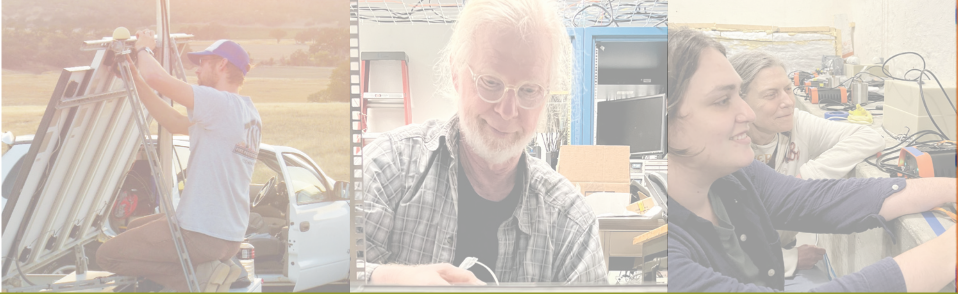
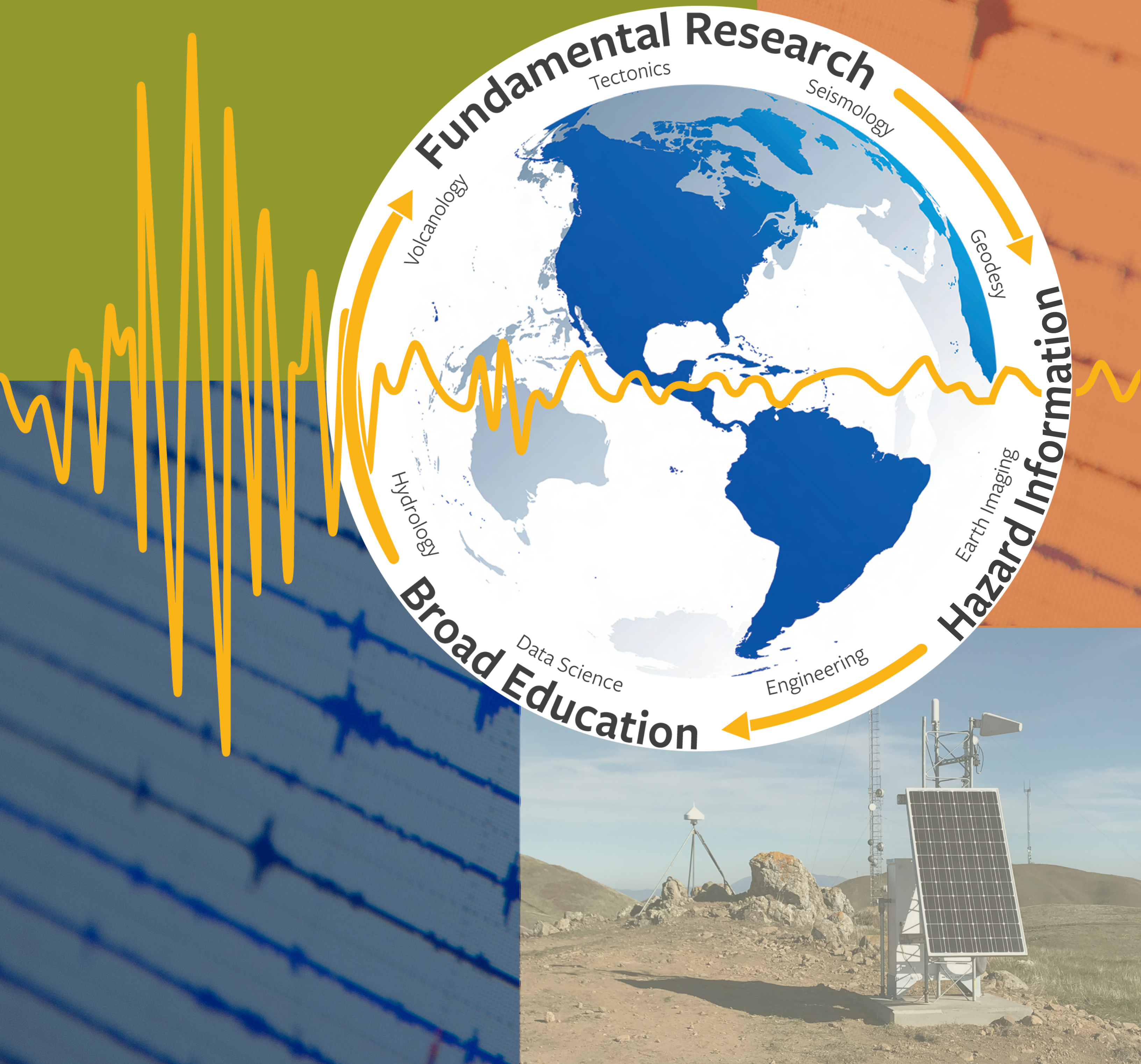


Berkeley Seismology Lab

Annual Report 2021-22



Contents

Director's Report

SPRING 2022

Welcome to the 2021-22 report from the UC Berkeley Seismology Lab (BSL). While it has been a challenging couple of years for everyone in many ways, I continue to be energized by the community we enjoy at the BSL. In these pages, you will learn of the many achievements of the staff, students, and faculty throughout the pandemic as our community has adapted time and time again. While we mostly worked remotely for the 2020-2021 academic year, we have returned to largely in-person activities for the last year, a transition much appreciated by all.

While our mode of operation has evolved, our central mission is of course unchanged: sound science, serving society. We cherish the breadth of our efforts across the fundamental science of earthquake processes and Earth structure, the development and operation of geophysical observation systems, and the applications of our data and science to hazard reduction, communication, and education of students, governments, institutions, and the public. The BSL continues to be an engine of ideas as the many disciplines listed above collide across the Berkeley campus.

This year's report starts at the center of the Earth, explodes onto the surface with geysers and nuclear tests, and touches communities around the world who now receive earthquake alerts. As the network of seismic stations around the world grows, we can make ever more detailed measurements of the Earth's internal structure. Researcher Dan Frost has been looking at the inner core and finds evidence that it is not growing symmetrically as the Earth cools, but is instead expanding more quickly in the eastern hemisphere. The 2019 Ridgecrest earthquakes in Southern California continue to provide a trove of data to constrain the physics of earthquakes and the mechanical properties of the Earth's crust and the faults dissecting California. Postdoc Kang Wang has been studying the deformation of Southern California following the Ridgecrest quakes and using it to map changes in crustal stress as it radiates away from the earthquakes and onto adjacent faults. You will also find "glimpses" of research into geysers, the Mendocino Fracture Zone, North Korean nuclear tests, slow earthquakes, rotational seismology, and smartphones.

The ongoing effort to maximize the potential of our ShakeAlert® earthquake early warning system to reduce the impact of future earthquakes continues with our partner universities, the California Office of Emergency Services, and the US Geological Survey. Statewide delivery of public alerts started in 2019 with the BSL's MyShake™ smartphone app. We are pleased to report that MyShake alert delivery was extended to the entire ShakeAlert region of California, Oregon, and Washington in late 2021. Thanks to the continuing research at the BSL, the EPIC algorithm continues to represent the gold standard in earthquake early warning, providing the first alert delivery to ShakeAlert users, and now being used in Canada, Israel, Chile, and South Korea. Across Northern California, the BSL's seismic and geodetic networks continue to rapidly expand in support of enhancing earthquake early warning and generating datasets for research efforts around the world. The BSL has added 55 seismic stations to ShakeAlert in the last three years as our field engineering team continues to work in Northern California throughout the pandemic.

The reach of the BSL's early warning efforts has also been extended globally in the last year through an industrial partnership. Google licensed the MyShake technology for integration into the Android™ ecosystem, and members of the BSL have joined the earthquake team at Google to build the Android Earthquake Alerts System (Android is a trademark of Google LLC). The Android system now detects earthquakes globally using smartphones and delivers alerts to an expanding list of countries.

The growth of the BSL activities has been supported by a growth in staff and our energetic students, postdocs, and faculty. I want to thank all the members of the BSL for their continuing efforts to further our mission and to the community that makes working at the BSL so much fun. I also want to thank Dr. Peggy Hellweg, who recently retired, for her contributions over many years as our operations manager—more about that later in this report. Also, welcome to Dr. Julien Marty, our new operations manager who joined us from the Comprehensive Nuclear-Test-Ban Treaty Organization in Vienna. We are also fortunate to have fantastic colleagues, partners, and friends at the US Geological Survey, the California Office of Emergency Services, and the other network-operating universities: Caltech and the Universities of Washington, Oregon, and Nevada.

To learn more about BSL activities, please visit our website http://earthquakes.berkeley.edu where you can also get real-time earthquake information. Download the MyShake app (free from the Apple App or Google Play stores), which provides earthquake information, safety tips, and early warning for magnitude 4.5 and above earthquakes in California, Oregon, and Washington. Our weekly BSL seminar is open to all, and is now provided in hybrid mode, meaning you can join us in person or over Zoom. You can ask any member of the BSL to be added to the seminar email list. Finally, if you are in a position to support the research efforts and enhance the experiences 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 BSL. I wish you a safe and productive year, and hope you enjoy perusing the pages of this report.

Best wishes,
Richard Allen
Director, Berkeley Seismology Lab
Class of 1954 Endowed Professor,
Dept. Earth & Planetary Science

MISSION STATEMENT

We conduct essential research on earthquakes and solid earth processes while collecting and delivering high quality geophysical data.

We provide robust earthquake and hazard information including real-time alerts to the public, in collaboration with our partners.

We enable the broad consumption of earthquake information by everyone while educating and training students at all levels and from all backgrounds.

