CECIL H. & IDA M. GREEN

INSTITUTE OF GEOPHYSICS AND PLANETARY PHYSICS

2015

Okmok Volcano

Umnak Island, eastern Aleutian islands

In 2015, Kerry Key, in collaboration with USGS, Alaska Volcano Observatory, and University of Wisconsin Madison colleagues, traveled to Umnak Island to commence study of the magma—how it's formed, where it's stored—beneath Okmok Volcano. The study, "Magnetotelluric and Seismic Investigation of Okmok Volcano," included the installation of an array of seismic and magnetotelluric sensors across Okmok will allow Key and his colleagues to image the volcano's magma "plumbing system." Photo: Kerry Key

2015

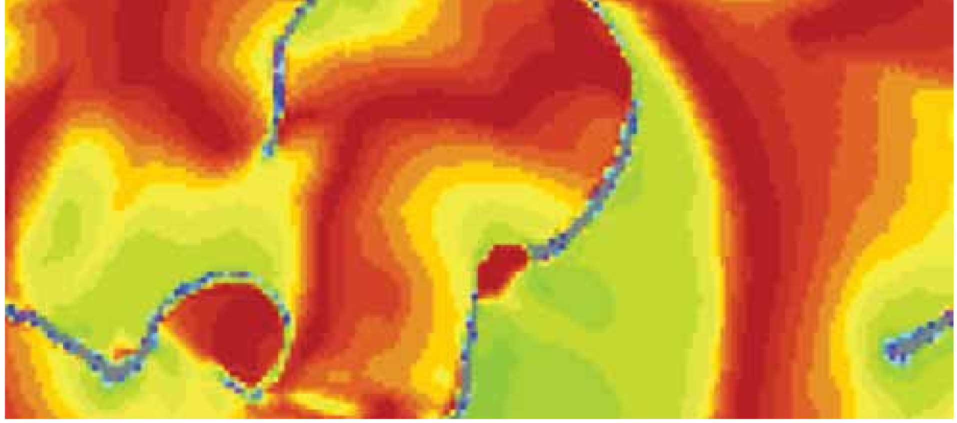
IGPP DIRECTOR'S WELCOME

In this 2015 Annual Report of the **Cecil and Ida Green Institute of Geophysics and Planetary Physics**, we aim to provide a description of our research activities during the past academic year for prospective graduate students and for anyone else who has an interest in the Earth Sciences, particularly geophysics. While most of our research is basic in nature, many, if not most, of the subjects covered are areas of broad societal concern. These include: understanding the earthquake cycle, developing earthquake early warning systems, understanding the behavior of ice sheets, improved methods of energy exploration, monitoring of carbon dioxide sequestration, and so on.

Our work spans a broad range of subject matter in geophysics and oceanography. A wide range of observations are accomplished on global, regional, and local scales by extensive shipboard and ground-based operations and also include remote sensing by satellites and the use of wide-ranging instrument networks. Theoretical developments and modeling play a strong role in data interpretation.

It is our hope that you will find this a useful description of our ongoing work and that you will agree that IGPP continues to be one of the foremost research centers for geophysics in the nation.

Guy Masters, Director, IGPP



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RESEARCHERS

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2015 **HIGHLIGHTS**

Many IGPP researchers were recognized for their outstanding work with awards and honors in 2015. They have also provided news agencies with responsive insight to tectonic and climate concerns. What follows is an incomplete compilation of recognized achievement in 2015:

MARCH

Helen Fricker appeared on ***BBC World Service Science in Action*** to share Scripps Glaciology Groups's findings—from 18-years of satellite data—which show accelerating rates of ice loss from floating shelves around Antarctica. (*www.bbc.co.uk/programmes/p02mtgqg*)

APRIL

Zhitu Ma won the ***Geophysical Journal International*** prize for best student paper in 2014 for his paper *"A comprehensive dispersion model of surface wave phase and group velocity for the globe,"* Ma, Z., Masters, G., Laske, G. and Pasyanos, M. (2014) 199 (1): 113-135. (*http://bit.ly/1ynAVQm*)

JUNE

Debi Kilb's SIO Games DEEP game is among those featured at World Ocean Day 2015 at the Smithsonian National Museum of Natural History.

JULY

The Dalai Lama and Walter Munk hosted a panel on Climate Change as part of the July 5-7 world celebration of the Dalai Lama's 80th Birthday.

AUGUST

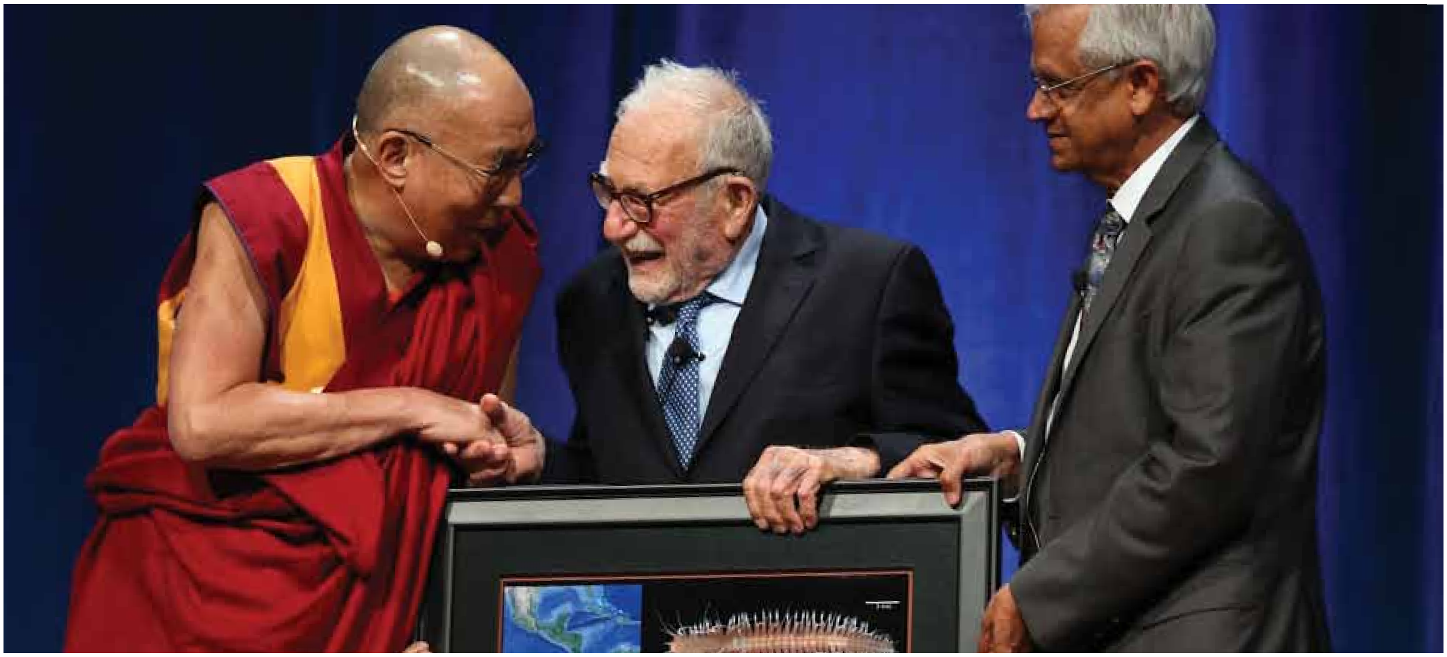
Walter Munk is featured in the ***New York Times*** Science section as "*Einstein of the Oceans.*" (*nyti.ms/1U22GLU*)

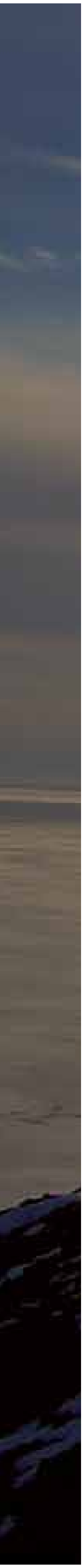
SEPTEMBER

The Del Mar Foundation speaker series featured Debi Kilb to present "Our Next Earthquake."

NOVEMBER

News of the Seismic Warning Systems (SWS)'s financial donation to Frank Vernon's ANZA network, which will keep the ANZA Seismic Network, and its 28 monitoring stations along the San Jacinto Fault, operating through 2020, was shared by Fox 5 San Diego and the San Diego Union Tribune (*www.sandiegouniontribune.com/news/2015/nov/12/ucsd-quake-monitoring*)





GRADUATE EXPERIENCE

More than the Oceans...

Our multidisciplinary program offers graduate students a unique hands-on, collaborative learning environment. In addition to our core academic curriculum, we emphasize observational techniques and the collection of novel datasets. IGPP students participate extensively in field experiments, instrument development, laboratory investigations, and shipboard expeditions.

Our graduates go on to careers in research, education, industry, and public policy. Scripps has strong working relationships with the National Science Foundation, NASA, NOAA, the US Geological Survey, and the Office of Naval Research, and can provide graduates with long-term networking and professional support.

Graduate Students who successfully defended in 2015

Eric Lindsey *(Yuri Fialko)*: ***Fault properties, rheology and interseismic deformation in Southern California from high-precision space geodesy***
currently: Postdoctoral Research Associate, Earth Observatory of Singapore, Nanyang Technological University

Zhitu Ma *(Guy Masters)*: ***Lithosphere structure of the Earth from surface wave tomography***
currently: Postdoctoral Research Associate, Brown University

Erica Mitchell *(Yuri Fialko and Kevin Brown)*: ***Temperature Dependent Frictional Properties of Crustal Rocks***

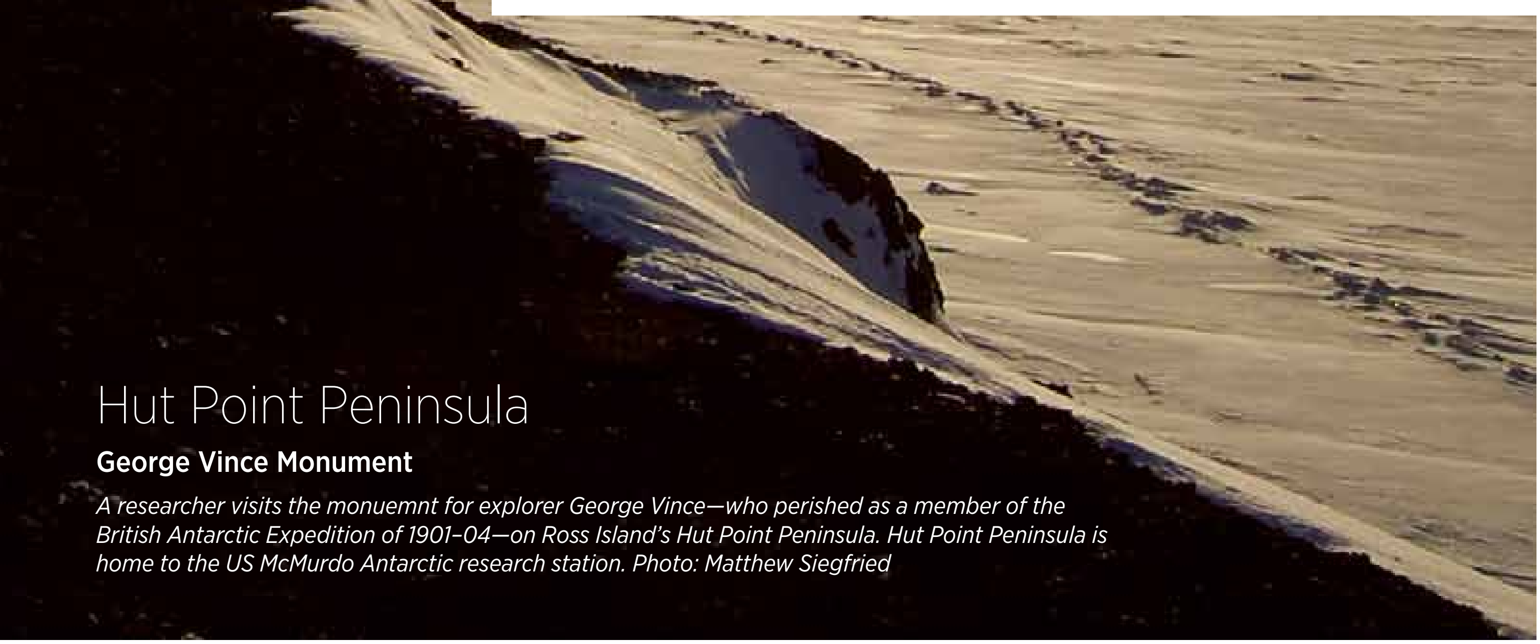
Samer Naif *(Steven Constable and Kerry Key)*: ***Marine electromagnetic experiment across the Nicaragua Trench : Imaging water-rich faults and melt-rich asthenosphere***
currently: Lamont-Doherty Earth Observatory

Fernando Paulo *(Helen Fricker)*: ***Interannual and decadal variations of ice shelves using multi-mission satellite radar altimetry, and links with oceanic and atmospheric forcings***
currently: Postdoctoral Research Associate, IGPP

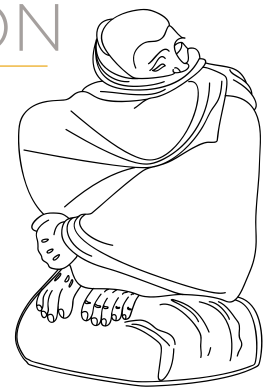
Matt Siegfried *(Helen Fricker)*: ***Investigating Antarctic ice sheet subglacial processes beneath the Whillans Ice Plain, West Antarctica, using satellite altimetry and GPS***
currently: Postdoctoral Research Associate, IGPP

Valerie Sahakian* *(Neal Driscoll and Alistair Harding)*: ***Architecture and Segmentation of Strike-Slip Faults in Southern California***
currently: Postdoctoral Research Associate, Geosciences Research Division (GRD)

**Research conducted at both IGPP and GRD*



GREEN FOUNDATION



The Cecil H. and Ida M. Green Foundation for Earth Sciences supports visiting scholars and resident scientists at the La Jolla branch of the University of California's multi-campus Institute of Geophysics and Planetary Physics (IGPP). Established with a gift from the late Cecil Green in 1971, the Green Foundation holds an endowment managed by the UCSD-IGPP Director and overseen by an independent Board of Directors. A selection committee comprised of IGPP faculty screens nominees and applicants for both the Green Scholar and the Miles Fellowship. The scholarship funds come from the income that the Foundation receives on its capital. Being an independent entity, the Foundation has some flexibility in how funds are earmarked within the University of California guidelines. In addition to funding visiting scholars, the selection committee considers requests from IGPP scientists for funds to support research via purchase of equipment or construction of facilities. Such awards are usually directed as seed money for new projects or for equipment that is difficult to obtain via traditional extramural funding sources.

The Green Foundation is currently supporting:

Green Scholar Marine Denolle, postdoc

Miles Fellow Noel Bartlow, postdoc

Green Scholar Chris Davies

Green Scholar Dan Bassett, postdoc

UCSD membership in Southern California Earthquake Center *www.scec.org*

Hut Point Peninsula

George Vince Monument

A researcher visits the monuemnt for explorer George Vince—who perished as a member of the British Antarctic Expedition of 1901–04—on Ross Island's Hut Point Peninsula. Hut Point Peninsula is home to the US McMurdo Antarctic research station. Photo: Matthew Siegfried

PAUL G. SILVER

YOUNG SCHOLAR RESEARCH ENHANCEMENT AWARD

Paul G. Silver received his PhD in geophysics from **Scripps Institution of Oceanography**, UCSD in 1982 and went on to a highly distinguished career. He applied seismology in innovative ways to study a range of topics from earthquake triggering, through upper mantle flow, to core-mantle boundary structure. He led several international projects that resulted in new insights on directionally-dependent wave propagation associated with crust and/or mantle deformation. Paul was particularly well-known for his creativity and successful mentoring of young scholars, both being outcomes of his inquisitive and open, yet focused on the end-result, approach to science.

In recognition of Paul's mentorship, and to enable young scholars to pursue a new idea, the Paul G. Silver Young Scholar Research Enhancement Award will provide funds to extend work beyond what would typically be within reach for a young investigator. Awards of $2000-5000 will be offered annually through a competitive application process, open to undergraduates, graduate students, or new researchers (< 4 yr post PhD) who are pursuing geophysical research at Scripps Institution of Oceanography, UCSD. Applicants should provide a single page description of the objectives and status of their ongoing research project, of the aspect(s) that would be supported by an award, and details of how funds would be used. A 1-2 page (maximum length) CV should be included in the same document. Examples of request type include, but are not limited to: support for a visit to another lab to acquire or process data; conduct of a pilot field study; acquisition fees for agency or commercially served data; travel to an in-depth topical workshop where significant interaction with colleagues could enhance research outcomes.

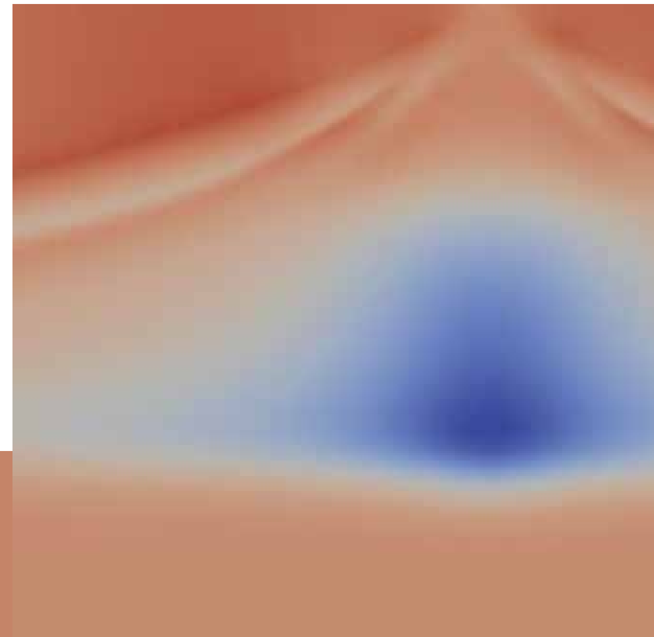
The call for applications will be announced yearly by early April and the deadline for receipt of materials will be a month later. The IGPP Green Foundation Selection Committee will evaluate applications and final selection will be made in consultation with Nathalie Valette-Silver, PhD.

Applications for 2016 are now being accepted. To fill in the application form and submit documents, go to *igpp.ucsd.edu/greenfoundation/paulgsilverapplication*. Deadline for receipt of all materials is April 30, 2016.

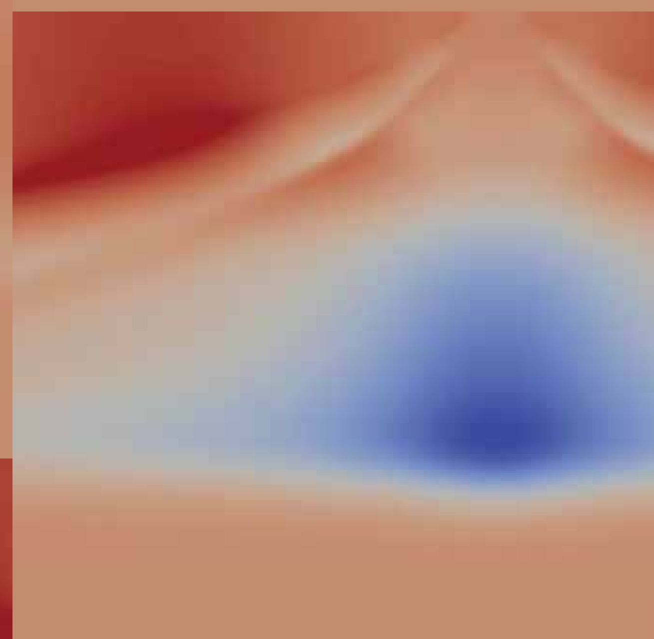
2015 Recipients:

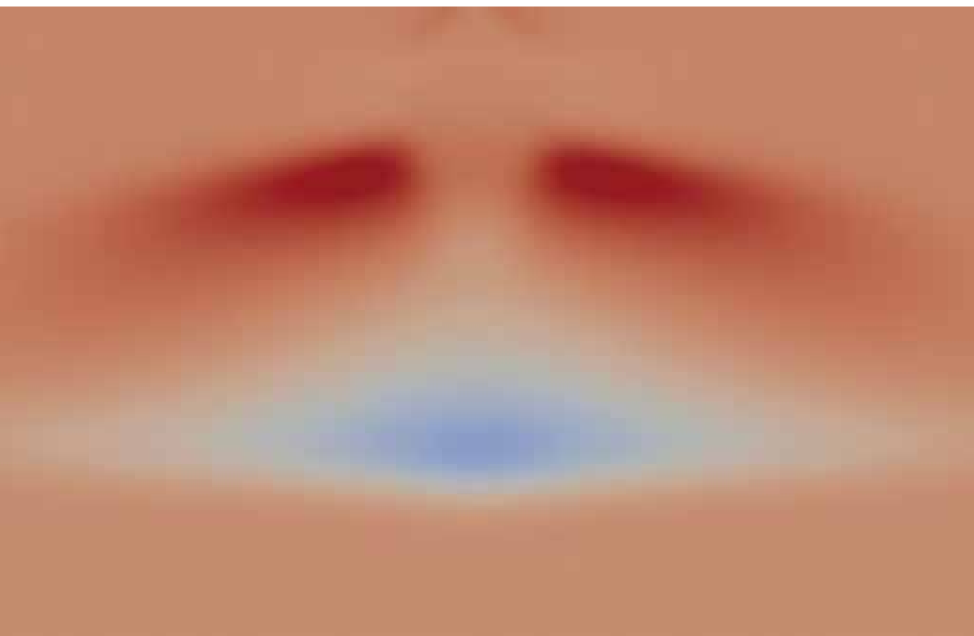
Shi Sim: *Collaboration visit to LDEO-numerical modeling of mantle flow, melting, and melt migration*

