month, the seismicity died down again and it has been quiet since then. Although the cause of the quakes remains unclear, seismologists have long assumed that their occurrence might be related to the status of the reservoir. The recent California drought caused the water level in the reservoir to drop to historically low levels. Thus, when this year's heavy rains rapidly refilled the reservoir, the problems with the Oroville Dam's spillways made headlines and caused the evacuation of almost 190,000 nearby residents. Seismologists now wonder whether some nearby fault may again be brought to failure.

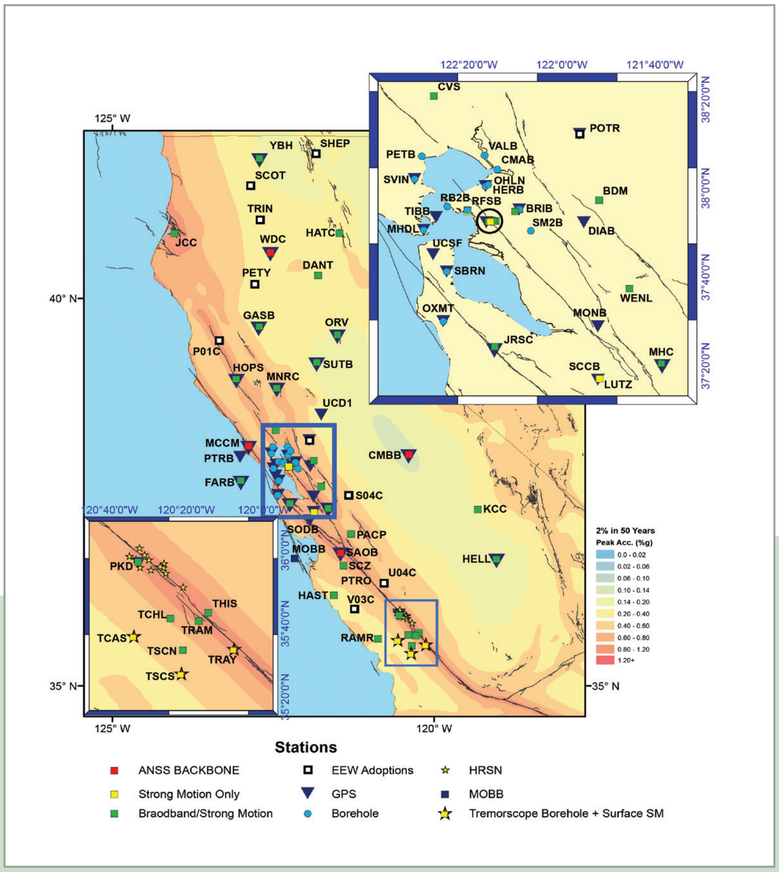
The BSL's continuous, high dynamic range, digital recordings from 1992 to the present form the basis for an ongoing search for previously unnoticed, tiny earthquakes that might have happened near the reservoir as water levels rose and dropped over the past 25 years. If this "crackling" in the rocks exists and tracks the water level, strong changes in its rate may be an indicator that something is brewing.

The Northern California Earthquake Data Center (NCEDC): Data from a variety of geophysical stations in Northern California are archived, curated, and available for download by the general public at the NCEDC. Data include those from seismic networks in the region, including the Northern California Seismic Network, operated by USGS Menlo Park (NCSN, Network Code NC), the Berkeley Digital Seismic Network operated by the BSL (BDSN, Network Code BK), the Parkfield High Resolution Seismic Network operated by the BSL (HRSN, Network Code BP), as well as from contributing networks operated by the California Geological Survey (Network Code CE), LBNL and Calpine in the Geysers (Network Code BG), Pacific Gas and Electric Company (Network Code PG), California Department of Water Resources (Network Code WR), and from other induced seismicity networks under the auspices of LBNL (Network Codes 3B, 4B, 5B). In addition, data are stored from continuous and campaign geodetic stations in Northern California.

Northern California Earthquake Catalog: The earthquake catalog for Northern California is available through the NCEDC. In particular, 2016 brought two catalog-related activities toward completion. Before 2003, two earthquake catalogs were collected for the region, one by USGS Menlo Park and one at the BSL. The two catalogs are now merged, though the combined dataset is not yet entered into the database, but is awaiting the resolution of several open questions. The second activity involved ComCat, the USGS Composite Catalog, which in the past few years was declared the authoritative source for earthquake information from all US regional networks. It began collecting data through submissions in 2013, but had no information for past earthquakes from the regional networks. Through the hard work of Pete Lombard, the BSL has finally completed the submission of Northern California's catalog from 1974 to the present. The submission includes all quakes of all sizes, including all event products except for ShakeMaps from our reporting region (state borders, Byerly-Gutenberg line). Several steps remain to be completed, and the BSL needs to resubmit events once the Berkeley and Menlo Park catalogs are entered. In addition, both catalogs contain a number of events outside our reporting boundaries, many of which may be of historical interest. The BSL is reviewing the quality of these events before submitting them. Further, no events from before 1974 were sent to ComCat. These events are also awaiting more review.