By the Numbers

Postdocs
60+

Grad students
100+

MyShake
1.7M+
users

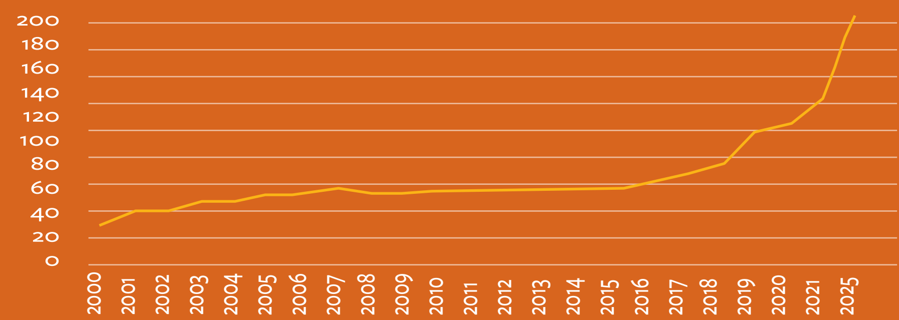
51
live alerts sent

100+
Visiting scholars

700+
Seminars

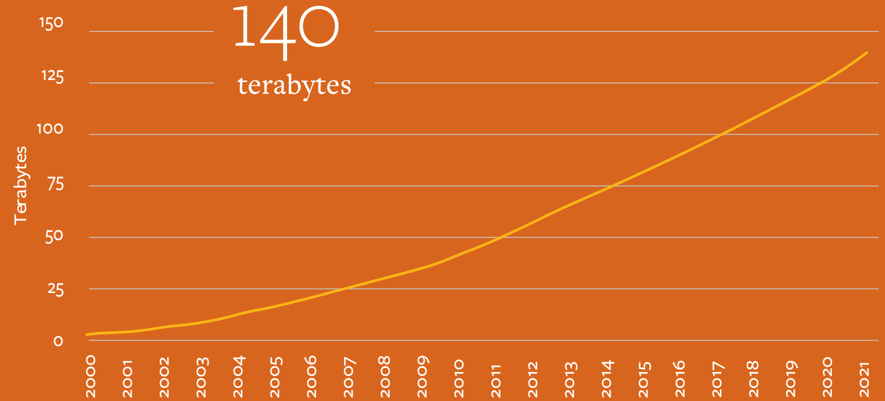
Operational stations
138

By 2025
210



Size of NCEDC data archive

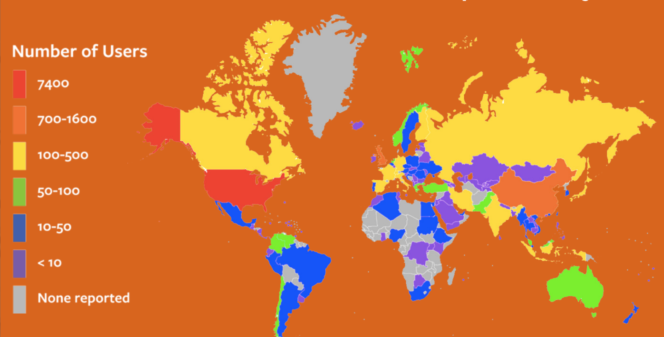
140
terabytes



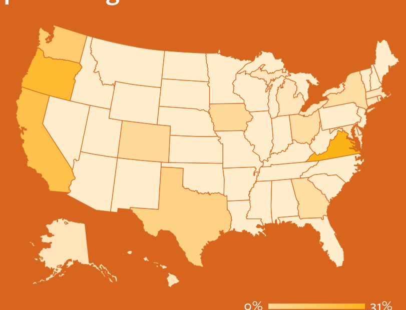
Active funding
$22M

Annual funding
$10M

Total number of NCEDC users per country



Distribution of NCEDC users as a percentage of total known US users



Research Highlights

The dynamic history of the inner core

Dan Frost

When earthquakes rattle us living on Earth's surface, they also reveal the life of our planet deep inside. Waves from earthquakes penetrate all the way through the Earth and can be detected on the other side of the planet at the global network of seismic monitoring stations, and like medical practitioners use ultrasound waves to look inside our bodies, seismologists use earthquake waves to look inside the Earth. Frost and others at the Berkeley Seismology Lab have recently made an exciting discovery about the history of our planet by measuring these deep seismic waves.

Since just after the turn of the century, seismologists, mineralogists, and astronomers supposed that the Earth was made of three main layers: the thin, rocky crust on which we stand, the solid rocky mantle, and a metallic core of mostly iron. At first it was thought that the core was entirely liquid. In 1936, the seismologist Inge Lehmann detected reflected seismic waves and deduced that in the very center of the Earth sits a solid inner core, inside the liquid iron outer core. The Earth's inner core is under some of the most extreme conditions on the planet, at nearly the same temperature as the surface of the sun and three million times atmospheric pressure. Beyond its existence, little is known about what it's made of and how it got there.

Buried 4000 miles beneath us, the Earth's inner core may sound remote, but we feel its effects through the Earth's magnetic field. As well as use for navigation, the field shields the Earth from charged particles of the Solar Wind, which causes the Auroras. The magnetic field is dynamic and always changing. On the surface, we measure the magnetic north pole moving through time: a slow westward rotation of the magnetic field, and the strength of the field changing. The Earth's magnetic field is generated by rapid movement of the hot liquid iron in the outer core. The fate of the magnetic field is linked to that of the inner core since, at the present day, the outer core is heated by the slow

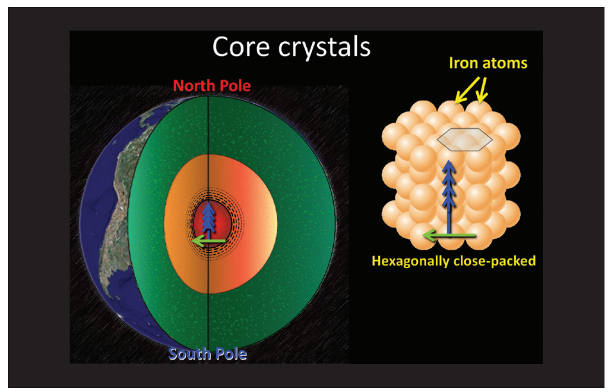


Figure 1. A cut-away of Earth's interior shows the solid iron inner core (red) slowly growing by freezing of the liquid iron outer core (orange). Seismic waves travel through the Earth's inner core faster between the north and south poles (blue arrows) than across the equator (green arrow). The researchers concluded that this difference in seismic wave speed with direction results from a preferred alignment of the crystals — hexagonally close packed iron-nickel alloys, which are themselves anisotropic — parallel with Earth's rotation axis. (Graphic by Daniel Frost.)

crystallization of the inner core as it freezes and grows by about 1 mm every year. The speed at which the inner core grows changes the amount of heat supplied to the outer core, and possibly the strength of the magnetic field (Figure 1).

To know the magnetic field, we must know the inner core. While the inner core is spherical in shape, about 40 years ago it was discovered not to be uniform. The speed of seismic waves traveling through it depends on the direction traveled, a feature known as anisotropy. Seismic waves traversing the inner core along a north-south path (near-parallel to the Earth's rotation axis) go faster than those propagating along an east-west path (in the plane of the equator). Recently, seismologists at the BSL measured the seismic waves traveling between rare earthquakes in the Arctic and new seismometers installed across Antarctica. These waves nearly travel through Earth's very center and can be used to measure how seismic anisotropy changes with depth. It was found that, unlike most properties in the Earth that increase with depth, the anisotropy was strongest not at Earth's center, but displaced 250 miles from the center in the direction of Brazil.

Inner-core seismic anisotropy carries information about the conditions at the time of iron freezing. This anisotropy has been attributed to alignment of iron crystals in specific directions, which themselves have different properties depending on the direction. Materials align due to flow: sticks floating in a river point in the direction that the water moves. The alignment of iron crystals in the inner core may be recording the direction of flow in the inner core. Moreover, like the thickness of the rings of a tree record the conditions of each growing season, the properties of the solid iron record the conditions at the time of freezing. Since the inner core grows from the center out, the deeper we look into the inner core the further back in time we see.

Explaining the pattern of seismic anisotropy in the inner core requires considering the whole Earth. The Earth's rotation is calculated to cause more heat to be lost to the outer core at the equator, leading to faster crystallization of the inner core. This would cause the inner core to grow oblate, like a squashed sphere, except that gravity keeps the inner core spherical. Researchers at the BSL used a computer simulation to test how gravity would cause the solid but soft inner core to flow from the equator up to the poles. In the simulation the flow aligned the iron crystals north-south creating anisotropy. We found that if the inner core grew slightly faster on the east side of the equator, under Indonesia, and slightly slower in the west, under Brazil, it would move the strongest anisotropy over into the western hemisphere, matching the seismic observations (Figure 2). By matching the observed seismic properties, the researchers were able to read the history of the inner core.

These questions remain: What does an asymmetrically growing inner core mean for the Earth? Most importantly, is there an impact on the magnetic field? If the inner core is growing faster in the east than the west then the outer core will move more on the east than the west, this may change the strength of the magnetic field and may be responsible for the changes that we measure on the surface. The other question is why would the inner core be growing faster on the east side than the west? The Earth's mantle is cooled by cold tectonic plates that dive down from Earth's surface into the mantle and reach the bottom of the mantle, which is also the top of the outer core. The mantle cools the outer core below it, and then the outer core cools the inner core. The inner core growth may be asymmetric because subducted tectonic plates at the bottom of the mantle are cooling the east side more than the west. These are all questions to tackle with further research.