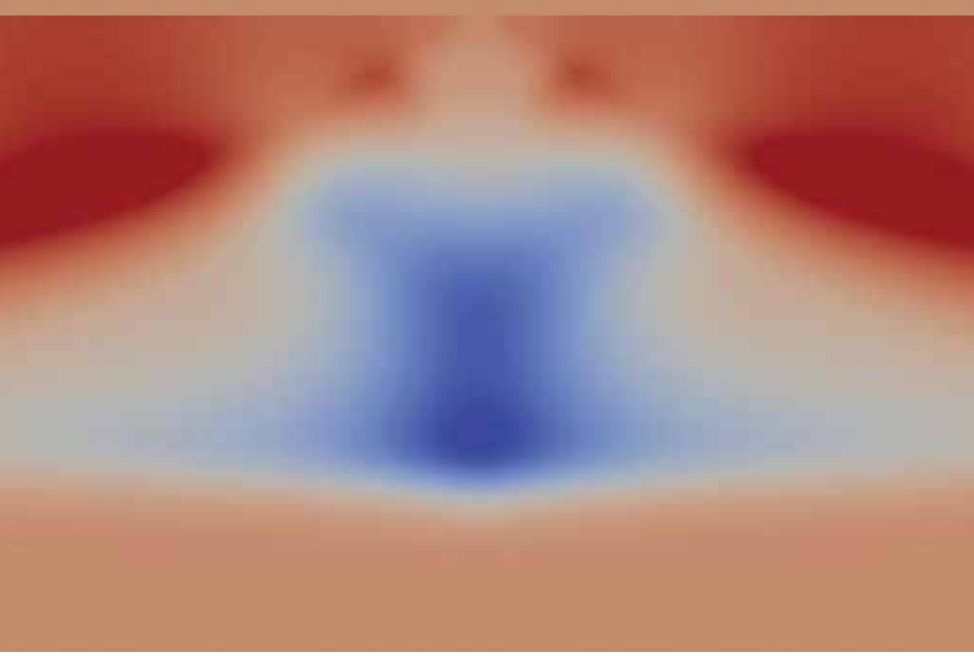
Adrian Doran: *Seismicity on Patton Escarpment, OBS deployment*



COMPACTION PRESSURE **MELT FLUX** AND POROSITY







*Captures from a movie produced by **Paul G. Silver Young Scholar Research Enhancement award Award recipient Shi Sim**. Sim worked with Marc Spiegelman and Cian Wilson at Lamont Doherty Earth Observatory (Columbia University) using their code, TerraFERMA on models of magma/mantle—two phase flows beneath mid-oceanic ridges. The movie these captures came from model fluid phase (compaction pressure, melt flux and porosity). Sim used her award to work from Lamont for three weeks in October 2015 and found the experience crucial to her project.*

SIO GAMES GROUP

Housed within IGPP is the **Scripps Institution of Oceanography Games (SIO Games)** group, a team developing educational videogames pertaining to geoscience research. These unconventional outreach tools (think video games and interactive displays) are designed to teach youth and the young-at-heart about Scripps research and the thrill of scientific discovery. SIO Games team members interact with hundreds of young students every year through a multitude of custom-designed games and activities, including virtual reality goggles that take viewers on a "behind the scenes" tour of the Scripps Pier and the research vessel Revelle, a hands-on Kinect "Quake Catcher" game in which players become seismologists responding to a large earthquake, and the Xbox game Deep-Sea Extreme Environment Pilot (DEEP), which teaches players about how today's scientists study deep-ocean environments. This year the SIO Games team has participated in multiple events focused on STEAM (science, technology, engineering, arts, and math), including the "Tech to Reconnect" event at the San Diego Zoo, the "Great California Shake Out" event at Birch Aquarium at Scripps, and a science showcase at the Elementary Institute of Science to name just a few. They have also brought the games to science programs at local schools throughout the San Diego region reaching ~1000 student this year.

DUNCAN CARR AGNEW, PROFESSOR

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FRANK K. WYATT, PRINCIPLE DEV. ENGINEER, RTAD

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Research Interests: Crustal deformation measurement and interpretation, Earth tides, Southern California seismicity.

We have long used long-base laser strainmeters to collect continuous deformation data at locations close to the two most active faults in Southern California. Pinyon Flat Observatory (PFO, operating since 1974) is 14 km from the Anza section of the San Jacinto fault (2-3 m accumulated slip since the last large earthquake) and Salton City (SCS, since 2006) within 15 km of the same fault further SE. Two other sites (Cholame, or CHL, since 2008, and Durmid Hill, or DHL, since 1994) are within three km of the San Andreas fault (SAF): CHL, at the N end of the segment that ruptured in 1857, and DHL at the S end of the Coachella segment (4-6 m accumulated slip). Surface-mounted laser strainmeters (LSM's), 400 to 700 m long and anchored 25 m deep, provide long-term high-quality measurements of strain unmatched anywhere else: though in geological settings ranging from weathered granite to clay sediments, the LSM's record secular strain accumulation consistent with continuous GPS, something not otherwise possible. The LSM's record signals from 1 Hz to secular; at periods less than several months, they have a noise level far below that of fault-scale GPS networks.

The high installation and operating costs of these LSM's has created a need for a cheaper, if lower-quality sensor. With Dr. Mark Zumberge, we continue to develop long-base laser strainmeters that use optical fiber, rather than a vacuum pipe, for the optical path, to provide a robust, widely deployable, inexpensive, and sensitive instrument. Since optical fibers have long-term drift and are temperature sensitive they cannot provide the same data quality over as wide a range of frequencies, but can still be useful for studying seismic waves, Earth tides, and slow slip events.

At PFO we have installed a 250-m-long borehole optical fiber vertical strainmeter, and two horizontal optical fiber strainmeters installed in trenches (about 1m deep). The first, a 180 m instrument, is parallel to the NWSE vacuum laser strainmeter. It consists of optical fiber stretched between two points anchored to the Earth; length changes in this are measured using an interferometer, in which light from a laser is split by an optical fiber coupler into two fibers, one the Earth strain sensing fiber, the other a fixed reference length. Light travels the lengths of the two arms and recombines coherently: in a Michelson interferometer Faraday mirrors at the far end of each fiber reflect the light back, so the light recombines in the original coupler. By making the two arms of equal optical length the laser used can have relatively poor frequency stability. The reference arm is coiled around a quartz mandrel next to the laser and coupler, so that its temperature can be kept constant.

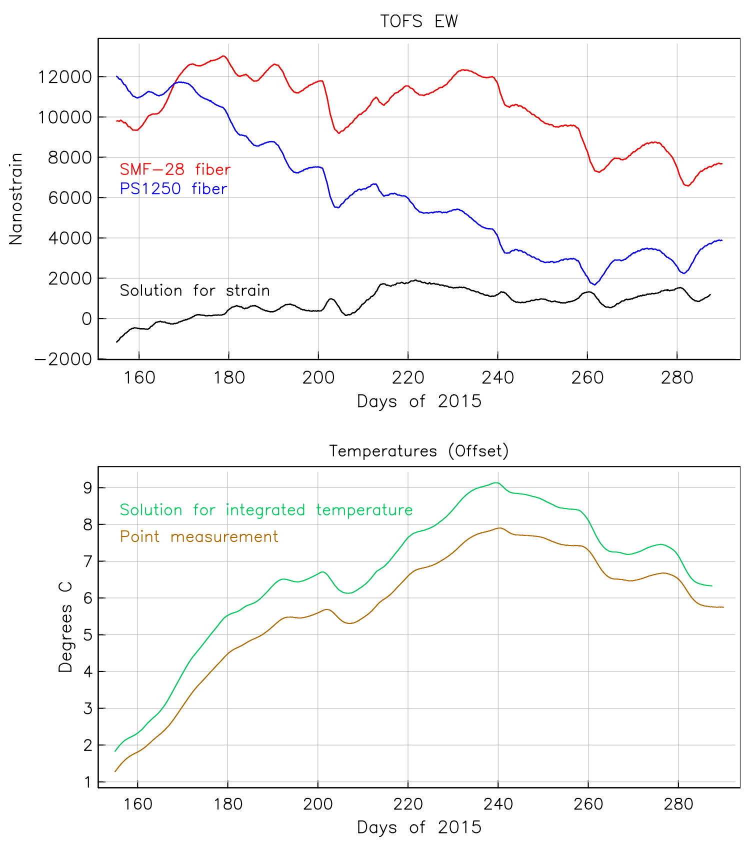

Figure 1. Data from the EW TOFS (Trench Optical-Fiber Strainmeter) installed at PFO. The upper panel shows the apparent strains observed on the two fibers, and the estimated strain from the temperature-neutral combination (black). The lower panel shows the estimated temperature and that measured at one point.

The extended fiber, though buffered from very rapid temperature changes by the overlying soil, still shows the effect of temperature at periods longer than a few hours. To reduce this effect, we have built (and installed at PFO) an instrument in which two optical fibers are both part of the strain sensing cable, with one being a normal fiber and the other using a different type of glass with a different temperature coefficient of the index of refraction. The two fibers undergo identical strain and temperature changes, but their different temperature coefficients allow the strain and temperature effects to be separated by forming appropriately scaled differences between the two fiber outputs. Extensive lab testing showed that an alternatively-doped fiber had a 14% difference in temperature coefficient.

We have installed a two-fiber system at PFO, extending over 230 m, and parallel to the EWvacuum strainmeter. The figure shows the data from the two fibers, along with the estimated strain and 1 temperature. The temperature changes agree well with a point measurement made at one location along the fiber, and the estimated strain shows much less variability after the temperature correction.

Recent Publications

D. C. Agnew (2015). Equalized plot scales for exploring seismicity data, *Seismol. Res. Lett.* **86**, 1412-1423, http://dx.doi.org/10.1785/0220150054

A. J. Barbour, D. C. Agnew, and F. K. Wyatt (2015). Coseismic strains on Plate Boundary Observatory borehole strainmeters in southern California, *Bull. Seismol. Soc. Am.*, **105**, 431-444, http://dx.doi.org/10.1785/0120140199

JONATHAN BERGER, EMERITUS RESEARCHER RTAD

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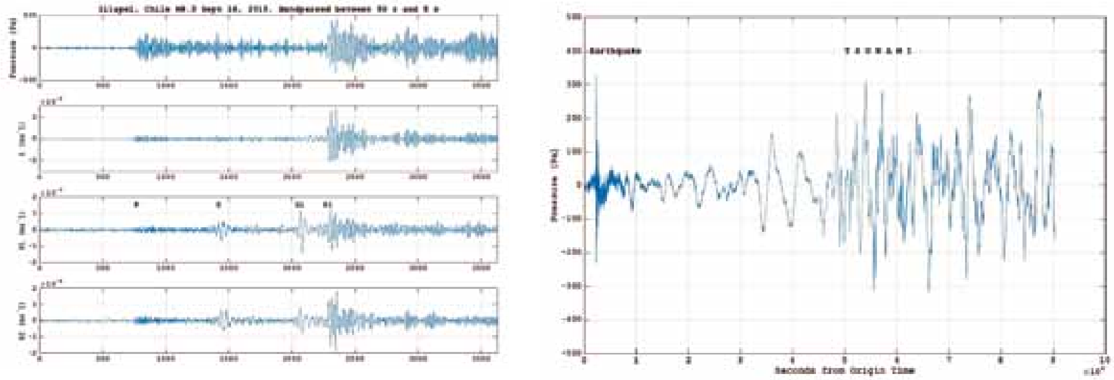
Research Interests: Global seismological observations, marine seismoacoustics, geophysical instrumentation, deep ocean observing platforms, ocean robotics, global communications systems.

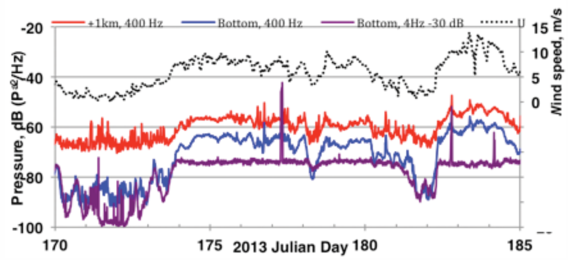
With my collaborators John Orcutt, Gabi Laske, and Jeff Babcock we continued testing of the Autonomous Deployable Deep Ocean Seismic System. With a new tow cable and acoustic modem power system, we deployed the ADDOSS in August in 4000 m of water 300 km west of Point Loma within a few km of the site of the DSDP Hole 469, drilled in 1978. We are now third month of successful operation with sensor data being telemetered to IGPP in near real-time.

I continued my research with Bill Farrell, Walter Munk, and Peter Worcester on trying to understand the relationship between the wind and wave environment, and bottom acoustics. We analyzed data collected from an experiment in the deep ocean of the northeastern subtropical Pacific. The figure to the left shows spectra on the bottom (purple, blue) and at +1,000 m (red) at OBSANP location. Wind recorded on R/V Melville (up to 100 km away from the study area) is shown in black dashes. The comparison between the bottom pressure at 4 Hz (purple, shifted by 30 dB) and 400 Hz (blue) is extraordinary and as far as we know, never before been reported. Of particular interest is the a quick (1 hr, 1 < f < 400 Hz) increse in pressure and



The figure to the left shows the telemetered sensor data recorded from the Illapel, Chile earthquake of Sept. 16 and on the right the seafloor pressure showing the arrival of the tsunami at the site.

vertical velocity on the deep seafloor observed during day 182 on seven instruments comprising a 20 km array. We associate the jump with the passage of a cold front. The changes in the power spectra through the jump, at 4 and 400 Hz, were characterized by a half-way time and the time derivative of the spectra at the half-way time. At every station the half-way time of the jump is consistent with the front coming out of the northwest. The apparent rate of progress, 10-20 kmhr^{-1} (2.8-5.6 ms^{-1}), agrees with meteorological observations. The deep signature of the front is modeled as radiation from a moving half-plane of uncorrelated acoustic dipoles. The half-plane is preceded by a 10 km transition zone over which the radiator strength increases linearly from zero. With this model and the measurements of the time derivative of the jump in pressure at the time of passage, a second and independent estimate of the front's speed, 8.5 kmhr^{-1} (2.4 ms^{-1}), is obtained. For the 4 Hz spectra, we take the source physics to be Longuet-Higgins radiation. Its strength depends on the wave amplitude spectrum and the overlap integral. Thus, the one-hour time constant observed in the bottom data implies a similar time constant for the growth of the wave field quantity as the front crosses a patch of ocean overhead. The spectra at 400 Hz have a similar jump and a similar time constant, but the half-way times are about 25 minutes later than those for 4 Hz. We are now trying to understand the implications of this difference for the source physics behind the high frequency acoustics at depth.



Recent Publications

Jonathan Berger, John Orcutt, Gabi Laske, and Jeffrey Babcock (2015). ADDOSS Annual Report, *NSF*, Sept 2015.

DONNA BLACKMAN, RESEARCH GEOPHYSICIST

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Research Interests: Understanding mantle flow, melting, and tectonic evolution along plate boundaries using marine geophysics and numerical modeling.

My work this year was split between program management, for the Marine Geology & Geophysics program at the National Science Foundation, and research conducted upon return to Scripps mid-year. My research focused in two areas– numerical modeling of mantle flow, associated rheologic and seismic anisotropy, and oceanic core complexes.

A collaborative Ridge 2000 project was completed this year, as we wrapped up analysis and publication of the Lau Integrated Studies Site seismic imaging study. Mantle wedge flow and seismic structure varies along the Lau Basin backarc spreading centers. The differences are partly due to kinematics of varying along-basin subduction and spreading rates, but narrowing of the distance between the Tonga trench and the back-arc spreading center from north to south is a stronger control. Observed seismic anisotropy patterns (Menke et al. 2015; Wei et al., 2015) indicate dynamic flow processes that impact mantle melt production and distribution.

Modeling of anisotropic viscosity that develops during mantle flow beneath an oceanic spreading center is the main focus of my ongoing research. In collaboration with colleagues at Cornell and Paris, we are testing feedbacks between mineral alignment and flow pattern, tracking grain scale deformation by dislocation creep and linking that to regional scale flow. We employ a second-order visco-plastic self consistent method, linking viscosity solutions to a FEM calculation of regional flow. Asthenosphere viscosities are calculated throughout the model, based on the response of an mineral aggregate with crystal preferred orientation (CPO) that develops along a flowline tracked from the base of the model to the given finite element. The figures shows results between CPO, viscosity tensors, and updated flow solution, near steady stateafter 15 iterations.

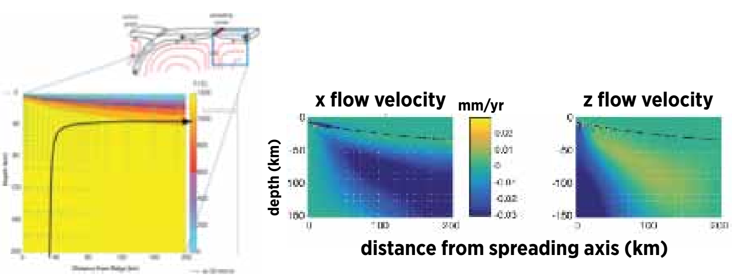

Figure 1a. Model geometry (left) and difference in mantle flow computed for isotropic asthenosphere and self-consistent CPO/rheology case. Black line shows base of rigid lithosphere. Horizontal (x) flow rates are up to 10% slower than an isotropic rheology model; vertical (z) flow rates are up to 10% slower in the upwelling zone beneath the spreading axis and ~5% faster through the corner in the flow field.

Oceanic core complex work included documentation of the seafloor character at Atlantis Massif and preparation for an International Ocean Discovery Program coring/logging expedition at Atlantis Bank, on the Southwest Indian Ridge. Undergraduate John Greene was co-mentored by Masako Tominaga (Michigan State) and I for the Mid-Atlantic Ridge work at Atlantis Massif. Complete photo-mosaicking of seafloor imagery showed that there is no systematic pattern in the occurrence of lithified carbonate cap on the detachment-fault-exposed domal core. The scale of the area affected by low level hydrothermal flow was assessed, this process being responsible for rapid lithification of young marine sediments. John applied this information to estimate the volume of carbon storage associated with carbonate cap lithification at oceanic core complexes in the write up for a special volume of Deep Sea Research honoring Peter Rona.

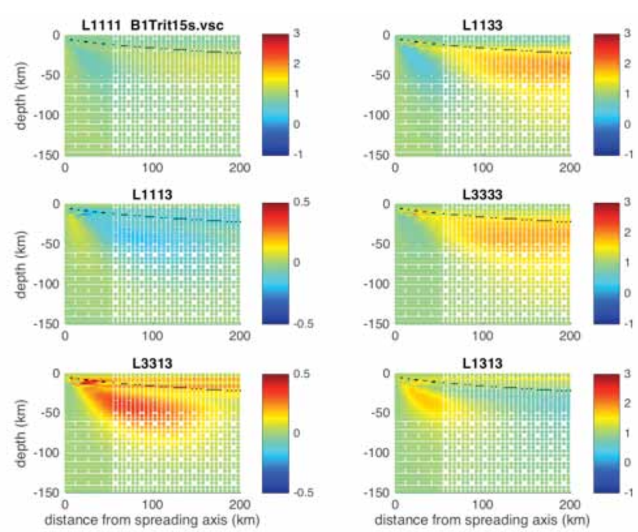

Figure 1b. Independent components of the 6x6 viscosity tensor based on asthenosphere CPO. Green indicates value near isotropic viscosity. Greatest rheologic anisotropy is predicted in the tight flow corner near the spreading axis (L3313 & L1313) and below the base of aging lithosphere (L1133 & L3333).

Recent Publications

Greene, J.A., M. Tominaga, D.K. Blackman, Geologic implications of seafloor character an carbonate lithification imaged on the domal core of Atlantis Massif, *Deep Sea Res.* **II**, 2015.

Menke, W., Y. Zha, S.C. Webb, D.K. Blackman, Seismic anisotropy indicates ridge-parallel asthenospheric flow beneath the E Lau Spreading Center, *J. Geophys. Res.*,doi: 10.1002/2014JB011154, 2015.

Wei, S.S., D.A. Wiens, Y. Zha, T. Plank, S.C. Webb, D.K. Blackman, R.A. Dunn, J.A. Conder, Seismological evidence of effects of water on mantle melt transport beneath the Lau back-arc basin, *Nature* **518**, doi:10.1038/nature14113, 2015.

YEHUDA BOCK, DISTINGUISHED RESEARCHER & SENIOR LECTURER

Director, Scripps Orbit and Permanent Array Center (SOPAC)

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Research Interests: GPS/GNSS, space geodesy, crustal deformation, early warning systems for natural hazards, seismogeodesy, GPS meteorology, data archiving and information technology, sensors

Our research group is application oriented with an emphasis on mitigating effects of natural hazards on people and critical infrastructure through improved forecasting, early warning and rapid response to events such as earthquakes, tsunamis, volcanoes and severe weather. We approach this in a holistic manner from the design and deployment of geodetic and other sensors, real-time data collection and analysis, physical modeling, for example a kinematic earthquake source model followed by tsunami prediction, to communicating actionable information the "last mile" to emergency responders and decision makers during disasters. We maintain a global archive of GNSS data including a growing database of high-rate measurements of large earthquakes, with accompanying IT infrastructure and database management system. In 2014-2015, the SOPAC group included Peng Fang, Jennifer Haase, Jianghui Geng, graduate students Diego Melgar, Dara Goldberg, Jessie Saunders and Lina Su (visiting from China), and Mindy Squibb, Anne Sullivan, Maria Turingan, Glen Offield and Allen Nance.