COMING IN 2017

The ShakeAlert Earthquake Early Warning System is rapidly moving toward a public rollout. The densification of the seismic monitoring network in Northern California is now a top priority to ensure robust performance of the system. In 2016, the BSL started to expand its networks to fulfill these needs and installed seismometers and data loggers at two sites in the region near the border with Oregon. An additional three sites are currently being installed in the area, and an additional five stations will be installed in the Coast Ranges along the San Andreas fault, all in 2017. These are just the initial steps toward the permitting, scouting and installation of monitoring equipment at ~80-90 additional stations that will be operated by the BSL to support ShakeAlert.



BSL COMINGS AND GOINGS

This year, as always, scientists from several different countries visited the Berkeley Seismology Lab to take advantage of face-to-face collaborations, opening up new research directions. Roland Bürgmann welcomed Gaspard Farge who refined the shallow creep pattern near the junction of Hayward and Calaveras Faults, in California, with UAVSAR and GPS data. Zhao Bin also worked with the Bürgmann group, analyzing crustal deformation in East Asia. Barbara Romanowicz's group hosted Sévan Adourian, who worked on synthetic tests to resolve a fat mantle plume located in the South Pacific. Richard Allen's group currently works with David Pedreira from Universidad de Oviedo, Spain, while Maria Theresa Ramirez Hernandez ended her one year visit with the group. BSL had the pleasure of two summer undergraduate visiting interns working with Taka'aki Taira on geothermal projects: Ashley Chabbar and Mathilde Wimez. The lab also has one undergraduate intern, Jonathan Rich, who continues to aid the lab in the development of outreach materials with Jennifer Strauss, Peggy Hellweg, and Noah Luna.

Roland Bürgmann's group welcomed three postdoctoral researchers this past year. Eric Lindsey studies tectonic deformation, interseismic processes, and fault geometry. Christopher Milliner focuses on geodetic imaging of fault deformation and Lian Xue researches earthquake physics using hydrology and geology. One postdoc completed his tenure in the Bürgmann group: Wenbin Xu contributed work on an improved geodetic source model for the Chamoli earthquake in India and crustal deformation of the North San Francisco Bay Area using InSAR and GPS.

Barbara Romanowicz's group welcomed two postdoctoral researchers and one graduate student this past year. Dan Frost's area of interest is deep earth structure, while Satish Maurya looks into Earth's hum using the amphibious array. Graduate student Li-Wei Chen began his studies on global seismology

Eric Lindsey

Christopher Milliner

Dan Frost

Satish Maurya

and tomography this year. The Romanowicz group also saw the graduation of Laura MacLean, with a master's degree in Global tomography.

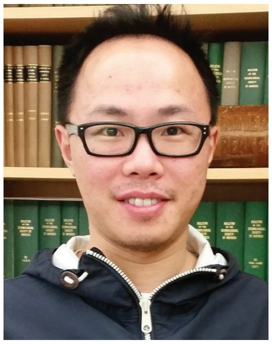
Doug Dreger's group expanded this year with the introduction of graduate student Nate Lindsey. Lindsey is pushing the limits of seismic monitoring by looking at fiber optic geophysics, ambient noise, and impacts of permafrost.

Richard Allen's group has also grown over the past year. Fabia Terra joined the lab as the new Earthquake Early Warning Project Manager. Diego Melgar ended his postdoc and transitioned to the role of Assistant Geodetic Researcher. Christine Ruhl joined the lab as a postdoc working with Richard Allen on the GlarmS geodetic algorithm. Allen also welcomed new postoc Asaf Inbal, who is using array physics to investigate the MyShake smartphone network. Clothilde Venereau is a visiting Imperial College student in the group analyzing Alaska shear-wave splitting. In December, Cheng Cheng completed his PhD with the Allen group.

All of the scientific research at the BSL is supported by administrative staff who keep the business side of things running, both for the Earth and Planetary Science Department and the lab. Andrew Jan supports Department Chair Richard Allen as his executive assistant. Rachel Kowalik is our new EPS Office Manager. Veronica Padilla took over managing the department when Judith Coyote retired after many years of dedicated service. Judith: you will be missed.

Nate Lindsey

Fabia Terra



Cheng Cheng

Christine Ruhl

Clothilde Venereau

Asaf Inbal

The Berkeley Seismology Lab conducts essential research on earthquakes and solid earth processes while collecting and delivering high quality geophysical data.

We provide robust and real-time earthquake and hazard information on Northern California earthquakes, in collaboration with our partners.

We enable the broad consumption of earthquake information by the general public while educating and training students at all levels.

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