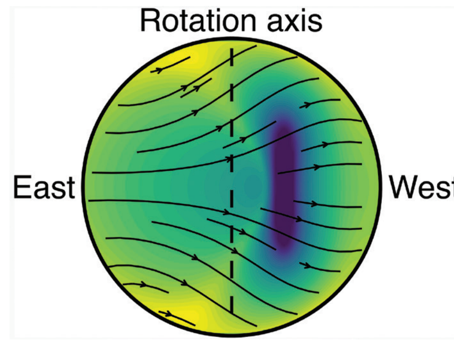


Figure 2. The new model proposes that Earth's inner core grows faster on its east side (left) than on its west. Gravity equalizes the asymmetric growth by pushing iron crystals toward the north and south poles (arrows). This tends to align the long axis of iron crystals along the planet's rotation axis (dashed line), explaining the different travel times for seismic waves through the inner core. (Graphic by Marine Lasbleis.)

To read more, go to https://www.nature.com/articles/s41561-021-00761-w

Ridgecrest earthquake-cycle deformation

Kang Wang

In July 2019, a remarkable sequence of strong earthquakes occurred near the town of Ridgecrest in Southern California. It was the third major seismic event (the last two being the 1992 Mw 7.3 Landers and the 1999 Mw 7.1 Hector Mine earthquakes) to occur in the Eastern California Shear Zone since the advent of satellite space geodesy in the 1980s. Using data from satellite radar interferometry (InSAR), nearby seismic networks, and Global Navigation Satellite System (GNSS), Wang and colleagues studied how the surface changed during and at the early stages of the sequence, as well as the rupture process.

Both the Mw 6.4 foreshock on July 4th and the Mw 7.1 mainshock on July 5th produced significant surface displacement. The maximum relative displacement reached over 5 meters along a segment near the Mw 7.1 mainshock epicenter. Inversion of the surface displacement and seismic data showed that the Mw 6.4 foreshock rupture started on a northwest-striking right-lateral fault, and then continued on a southwest-striking fault with mainly left-lateral slip. Although most moment release during the Mw 6.4 foreshock was along the southwest-striking fault, slip on the northwest-striking fault seems to have played a more important role in triggering the subsequent Mw 7.1 mainshock ~34 hours later.

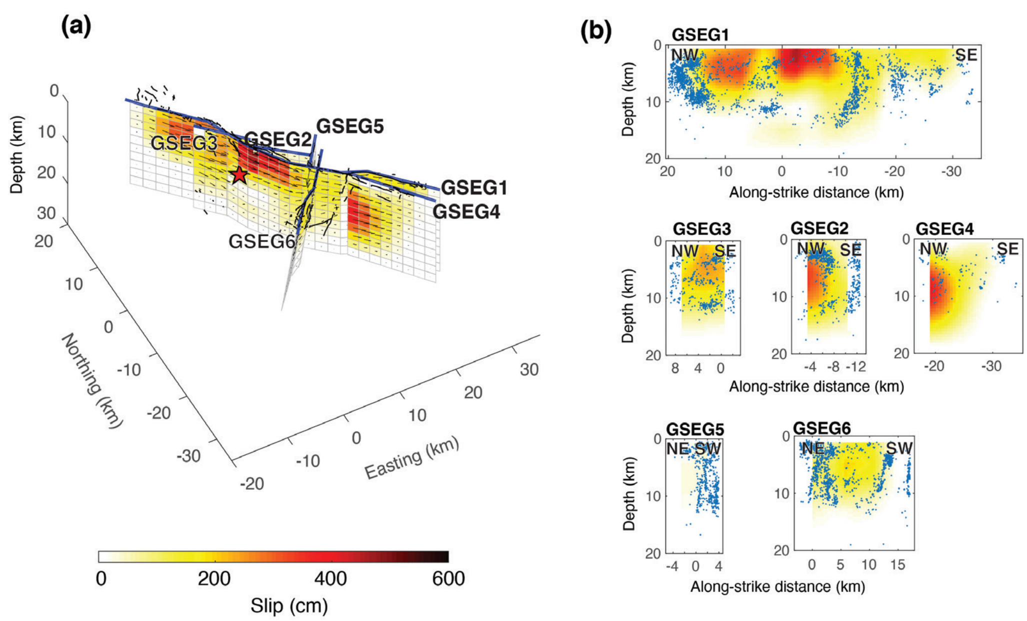


Figure 1. Coseismic slip model of the 2019 Ridgecrest earthquake sequence inverted from static GNSS and Sentinel-1 InSAR data. (a) 3D Slip distribution. Black lines represent the surface traces of the 2019 Ridgecrest rupture verified by the USGS field survey. (b) Slip distribution along average strike of the different fault segments. Dots are relocated aftershocks within 1 km from model surface trace during 5 days after the Mw 6.4 foreshock. The M 6.4 event started on the NW-striking fault segment GSEG2 but most of its slip occurred on GSEG6. The M 7.1 mainshock involved all the shown segments except for GSEG6.

The mainshock was characterized by dominantly right-lateral slip on a series of northwest-striking fault strands, including the one that likely activated during the onset of the Mw 6.1 foreshock (Figure 1). The models also revealed that the 2019 Ridgecrest earthquake produced significant stress changes on nearby fault networks, which included the Garlock fault segment immediately southwest of the 2019 mainshock rupture. This segment hosted a cluster of microseismicity soon after the mainshock and surface creep during or shortly after, and the Coulomb stress increased by up to 0.5 MPa. The researchers also compiled rupture models for the same event derived from different research groups. They showed that despite the good coverage of both geodetic and seismic observations, published coseismic slip models of this earthquake sequence are varied. This highlights the true uncertainties of earthquake rupture inversions and challenges the interpretation for underlying rupture processes. Wang and colleagues also studied the early surface changes directly after the rupture for this event. Using Sentinel-1 and CosmoSky-Med InSAR and GNSS observations, they obtained a robust surface displacement time series for ~1.5 years after the mainshock (Figure 2).

Preliminary analysis suggests that the observed surface movement results from at least three causes: continued motion on the fault, fluid motion within the rock, and viscous flow of the rock. Detailed modeling of these surface changes will help us better understand mechanical properties of the fault zone and the surrounding rocks, as well as the stress evolution and the associated seismic hazard on the surrounding fault systems.

To read more, go to: doi.org/10.1785/0220190299

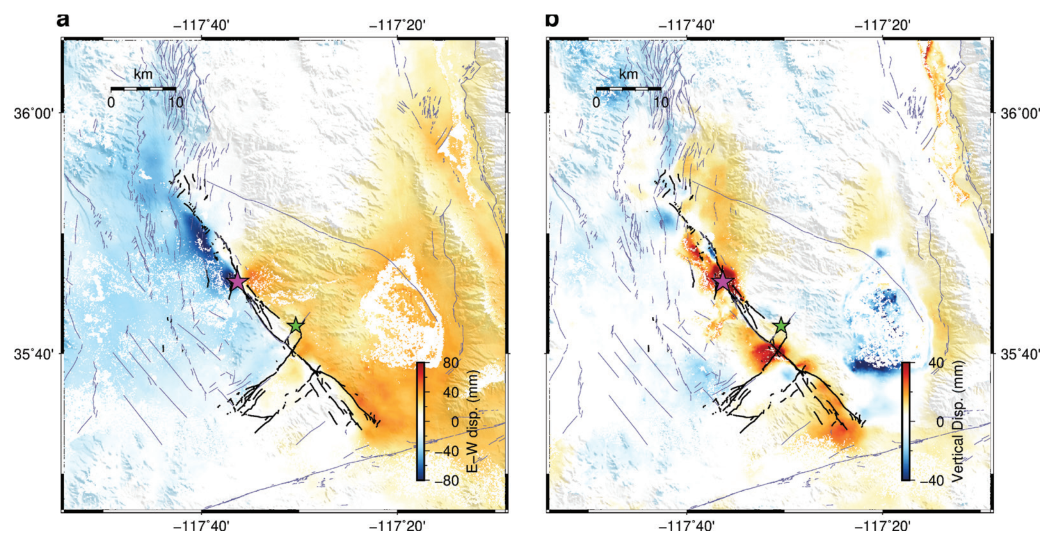
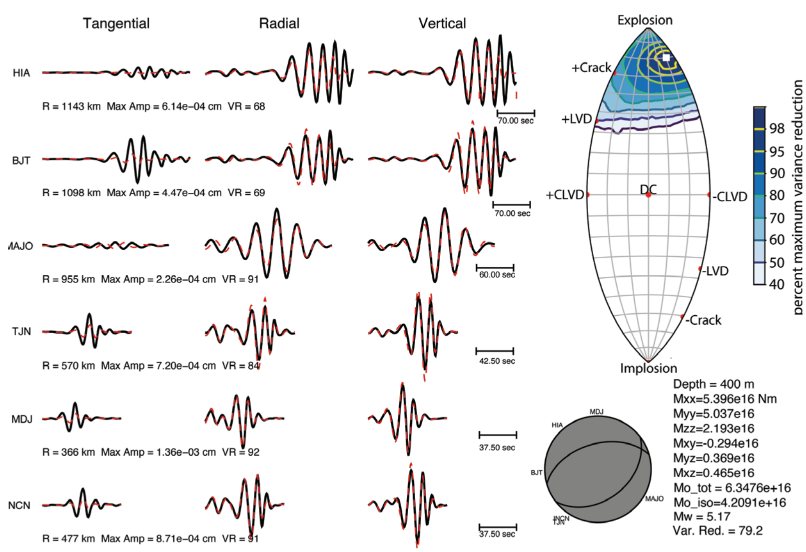


Figure 2. Postseismic deformation following the 2019 Ridgecrest earthquake sequence derived from Sentinel-1 InSAR observations of ~1.5 years after the mainshock. (a) East-West and (b) vertical displacements derived from the InSAR line-of-sight displacements. The green and magenta stars represent the epicenters of the Mw 6.4 foreshock and the Mw 7.1 mainshock respectively. The deformation pattern of eastward motion on the eastern side of the fault and westward motion on the western side of the fault in the near- to medium field can be well explained by afterslip. Vertical deformation in areas near the Mw 7.1 mainshock epicenter, the fault junction between the Mw 6.4 and the Mw 7.1 ruptures, as well as the rupture tips is consistent with model predictions of poroelastic rebound. GNSS-measured displacements in the far-field (not shown) are indicative of viscoelastic relaxation in the lower crust and upper mantle.