Earthquake Early Warning and Rapid Response

Reducing warning time is the key goal in early warning and rapid response to earthquakes of medium magnitude and greater in the near-source where losses are most severe. Rapid earthquake characterization requires real-time near-field displacement data in addition to strong motion data. Accurate broadband displacement and velocity waveforms can be estimated by seismogeodesy, the optimal combination of high-rate GNSS displacement observations with collocated very-high-rate accelerom-

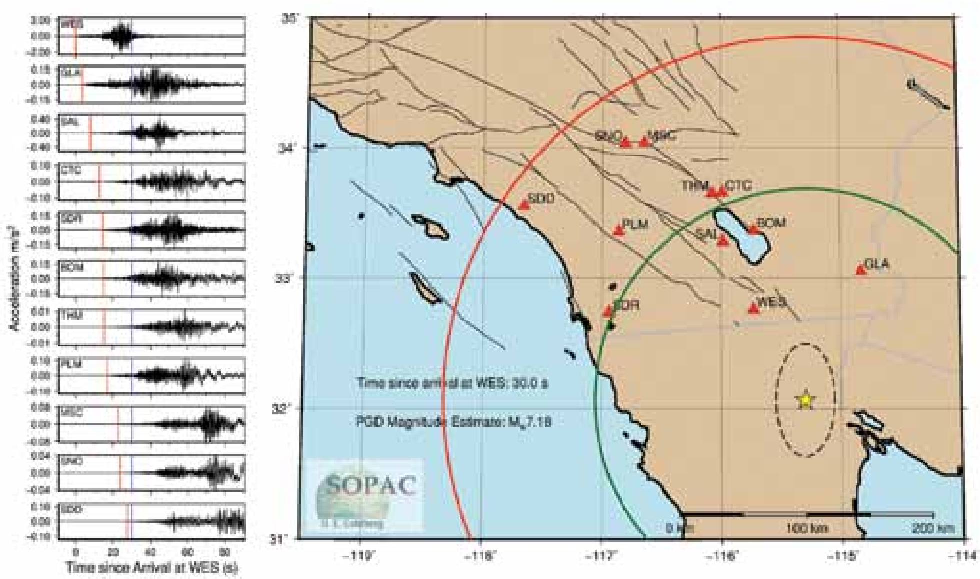

Figure 1. Example of earthquake early warning. 100 Hz seismogeodetic displacement and velocity waveforms were analyzed retrospectively in simulated real-time mode for the 2010 Mw 7.2 El Mayor-Cucapah earthquake in northern Baja California, Mexico. On the left are shown the acceleration waveforms at 11 GPS/seismic stations sorted by order of P-wave detection. The continuous blue vertical line denotes the current epoch. The preceding red lines indicate when the P wave was detected at each station. Once 4 stations have triggered, an estimate of the hypocenter can be made, denoted by the yellow star with one-sigma error ellipse on the map. Propagation of P and S waves can be determined as shown by the partial circles (red and green, respectively), with the S wave trailing the P wave. In this scenario, it would take the S wave front about 80-90 seconds until it arrived in the heavily-populated regions of Riverside and Los Angeles Counties. Shown here is one frame at 30 s after earthquake origin time using peak ground displacement (PGD) magnitude scaling providing an estimate of Mw 7.18, .02 magnitude units smaller than the final magnitude. Prepared by Dara Goldberg. A video showing the complete sequence can be obtained from Dara (degoldberg@ucsd.edu).

eter data. Currently, few collocated GNSS/strong-motion stations exist along the western coast of the U.S. where large earthquakes, including tsunamigenic earthquakes, can occur. For the purposes of affordable monitoring, we developed SIO Geodetic Modules and low-cost MEMS accelerometer packages ("GAPs"), designed as a simple plug-in for existing GNSS stations. The Geodetic Module is an instrument that receives, time tags, buffers, analyzes and transmits data from multiple sensors, including a GNSS receiver, accelerometer, and meteorological instruments (pressure and temperature).

Testing of the GAPs against observatory-grade accelerometers was conducted in an experiment on the Large High-Performance Outdoor Shake Table (LHPOST) at UCSD in December 2013 through January 2014, which used large-magnitude earthquake simulations based off of the seismic hazard for Berkeley, CA and Seattle, WA. Jessie Saunders and Dara Goldberg, third year PhD students, helped collect and analyze the data. Direct comparison of SIO MEMS accelerometers with observatory-grade accelerometers indicate that the two types of accelerometers agree within frequency ranges of engineering and seismological interest.

Currently, there are 25 collocated GNSS stations equipped with SIO GAPs in the field, 10 in the San Francisco Bay Area and 15 in southern California. The first assessment of the SIO MEMS packages in the field is underway thanks to four earthquakes of magnitude ~4 that occurred in the past year within this network. These earthquakes are too small to be of interest to earthquake early warning (typically magnitude 5.5 and higher) and have surface displacements well below the uncertainty level of the GNSS data. However, the SIO MEMS were sensitive enough to record the shaking within several tens of kilometers from the epicenters of these events, and the seismogeodetic combinations at these stations produced stable displacement and velocity time series. The seismogeodetic waveforms for these events showed that while an earthquake was occurring, the event was not developing into large ruptures with significant displacement, an important datum for whether or not to issue a warning for an earthquake of consequence. The combination of the analyses in the field and at the LHPOST demonstrate that GAPs are sufficient for early warning and that there is little benefit to investing in higher-cost upgrades to GNSS stations for the purposes of earthquake early warning.

We are implementing an automated detection algorithm that recognizes P waves on an individual station basis. This is followed by an automatic hypocenter estimation and earthquake magnitude scaling according to peak ground displacements (PGD), which will comprise a preliminary warning (Figure 1). The seismogeodetic dataset is uniquely fit for determining earthquake magnitude as the inclusion of GNSS data avoids underprediction (saturation) associated with acceleration data alone. Finally, a CMT solution, finite fault slip model, and tsunami model are estimated to provide a more detailed description of rupture parameters and potential hazard.

Using a combination of GNSS and inexpensive pressure and temperature sensors, we can also estimate the variations of water vapor in the lower atmosphere (troposphere), a critical driver of extreme weather such as the southern California summer monsoons. NOAA's weather forecasting offices in San Diego and Los Angeles Counties successfully used our data to forecast and track a monsoon in the summer of 2013 and issue an accurate flash flood warning for the region (Moore et al., 2014).

Recent Publications

Bock, Y. and D. Melgar (2015), Physical Applications of GPS Geodesy: A Review, Reports on Progress in Physics, in press.

Galetzka, J., et al. (2015), Slip pulse and resonance of Kathmandu basin during the 2015 Mw 7.8 Gorkha earthquake, Nepal imaged with space geodesy, *Science,* **349**, 1091. doi: 10.1126/science.aac6383

Melgar, D. and Y. Bock (2015), Kinematic earthquake source inversion and tsunami inundation prediction with regional geophysical data, *J. Geophys. Res.*, doi: 10.1002/2014JB011832.

Melgar, D., J. Geng, B. W. Crowell, J. S. Haase, Y. Bock, W. C. Hammond, and R. M. Allen (2015), Seismogeodesy of the 2014 Mw6.1 Napa earthquake, California: Rapid response and modeling of fast rupture on a dipping strike-slip fault, *J. Geophys. Res. Solid Earth,* **120**, doi:10.1002/2015JB011921.

Melgar, D., et al. (2015), Earthquake Magnitude Calculation without Saturation from the Scaling of Peak Ground Displacement, *Geophys. Res. Lett*. **42** (13), 5197-5205. doi: 10.1002/2015GL064278

Moore, A., I. Small, S. Gutman, Y. Bock, J. Dumas, J. Haase, M. Jackson, J. Laber (2015), Densified GPS Estimates of Integrated Water Vapor Improve Forecaster Situational Awareness of Variable Moisture Fields in the Southern California Summer Monsoon, *Bull. Amer. Meteorol. Soc.* (BAMS), doi:10.1175/BAMS-D-14-00095.1

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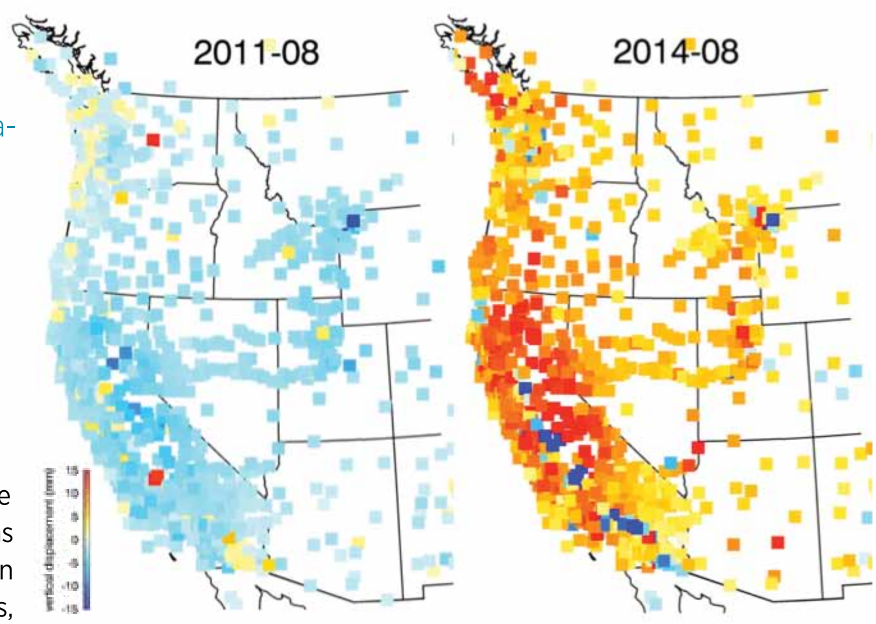
Research Interests: Remote hydrology from GPS and GRACE. Satellite altimeter calibration/ validation and measurements of topographic change. Differential lidar techniques applied to problems in geomorphology and tectonic geodesy. Kinematic GPS for positioning, mapping, and recording transient deformation due to earthquakes, fault creep and short-period crustal loading. GPS multipath and other noise sources. Dry lake geomorphology.



My recent research involves the characterization of the hydrological cycle using crustal loading observations from GPS, in collaboration with SIO colleagues Duncan Agnew and Dan Cayan. Changes in water storage in lakes, aquifers, soil moisture, and vegetation results in elastic deformation of the crust that yields measureable vertical displacements of the surface. The seasonal signal from water loading has been extensively studied, but loading changes over longer periods are typically smaller and have not been broadly documented. Since 2013, however, drought in the western USA has caused rapid and widespread uplift of mountainous areas of California and the West. The vertical displacements from the drought are unprecedented in magnitude over the past decade of continuous GPS observations.

The drought uplift signal, which exceeds 15 mm at locations in the Sierra Nevada, is large enough to be obvious by inspection of GPS time series. We apply a seasonal filter derived from the econometrics literature (the Seasonal-Trend-Loess estimator) to completely remove the annual signal due to water loading and pumping, and we invert the filtered GPS position data to recover the spatiotemporal loading required to account for observed uplift. In the case of the current drought, our estimate of the accrued water deficit ranges up to 50 cm and totals 240 gigatons, equivalent to a 10 cm uniform layer of water over the land area east of the Rocky Mountains. Currently, we are extending our analysis to look at short-term changes in loading from individual storms, and we are investigating drought-induced Coulomb stress changes on all faults in the UCERF3 fault model.

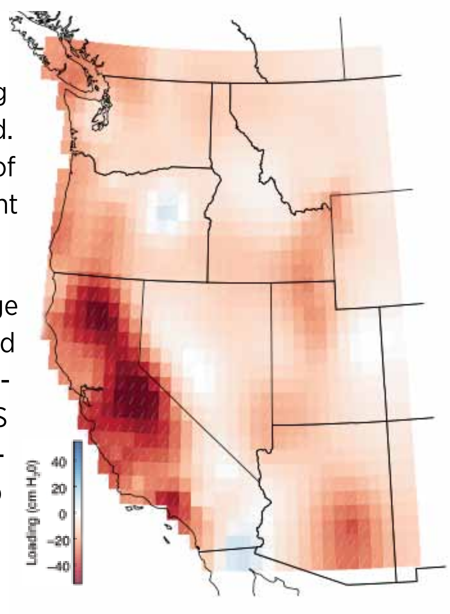
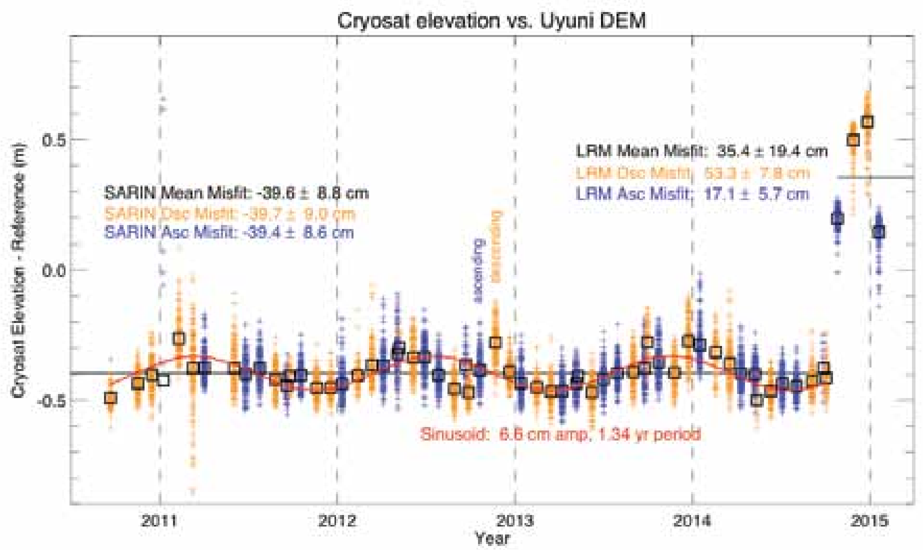


Figure 1. ***Above:*** *Spatial distribution of vertical displacements from Plate Boundary Observatory continuous GPS stations in the western USA in March of 2013 and 2014. Color indicates deviations of seasonally-adjusted elevations from decadal mean, with blues related to subsidence and yellow-reds related to uplift.* ***Below:*** *Mass load in mm of water equivalent derived from inversion of March 2014 vertical displacements, assuming elastic strains on a spherical Earth.*

My other primary area of research has been the calibration and validation of satellite altimeter measurements using a reference surface at the salar de Uyuni, Bolivia. In collaboration with SIO colleague Helen Fricker, I have led three expeditions to the salar de Uyuni (in 2002, 2009 and 2012) to survey the surface with kinematic GPS. We have established that the surface is both exceptionally flat (80 cm total relief over 50 km) and stable (< 3 cm RMS elevation change over a decade), while maintaining coherent geoid-referenced topography at wavelengths of tens of kilometers. In 2013, using our salar digital elevation model (DEM), I found and was able to identify the source of an inadvertent error in ICESat-1 processing that was the source of large shot-to-shot errors late in the mission period and that significantly changed ICESat-derived elevation change trends for the stable portions of the Greenland and Antarctic ice sheets.



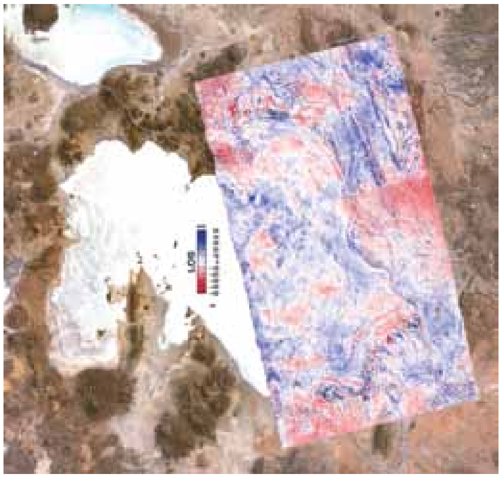


Figure 2: Left: Cryosat elevation validation relative to the salar de Uyuni DEM, with residuals showing a.) a uniform range bias of -40 cm for SARIN mode and +35 cm for LRM mode, b.) an 7 cm amplitude sinusoidal anomaly of 1.34 yr period that is still unexplained, and c.) higher range resolution than reported elsewhere, even with the sinusoidal anomaly. Right: ALOS InSAR results over the salar de Uyuni for the period 8/27/2010 ~ 1/12/2011, indicating that seasonal elevation change is <1 cm averaged over the salar surface.

Recently we have began to explore surface change at the salar using ALOS InSAR observations, with the goal of linking absolute GPS measurements with relative motions provided by InSAR to provide a continuous time series of surface displacement for calibration purposes. We have also expanded our cal/val activity to the CryoSat mission and are currently evaluating improvements between Baseline B and Baseline C datasets. Our ongoing interaction with the CryoSat mission team has led ESA to switch CryoSat from SARIN to LRM mode for all passes over the salar de Uyuni from 2015 onward, allowing us to provide a cross-calibration of elevations from these different operational modes.

Recent Publications

Becker, T.W., A.R. Lowry, C. Faccenna, B. Schmandt, A. Borsa, C. Yu (2015). "Western U.S. intermountain seismicity caused by changes in upper mantle flow." *Nature*, **524**, 458–461

Trugman, D.T., A.A. Borsa, D.T. Sandwell, (2014). "Did Stresses From the Cerro Prieto Geothermal Field Influence the El Mayor-Cucapah Rupture Sequence?" *Geophysical Research Letters*, **41**(24)

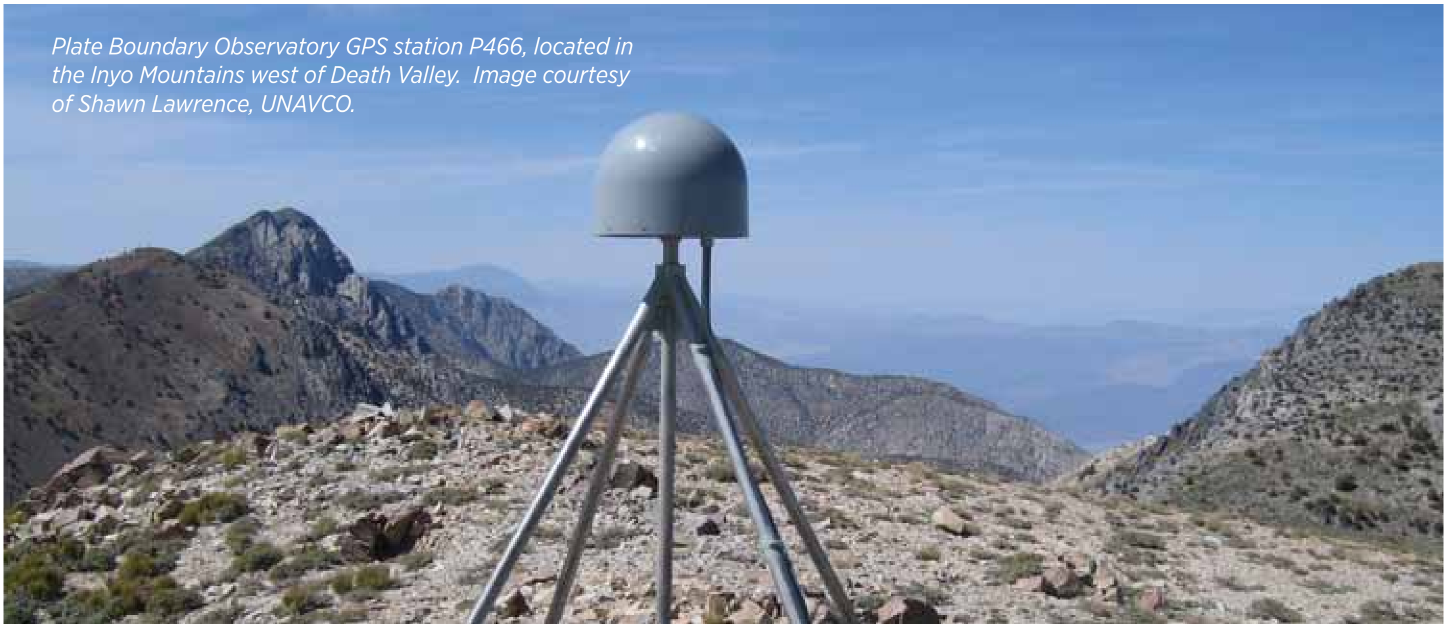


Plate Boundary Observatory GPS station P466, located in the Inyo Mountains west of Death Valley. Image courtesy of Shawn Lawrence, UNAVCO.

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Research Interests: Earth's magnetic field and electromagnetic environment; Paleo and geomagnetic secular variation; Linking paleomagnetic observations to geodynamo simulations; Paleomagnetic databases; Electrical conductivity of Earth's mantle; Inverse problems; Statistical techniques.

The natural spectrum of geomagnetic variations at Earth's surface extends across an enormous frequency range, and is controlled by a variety of internal and external physical processes. As indicated in the grand spectrum of field strength variations in Figure 1(a) the spatial origin of the sources can be roughly divided according to the characteristic time scales of their variations, into internal fields produced by the geodynamo in Earth's core, external fields generated in the magnetosphere and ionosphere as result of interactions with the solar wind and sferics (lightning) and anthropogenically generated signals. There are also lithospheric contributions to the field which are essentially static and make no contribution to the frequency spectrum.

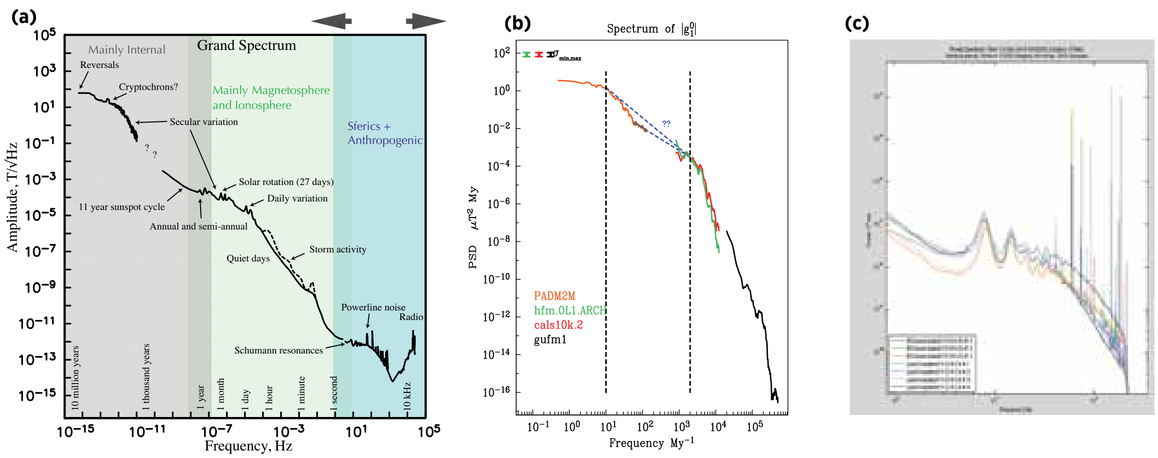

Figure 1. Amplitude spectrum of geomagnetic field variations at Earth's surface: (a) composite extending from 10^{-15} to 10^{5} Hz, based on paleomagnetic and direct surface magnetic field observations; (b) power spectrum of axial dipole moment variations based on models constructed from paleomagnetic (PADM2M, hfm.OL1.ARCH, cals10k.2) and geomagnetic data (gufm1); (c) uncalibrated spectrum from 1-500 Hz in ELF range showing sferics, Schumann resonances, and anthropogenic signals.