Joint waveform, deformation and first-motion source-type moment tensor inversion for the September 3, 2017 DPRK nuclear test

Rodrigo Chi, Douglas Dreger, Arthur Rodgers, and Avinash Nayak

On September 3, 2017, the Democratic People's Republic of Korea conducted a nuclear test, which was the largest man-made underground explosion ever carried out by this country. The test permanently moved the nearby surface up to 3.5 meters horizontally. The largest movement was seen on the steep slopes of Mt. Mantap, and the distribution of surface changes strongly correlate with the local landscape. Although regional seismic MT inversion methods have identified this event as an explosion, Chi and colleagues found that the best solution fails to fit the observed surface changes. Encouraged by this result, they developed a joint moment tensor inversion (extending Nayak and Dreger' previous work). They used the SW4 finite-difference code to develop Green's functions that take into account the severe local terrain. The figure below shows the fit to the waveform and surface data. These joint inversion results fit the data more cleanly, reduce uncertainties, and provide a stronger case that the event was an explosion.

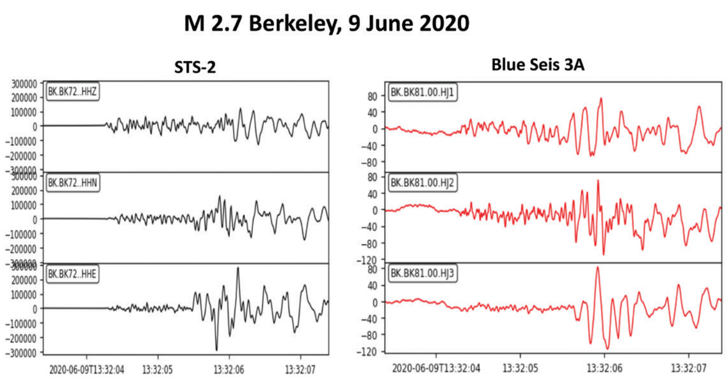


Source-Type moment tensor inversion for the September 3, 2017 DPRK nuclear test. Observed (black) and synthetic (red) seismograms illustrate good model fit. The source-type lune shows the best solution (white square) is located significantly off the deviatoric (CLVD-DC) line where earthquakes plot. The joint inversion results in smaller uncertainty that when the geodetic data is not utilized.

Rotational seismometer in the Byerly Vault

Peggy Hellweg and Horst Rademacher

The BSL tested an iXblue BlueSeis 3A rotational seismometer in the Byerly Vault, the BSL's seismic station above campus, between March 23 and June 18, 2020. This innovative instrument uses optical fiber sensors to measure roll, pitch and yaw, providing the ability to characterize seismic activity in all dimensions. The clearest and most interesting waveform occurred during a M2.7 earthquake on the Hayward Fault at a depth of 8 km (shown left). After testing, the BSL chose to purchase the instrument, which will give us the opportunity to investigate future events with larger rotational signals.

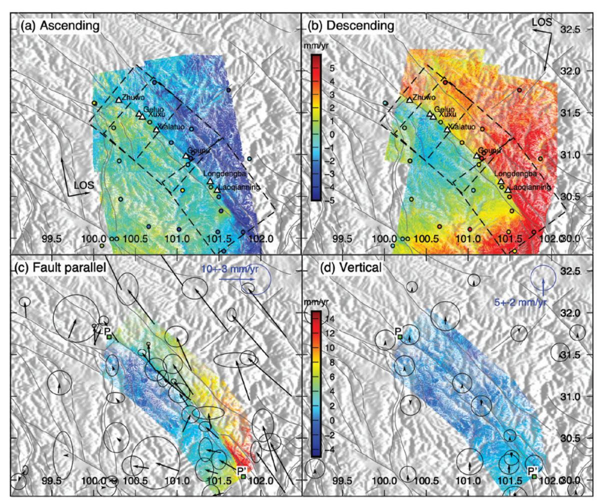


Ground velocity (left) and rotation rate (right).

Coupling distribution and earthquake potential along Xianshuihe fault

Yuexin Li

The Xianshuihe Fault is located at the eastern boundary of the Tibetan Plateau and is one of the most active faults in China associated with substantial seismic risk. By using the Interferometric Synthetic Aperture Radar (InSAR) technique, Li and colleagues were able to map the high-resolution surface changes occurring between seismic events along the 350-km-long Xianshuihe Fault from ~5 years of Sentinel-1 interferograms. The velocity maps reveal multiple creeping sections and the estimated surface creep rates show high along-strike variations. They further derived distributed shallow slip and coupling models along the fault. A time series analysis of near-surface slip in the Kangding earthquake rupture region shows a logarithmic decay pattern, indicating the higher slip rates in the southeast are associated with afterslip of the 2014 Kangding earthquake (shown right).

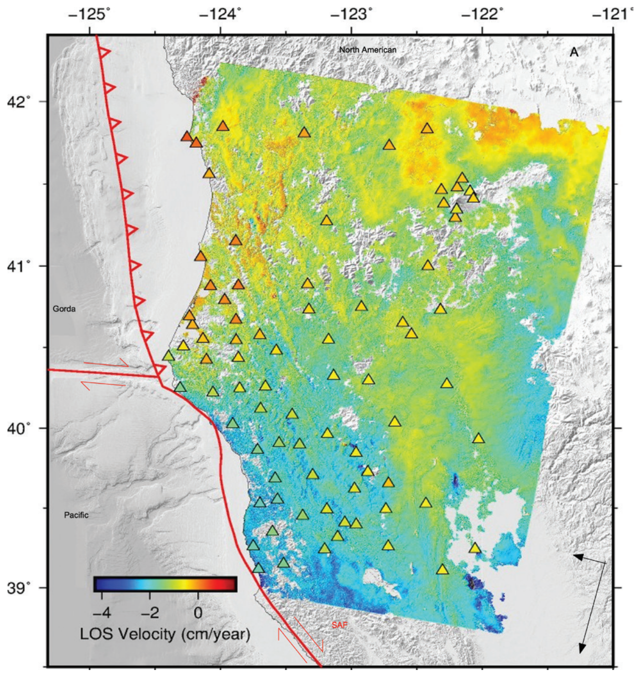


Average Line of Sight (LOS) velocity maps from ~5 years of Sentinel-1 InSAR along the Xianshuihe Fault, China. The shallow creep is visible from both the (a) ascending track 26 and (b) descending tracks 33 and 135. Slip on the fault is mainly fault parallel (c) and has an insignificant vertical component (d). Higher slip rates in the southeast are associated with afterslip of the 2014 Kangding earthquake.

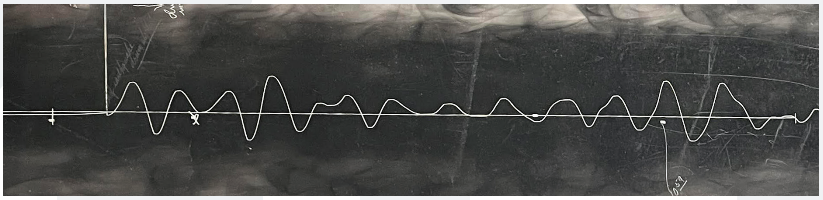
From satellite to serpentinite: Using space geodesy to determine mantle dynamics at the Mendocino Triple Junction

Danielle Lindsay

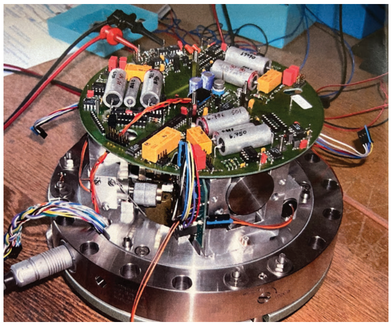
Surface uplift rates, the lithospheric structure, and the flow of mantle below are intrinsically linked. Vertical surface motions driven by dynamic geological processes can be broken down into isostatic (gravitational equilibrium) and dynamic components sensitive to crustal thickness and mantle convection. Small-scale mantle convection has been attributed to vertical surface motions correlated at distances of up to a few hundred kilometers. This project focuses on using space-geodetic observations of vertical velocities from InSAR and GPS to determine contributions from mantle dynamics at the Mendocino Triple Junction (MTJ), Northern California. Lindsay et al asked: What are the driving forces controlling active uplift around the MTJ? By better characterizing the dynamics between Earth's interior and present-day surface changes, we can improve our capability to assess and respond to natural hazards. In approaching this problem with InSAR, they asked: What do present-day surface changes happening between earthquake events tell us about the long-term driving forces responsible for building landscape and stimulating earthquake cycles of faults in the MTJ region?



Mean surface velocity field from a stack of ~100 ALOS-2 interferograms show agreement with GPS (negative line-of-sight (LOS) velocity is motion away from satellite). Missing signal corresponds to regions with agriculture or seasonal snow cover.



A smoked paper seismograph of an event at Pleasant Valley, Nevada, 1915. From the BSL archives.

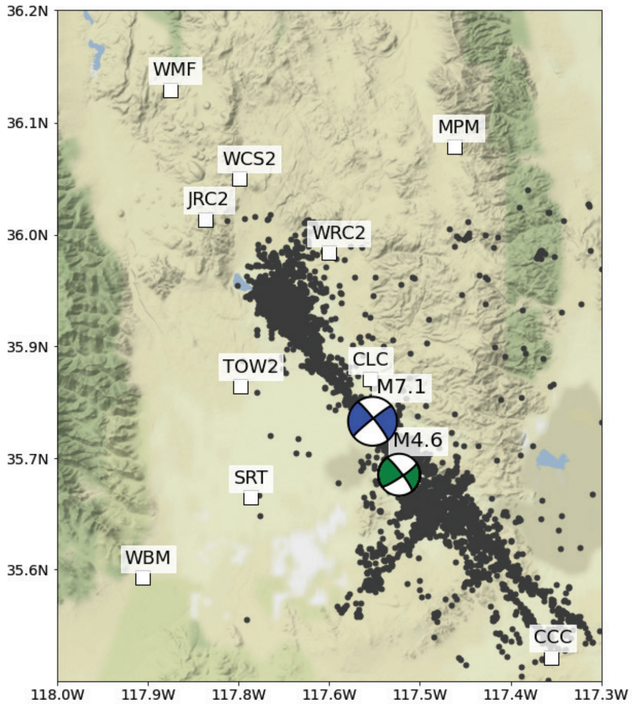


The assembly of a Streckeisen STS-2 broadband seismometer.

Finite source modeling of aftershocks

José Magana, Douglas Dreger, and Taka'aki Taira

Undergraduate student Magana worked with Dreger and Taira on finite source analysis. Their latest work analyzes the Ridgecrest Aftershock sequence of 2019, where they use Empirical Green's Functions (EGF) and seismic Moment Rate Function (MRF) inversion to obtain a description of how fault slip varies over space and time, an estimate of the stress drops, and a determination of which rupture plane caused the event. Magana's work has been included in the SCEC Ridgecrest Stress Drop Community Comparison Study to understand the scaling of earthquake source processes.



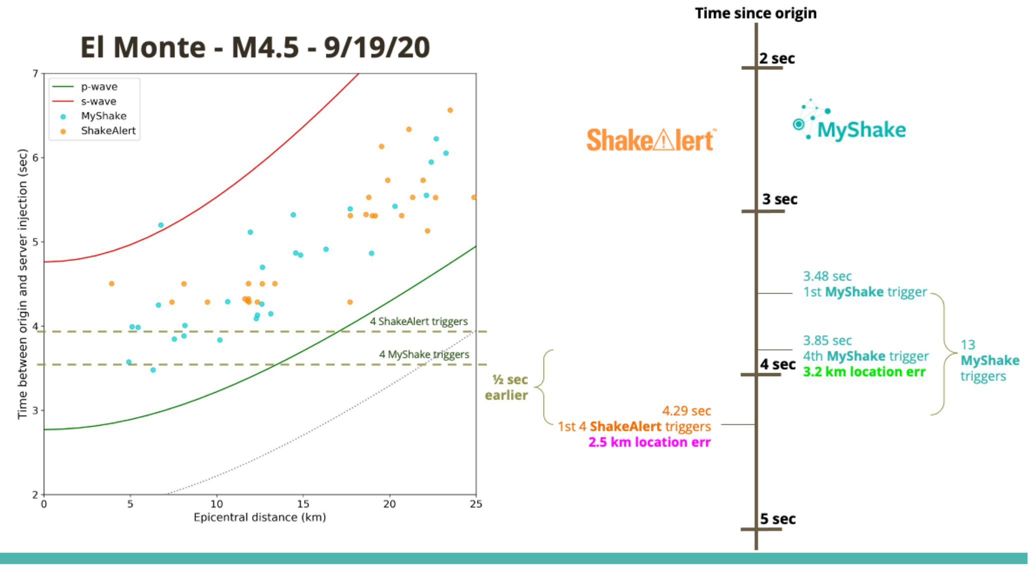
Location map of the Ridgecrest sequence, nearby broadband stations in the study area located with white squares. Image shows the location of one of the Mw 4.6 aftershock from July 04, 2019, and its focal mechanism (green) along with the focal mechanism of the Mw 7.1 mainshock (blue). Four months of aftershocks (gray dots) from the SCSN catalog within 50 km of the mainshock epicenter show complexity of the ruptured faults.

PSES

Making ShakeAlert faster

Sarina Patel

Patel works on incorporating crowd-sourced data to improve earthquake early warning. The MyShake app, which delivers ShakeAlert-powered alerts to users in California, Oregon, and Washington, also contains the capability to collect and transmit small amounts of accelerometer data from user's phones in real time. Similar in content to the data streamed from traditional seismometers into the ShakeAlert system, these MyShake data could densify the station network used by ShakeAlert for earthquake detection and parameter calculations, including determining epicentral location and magnitude. Preliminary assessments suggest the incorporation of smartphone data could speed the initial event detection by a half a second or more in populated areas — a significant change for a system where latencies are timed in milliseconds.



Left: a distance vs time plot depicting the arrival of earthquake-motion triggers for the traditional seismic network (orange) and MyShake phones (turquoise) at a centralized computer for a small earthquake near Los Angeles in Sept 2020. ShakeAlert requires four stations to trigger to confirm that an event is in progress and may warrant an alert. When MyShake triggers are added, it can decrease the total elapsed time before four triggers have arrived. Right: a timeline of alert estimations. When a comparable number of MyShake triggers contribute to the initial alert estimate as ShakeAlert triggers, we are able to speed detection by a half second.

Steamboat Geyser

Mara Reed

After 34 years of sporadic activity, the world's tallest geyser, Steamboat Geyser in Yellowstone National Park, began regularly erupting in 2018. Mara's study investigated possible reasons for the reactivation and factors that influence the time between its eruptions. Prior to 2018, the local geyser basin experienced uplift, a slight increase in radiant temperature (inferred from satellite data), and increased regional seismicity, which

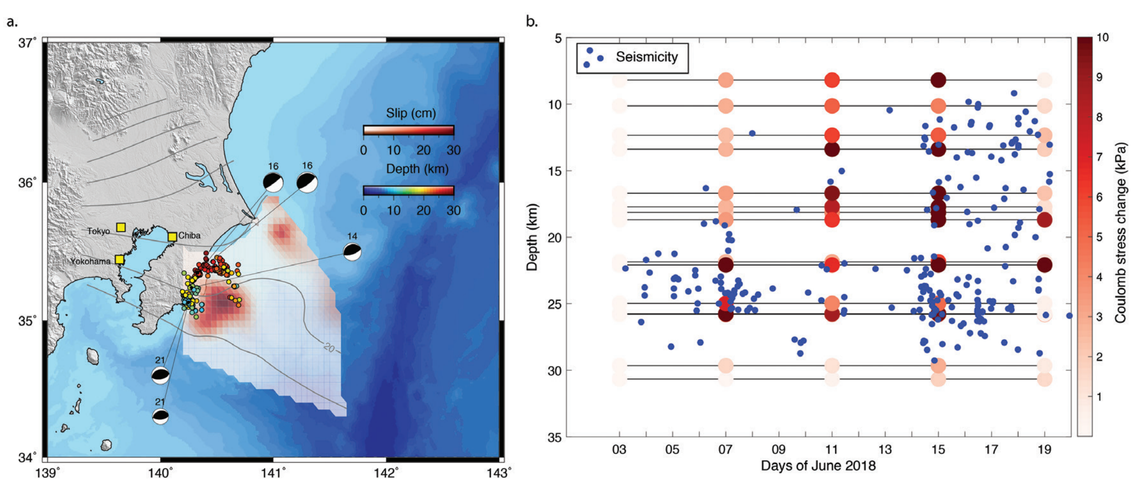
Steamboat Geyser, Yellowstone National Park.

may suggest a link between the reactivation and magmatic processes. However, other observations contradict this interpretation, and the reason for reactivation remains unclear. Using data from geysers worldwide, Mara and colleagues identified a correlation between eruption height and inferred depth to the shallow water supply: providing the simple explanation that Steamboat is the tallest because water is stored deeper there than at other geysers, which means more energy is available to drive eruptions.

Modeling the updip migration of the 2018 Boso slow slip event with geodesy and seismicity observations

Baptiste Rousset, Asaf Inbal, Roland Bürgmann, Naoki Uchida, Anne Socquet, Lou Marill, Takanori Matsuzawa, and Takeshi Kimura

Researchers from the US, Japan, Israel, and France collaborated under an NSF proposal to study a shallow slow slip event below the Boso Peninsula, Japan in June 2018. Slow-slip events on the Sagami trough occur every ~5 years. They are always accompanied by swarms of Mw 1-5 earthquakes on their northern and western flanks. During the two-week-long June 2018 event, both geodetic slip inversions and double-difference relocated seismicity indicate updip migrations, at a speed of a few km/day. The migrating transient event is modeled as a single process (reconciling both geodetic and seismicity observations). This research shows that the nucleation of the seismic events coincides with the timing of Coulomb stress increases caused by the slow slip event, with amplitudes as large as 10 kPa.