The overall shape of the spectrum is red, reflecting the time scale of variations in the predominantly dipolar internal field produced by the geodynamo in Earth's liquid outer core. Fluid flow in the highly electrically conductive (~ 10^6 Sm^{-1}), core produces a secular variation in the magnetic field, which propagates upward through the much lower conductivity mantle and lithosphere. The dipole part of the field has the longest term changes, associated with geomagnetic excursions and reversals which require the axial dipole part of the field to vanish as it changes sign. Finite electrical conductivity of the mantle effectively filters variations in the core field on time scales much less than a year. Thus the internal part of the spectrum is greatly diminished in the frequency range dominated by the solar cycle, and magnetospheric processes.

Ongoing research projects (with postdoc Sanja Panovska (IGPP) and Monika Korte of Geo- Forschungs Zentrum, Helmholtz Center, Potsdam) have been concerned with analysis of behavior of the geomagnetic field on centennial to 100 kyr timescales helping to fill the gap in Figure 1(a). Figure 1(b) shows new power spectra: the gap between 1 ky and 10 ky periods will be filled when 100 ky field models become available. This work has relied on compilations of published datasets for the MagIC (Magnetics Information Consortium with Lisa Tauxe, Anthony Koppers), and GEOMAGIA50.v3 database projects with Maxwell Brown (GeoForschungs Zentrum, Helmholtz Center, Potsdam). The 100 ky model being finalized now also allows a study of field structure during the Laschamp excursion which occurred around 40 ka. Work is continuing with PhD student Margaret Avery, postdoctoral researcher Christopher Davies (Leeds University, U.K.) and research associate David Gubbins on compatibility of numerical geodynamo simulations with paleomagnetic results.

Very long geomagnetic observatory records are being used to isolate external magnetic variations for deep mantle induction studies using geomagnetic depth sounding. Above the insulating atmosphere is the relatively electrically conductive ionosphere, which supports Sq currents as a result of dayside solar heating. Outside the solid Earth the magnetosphere, the manifestation of the core dynamo, is deformed and modulated by the solar wind, compressed on the sun side and elongated on the nightside. Inside the magnetosphere are the Van Allen Radiation belts, which are layers of energetic charged particles: usually there are two main belts typically ranging in altitude from about 1000 to 60 000 km. The outer belt, at about 3 Earth radii, contains the magnetospheric ring current which acts to oppose the main field is also modulated by solar activity. Magnetic fields generated in the magnetosphere and ionosphere propagate by induction into the conductive Earth, providing information on electrical conductivity variations in the crust and mantle.

At frequencies >1 Hz, the spectrum is dominated by sferics and anthropogenic noise, as in the local Californian data in Figure 1(c) This frequency range is useful for near-surface audiomagnetotelluric and global lightning studies. At frequencies higher than 104 Hz the global EM spectrum becomes blue, rising in response to man-made signals. In the spectrum of Figure 1(a) one can clearly see a frequency separation in the various natural sources, with signal from magnetic storms, and daily variation in the ionosphere dying away around 1 Hz, and the sferics losing energy around 1-3 kHz. These are well known as "dead bands" with very low signal in the MT source field.

Recent Publications

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Panovska, S., M. Korte, C.C. Finlay, and C.G. Constable (2015). Limitations in paleomagnetic data and modeling techniques and their impact on Holocene geomagnetic field models, *Geophysical Journal International,* **202**, 402–418, 10.1093/gji/ggv137

Brown, M.C., F. Donadini, M. Korte, A. Nilsson, K. Korhonen, A. Lodge, S.N. Lengyel and C.G. Constable (2015). GEOMAGIA50. v3: 1. General structure and modifications to the archeological and volcanic database, *Earth Planets Space,* **67**, 1–31, 10.1186/ s40623-015-0232-0

Brown, M.C., F. Donadini, A. Nilsson, S. Panovska, U.Frank, K. Korhonen, M. Schuberth, M. Korte, C.G. Constable (2015). GEOMAGIA50.v3: 2. A new paleomagnetic database for lake and marine sediments, *Earth Planets Space,* **67**, 1-19, 10.1186/ s40623-015-0232-0

Constable, C.G. & M. Korte (2015). Centennial to millennial-scale geomagnetic field variations , *Treatise on Geophysics (Second Edition), Volume 5, Geomagnetism,* Editor, M. Kono, Ed in Chief: G. Schubert, Elsevier, Amsterdam, Chapter 9, pp 309-341, ISBN: 978-0-444-53803-1, 10.1016/B978-0-444-53802-4.00103-2

Constable, C.G. (2015). Earth's Electromagnetic Environment, Surveys in Geophysics, submitted

STEVEN CONSTABLE PROFESSOR

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Research Interests: Marine EM methods, electrical conductivity of rocks

Steven Constable runs the SIO Marine Electromagnetic (EM) Laboratory at IGPP, and along with Kerry Key oversees the Seafloor Electromagnetic Methods Consortium, an industry funding umbrella which helps support PhD students and postdocs working in the group. The two main field techniques we use are controlled-source EM (CSEM), in which a deep-towed EM transmitter broadcasts energy to seafloor EM recorders, and magnetotelluric (MT) sounding, in which these same receivers record natural variations in Earth's magnetic field. Both methods can be used to probe the geology of the seafloor, from the near surface to hundreds of kilometers deep, using electrical conductivity as a proxy for rock type.

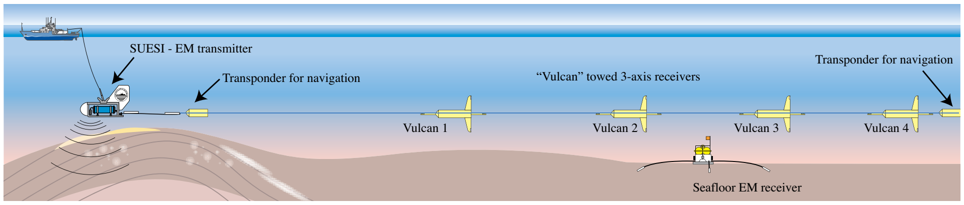

Figure 1. "Vulcan" array of towed, 3-axis electric field recorders.

The lab had another busy year, with an oshore geothermal study in Mexico, a second field season in the Arctic, and a second year of gas hydrate mapping oshore Japan. Kerry took the gear out on NSF-funded projects to the Aleutians and east coast USA.

Gas hydrate, a frozen mixture of water and gas (usually methane), is important as a seafloor hazard, a potential energy resource, and a source of a potent greenhouse gas. Our gas hydrate mapping work uses an array of electric field recorders that are towed behind our EM transmitter close to the seafloor (Figure 1). These "Vulcan" instruments (background and Figure 2) have been in development for a long time, but we made several significant upgrades this year which we tested on a short 2-day cruise in the San Diego Trough in March. We chose to tow over a known methane vent and cold seep near the north end of the Trough, just to see what we might see (Figure 3).

Background: EM transmitter being recovered during a gas hydrate survey for the Japanese government (photo courtesy Ocean Floor Geophysics).

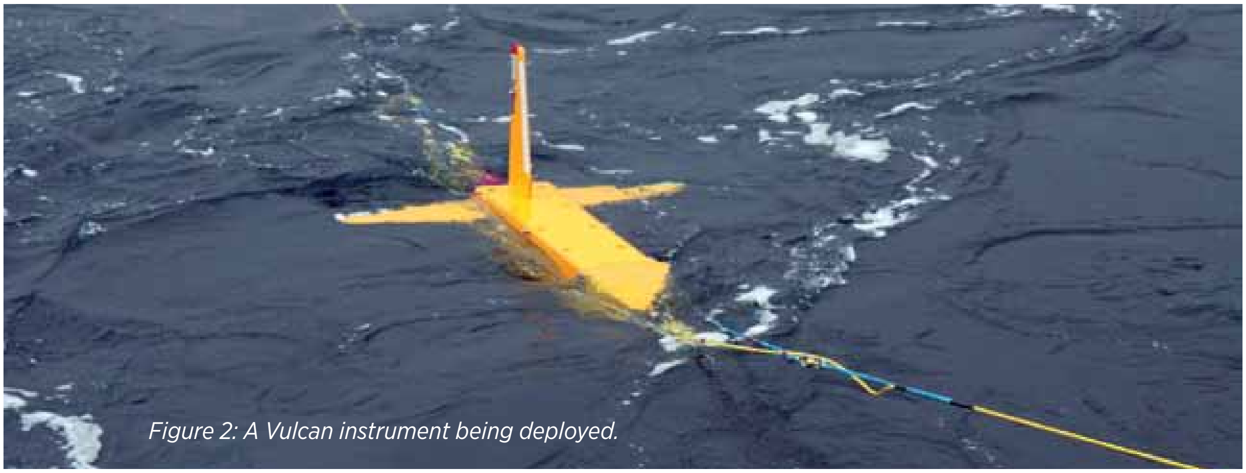

Figure 2: A Vulcan instrument being deployed.

The instrument upgrades resulted in very high quality data. Graduate student Peter Kannberg inverted the data and Figure 3 shows the result of one tow across the methane vent. Beneath the seep there is a tabular resistor about 1 km across extending from a depth of about 50 m below the sea floor to a depth of around 150 m. At the location of the methane vent we see the high resistivities coming up to the sea floor. The high electrical resistivity of this body (nearly 100 m) and its location within the gas hydrate stability field implies that the resistor is massive hydrate. The methane vent is associated with the San Diego Trough Fault, which presumably provides a path for methane migration from depth.

During the summers of 2015 and 2016 we helped carry out large surveys of oshore gas hydrate for the Japanese geological survey. Although this work is proprietary, it is very exciting to be playing an important part in Japan's alternative energy program.

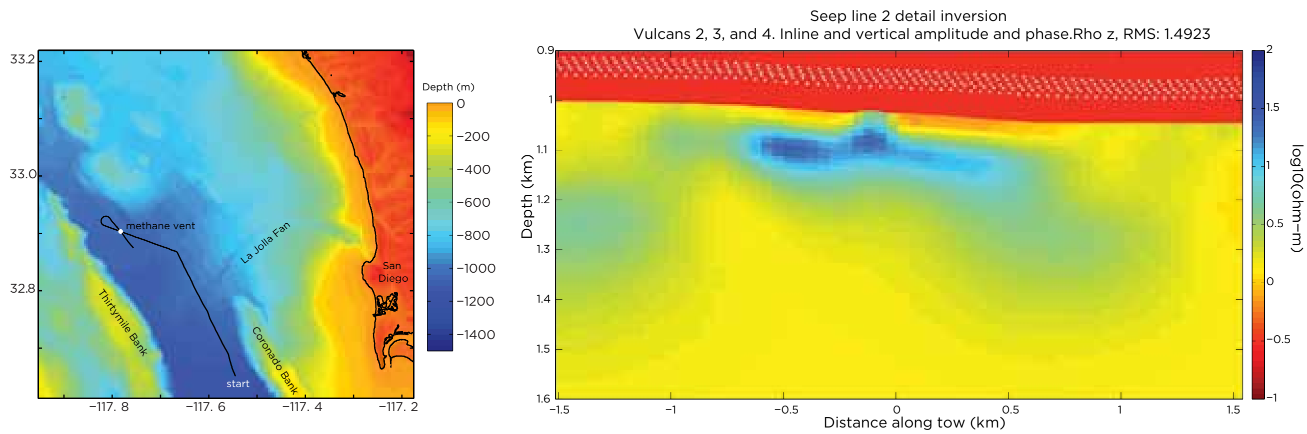

Figure 3: Left: Map of our test tow. Right: Electrical conductivity image of methane seep in the San Diego Trough.

Recent Publications

Du Frane, W., L.A. Stern, S. Constable, K.A. Weitemeyer, M.M. Smith, and J.J. Roberts (2015) Electrical properties of methane hydrate + sediment mixtures, *Journal of Geophysical Research,* **120**, 4773–4783, 10.1002/2015JB011940

Constable S. (2015) Geomagnetic Induction Studies, in: *Treatise on Geophysics, 2nd edition*. Gerald Schubert, editor. Oxford: Elsevier 219-254. 10.1016/B978-0-444-53802-4.00101-9

Wheelock, B., S. Constable, and K. Key (2015) The advantages of logarithmically scaled data for electromagnetic inversion, *Geophysical Journal International*, **201**, 1765–1780, 10.1093/gji/ggv107

Myer, D., K. Key, and S. Constable (2015) Marine CSEM of the Scarborough gas field, Part 2: 2D inversion, *Geophysics,* **80**, E187–E196, 10.1190/GEO2014-0438.1

Constable, S., A. Orange, and K. Key (2015) And the geophysicist replied: "Which model do you want?", *Geophysics*, **80**, E197–E212, 10.1190/GEO2014-0381.1

Further information can be found at the lab's website, http://marineemlab.ucsd.edu/

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Research Interests: seismology, time series analysis, geophysical data acquisition

My research responsibilities at IGPP center upon managing the scientific performance of Project IDA's portion of the Global Seismographic Network (GSN), a collection of 40 seismographic and geophysical data collection stations distributed among 26 countries worldwide. IDA recently concluded upgrading the core data acquisition and power system equipment at all stations using funding provided by NSF via the IRIS Consortium.

During the next phase of network operation, IDA's staff will fine-tune each station's instruments to enable scientists to extract the most accurate information possible from the data collected. One method for accomplishing this task is by examining key phenomena such as Earth tides and normal modes that should register the same on these important geophysical sensors. To the extent that measurements made with multiple instruments that have been calibrated in very different fashions match, we may have greater confidence that the instrument response information IDA distributes with GSN waveform data is accurate. Investigators use this information to compensate for the frequency-dependent sensitivity of sensors so that they may study true ground motion and its underlying physical causes. One test of these methods is illustrated below.

Figure 1 shows very long period normal modes excited by a large earthquake that occurred recently in Chile and recorded on the vertical components of three seismometers installed at IGPP's Seismic Test Facility at the Pinyon Flat Observatory. The upper portion of the figure shows prominent spectral peaks whose frequencies tell us much about the internal structure of the Earth. To the extent that the peaks observed on the three separate instruments overly one another indicates that the responses of each instrument are well determined. Where the spectra do not agree may be attributed to instrument noise.

The consistency of the spectral measurements is clarified in the lower portion of the figure. Here are plotted the ratio of the peak amplitude observed on each of the two instruments (XPFO.*) under test compared to the standard instrument (PFO.*). Any deviation of the mean of these distributions away from unity or linear trend would indicate a problem with the instrument response. That is not observed here. The scatter in the points, which is a measure of instrument noise, begins to increase substantially below 1.5 mHz.

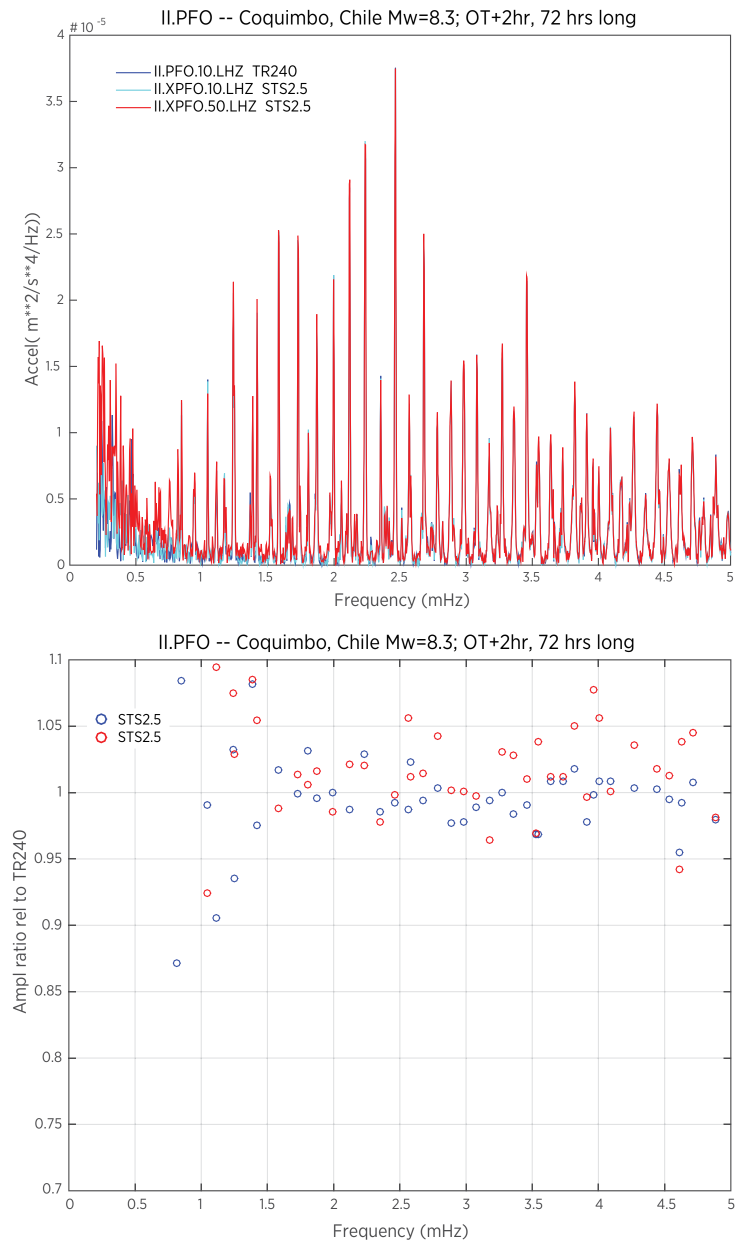

Figure 1. Top: Long period spectra computed from 72-hr long time series beginning 2 hours after the origin time of the 2015 Mw=8.3 Coquimbo, Chile earthquake. The spectra largely overly one another above 1.5mHz indicating the instrument responses are well known. Instrument noise contributes to disagreement below that frequency. Bottom: Amplitude ratio of the test instruments' (XPFO) peaks to the known standard (PFO.10.LHZ). Ideally all points should be unity. That they average to unity indicates the instrument responses are well known; the scatter is a measure of noise.*

IDA is playing a leading role in a program to evaluate new models of seismometers that may be deployed within the GSN in the future. The two instruments under test here are part of that effort. With new instrumentation and continued data collection from the present instruments of the GSN, we can expect steady scientific progress in understanding Earth structure and earthquakes.

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Research Interests: Acoustic propagation modeling with application to infrasound; application of infrasound to nuclear test-ban verification and hazard monitoring; use of dense seismic and infrasound networks to analyze infrasound signals and also very long wavelength gravity waves.

My main research area is in the physics of infrasound – sound at frequencies lower than human hearing – as well as its applications to investigating large scale atmospheric processes, as well as explosive processes such as bolides and large explosions. Two of the projects that I have been involved in for the past several years are outlined below.

An automated event detector and locator: In the past year, I have worked on the development of a new, automated, method to detect and locate events in two-dimensional space and time using large volumes of data. The method is used to create a catalog of infrasound sources in the eastern United States and southeastern Canada using infrasonic and seismic data recorded by the USArray Transportable Array (TA). The purpose of developing this catalog is twofold. First, the catalog provides a list of sources that can be used for basic infrasound research, either for remote study of the events themselves or to study of properties of the atmosphere. Second, we need to understand and document the noise field or other sources that may hamper the performance of International Monitoring System infrasound arrays in monitoring the Comprehensive Nuclear Test Ban Treaty. The method has been successfully applied to TA data – over 1000 events were found in the Midwest and on the east coast in 2013 as shown in the figure below. The method is currently being tested on seismic data to improve current methods of finding small seismic events.

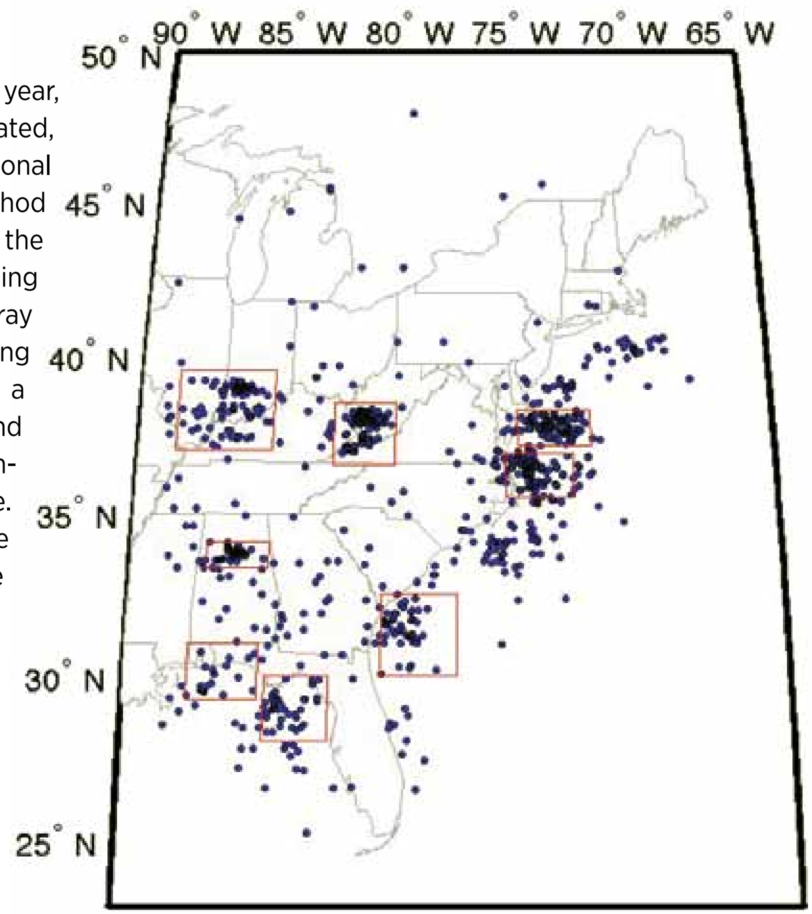

Figure 1. Infrasound events locations for 2013. The tightly clustered events outlined by the red rectangles occur mostly from 08:00 to 18:00 local time, so we associate them with anthropogenic activity. Several clusters are associated with known mining regions. Very few events are detected between 00:00 and 04:00 local time despite particularly low noise levels at this time that would improve detection rates. These events are randomly distributed across the study area. Several of these isolated events are associated with the terminal burst of meteors entering Earth's atmosphere.