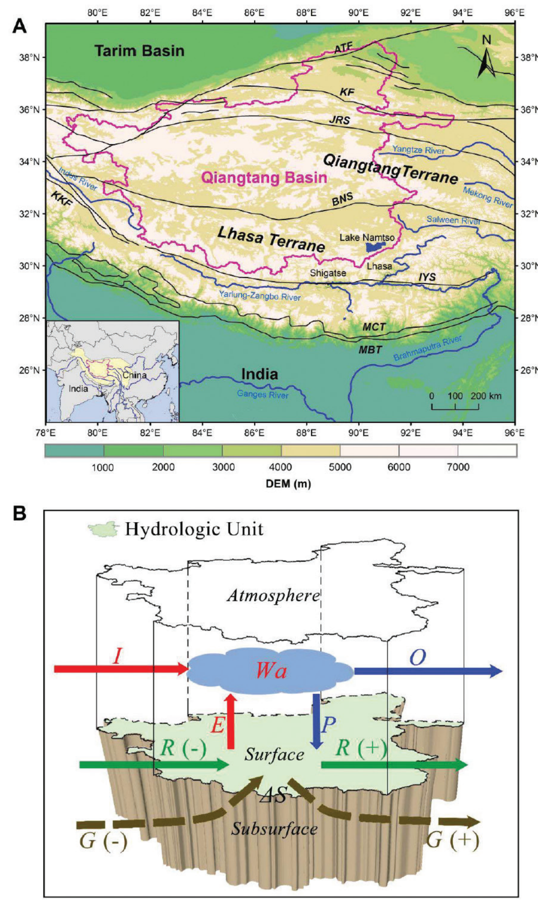


2018 Boso slow slip event. (a) slip amplitude during the June 2018 Boso slow slip event inverted from tiltmeters and GPS recordings. The associated seismicity color-coded by depth is surrounding the slow slip. Focal mechanisms are represented for the events of Mw > 4. (b) Time evolution of the Coulomb stress change induced by the slow slip and seismicity as a function of depth.

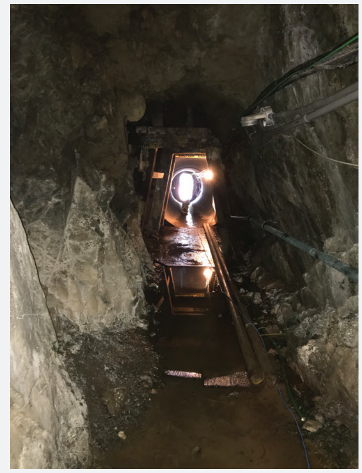
Missing water from the Qiangtang Basin

Chi-Yuen Wang

The Qiangtang Basin is located in the inner part of the Tibetan Plateau and is thought to be a dry region in contrast with the wet surrounding outer region that feeds all the major Asian rivers. Combining surface hydrological data with modeling and satellite data between 2002 and 2016, Wang's study reveals that an enormous amount of water, approximately 54 ± 4 km^3, is unaccounted for annually in the Qiangtang Basin — an amount comparable to the total annual discharge of the Yellow River. This is notable because the Qiangtang does not outflow into any other bodies of water. Data from the Gravity Recovery and Climate Experiment (GRACE) show little increase of local terrestrial water storage, thus, the missing water must have flowed out of the basin through underground passages. Interpreting this result in the context of recent seismic and geological studies of Tibet, Wang and colleagues suggest that the underground passages are likely deep normal faults and tensional fractures along the nearly North-South rift valleys. Cross-basin groundwater outflow of such a magnitude defies the traditional view of basin-scale water cycle and leads to a very different picture from the previous view of the Qiangtang Basin.



(A) Topographic map showing the geographic locations of Tibet, the Qiangtang Basin, major rivers, and the surface exposures of sutures that bound the major tectonic blocks. KF, the Kunlun fault; JRS, the Jinsha River Suture; BNS, the Bangong-Nujiang Suture; IYS, the Indus-Yarlung Suture; MCT, the Main Central Thrust; and MBT, the Main Boundary Thrust. (B) Conceptual diagram of atmospheric and terrestrial water balance in the Qiangtang Basin. The atmospheric components include water vapor content in atmosphere (Wa), precipitation (P), evapotranspiration (E), and water vapor fluxes into (I) and out of (O) the area of the basin. The terrestrial components include the change in water storage (S), net river discharge (R) and net groundwater flow (G).

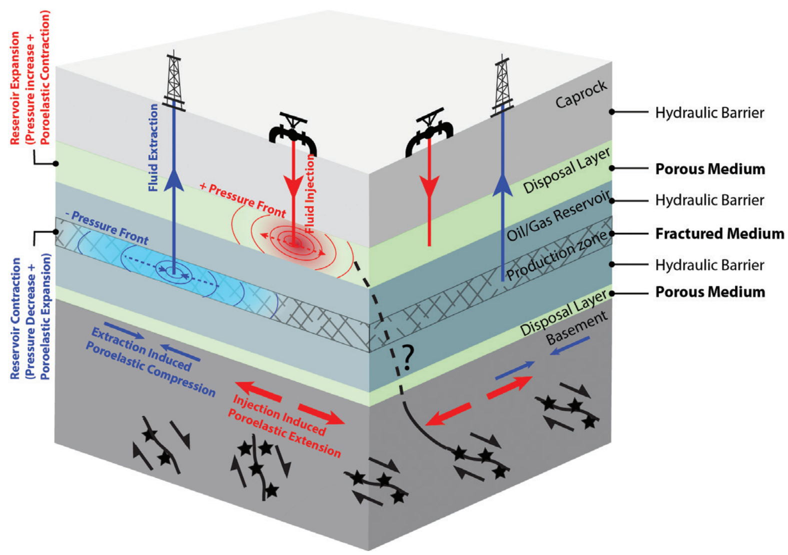


The tunnel at the YBH station in Yreka, CA.

Induced seismicity

Guang Zhai

The increase in seismic activity throughout the central and eastern U.S. is thought to be linked to wastewater injection. Zhai and colleagues investigated the Delaware Basin in Western Texas and established a framework explaining how shallow wastewater injection could induce earthquakes, which are much deeper and hydraulically isolated from the injection formations. Zhai investigated the basin-wide seismic, hydrogeologic, industrial, and geodetic data spanning 1993-2020. They demonstrated that the basin-wide seismicity is dominated by the stresses caused by the shallow sandstone injections due to a vertical interaction that is sensitive to the shallow aquifer's properties: particularly the speed of pressure disturbances in the groundwater system.



Schematic showing stress interaction between the shallow wastewater injection and deep basement fault activation.

PSES

Updates

The growing BSL seismic network

It has been a busy few years for our network operations staff. Our state-of-the-art observatory quality seismic network has doubled in size over the last four years. The size of the Berkeley broadband network has jumped from 35 stations a decade ago, to 51 in 2018, to 138 as of February 2022.

And we are not done; we are in the process of identifying sites, obtaining permits, pouring concrete and installing all the necessary equipment at another 72 sites that will bring our total number of stations to 210 in the next few years (Figure 1).

Why is this happening? The Berkeley network has always focused on the highest quality, very broadband continuous seismic data. This data is used by researchers around the world for research into earthquake fault processes, to study the structure of the crust, and as an array to view global Earth structure and earthquakes. In addition to facilitating fundamental research, it also streams into our real-time earthquake detection and monitoring system to provide earthquake early warning alerts, moment tensors and ShakeMaps to those affected by the quakes. It is these hazard-reducing applications of the seismic network that we at Berkeley have worked hard to develop and implement, and that provide the justification for the massive increased investment by the state and federal governments in seismic networks.

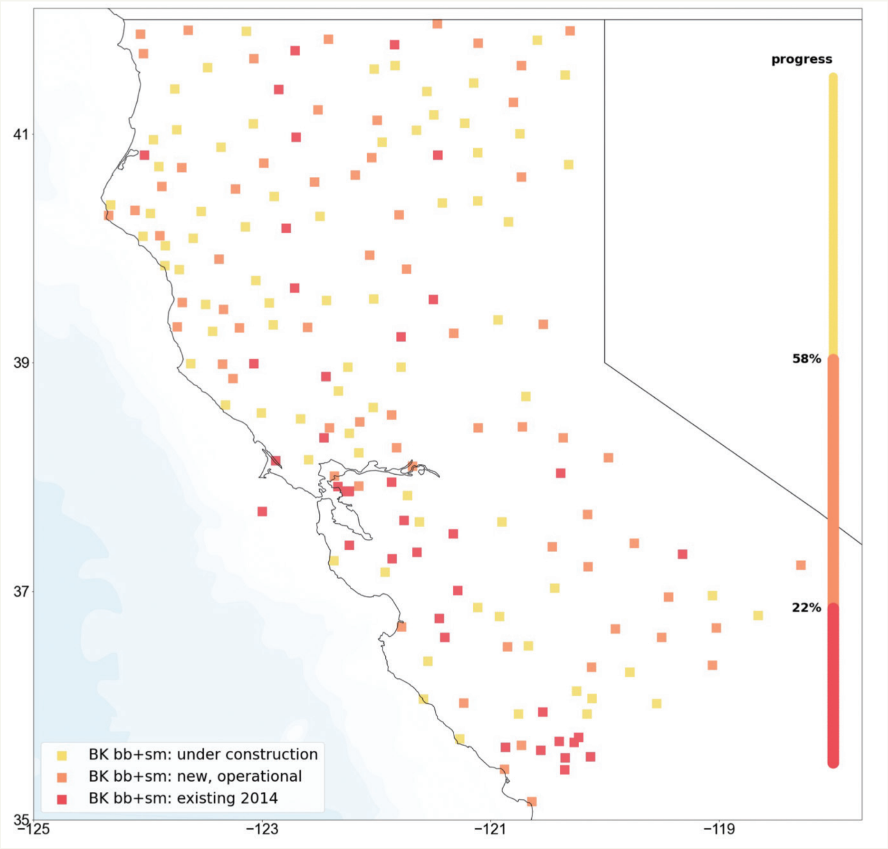


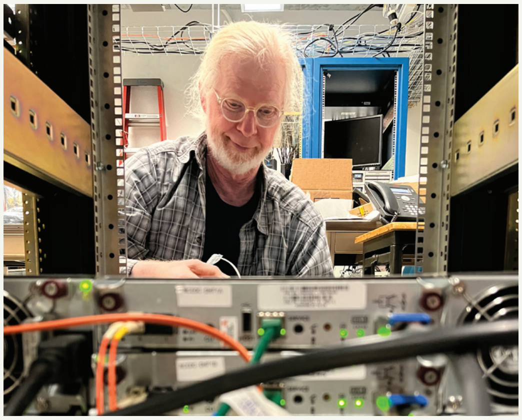
Figure 1. Growth of the BSL's seismic network in Northern California.

BSLUP

The BSL Engineering team has been managing the construction process for the new sites for ShakeAlert. In 2021, the team constructed 18 new stations that will contribute to this system, and instrumented many other new stations. Additionally, several legacy seismic and geodetic monitoring stations were upgraded with new sensors, data loggers, modern power infrastructure, and telemetry systems. Performing these tasks encountered many challenges, especially with the COVID-19 pandemic. The availability of necessary equipment, materials and supplies were in short supply, construction costs raised significantly and finding suitable lodging while traveling was often difficult. The wildfires in California also proved to be a barrier for the team. There were many areas where the team was unable to access to construct or install due to ongoing fires and closures of areas.

A utility terrain vehicle (UTV) is sometimes necessary to reach remote stations.

As network construction continues, it is also time to start exploring the massive new dataset being generated. All data from the Berkeley geophysical networks is made openly available in near-real-time at the Northern California Earthquake Data Center (ncedc.org). The expanded dataset is already being used to explore temporal changes in the seismic velocity of crustal rocks around active faults, to determine moment tensors for ever-smaller magnitude earthquakes, and to detect even smaller seismic events. All of these observables tell us about deformation and the state of stress in the crust as we continue in our endeavor to understand the physics of the earthquake cycle and the structure and dynamics of our restless planet.



Network maintenance and upgrades are essential support for the data we collect and provide to researchers around the world.

Global growth of earthquake early warning

Earthquake early warning (EEW) has its origins in the San Francisco Bay Area. Following the 1906 earthquake, J.D. Cooper, MD proposed the implementation of a warning system using the "new" telegraph cables radiating from the city to send a warning to a "characteristic bell." It was not until 1991 that the first public EEW system came online in Mexico City; it was another 16 years until Japan turned on their system; and then another decade until the next national system.

This slow progress was due to technological challenges. A network of sensors across the earthquake-prone region must be streaming data 24/7. Algorithms must be smart enough to filter real quakes from an array of other sources of seismic signal in a fraction of a second. Finally, comprehensible and actionable alerts must be delivered to users, all within a few seconds. While the development of EEW was slow to get started due to these challenges, since 2017 the rollout of EEW has been accelerating (Figure 1).

At Berkeley, we have worked on every part of the EEW problem. We developed the EPIC (formally called ElarmS) algorithm to process seismic data and generate the alerts. That algorithm has been used in South Korea to provide public alerts since 2018. Starting in 2019, ShakeAlert started to provide public alerts across California, also using EPIC. With alerts being generated, the next challenge is to deliver them to the public in a timely fashion. Berkeley's MyShake app (myshake.berkeley.edu) was originally developed to detect and record earthquake shaking using the onboard accelerometer, but in 2019 we added alert delivery and the app was relaunched by California Governor Gavin Newsom as the state's official EEW app. ShakeAlert rolled out to Oregon in 2021 and Washington in 2022 and MyShake is now delivering alerts across all three states, continuing the growth of EEW delivery around the globe.

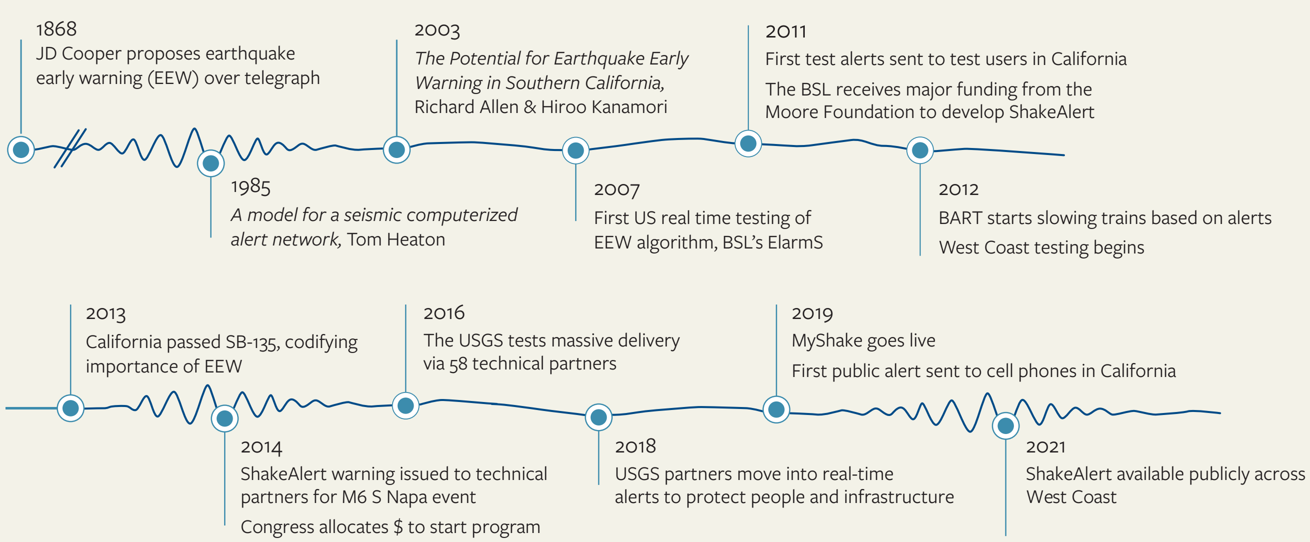


Figure 1. Timeline of EEW development.

BSL Director Allen with Governor Newsom announcing the MyShake Earthquake Early Warning App, October 17, 2019.

This expansion is only possible thanks to the collaboration of many organizations. Members of the BSL community continue to enjoy the partnership of the California Office of Emergency Services, the US Geological Survey, our fellow network operators at Caltech, and the Universities of Washington, Oregon and Nevada. Beyond the ShakeAlert community, partnerships include the Geological Survey of Israel, the Korean Meteorological Association, the University of Chile, and Google.

Building on the MyShake app experience, the BSL partnered with Google in 2019 to help transfer the MyShake technology into the Android ecosystem. This initially led to Android delivering ShakeAlerts to all Android phones in California, Oregon and Washington. But then in 2021, the Android Earthquake Alerts system started to deliver alerts generated using the same phones to detect the quakes. This means that earthquake alerts can be generated wherever there are phones, and there are phones wherever there are people. As of the end of 2021, Android alerts are delivered in New Zealand, Greece, Turkey, the Philippines and across Central Asia, with the promise of more regions to come.

The recent rapid growth in the number of people with access to EEW is shown in the plot (Figure 2). Berkeley has played a role in the last three systems to come online: South Korea, ShakeAlert and Android Earthquake Alerts. In early 2022 a fourth system was added as the Geological Survey of Israel turned on their TRUAA early warning system that again uses EPIC to generate alerts.

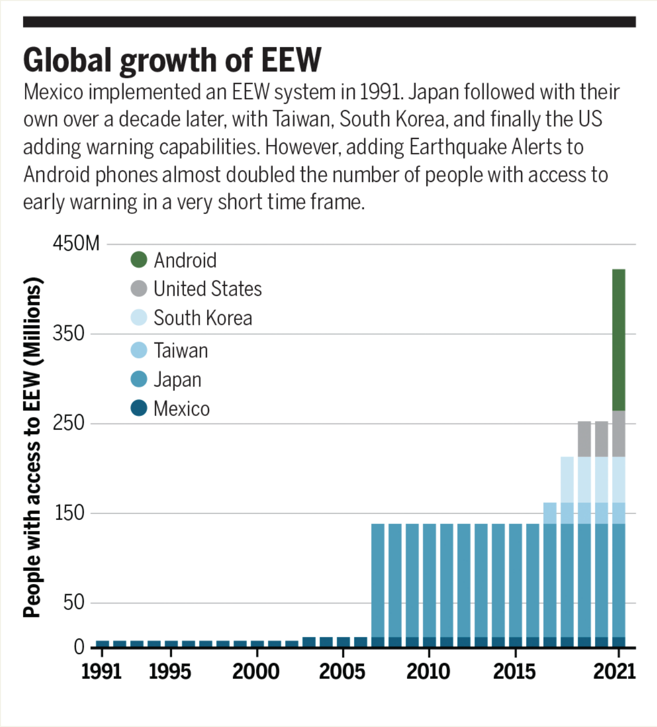


Figure 2. Growth of earthquake early warning systems around the globe.

For more on the growth of EEW, the opportunities and challenges, see: Allen R.M., M. Stogaitis (2022). Global growth of earthquake early warning: Public-private partnerships provide a method for vastly expanding sensor networks, Science, 375, 717-718 doi.org/10.1126/science.abl5435.

Thank you Dr. Margaret (Peggy) Hellweg

Peggy at the Parkfield station.