Numerical modeling: A basic research goal in infrasound is to understand the transmission of infrasound through variable atmospheric conditions. To this end I have developed a computationally efficient numerical method to synthesize the propagation of nonlinear acoustic waves through the atmosphere – this nonlinearity arises when pressure perturbations associated with acoustic waves are a significant fraction of the ambient atmospheric pressure. Such situations can arise from meteoroid explosions in the upper atmosphere, volcanic eruptions, or nuclear and chemical explosions. With support from the Air Force Research Laboratory (AFRL), work on this code has progressed to allow for the incorporation of realistic atmospheric effects, such as spatially varying sound speeds and wind speeds, topography, and atmospheric attenuation. The use of this code allows one to determine to what extent nonlinearity affects the estimated source yields for anthropogenic explosions.

Recent Publications

de Groot-Hedlin, C.D., Hedlin, M.A.H. 2015, A method for detecting and locations geophysical events using groups of arrays, *Geop. J. Int.,* doi: 10.1093/gji/ggv345

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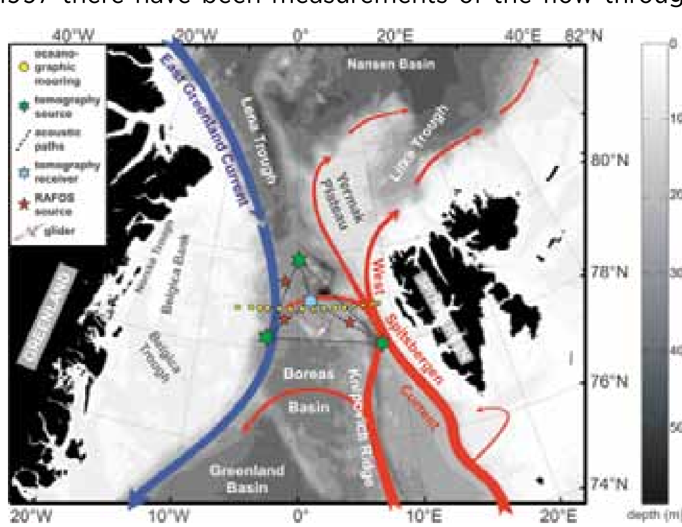
Research Interests: Acoustical Oceanography, signal processing for ocean acoustics.

My research has been on using the acoustical properties of sound transmission in the ocean to infer properties of the ocean. An example of this is recent work that I have been doing in the Fram Strait with Peter Worcester at IGPP and with colleagues in the Nansen Center in Bergen, Norway. The Fram Strait is the only deep-water connection between the Arctic and the rest of the world's oceans. It is a narrow channel, about 150 km across located between Greenland and Spitsbergen. There is a current along the eastern side of the strait that carries warm, salty water from the Atlantic into the Arctic. There is also a cold fresh current along the western side of the strait. These two currents exchange heat and mass between the basins.

A map of the Fram Strait is shown in the first figure. Since 1997 there have been measurements of the flow through the strait by a line of current meter moorings. These moorings have also measured temperature and salinity. Since 2010 there has also been an acoustic array in the strait that has measured the travel-time of sound propagating across it. This measurement is integral in its nature and thus captures small-scale variability that is invisible to the point measurements. The travel-time is a strong function of temperature due to the dependence of sound-speed on temperature. Reciprocal transmissions measure flow.



Learning how to interpret the acoustic measurements has not been straightforward. There are multiple propagation paths between each source-receiver pair and the receptions are highly variable. Nonetheless, accounting for the natural scattering results in stable, resolvable, and identifiable arrivals. An example of the acoustic arrival pattern is shown in the bottom panel of the second figure. Peaks in the pattern correspond to separate acoustic paths. We have recently learned that a standard interpretation of the sound propagation path as a ray path is not always appropriate.

The top panels of the second figure show the full-wave interpretation of the travel-time sensitivity of the arrival peaks to sound-speed changes in the ocean. The upper left panel shows an arrival (#1) that one interprets in the standard way, with a ray path. The ray path is shown in black and overlaid with the full-wave sensitivity. The upper right panel shows a full-wave sensitivity for an arrival (#2) that is markedly different than the ray path. There are areas of positive as well as negative sensitivity. Also the sensitivity is not confined to the first Fresnel zone. A two year time series of travel-time measurements is now being analyzed using these methods.

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Dzieciuch, M.A, "Signal processing and tracking of arrivals in ocean acoustic tomography", *J. Acoust. Soc. Am.,* **136**, 2512-2522 (2014).

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Research interests: earthquake physics, crustal deformation, space geodesy, volcanology

Professor Fialko's research is focused on understanding the mechanics of seismogenic faults and magma migration in the Earth's crust, through application of principles of continuum and fracture mechanics to earthquakes and volcanic phenomena. Prof. Fialko is using observations from space-borne radar satellites and the Global Positioning System (GPS) to investigate the response of the Earth's crust to seismic and magmatic loading.

One of the particular interests is nite slip models of large earthquake ruptures from inversions of dense space geodetic data. Prof. Fialko and graduate student Kang Wang used data from the ALOS-2 satellite and continuous GPS network to investigate the rupture pattern of the 2015 magnitude 7.8 Gorkha (Nepal) earthquake that occurred in the central Himalaya, on a tectonic boundary resulted from the India-Eurasia collision. The earthquake caused more than 8000 fatalities, and was the largest seismic event in the area over the last 50 years. The data used in the inversion include vector displacements measured at 13 GPS stations and Line-Of-Sight (LOS) displacements derived from Synthetic Aperture Radar (SAR) data from 3 tracks of the ALOS-2 satellite. The fault geometry (in particular, the dip angle) was found as part of the solution using a grid search. The best-tting model (Figure 1) has a shallow dip angle of 7˚. The rupture of the 2015 Gorkha earthquake was dominated by thrust motion that was primarily concentrated in a 150-km long zone 50 to 100 km northward from the surface trace of the Main Frontal Thrust (MFT), with maximum slip of 266 m at a depth of 268 km. Most of the aftershocks occurred along the eastern half of the fault, around the patches of relatively large coseismic slip, including the M_w 7.3 aftershock on May 12th, 2015 (magenta circle in Figure 1). The slip model shows that the 2015 rupture did not propagate into shallow part of the Main Hymalaian Thrust (MHT). GPS measurements made before the earthquake indicate that the MHT is locked from surface to a distance of approximately 100 km down dip. Recent investigations of the Quaternary geomorphology along the MFT showed that at least two great earthquakes had ruptured to the surface in Nepal in the past 1000 years. Particularly, the 1934 Bihar-Nepal M 8.2 earthquake ruptured a ~ 150 km-long segment of the MFT between 85.8˚E and 87.3˚E, immediately to the east of the 2015 rupture (Figure 1). Unless the degree of seismic coupling varies along the fault strike , the lack of shallow slip during the 2015 Gorkha earthquake implies future seismic hazard, in particular because this part of the fault has been brought closer to failure by the 2015 earthquake. Observations of post-seismic deformation (in particular, the occurrence of afterslip on the upper section of the MFT) will provide important constraints on the degree of seismic coupling and seismic hazard on this part of this fault.

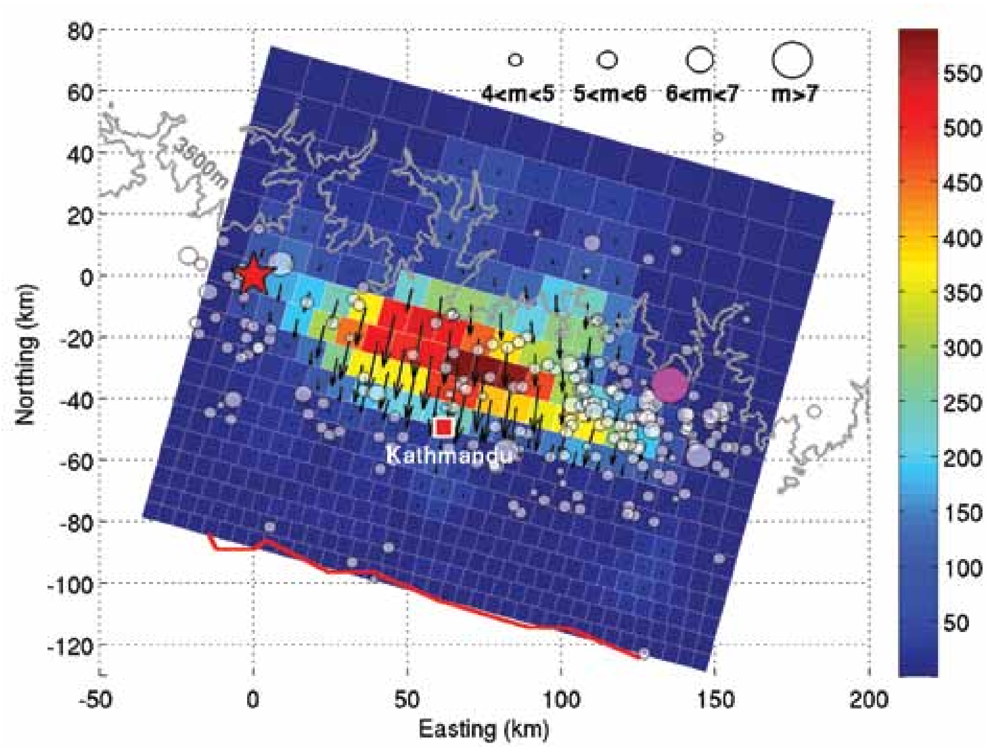

Figure 1. Surface projection of the coseismic slip model of the 25 April M_w 7.8 Gorkha earthquake. Red line represents the surface trace of MFT used to constrain the strike of the fault plane. Red star denotes the epicenter of the M_w 7.8 main-shock. Gray dots denote the aftershocks of m > 4 from 25 April to 31 May, 2015. The M_w 7.3 aftershock of 12 May 2015 is shown by a magenta circle. Color shows the slip magnitude in cm, and arrows correspond to the slip directions. The gray line represents the surface elevation of 3500m. Red square denotes the city of Kathmandu. The origin corresponds to the epicenter of the mainshock (84.731˚E, 28.230˚N). From Kang and Fialko [2015].

Another area of prof. Fialko's interests is observations and modeling of interseismic deformation. One of the main limitations to space geodetic measurements of low-amplitude (sub-centimeter) deformation is the atmospheric variability. In a recent study prof. Fialko and graduate student Katya Tymofyeyeva developed a new method for estimating radar phase delays due to propagation of electromagnetic waves through the troposphere and the ionosphere. The method takes advantage of the fact that the interferograms that share a common date also share the same propagation delay due to the atmosphere or long-wavelength "ramp" due to imprecise knowledge of spacecraft orbits. The respective signals can be estimated by averaging of radar interferograms that share a common scene. Estimated atmospheric contributions are then subtracted from the radar interferograms to improve measurements of surface deformation. Inversions using synthetic data demonstrate that this procedure is able to recover up to 95% of the atmospheric signal, and considerably reduce scatter in the timeseries of the line-of-sight displacements. Feasibility of the method was demonstrated by comparing the Interferometric Synthetic Aperture Radar (InSAR) time series derived from ERS-1/2 and ENVISAT data to continuous Global Positioning System (GPS) data from Eastern California.

Recent Publications

Wang, K. and Y. Fialko, Slip model of the 2015 Mw7:8 Gorkha (Nepal) earthquake from inversions of ALOS-2 and GPS data, *Geophys. Res. Lett.,* **42**, 7452-7458, 2015.

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Mitchell, E., Y. Fialko, and K. Brown, Frictional properties of gabbro at conditions corresponding to slow slip events in subduction zones, *G-cubed,* in press.

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Research Topics: cryosphere, Antarctic ice sheet, subglacial lakes, ice shelves, satellite remote sensing

My research focuses on the Earth's cryosphere, and specifically on understanding the processes driving changes on the Antarctic ice sheet. The Scripps Glaciology Group now has 3 postdocs, 1 Staff Researcher and 2 graduate students. Two of my postdocs were former graduate students Fernando Paolo and Matthew Siegfried who defended their PhDs in September and October 2015 respectively.

One of the primary questions in Antarctica is whether its mass is changing due to climate change, and its potential impact on sea-level rise. Due to its vast size, and the long time periods over which it can change, satellite data are crucial for routine monitoring of Antarctica, in particular data from radar and laser altimetry, and also imagery. My group specializes in monitoring the Antarctic Ice Sheet, focussing on two key dynamic components of the ice-sheet system: (i) active subglacial lakes and (ii) the floating ice shelves. We primarily uses satellite altimetry, either satellite radar altimetry from ERS-1/ERS-2 and Envisat which provides a long record (1994-2012) or NASA's Ice, Cloud & land Elevation Satellite (ICESat), which provides accurate elevation data for ice sheet change detection for the period 2003-2009. I describe these two major projects below:

SUBGLACIAL LAKES The Antarctic Ice Sheet is on average 2.2 km thick and rests on top of bedrock; the insulation, high pressures, and geothermal heat flux at the ice-bed interface leads to melting of the basal ice layers on the order of mm/year (Joughin et al., 2003). When averaged over the entire ice sheet, this produces high volumes of subglacial water (an amount of 65 Gt/yr was estimated by Pattyn et al., 2010), much of which is stored in subglacial lakes (Siegert et al., 2005) and subglacial aquifers (Christoffersen et al., 2014). In 2006 I discovered active subglacial water systems under the fast-flowing ice streams of Antarctica using ICESat data. This was inferred from observations of large height changes (up to 10m in some places) in repeat-track ICESat data, which corresponded to draining and filling of subglacial lakes beneath 1-2 km of ice. We continue to monitor active lakes, and we have found 124 in total throughout Antarctica. In the decade since the discovery of active Antarctic subglacial water systems, much progress has been made in our understanding of these dynamic systems. My former graduate student (now postdoc) Matthew Siegfried extended the record of volume change for all lakes under the CryoSat-2 mask up to 2015.

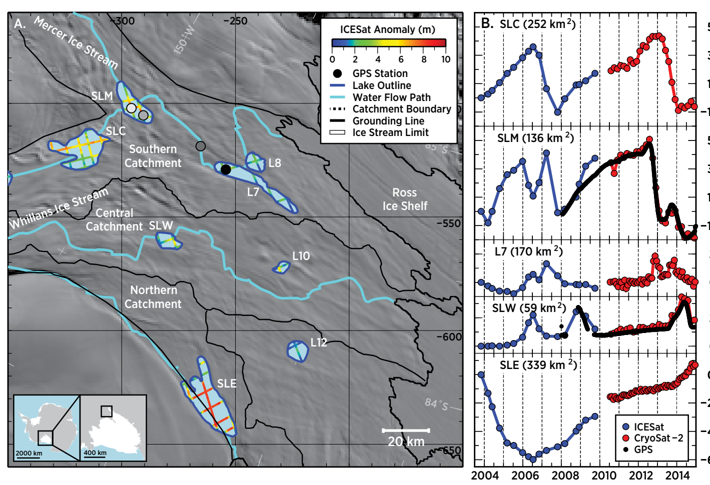

Figure 1. Subglacial water system of the Whillans/Mercer ice streams, West Antarctica. A. Map of the subglacial lakes in the system (blue outlines) annotated with ICESat track segments used to detect them (colour-coded by surface height change). The lakes are contained within three separate hydrologic systems, and the hydrologic flowpaths and catchment boundaries are shown. B. Time series of average height change over the four largest lakes from ICESat, CryoSat-2 and GPS.

I was a PI on a large, interdisciplinary 6-year NSF project (Whillans Ice Stream Subglacial Access Research Drilling (WISSARD)) to drill into one of the subglacial lakes that I discovered—Subglacial Lake Whillans (SLW) on Whillans Ice Stream (WIS; Figure 1)—and the region of the grounding line across which the subglacial water flows and enters the ocean. The final field season was 2015-2016 and my graduate student Matthew Siegfried led the GPS survey, which was centred on the lakes themselves, and the grounding line downstream.

ICE SHELVES The Antarctic Ice Sheet is surrounded by floating ice shelves that are several hundred metres thick. Since ice shelves have already displaced their weight in water, their melting does not contribute directly to sea level. However, ice shelves provide mechanical support to 'buttress' seaward flow of grounded ice, so that ice-shelf thinning and retreat result in enhanced ice discharge to the ocean (Scambos et al., 2005; Rignot et al., 2005). We used satellite radar altimeter data from a series of three ESA satellites to obtain estimates of ice-shelf surface height since the early 1990s. These data revealed accelerated losses in total Antarctic ice-shelf volume from 1994 to 2012 (Paolo et al., 2015; Figure 2).

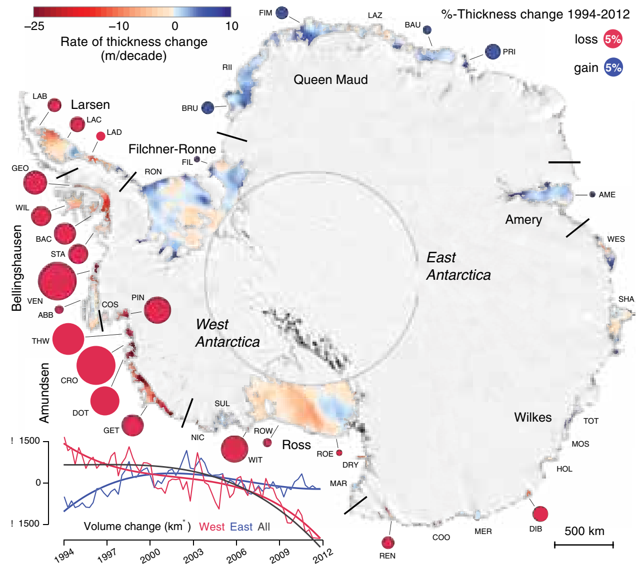

Figure 2. Eighteen years of change in thickness and volume of Antarctic ice shelves. Rates of thickness change (m/decade) are color-coded from -25 (thinning) to +10 (thickening). Circles represent percentage of thickness lost (red) or gained (blue) in 18 years. Lower left corner shows time series and polynomial fit of average volume change (km3) from 1994 to 2012 for the West (in red) and East (in blue) Antarctic ice shelves. Black curve is polynomial fit for All Antarctic ice shelves.

Changes in mass for East and West Antarctic ice shelves were not synchronous. In East Antarctica the first half of the record showed a mass increase, believe to be a result of increased accumulation. In West Antarctica, and in particular its Bellingshausen and Amundsen Sea regions, ice shelves lost mass throughout the record although with changes in rates on multi-year time scales. Ice-shelf thinning in these regions was substantial: some ice shelves thinned by up to 18% in 18 years. This thinning raises concerns about future loss of grounded ice and resulting sea level.

Recent Publications

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Bougamont, M., P. Christoffersen, S. Price, H. A. Fricker, S. Tulaczyk, S.P. Carter (2015). Reactivation of Kamb Ice Stream tributaries triggers century-scale reorganization of Siple Coast ice flow *Geo Res Lett*, in press.

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Massom, R. A., A.B. Giles, R. C. Warner, H.A. Fricker, B. Legrésy, G. Hyland, N. Young (2015). External influences on the Mertz Glacier Tongue (East Antarctica) in the decade leading up to its calving in 2010. *J of Geo Res: Earth Surface*, **120**(3), 490-506.

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Research Interests: Marine seismology, mid-ocean ridges, continental rifting, tectonic hazards in California

Axial Seamount is a large submarine volcano situated on the spreading axis of the Juan de Fuca Ridge offshore of Washington and Oregon. It has a history of frequent volcanic activity with the latest eruption occurring in April 2015. Due to its activity and proximity to shore, Axial Seamount is the most extensively studied seafloor volcano on earth and has been the object of numerous scientific expeditions over the last three decades covering geology, geochemistry, geophysics and biology. It is now home to a permanent seafloor observatory with nearly 40 instruments on its summit and east flank connected to shore and sending back real time data. Despite this interest, relatively little has been known about the subsurface structure of the seamount, with the primary information coming from a 3D seismic tomography experiment that used six Ocean Bottom Seismographs (West et al., 2001). Better knowledge of the subsurface structure can help to better constrain the response to magmatic intrusions, better locate earthquakes, and improve understanding of the tectonic history.

We have analyzed a grid of 12 multichannel seismic (MCS) profiles covering Axial Seamount in conjunction with travel times from the earlier OBS experiment. The individual MCS profiles have been downward continued and used for both travel time tomography and waveform inversion, producing high resolution velocity models of the upper 1+ km of the crust (Arnulf et al., 2014a). These models and MCS travel times have in turn be used for prestack depth migration and for a 3D tomographic inversion in combination with the earlier OBS travel times. The upper crustal velocity models capture the largest subsurface velocity variations and gradients outside of any magma chambers, facilitating much better imaging of deeper structure by both the migration and 3D tomography. The improved knowledge of upper crustal structure allows the travel time delays associated with long ray paths beneath the seamount to partitioned between an upper crustal delay due to the summit caldera and one associated with the deeper magma chamber structure, while the earlier image smeared the two together (West et al., 2001).