Dr. Peggy Hellweg recently retired after 20 years of service to the BSL and UC Berkeley. During the course of her time at Berkeley she influenced every aspect of the lab and we wanted to recognize these contributions and thank her for all her work. Peggy first arrived at the lab in 2001 when she joined as a postdoctoral scholar working with Prof Doug Dreger on moment tensor analysis and finite fault inversions for California earthquakes. She moved into a researcher position in 2004 and then became our Operations Manager in 2011. As Operations Manager Peggy has overseen all of the network activities of the lab and much more. Peggy was instrumental in the design and development of the network expansion over the last ~5 years. She helped develop the uniform station design that is now used by all networks in the western US for ShakeAlert stations. Then she oversaw Berkeley's implementation of that design at our new stations. She has a deep knowledge and understanding of geophysical instrumentation and has helped guide us in our decisions of how to instrument Northern California (see network growth map, page 18). Finally, this would not be complete without recognition of her outreach efforts. Peggy is always ready to give public talks about seismology and earthquakes, and always ready to respond to journalists' inquiries about earthquakes in California or around the world.

On behalf of everyone at the lab Peggy, thank you for your partnership over many years and we look forward to continuing collaboration in the future!

Richard Allen, Director

BSL UPDATES

Seismic instruments are frequently calibrated in the tunnel next to Byerly station located in the hills above campus.

Awards, Recognitions and News

José Magana (Undergraduate Student) worked with Professor Douglas Dreger and Dr. Taka'aki Taira on finite source analysis. His research glimpse is featured earlier in this report. José has been accepted to the Earthquake Engineering Dept. here at UC Berkeley.

Graduate student **Carolina Muñoz-Saez** completed her studies with Michael Manga in 2016 and moved on to postdoctoral work at the CEGA institute in Chile. She has now accepted a faculty position at the University of Nevada, Reno.

A more recent graduate, **Nate Lindsey**, completed his PhD work with dark fiber and then moved to Stanford for his postdoc. He is now VP of Science and Innovation at FiberSense.

Several BSL postdocs have moved on in their careers this past year. **Baptiste Rousset** completed his work on slow slip events with Roland Bürgmann and then took on a postdoc at the Institut des Sciences de la terre, Grenoble, France. He is now Chargé de recherche CNRS, Institut terre et environnement de Strasbourg. Another of Roland's students, **Xie Hu**, held an Assistant Professorship at the University of Houston from 2020-2021 until moving on to an Assistant Professor position at the College of Urban and Environmental Sciences, Peking University, Beijing, China. **Vashan Wright** worked briefly in collaboration with Michael Manga's group on controlled-source geophysics as a postdoc and has now accepted a position as Assistant Professor of Geophysics at Scripps.

We also have some new faces at the BSL. Our new Operations Manager **Julien Marty** comes to us from the Comprehensive Nuclear-Test-Ban Treaty Organization in Vienna, Austria. There he was the Seismo-Acoustic Unit Head and he brings those years of experience here to the lab to support the large-scale operations of the Northern California Seismic System, ShakeAlert, the California Earthquake Early Warning System, and the MyShake app. **Kang Wang** joined the lab as a Geodetic Postdoctoral Fellow in Roland Bürgmann's group. The lab also had three visiting scientists during this period: **Saeko Kita** from GRIPS, National Graduate Institute for Policy Studies; **Yann Klinger** from the Institut de Physique du Globe, a Visiting Miller Professor; and **Naoki Uchida** from the Graduate School of Science, Tohoku University.

Notable articles or books of this period include **Michael Manga's** inaugural article for the Proceedings of the National Academies of Science. The article focuses on the 2018 reawakening of the Steamboat Geyser. **Chi Wang** and **Michael Manga** also released a 400 page 'product of the pandemic' entitled *Water and Earthquakes*, which was published by Springer.

Finally, two of our scholars received important awards recently. **Sevan Adourian** is the recipient of the 2021 Hearts to Humanity Eternal (H2H8) research grant. H2H8 is a nonprofit organization that seeks to advance humanity through science. We would also like to congratulate **Barbara Romanowicz**, who won the 2021 Medal from the IASPEI (International Association of Seismology and Physics of the Earth's Interior) for international cooperation for better understanding of the earth.

Outreach to high school students interested in careers in STEM is an important aspect of the BSL's mission.

Faculty

Richard Allen, Director

Douglas Dreger, Associate Director

Norman Abrahamson, Civil and Environmental Engineering

Alexandre Bayen, Electrical Engineering and Computer Science

Jonathan Bray, Civil and Environmental Engineering

Bruce Buffett, Earth and Planetary Science

Roland Bürgmann, Earth and Planetary Science

Ken Goldberg, Electrical Engineering and Computer Sciences

Raymond Jeanloz, Earth and Planetary Science

Harriet Lau, Earth and Planetary Science

Michael Manga, Earth and Planetary Science

Burkhard Militzer, Earth and Planetary Science

Jack Moehle, Civil and Environmental Engineering

James Rector, Civil and Environmental Engineering

Barbara Romanowicz, Earth and Planetary Science

Nicholas Sitar, Civil and Environmental Engineering

Kenichi Soga, Civil and Environmental Engineering

Chi-Yuen Wang, Earth and Planetary Science

Hans-Rudolf Wenk, Earth and Planetary Science

Postdoctoral Scholars

Li-Wei Chen, Global seismology and tomography

Yifang Cheng, Seismic source properties, spatiotemporal variation of seismicity, and fault zone structures

Utpal Kumar, Computational seismology, Geodesy, Geophysical data analysis

Diogo Lourenco, Geodynamics, Earth and other rocky bodies' evolution and dynamics

Chao Lyu, Computational seismology, homogenized full waveform inversion, hybrid wave numerical simulation

Federico Munch, Upper mantle and transition zone thermo-chemical structure, probabilistic inverse methods, seismology, deep electromagnetic studies, mineral physics, mantle water content

Artie Rodgers, Earthquake strong motion simulation, Bay Area earthquakes

Heather Shaddox, Interplay of seismic and aseismic slip on faults, seismic detection of oceanic waves

Kang Wang, Geodetic Postdoctoral Fellow

Amy Williamson, Earthquake and tsunami early warning

Yuankun Xu, Physics of landslide processes

The BSL Seminar is a long-standing weekly event for faculty, postdocs, students, and everyone interested in seismic research.

Students

Sevan Adourian, Imaging of the lowermost mantle

Manar Al Asad, Core-mantle coupling, geophysical flows and planetary potential fields

Tyler Cadena, Volcanology

Rodrigo Chi, Earth's core dynamics and seismic sources

William Davis, Earth and planetary sciences

Claire Doody, Subduction zone imaging in Japan

Mrinal Dursun, Geodynamics

Yuancong Gou, Seismology

Yuexin Li, Earthquake physics and crustal deformation

Danielle Lindsay, Geodetic observations, active tectonics, slow earthquakes

José Magana, Engineering

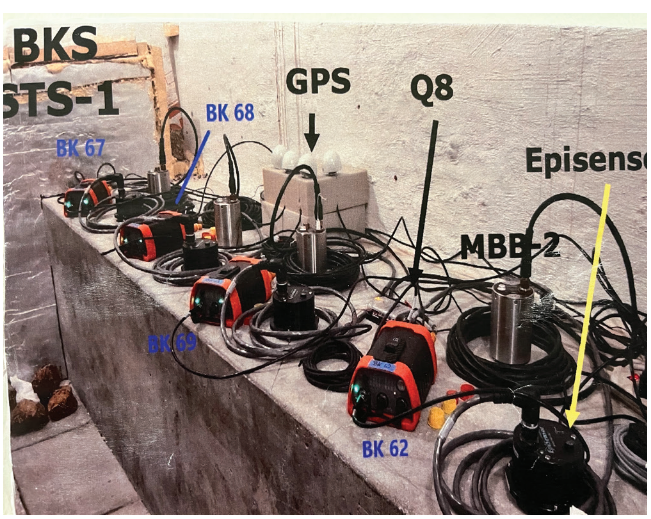
Nam Maneerat, Structural geology and active tectonics

Sarina Patel, Real-time seismology, earthquake hazard, MyShake, mapping

Zach Smith, Interaction between tectonics and fluid flow

Heng-Yi Su, Global tomography, seismology

Samantha Goldstein Seismicity of foreshocks and mainshocks in California (Undergraduate)



A series of instruments in testing in the Byerly tunnel.

Operations and Research Staff

Julien Marty, Operations Manager

Andrei Akimov, Applications Programmer

Zack Alexy, Engineer

Steve Allen, Applications Programmer

Mario Aranha, IT Applications Programmer

Theron Bair, DevOps Engineer

Sierra Boyd, Research Data Analyst

Dylan Cembalski, Engineer

George Dorian, Engineer

Tal Edgecomb, EEW Outreach and Administrative Coordinator

Dan Frost, Project Scientist

Ivan Henson, IT Applications Manager

Angela Lux, Project Scientist

Alvaro Medina, Engineer

Akie Mejia, IT Applications Programmer

Jonah Merritt, Field Operations Manager

Paul Milligan, Information Systems Analyst

Robert Nadeau, Research Seismologist

Doug Neuhauser, IT Systems Manager

Charley Paffenbarger, IT Systems Administrator

Brian Pardini, Systems Administrator

Aileen Paterson, Administrative Officer

Nicholas Stein, Engineer

Jennifer Strauss, External Relations Officer

Jennifer Taggart, Web & Ops Developer

Taka'aki Taira, Research Seismologist

Fabia Terra, Project Manager

Stephen Thompson, IT Systems Manager

Christina Valen, Data Analyst

Junli Zhang, Applications Programmer

Design services: Meg Coughlin Design

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