The depth migrated images reveal a very large primary magma chamber approximately 14 km long, 3 km wide and up to 1 km thick centered ~1.5-2.5 km beneath the large horseshoe shaped caldera at the summit of the seamount (Figure 1; Arnulf et al., 2014b). The magma chamber width is similar to that of the caldera, but lengthwise it extends beyond the northwest and southeast limits of the caldera. The imaging also reveals a secondary, smaller magma chamber to the Northwest

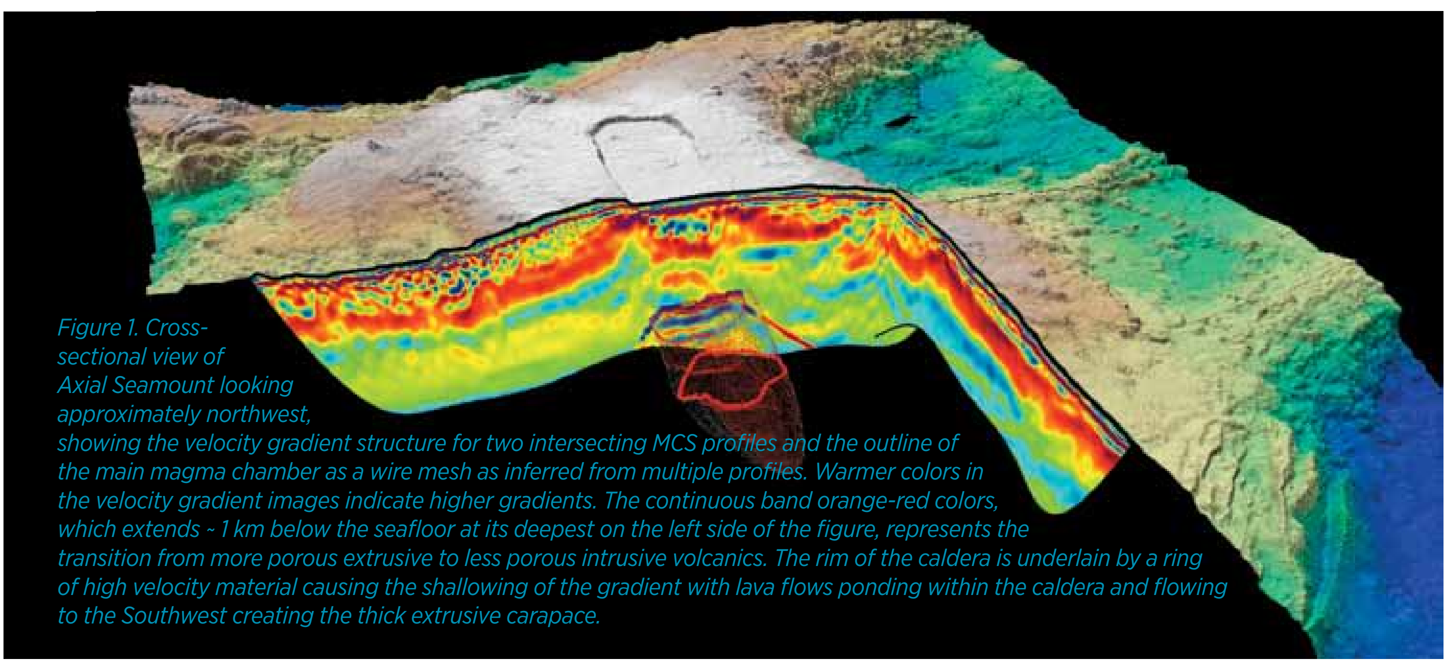

Figure 1. Cross-sectional view of Axial Seamount looking approximately northwest, showing the velocity gradient structure for two intersecting MCS profiles and the outline of the main magma chamber as a wire mesh as inferred from multiple profiles. Warmer colors in the velocity gradient images indicate higher gradients. The continuous band orange-red colors, which extends ~ 1 km below the seafloor at its deepest on the left side of the figure, represents the transition from more porous extrusive to less porous intrusive volcanics. The rim of the caldera is underlain by a ring of high velocity material causing the shallowing of the gradient with lava flows ponding within the caldera and flowing to the Southwest creating the thick extrusive carapace.

at approximately the same depth as the main chamber and a possible connection between the two. Extrusive volcanics within the caldera appear to thicken rapidly towards the northwest end of the caldera where the boundary scarp is the highest, suggesting that caldera subsidence has persistently been greater at this end of the caldera. The magma chamber is shallowest at the southeast end of the caldera and this is the site of both the 2011 eruption and known hydrothermal vents. This region of the chamber also appears to have the highest melt concentration based on variations in reflection amplitude in the migrated images, which indicates the magma chamber is zoned between melt and mush rich regions. The 3D tomography results indicate that the deeper travel time delays can be explained by a ~1-2 km/s velocity reduction within the main magma chamber and a slightly smaller reduction associated with the secondary chamber without the need for an additional reservoir.

Recent Publications

Arnulf, A. F., A. J. Harding, S. C. Singh, G. M. Kent, and W. C. Crawford (2014a), Nature of upper crust beneath the Lucky Strike volcano using elastic full waveform inversion of streamer data, Geophys. J. Int., 196(3), 1471–1491, doi:10.1093/gji/ggt461.

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West, M., W. Menke, M. Tolstoy, S. Webb, and R. Sohn (2001), Magma storage beneath Axial volcano on the Juan de Fuca mid-ocean ridge, Nature, 413, 833–836, doi:10.1038/35101581.

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Research Interests: Study of large atmospheric phenomena, study of long-range propagation of subaudible sound in the atmosphere, seismo-acoustics

INFRASOUND: The study of subaudible sound, or infrasound, has emerged as a new frontier in geophysics and acoustics. We have known of infrasound since 1883 with the eruption of Krakatoa, as signals from that event registered on barometers around the globe. Initially a scientific curiosity, the field briefly rose to prominence during the 1950's and 1960's during the age of atmospheric nuclear testing. With the recent Comprehensive Test-Ban Treaty, which bans nuclear tests of all yields in all environments, we have seen renewed interest in infrasound. A worldwide network of infrasound arrays, being constructed for nuclear monitoring, is fueling basic research into man-made and natural sources of infrasound, how sound propagates through our dynamic atmosphere and how best to detect infrasonic signals amid noise due to atmospheric circulation. This network has been supplemented with deployments, such as the 400-station seismo-acoustic USArray Transportable Array (TA), for basic research and enhanced monitoring of regions of great interest.

RESEARCH AT L2A: The Laboratory for Atmospheric Acoustics (L2A) is the home of research in this field at IGPP. Several faculty, post-docs and PhD students work full or part time in L2A, supported by engineers and technicians in the lab and the field. More information about this lab can be found at l2a.ucsd.edu. Presently we study a broad suite of problems related to both natural and man-made sources.

DENSE NETWORK STUDIES: The global infrasound network is unprecedented in scale however it is still very sparse, with ~ 100 stations operating worldwide. To increase the density of sampling of the infrasonic wavefield we have used acoustic–to-seismic coupled signals recorded by dense networks, such as the 400-station USArray Transportable Array (TA) and various PASSCAL deployments. We have used the original (seismic-only) TA network to create a catalog of atmospheric events in the western United States similar to commonly used seismic event catalogs. The acoustic catalog is used in part to find sources of interest for further study and to use the recorded signals to study long-range infrasound propagation. Recorded signals from instantaneous sources are commonly dispersed in time to several 10's of seconds. Modeling indicates that this is due to interaction of the sound waves with fine-scale structure in the atmosphere due to gravity waves. We are currently using infrasound to constrain the statistics of this time-varying structure.

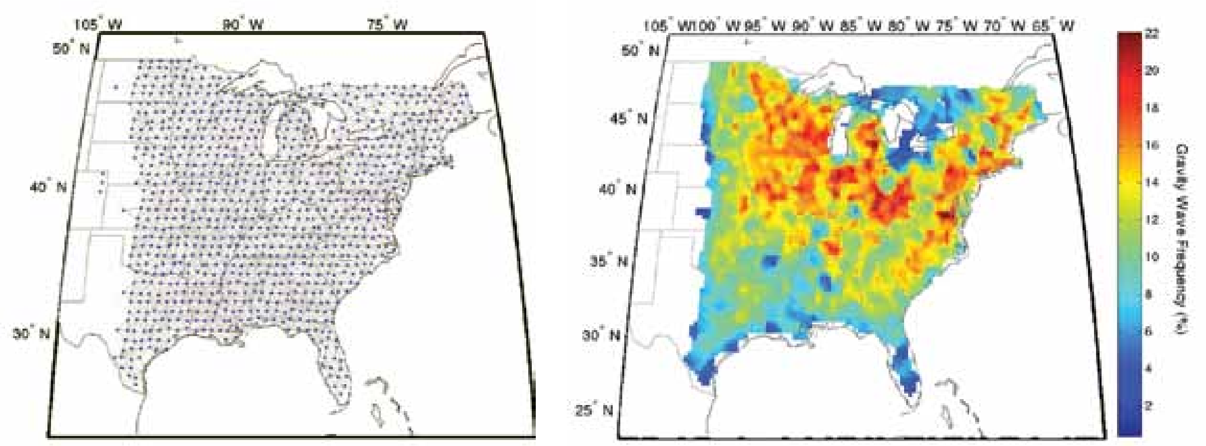

Figure 1. left) sites occupied by stations in the TA from January 1, 2010 through Sept 30, 2014. These stations have been grouped into 3-element arrays (triads) for the study of long-period atmospheric gravity waves. The panel on the right shows the frequency of gravity waves in this time period with the count weighted by the amplitude of each detected wave. The most vigorous activity occurs to the west of the Great Lakes, as expected from satellite studies.

The National Science Foundation funded our group to upgrade the entire TA with infrasound microphones and barometers. Our sensor package is sensitive to air pressure variations from D.C. to 20 Hz, at the lower end of the audible range. The upgrade converted the TA into the first-ever semi-continental-scale seismo-acoustic network. The network has moved east across the US as stations are redeployed. Figure 1 (left panel) shows station locations from January 1, 2010 through the end of September, 2014. We have divided this collection of stations into 3,600 elemental arrays (triads) to study atmospheric gravity waves. An early result is shown in the right panel of figure 1. This map shows a histogram of gravity waves in the 2-6 hour pass-band weighted by the amplitude of each detected wave. As expected, large gravity waves are common to the west of the Great Lakes due largely to convective activity. Other structure apparent in the image, such as the low along the Appalachian mountain trend, with the string of hotspots to the east, is actively being studied.

FIELD OPERATIONS: Our group has built infrasound arrays for nuclear monitoring in the US and Africa. We operate research arrays located near San Diego.

Recent Publications

Brown, P., Assink, J., Astiz, L.,Blaauw, R., Boslough, M., Borovicka, J., Brachet, N., Brown, D., Campbell-Brown, M., Ceranna, L., Cooke, W., de Groot-Hedlin, C., Drob, D., Edwards, W. Evers, L., Garces, M., Gill, J., Hedlin, M.A.H., Kingery, A., Laske, G., Le Pichon, A., Mialle, P., Moser, D., Saffer, A., Silber, E., Smets, P., Spalding, R., Spurny, P., Tagliaferri, E., Uren, D., Weryk, R., Whitaker, R., Krzeminski, Z., 2013, The Chelyabinsk airburst: Implications for the Impact Hazard, *Nature,* doi: 10.1038/nature12741.

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de Groot-Hedlin, C.D. and Hedlin, M.A.H., 2014, Infrasound detection of the Chelyabinsk Meteor at the USArray, *Earth and Planetary Sciences Letters* http://dx.doi.org/10.1016/j.epsl.2014.01.031

Edwards, W.N., de Groot-Hedlin, C.D. and Hedlin, M.A.H., 2014, Transportable Array Acoustic capabilities confirm apparent meteor sighting, in press with *Seismological Research Letters*.

Hedlin, M.A.H. and Drob, D.P., 2014, Statistical characterization of atmospheric gravity waves by seismoacoustic observations, *J. Geophys. Res. Atmos.,* doi: 10.1002/2013JD021304

Ship Rock in Umnak Pass

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Research Interests: Marine electromagnetic exploration, subduction zones, mid-ocean ridges, continental margins, hydrocarbon exploration, finite element methods, parallel computing, geophysical inversion.

My research uses electromagnetic geophysical methods to study the geologic structure and fluids of the oceanic crust and upper mantle. Along with Steven Constable, I manage the Seafloor Electromagnetic Methods Consortium at Scripps, an industry funded program that brings in support for the PhD students and postdocs working in our group.

This year my graduate student Samer Naif completed his PhD thesis (Naif, 2015), which focused on the Serpentinite, Extension and Regional Porosity Experiment across the Nicaraguan Trench (SERPENT). We collected this data set several years ago, but as is often the case with new research endeavors, it takes some time to develop the tools required by the unique aspects of each data set. We think the results have been worth the wait. Figure 1 shows the complete electrical conductivity model derived from non-linear 2D inversion of the controlled-source electromagnetic data. We decided that trying to publish the complete story in one paper was going to be too much material, so we've split this image at the trench and first published the incoming plate story (Naif et al., 2015), which describes how bending faults that form in the trench outer rise are high porosity channels that increase the bulk water content of the subducting plate by about a factor of two. We are currently working on a manuscript describing the results from the right side of the image, where the subducting plate carries down fluid rich sediments beneath the forearc margin.

The other papers published this year are associated with our work with the offshore exploration industry. Myer et al. (2015), Constable et al. (2015) and Hoversten et al. (2015) look at controlled-source EM data collected for imaging geologic structures at oil and gas fields offshore Australia, the Gulf of Mexico and near the Faroe and Shetland Islands, respectively. Wheelock et al. (2015) looks at a particular aspect of EM data analysis with the unexpected result that scaling the data into the logarithm domain offers a better chance for robust interpretation.

We also had a string of luck this year with funding from the National Science Foundation. The MOCHA magnetotelluric survey described in last year's annual report received funding for the data interpretation phase. Early in the year we also found out that two field surveys were going to be funded and that both had accelerated schedules with cruises on the books for the summer. The first of these was an amphibious survey of Okmok volcano in the Aleutian islands of Alaska that involved collecting seafloor magnetotelluric data across the volcanic arc and a three week onshore campaign of magnetotelluric data collection and broadband seismometer installation inside and around Okmok caldera, done in collaboration with colleagues at UW Madison, the USGS and Alaska Volcano Observatory. I will include results from this project in next year's report, but in the mean time you can check out photos and videos of the field work on our blog at http://okmok.ucsd.edu. The second field survey this summer involved collecting controlled-source EM data to map offshore groundwater on the continental shelf off New Jersey and Martha's Vineyard, with a successful cruise in early September.

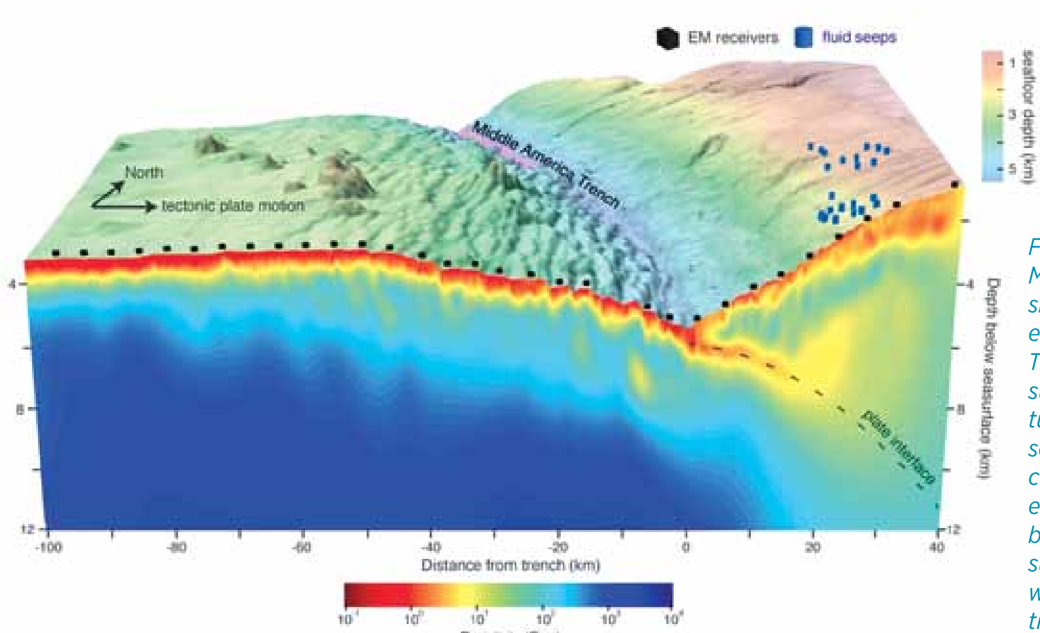

Figure 1. The electrical structure of the Middle American subduction zone offshore Nicaragua obtained from nonlinear inversion of deep-towed CSEM data. The vertical cross-section shows the sub-seafloor electrical resistivity structure and the stitched upper panel shows seafloor bathymetry. The dark blue cubes show the location of EM receivers. The region of the seafloor marked by steeply dipping relief correlates with sub-vertical conductive channels, which we interpret as evidence for the migration of seawater along bending faults. From Naif (2015).

Recent Publications

Naif, S., K. Key, S. Constable, and R. L. Evans (2015), Water-rich bending faults at the Middle America Trench, *Geochemistry, Geophysics, Geosystems*, **16**(8), 2582–2597, doi:10.1002/2015GC005927.

Naif, S. N. (2015), Marine electromagnetic experiment across the Nicaragua Trench: Imaging water-rich faults and melt-rich asthenosphere, PhD thesis, University of California, San Diego.

Constable, S., A. Orange, and K. Key (2015), And the geophysicist replied: "Which model do you want?," *Geophysics*, **80**(3), E197–E212, doi:10.1190/geo2014-0381.1.

Hoversten, G. M., D. Myer, K. Key, D. Alumbaugh, O. Hermann, and R. Hobbet (2015), Field test of sub-basalt hydrocarbon exploration with marine controlled source electromagnetic and magnetotelluric data, *Geophysical Prospecting*, **63**, 1284–1310, doi:10.1111/1365-2478.12278.

Wheelock, B., S. Constable, and K. Key (2015), The advantages of logarithmically scaled data for electromagnetic inversion, *Geophysical Journal International*, **201**(3), 1765–1780, doi:10.1093/gji/ggv107.

Myer, D., K. Key, and S. Constable (2015), Marine CSEM of the Scarborough gas field, Part 2: 2D inversion, *Geophysics*, **80**(3), E187–E196, doi:10.1190/geo2014-0438.1.

DEBORAH LYMAN KILB, PROJECT SCIENTIST

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Research Interests: Deborah Kilb's current research areas include crustal seismology and earthquake and icequake source physics, with an emphasis on understanding how one quake can influence another.

EXPLORING REMOTE EARTHQUAKE TRIGGERING POTENTIAL USING FREQUENCY DOMAIN ARRAY VISUALIZATION *[Linville et al., 2014]*. To better understand earthquake source processes involved in dynamically triggering remote aftershocks, we use data from the EarthScope Transportable Array (TA), an array of over 400 seismic stations deployed in a grid pattern in the continental US. These stations provide uniform station sampling, similar recording capabilities, large spatial coverage, and in many cases, repeat sampling at each site. To avoid spurious detections, which are an inevitable part of automated time-domain amplitude threshold detection methods, we developed a frequency domain earthquake detection algorithm that identifies coherent signal patterns through array visualization (Figure 1). This method is tractable for large datasets, ensures robust catalogs, and delivers higher resolution observations than what are available in current catalogs. We explore to what extent there is an increase or decrease in small earthquake activity (i.e., seismicity rate changes) local to the TA stations following 18 global mainshocks (M≥7) that generate median peak dynamic stress amplitudes of 0.001- 0.028 MPa across the array. For these 18 mainshocks, we find no evidence of prolific or widespread remote dynamic triggering in the continental U.S. within the mainshock's wavetrain or within the next 2 days following the mainshock stress transients. There is, however, limited evidence of seismicity rate increases in localized source regions. These results suggest that for these data, prolific, remote earthquake triggering is a rare phenomenon. We further conclude that within the lower range of previously reported triggering thresholds, surface wave amplitude does not correlate well with observed cases of dynamic triggering. Therefore, other characteristics of the triggering wavefield, in addition to specific site conditions, must contribute to triggering at these amplitudes.

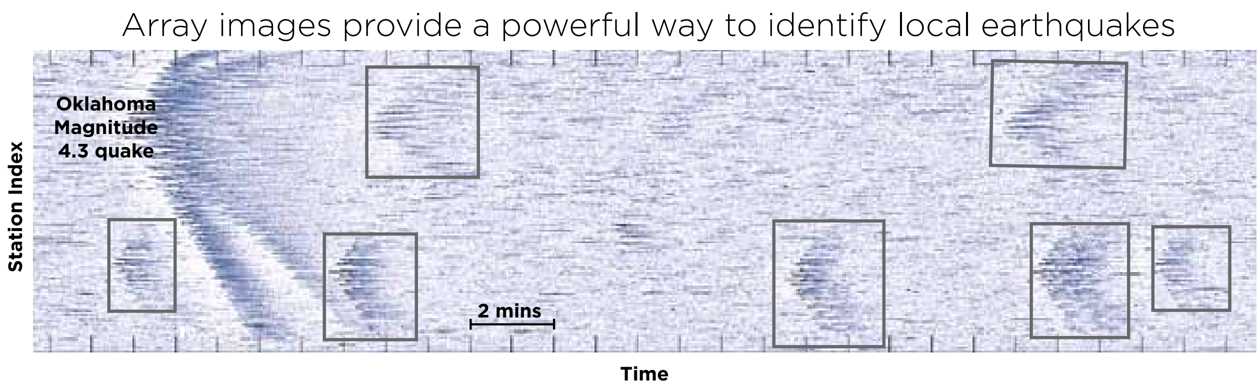
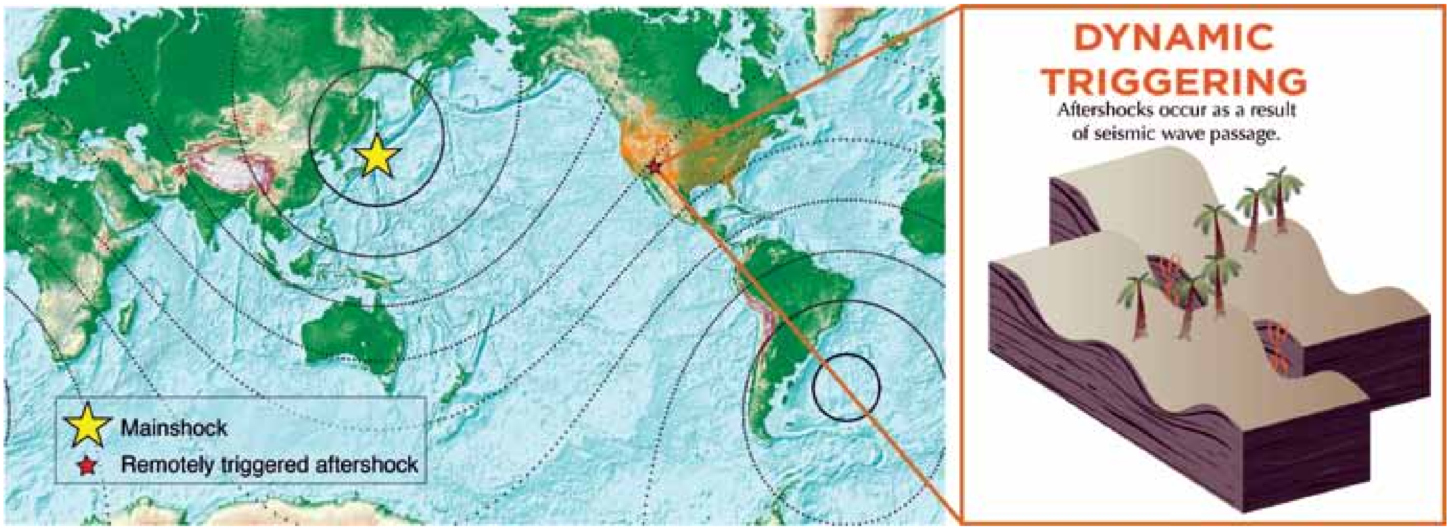


Figure 1. Data from the 02/27/2010 Chile M8.8 mainshock recorded by 415 USArray stations. In these "array images" we assign each pixel element a hue that represents amplitude intensity (higher amplitudes in darker hues). We use these array images to identify local and remote earthquakes based on amplitude variations in combination with appropriate seismic move-out. For example, a magnitude 4.3 earthquake in Oklahoma is visible across the entire array (upper left of the image, unboxed). We examine these high-frequency signals to identify those that are likely local (black boxes) or regional earthquakes.

HUMMING ICEQUAKES *[Heeszel et al., 2014]*: Mountain glaciers represent one of the largest repositories of fresh water in alpine regions globally. However, little is known about the processes by which water moves through these systems. Gornersee is a lake that forms each spring at the confluence of two glaciers in the Swiss Alps. This lake drains during most summers, sometimes suddenly. Because glacial lake drainage events can occur with little or no warning, there is the potential for damaging floods in valleys below the glacier. We use seismic recordings collected near the lake to look for signs of water moving through fractures near the glacier bed. We see tremor, signals that are stronger at specific frequencies, in both single icequakes and over long periods. These observations suggest there is a complex network of fluid induced fracture processes at the glacier base. Modeling changes in the observed harmonic frequencies indicates that seismic data's spectral characteristics can provide important information about hydraulic fracture geometry and fluid pressure at depth. Similar to industrial fracking, this hydraulic fracturing at the base of a glacier can provide a mechanism to track fluid flow within glaciers in near real-time.



GLACIER AMBIENT NOISE STUDY *[Walter et al., 2015]*: We use seismic ambient noise data from the Greenland Ice Sheet and a Swiss Alpine glacier. Using the direct and scattered wave fields from the vast numbers of icequake records (tens of thousands per month), we can measure small changes in englacial (within the glacier) velocities, and in turn monitor bedrock depth and structural changes within the ice. In this way, seismic networks can be used to monitor a glacier's subsurface structure at sub daily time scales over months or longer. This constitutes a clear advantage over active source techniques that require considerable manpower for data acquisition.

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Walter, F., P. Roux, C. Roeoesli, A. Lecointre, DL Kilb, P-F. Roux [2015]. "Using glacier seismicity for phase velocity measurements and Green's function retrieval", *Geophysical Journal International*, **201**: 1722-1737, doi: 10.1093/gji/ggv069.

GABI LASKE, PROFESSOR IN RESIDENCE

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Research interests: regional and global seismology; surface waves and free oscillations; seismology on the ocean floor; observation and causes of seismic noise; natural disasters and the environment

Gabi Laske's main research area is the analysis of seismic surface waves and free oscillations, and the assembly of global and regional seismic models. She has gone to sea to collect seismic data on the ocean floor. Laske's global surface wave database has provided key upper mantle information in the quest to define whole mantle structure. Graduate students Christine Houser and Zhitu Ma as well as students from other universities have used her data to compile improved mantle models.

GLOBAL REFERENCE MODELS: Laske has collaborated with Guy Masters, graduate student Zhitu Ma and Michael Pasyanos at LLNL to compile a new lithosphere model, LITHO1.0. A 1-degree crustal model, CRUST1.0 was released in 2013 for initial testing. Applications relying on CRUST1.0 are found across multiple disciplines in academia and industry, and sometimes reach into quite unexpected fields such as the search for Geoneutrinos. Laske has continued to compile community feedback and provides updates to the distribution website and links to related research outside of IGPP.

THE PLUME PROJECT: For the past decade or so, Laske has been focusing on waveforms collected on ocean bottom seismometers (OBSs). She was the lead-PI of the Hawaiian PLUME project (Plume–Lithosphere–Undersea–Mantle Experiment) to study the plumbing system of the Hawaiian hotspot. Results from both body wave and surface wave tomography were published. During the last two years, Laske has collaborated with Kate Rychert to identified two upper-mantle boundaries that align with anomalies found in the surface wave study. The published images suggest a restite root beneath the Island of Hawaii around which ascending plume material has to flow, providing a possible cause for the low-velocity anomaly to the west of Hawaii. Laske has worked with Christine Thomas at M¨unster University, Germany to search for new and previously unmapped D” precursors in the PLUME database. The good quality of vertical-component records allowed the team to detect PdP waves for some areas and found convincing null-results for other areas. This is the first study of its kind using OBS data.

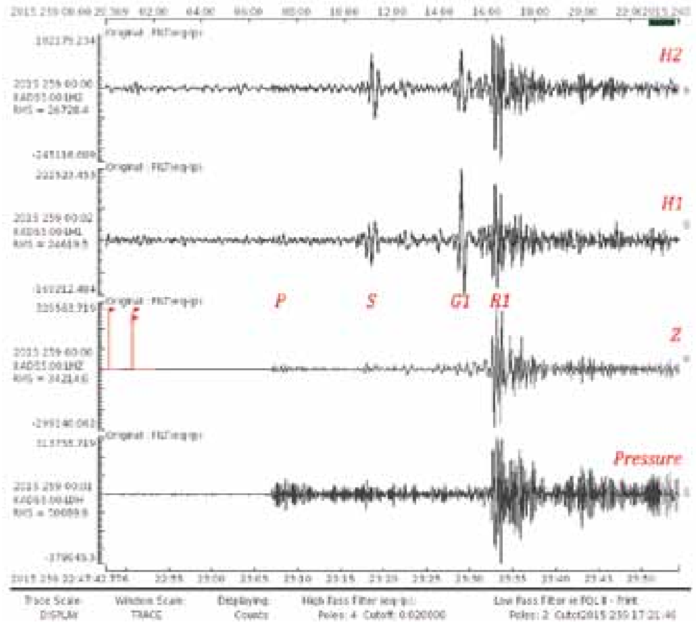

Figure 1. Near-real-time fourcomponent OBS time series of the of the great tsunamigenic Sep 16, 2015 Illapel, Chile earthquake. Top three traces are the two horizontal and the vertical component of a Nanometrics Trillium T-240 seismometer. The bottom record is from a differential pressure gauge (DPG) developed at SIO. The traces are bandpass filtered to emphasize long-period seismic waves. Laske and Programmer Analyst David Chavez witnessed how the waveform arrived on IGPP computer screens in near-real time.

We are continuing the analysis of frequency-dependent Rayleigh-wave azimuthal anisotropy. While shear-wave splitting results appear to be sensitive only to the fossil spreading direction “frozen” into the lithosphere, Laske found a clear signal in the longperiod data that suggests a plume-related flow in the asthenosphere beneath Hawaii. This served served as project for IRIS intern Rachel Marzen who presented an AGU poster at the 2013 Fall meeting.

PhD student Adrian Doran continues the analysis of PLUME seafloor compliance as well as ambient-noise Green’s functions. The combined analysis will help constrain elastic parameters in the shallow sediments and crustal layers that were not resolved by the surface wave study.

THE ADDOSS PROJECT: For the ADDOSS (Autonomously Deployed Deep-ocean Seismic System) Laske collaborates with Jon Berger, John Orcutt and Jeff Babcock and Liquid Robotics Inc. to develop an untethered OBS system that is capable of providing near-real time data collected on the ocean floor. A wave glider towing an acoustic modem in a tow body maintains a communications link to the OBS, where the glider then sends data to shore via satellite. The group has performed several tests in shallow (1000 m) and deep (3800 m) water. During a 3-month deep-water test about 300 km west of La Jolla in the winter of 2013 provided crucial new seismicity data. The group has identified several magnitude 2 seismic events that remained undetected by shore-based seismic monitoring networks that include island stations in the Inner California Borderland. In addition, a pair of seismometers picked up numerous micro earthquakes, for which the location determination is still ongoing. Doran and Laske successfully competed for UC ship funds and smaller UC grants for a follow-up deployment near the 2013 site, and ADDOSS joined as a piggy-back experiment. Due to needed repairs, the wave glider was sent from shore later. It successfully established communication after a 10-day ride. On Sep 16, 2015, the group witnessed how the waveforms of the great Illapel, Chile earthquake arrived in near-real time. The instrument also successfully recorded the tsunami that arrived some 12 hours later. A nearby DART buoy was not operational at the time.

Recent Publications

Ma., Z., Masters, G., Laske, G. and Pasyanos, M., A comprehensive dispersion model of surface wave phase and group velocity for the globe, *Geophys. J. Int.,* **199**, 113-135, DOI: 10.1093/gji/ggu246, 2014

Thomas, C. and Laske, G., D" observations in the Pacific from PLUME Ocean Bottom Seismometer recordings. *Geophysical Journal International,* **200**, 851–862, doi:10.1093/ gji/ggu441, 2015.

Laske, G., Berger, J., Orcutt, J. and Babcock, J., ADDOSS: Autonomously Deployed Deep-ocean Seismic System - Communications Gateway for Ocean Observatories, Proceedings of the IUGG eGeneral Assembly, Prague, Czech Republic, July 2015.

Berger, J., Laske, G., Babcock, J. and Orcutt, J., An Ocean Bottom Seismic Observatory with Real-time Telemetry. *Earth and Space Science,* in revision, 2015.

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Research Interests: Seismology, Geodesy, Data Science and Policy

After chairing the ICSU World Data System (ICSU-WDS) Scientific Committee (SC) since 2008, I have rotated off that position in July, 2015, and the new chair is Professor Sandy Harrison of the University of Reading.

Of the six years of my tenure as Chair of the SC, WDS has grown from an idea proposed by the International Council of Science (ICSU) at their 2008 General Assembly in Maputo, Mozambique, to a global system, counting 94 members. These include

- *61 Regular Members,* organizations that are data stewards and/or data analysis services,
- *10 Network Members,* umbrella bodies representing groups of data stewardship organizations and/or data analysis services,
- *5 Partner Members,* organizations that are not data stewards or data analysis services, but that contribute support or funding to ICSU-WDS and/or WDS Members, and
- *18 Associate Members,* organizations that are interested in the WDS endeavor and participate in our discussions, but that do not contribute direct funding or other material support.

ICSU World Data System Scientific Committee meeting at IGPP, February 8, 2015.

In addition, thanks to the generosity of the Japanese Government, and in particular the National Institute of Information and Communications Technology (NICT), ICSU-WDS enjoys the support of an International Programme Office (WDS-IPO). The agreement between ICSU and NICT to host the IPO has recently been extended until March 31, 2021, thereby providing WDS with a stable home base for the next 5 years, and to live up to its motto *"Trusted Data Services for Global Science."*

The World Data System continues to animate and lead several international working groups to address difficult data science problems. As Chair of the SC, I have participated in their work and continue to do so. These include:

- Data Publishing
- Creation of a Knowledge Network
- Streamlining the Certification of trusted data repositories (in partnership with the Data Seal of Approval (DSA)

In addition, WDS sponsors a series of worldwide webinars on current data community issues.

In the course of this past year, WDS has been engaged in numerous global activities. First and foremost, the First international Scientific Data Conference (SciDataCon-2014) was held in New Delhi, India in collaboration with ICSU Committee on Data for Science and Technology (CODATA). The theme of the conference was *"Data Sharing and Integration for Global Sustainability."* On that occasion, WDS awarded its first two Data Stewardship Awards to Dr. Robert Redmon and Dr. Xiaogang Ma for "exceptional contributions to the improvement of scientific data stewardship by early career researchers through their (1) engagement with the community, (2) academic achievements, and (3) innovations."

Recent work of the WDS-SC involved a reworking of its Data Policy, necessitated to accommodate the special requirements of disciplines such as Health Sciences, and Social Sciences. The revised policy us currently being aligned with that of the Group on Earth Observations (GEO). Special attention is being accorded to the rapidly expanding concept of Open Access worlswide. In my report to the 2014 ICSU General Assembly in Auckland I emphasized the potential blind applications of metrics to evaluate the value of data sets. This caution is now part of the ICSU record.

In the past year, WDS was represented in innumerable scientific meetings and forums. WDS is now a partner with GEO/GEOSS, and a significant participant in the new *Future Earth* ICSU program. I have participated on a number of these, too numerous to list here.

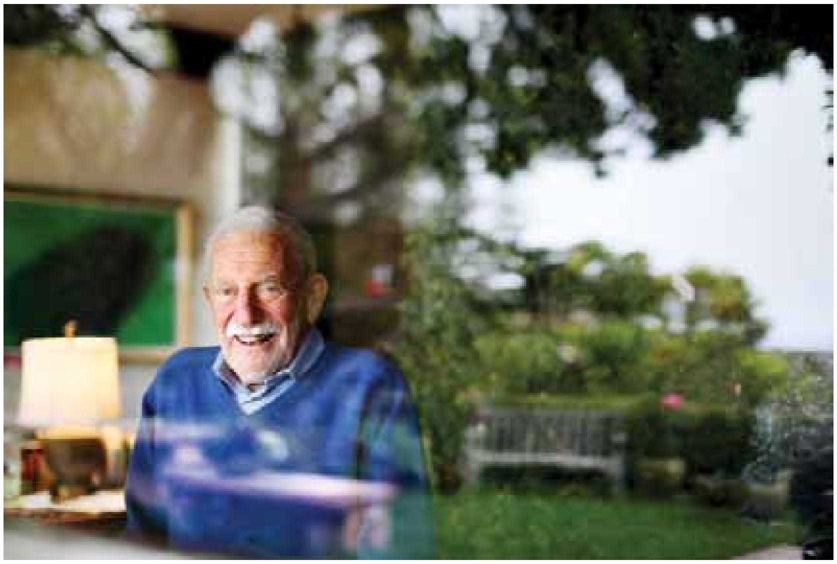
The final meeting of the WDS-SC that I chaired was held, appropriately, at IGPP on February 7-8, 2015 (see picture). The gavel was passed to Sandy Harrison during the September meeting of the SC at ICSU Headquarters in Paris. I leave WDS in good shape and in good hands.

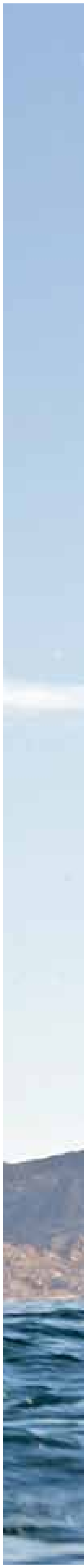
A recent entrant on the international data scene is the *Research Data Alliance* (RDA). I have participated in several of RDA's plenary meetings, notably the one held in San Diego in February, 2015. I am an active participant in several of the innumerable RDA Working Groups and Interest Groups, in particular:

- Repository Audit and Certification DSA–WDS Partnership WG
- Libraries for Research Data IG
- RDA/CODATA Legal Interoperability IG
- RDA/WDS Certification of Digital Repositories IG
- RDA/WDS Publishing Data IG
- Digital Practices in History and Ethnography IG

The Fall 2016 RDA Plenary meeting will be co-located with the SciDataCon-2016 (CODATA ands WDS) to support a new International Data Week in Denver, CO September, 2016.

Finally, I continue my participation in the NASA planning and review activities surrounding two important Low-Earth-Orbit geophysical missions planned for the end of the decade, namely ICESAT-2 and NISAR.





WALTER MUNK RESEARCH PROFESSOR

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DEEP PRESSURES. According to linear wave theory, surface waves $y = A\cos(kx - \omega t)$ have a pressure signature $\rho g a \exp(-kz)$ that becomes infinitesimal at the depth of a few wavelengths. Longuet-Higgins has explained the deep pressures in terms of some oppositely traveling wave energy (the microseism theory). The theory works well at frequencies of less than 1 Herz, but we have some doubts at high frequencies (100 Hz, say). Continuing work with J. Berger and W. Farrell, we have joined forces with Ken Melville and are developing plans for a 6 month simultanous deployment of bottom sensors and near surface observations, including a vertical hydrophone array, wave gliders and aircraft flights.

WIND DRAG. For half a century Cox's observation that sea surface slope increases linearly with wind speed has remained unexplained. Nor has the surprisingly large slope perpendicular to the mean wind direction. New insight comes from a reexamination of Lord Kelvin's classical explanation of ship wakes. Looking at much higher wave numbers than usual, and accounting for the effect of surface tension, a wide angular spread in the wave field is obtained. We imagine that pressure pulses from moving turbulent cells in the atmospheric boundary layer constitute a moving source, analogous to Kelvin's ship. The problem is important for the understanding of wind drag.

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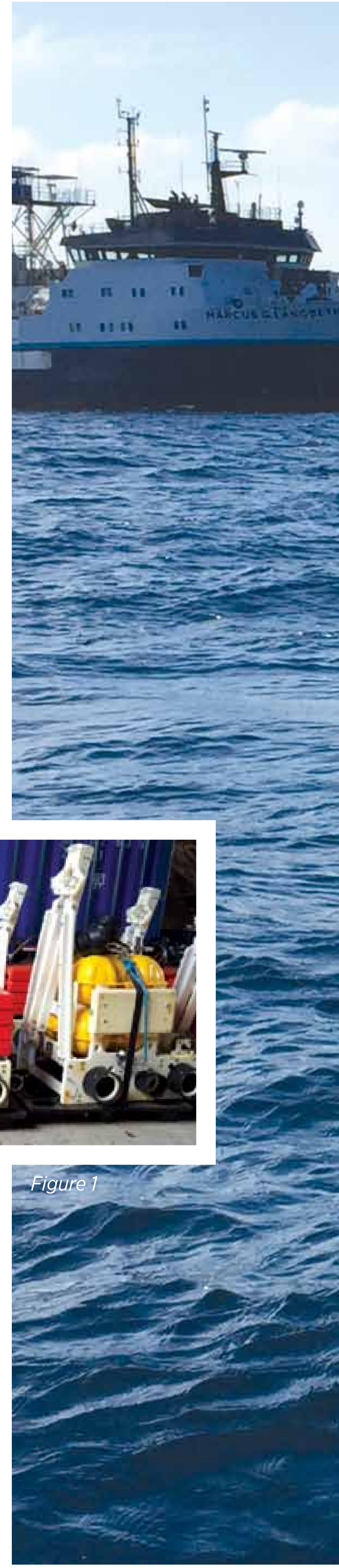
Cox, C. and W. Munk (1956). Slopes of the sea surface deduced from photographs of sun glitter. *Scripps Inst. Oceanogr. Bull.*, **6**(9), 401-488.

Thompson, W. (1887) On the waves produced by a single impulse in water of any depth, *Proc. R. Soc London, Ser. A.,* **42**, 80-83.

Munk, W. (October 30, 2015) Wind drag and Kelvin's 1877 popular lecture on Ship Waves, in preparation.



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Ocean Bottom Seismology *(with Martin Rapa and Sean McPeak)*

Seafloor seismology has a long history at Scripps beginning in the 1950's. A number of "firsts" include the first studies of seafloor seismology for nuclear test monitoring, the first broadband seismometer deployments (late 60's), the first digital seafloor seismometers (70's), the first use of 24-bit recordings on the seafloor (80's) and the first trawl-resistant, shielded packages during the past few years. In the early days the numbers of seismometers, which exploited 1Hz NASA Ranger geophones, were small in number (<10). Currently IGPP operates approximately 120 ocean bottom seismographs and supports several seafloor experiments around the world each year. Throughout this development history, the deployment times have increased from a few weeks or days to nearly two years. Advances in electronics have reduced power requirements while, at the same time, expanding the fidelity of the seafloor recordings. We dubbed our instruments in the past century "Low-Cost Hardware for Earth Applications and Physical Oceanography" or L-CHEAPO and initiated the first facility allowing outside users to conduct experiments independently of Scripps scientists. Project support has expanded in the past decade to the Incorporated Research Institutions for Seismology (IRIS) Ocean Bottom Seismograph Instrumentation Pool (OBSIP), which now includes additional instruments at Woods Hole and Lamont. Altogether, OBSIP has access to over 200 OBSs.

Figure 1 shows the evolution of the top end of our instruments. The seismometer (not mounted in the image) is a small spherical package incorporating a Nanometrics Trillium-240 fed-back instrument with a natural period of 240s or 4.2mHz. The instrument is comparable to seismometers in the Global Seismic Network (GSN) and has recorded semidiurnal tides (23.2μHz), normal modes of the Earth and frequencies as high as 20Hz. From low to high frequencies, these instruments are the quietest seafloor instruments available today.

Figure 1

The frame is primarily built of polyethylene and anodized aluminum tubes are used as pressure cases for the acoustic release, the data logger and the Lithium primary battery cells used for power. The floatation has changed with time as shown in Figure 1, with the original package on the right, which uses glass balls for floatation. After a number of losses of seafloor instruments during deep deployments in excess of 6km, we have replaced the glass balls with syntactic foam. The middle package was the first step, while the last uses foam in a single block.

A new instrument was constructed specifically for a group experiment to record open data in the Cascadia fault zone. In this case, we developed a new package, which we termed ABALONES (Autonomous Broad Application Low Obstruction Noise Exempt System). The package comprises a molded syntactic foam instrument, which also houses the tubes necessary for releases, batteries and electronics. ABALONES, like the marine mollusk, is a protective

shell and hard to pry off the seafloor. The package is, by design, trawl resistant. A Nanometrics Trillium Compact sensor (120s, 8.3mHz) was used and the sensor itself is dropped in a well in the center of the instrument to mechanically decouple from the main frame while providing protection from local currents. Like the other designs, the package is capable of operating to 6km depth and data are stored internally on compact flash (CF) cards with enough storage for several years of continuous recording. The use of syntactic foam for structural support as well as floatation is a new departure that minimizes instrument weight and size. Generally other OBSs with these capabilities are 2-4 times as heavy since they rely upon metal structures for housing pressure cases and seismometers. It is likely that future packages will take advantage of this innovation in the use of syntactic foam.

Figure 2

One of our earliest packages is particularly suited for active source and microseismicity experiments and is termed the LC4x4-SP OBS. This includes a triaxial 4.5 Hz geophone and a HTI hydrophone. A Scripps Differential Pressure Gauge (DPG) can be substituted for the hydrophone. The package is approximately a meter cube and floatation is largely glass balls. Recently we have built and tested a new package (Figure 2) that is significantly smaller and depends, again, on syntactic foam to support electronics and battery tubes.

This year we have completed the design, construction and testing of a "Backpack" for the broadband OBSs that extends the duration of seafloor deployments to two years or more. A new "Super ABALONES" is being designed to provide more space and floatation for batteries, a broadband T-240 sensor, and with the goal of extending the seafloor recording time for the broadband instruments to greater than two years while keeping weight as low as possible by using syntactic foam for structural support. We are presently developing an interface to integrate an atomic clock to enhance the accuracy of timing. The CSAC (Chip Scale Atomic Clock) is compact, low power and should provide an accuracy approaching $1\mu s$ over a year-long period. Finally, in another section of this report, a new system (based on similar technology) has been built and tested for providing continuous telemetry of data with four components from the seafloor with latencies of approximately three minutes. The Super ABALONES provides an early design for a towable package the will rely solely on a surface wave glider to tow the OBS to sea and provide telemetry for at least three years.

Experiments supported this year include:

PI	CRUISE NAME	LOCATION	# OBS	VESSEL
Shillington	Malawi	Africa	28 SP	Ndundum
Shillington	Malawi	Africa	7 BB	Chilembwe
Nabelek	Gorda/Cascadia	Cascadia	24 SP/BB	Oceanus
Toomey	Cascadia	Cascadia	15 BB	Oceanus
Hooft	Santorini	Italy	61 SP	Langseth
Berger (several)	ADDOSS	San Diego	1 prototype	Sproul

These experiments as well as test deployments off the local coast provide a great opportunity for student participation in oceanography.

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Research Interests: physics and chemistry of silicate melts; role of magma in planetary interiors, from the scale of volcanic magma reservoirs to planetary-scale magma oceans; evolution of planetary interiors from "deep time" (e.g., planet evolution) to the present.

Ongoing research projects have mainly focused on (i) the experimental investigation of the electrical properties of Earth's upper mantle rocks under pressure, (ii) the experimental investigation of the deep Lunar mantle, and (iii) the time-evolution of the Martian core.

(i) Sheared rocks are thought to explain electrical anomalies in a deformed uppermost mantle as their high electrical conductivity and anisotropy reproduce electromagnetic data. Although melt or water can reproduce asthenospheric electrical anisotropy, the electrical properties of the sheared polycrystalline matrix and its contribution to bulk electrical anisotropy at upper mantle conditions are not fully understood and require further investigation. Under funding from NSF Cooperative Studies Of The Earth's Deep Interior, my collaborators David Kohlstedt, Kurt Leinenweber, Stephen Mackwell, Ed Garnero, Chao Qi, James Tyburczy and I have investigated the effect of melt on the electrical conductivity of deformed materials at upper mantle conditions (Pommier et al., Nature, 2015). Based on electrical anisotropy measurements under pressure on mantle analogues, we observed that electrical conductivity is highest parallel to deformation direction and quantified the effect of shear on conductivity with increasing temperature. Our experimental results and modeling show that field data are best reproduced by an electrically anisotropic asthenosphere overlain by an isotropic, high-conductivity deep lithosphere. The high conductivity could arise from partial melting associated with localized deformation resulting from differential plate velocities relative to the mantle, with upward melt percolation from the asthenosphere. In a second study, we conducted a systematic experimental investigation of the effect of shear deformation on the electrical conductivity of (melt-free) polycrystalline olivine. Starting samples were previously sheared to a strain of up to 7.3 and

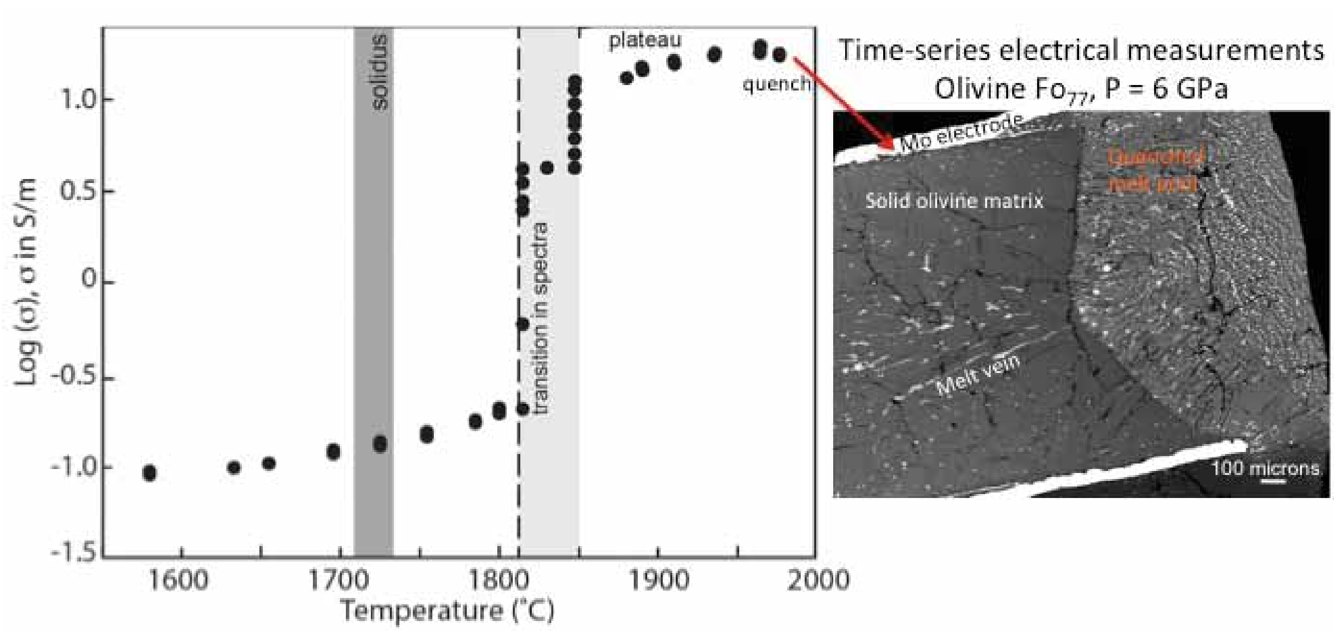


Figure Caption: Electrical conductivity σ during partial melting: example of dry olivine compact at 6 GPa. A slight change in the dependence of σ to temperature is observed after the solidus is crossed, attributed to the nucleation and low interconnectivity of the melt phase. The jump in σ is consistent with a transition from interconnected melt tubes to a completely wetted olivine matrix. At this stage of partial melting, significant changes in olivine chemistry occur caused by the partitioning of iron to the melt phase. Finally, a plateau in σ is reached and corresponds to melt migration and eventual melt pooling. See Pommier et al., EPSL, 2015 for details.

their electrical conductivity and anisotropy of the samples were then measured at 3GPa in a multi-anvil apparatus. We observe that shear deformation increases electrical conductivity and that conductivity is highest in the direction of shear, with the sample deformed to the highest strain being the most conductive. The role of grain boundaries and dislocations on conduction mechanisms are investigated based on textural analyses and previous electrical and diffusivity studies, in collaboration with Florian Heidelbach, Miki Tasaka, and Lars Hansen. Application of our results to field data indicates that electrical anomalies in the asthenosphere can be solely explained by the electrical properties of the sheared solid matrix.

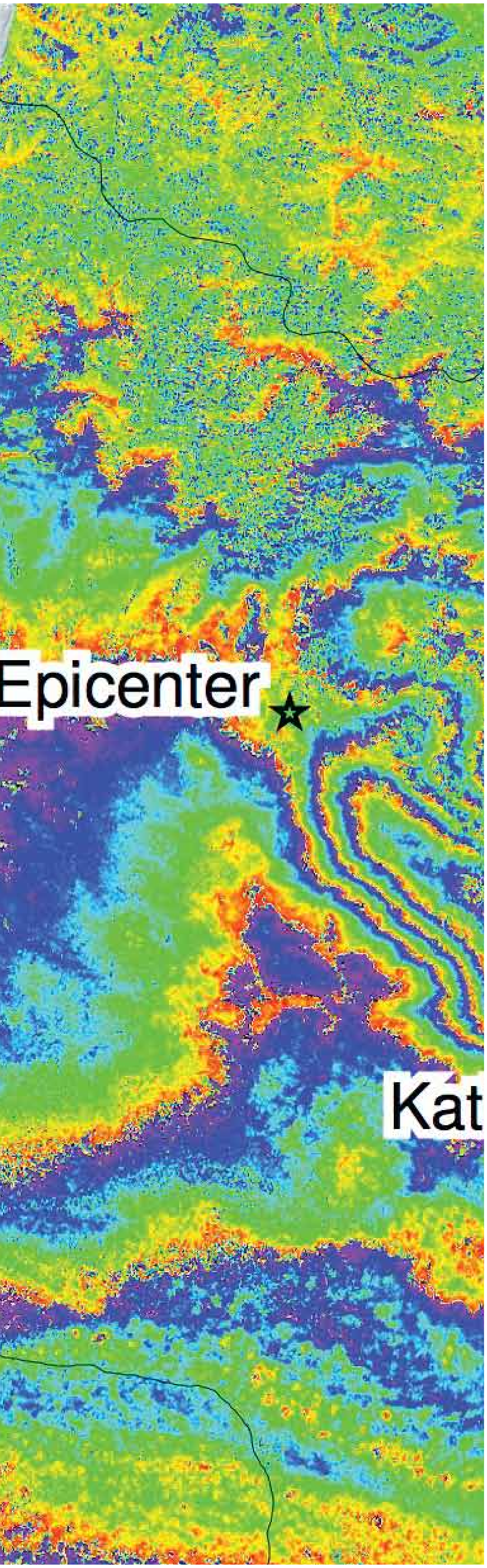
(ii) The presence of melt at the base of the lower mantle of some terrestrial bodies, such as the Earth and the Moon may indicate a remnant global magma ocean, remained partially molten due to the presence of trapped heat-producing elements. Together with collaborators Kurt Leinenweber and Miki Tasaka and under funding from NSF, I measured the electrical properties of dry and hydrous olivine compacts during melting at 4 and 6 GPa (corresponding to the pressure range for the core-mantle boundary of the Moon) in order to investigate melt transport properties and quantify the effect of partial melting on electrical properties (Pommier et al., EPSL, 2015). At temperature > $T_{solidus}$, we observed a significant increase in conductivity (by a factor ranging from > 30 to 100), consistent with the transition from a tube-dominated network to a structure in which melt films and pools become prominent features (see Figure). It is followed by a plateau at higher temperature, suggesting the sample lacks sensitivity to temperature at an advanced stage of partial melting. Our results can be reproduced satisfactorily by two-phase electrical models and provide a melt conductivity value of > 45 (±5) S/m. Comparison of our results with electromagnetic sounding data of the deep interior of the Moon supports the hypothesis of the presence of interconnected melt at the base of the lunar mantle. Our results underline that electrical conductivity can be used to investigate *in situ* melt nucleation and migration in the interior of terrestrial planets.

(iii) Though it is accepted that Mars has a sulfur-rich metallic core, its chemical and physical state as well as its time-evolution are still debated. Several lines of evidence indicate that an internal magnetic field was once generated on Mars and that this field decayed around 3.7-4.0 Gyrs ago. The standard model assumes that this field was produced by a thermal (and perhaps chemical) dynamo operating in the Martian core. Former Green Scholar Christopher Davies and I have used this information to construct parameterized models of the Martian dynamo in order to place constraints on the thermochemical evolution of the Martian core, with particular focus on its crystallization regime. Considered compositions are in the FeS system, and other parameters include core radius, density, melting curve and adiabat, core-mantle boundary heat flow and thermal conductivity. Successful models are those that match the dynamo cessation time and fall within the bounds on present-day CMB temperature. Possible crystallization regimes are: growth of a solid inner core starting at the center of the planet; freezing and precipitation of solid iron (Fe-snow) from the core-mantle boundary (CMB); and freezing that begins midway through the core. In parallel, I have conducted experiments in the Fe-S and Fe-S-O systems with collaborators Dan Frost and Vera Laurenz at BGI, Germany, with funding from the Alexander vonHumboldt Foundation. Our results will help place new constraints on the time- and space- evolution of the core of terrestrial bodies, including Mars.

Recent Publications

Pommier A., K. Leinenweber, and M. Tasaka, Experimental Investigation of the Electrical Behavior of Olivine during Partial Melting under Pressure and Application to the Lunar Mantle, *Earth and Planetary Science Letters,* **425** 242–255, 2015.

Pommier A., K. Leinenweber, D. L. Kohlstedt, C. Qi, E. J. Garnero, S. Mackwell, J. Tyburczy, Experimental Constraints on the Electrical Anisotropy of the Lithosphere-Asthenosphere System, Nature, doi: 10.1038/nature14502, 2015.



DAVID T. SANDWELL, PROFESSOR OF GEOPHYSICS

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Research Interests: Geodynamics, global bathymetry, crustal motion modeling, space geodesy

STUDENTS AND FUNDING: Research for the 2014-15 academic year was focused on understanding the dynamics of the crust and lithosphere. Our group comprises three graduate students Soli Garcia, Eric Xu, and John Desanto, two postdocs Dan Bassett and Alejandro Gonzalez-Ortega and two lab assistants Rachael Munda and Brenda Mendonca. Our research on improvement in the marine gravity field is co-funded by the National Science Foundation (NSF), the Office of Naval Research, and the National Geospatial Agency. In addition, we are funded by NSF and Google to improve the accuracy and coverage of the global bathymetry. The NSF EarthScope Program as well as the Southern California Earthquake Center funds our research on the strain rate and moment accumulation rate along the San Andreas Fault System from InSAR and GPS.

GLOBAL GRAVITY AND BATHYMETRY: We are improving the accuracy and spatial resolution of the marine gravity field using data from three new satellite radar altimeters (CryoSat-2, Jason-1, and Envisat). This is resulting in a factor of 2-4 improvement in the global marine gravity field. Most of the improvement is in the 12 to 40 km wavelength band, which is of interest for investigation of seafloor structures as small as 6 km (Garcia et al., 2013). The improved marine gravity is important

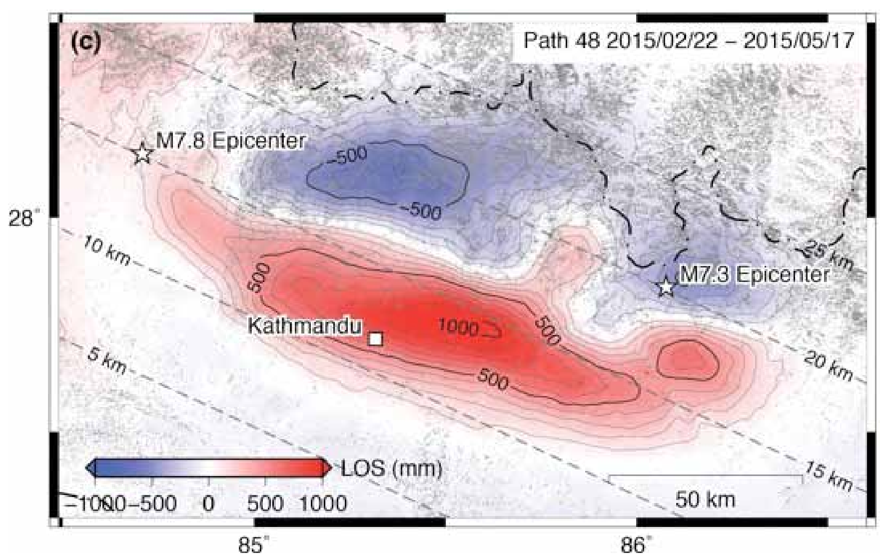
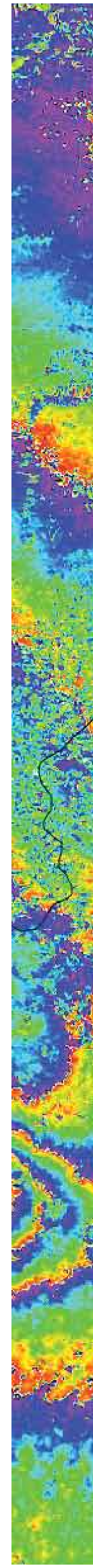
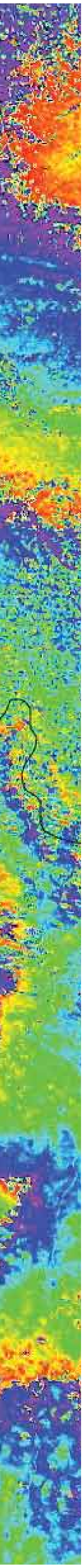


Figure 1. ALOS-2 ScanSAR interferogram of the M7.8 and M7.3 Nepal earthquakes, processed by our lab and publish recently in GRL (Lindsey et al., 2015), highlights the unique and advanced attributes of this InSAR system. The single 350 km-wide interferogram completely captures the extent of the deformation. This region of the Himalayas has the highest topography on Earth with snow-capped peaks, yet it was possible to unwrap and connect the phase of all 5 subswaths.





for exploring unknown tectonics in the deep oceans as well as revealing thousands of uncharted seamounts (Sandwell et al., 2014).

INTEGRATION OF RADAR INTERFEROMETRY AND GPS: We are developing methods to combine the high accuracy of point GPS measurements with the high spatial resolution from radar interferometry to measure interseismic velocity along the San Andreas Fault system. We analyzed InSAR observations, initially from ALOS ascending data, spanning from the middle of 2006 to the end of 2010, and totaling more than 1100 interferograms (Tong et al., 2013). These combined GPS/InSAR data are critical for understanding the along-strike variations in stress accumulation rate and associated earthquake hazard (Tong et al., 2015). The InSAR processing was performed with new software called GMTSAR developed at SIO (http://topex.ucsd.edu/gmtsar).

CRUSTAL MOTION MODELING: Early 2014, two new InSAR satellites became operational. Sentinel 1A is the first of a series of European Space Agency (ESA) SAR satellites to provide an operational mapping program for crustal deformation along all zones having high tectonic strain. The second new satellite is ALOS-2, launched by JAXA. The L-band radar aboard ALOS-2 operates in a ScanSAR mode having a 350 km wide swath (Figure 1). *These satellites have the measurement cadence and spatial coverage needed to revolutionize our understanding of earthquake cycle processes both globally and along the San Andreas Fault System.*

Recent Publications

Garcia, E., D. T. Sandwell, W. H. F. Smith. Retracking CryoSat-2, Envisat, and Jason-1 Radar Altimetry Waveforms for Improved Gravity Field Recovery, *Geophys. J. Int.,* doi: 10.1093/gji/ggt469, 2014.

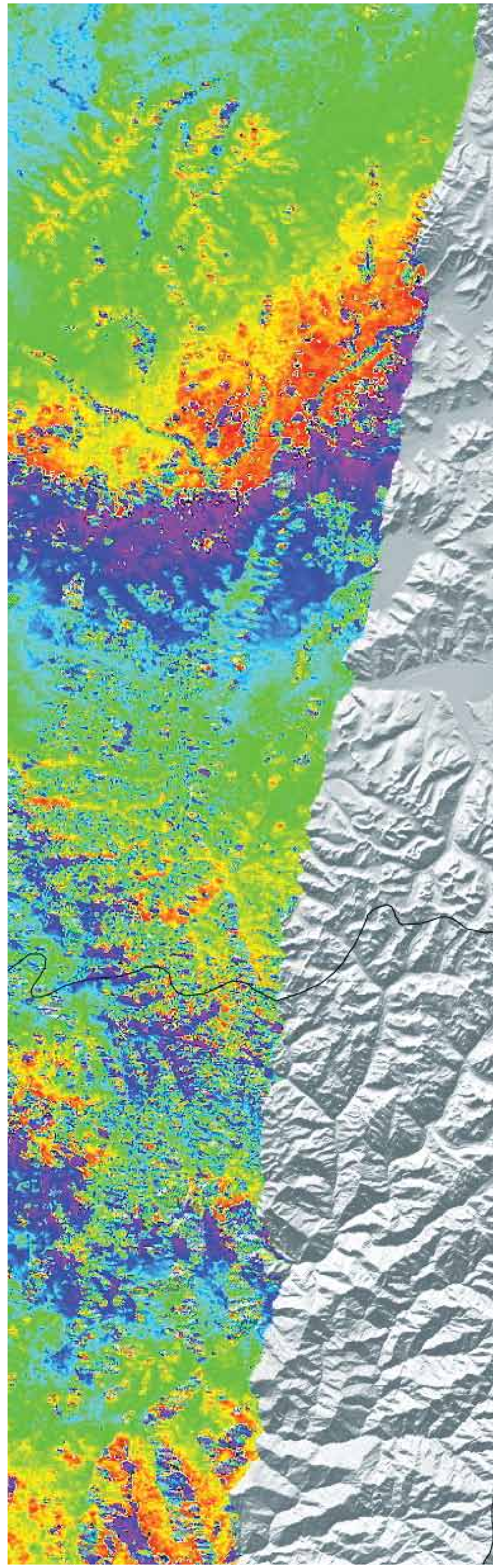
Garcia, E. S., D. T. Sandwell, and K. M. Luttrell, An Iterative Spectral Solution Method for Thin Elastic Plate Flexure with Variable Rigidity, *Geophys. J. Int.,* **200**, 1012-1028, doi: 10.1093/gji/ggu449, 2014.

Lindsey, E., R. Natsuaki, X. Xu, M. Shimada, H. Hashimoto, D. Melgar, and D. Sandwell, Line of Sight Deformation from ALOS-2 Interferometry: Mw 7.8 Gorkha Earthquake and Mw 7.3 Aftershock, *Geophys. Res. Lett.,* **42**. doi:10.1002/2015GL065385, 2015.

Sandwell, D. T., R. D. Müller, W. H. F. Smith, E. Garcia, R. Francis, New global marine gravity model from CryoSat-2 and Jason-1 reveals buried tectonic structure, *Science*, **346**, no. 6205, pp. 65-67, doi: 10.1126/science.1258213, 2014.

Tong, X., D. T. Sandwell, and B. Smith-Konter, High-resolution interseismic velocity data along the San Andreas Fault from GPS and InSAR, *J. Geophys. Res.; Solid Earth*, **118**, doi:10.1029/2012JB009442, 2013.

Tong, X., D.T. Sandwell, and B. Smith-Konter, An integral method to estimate the moment accumulation rate on the Creeping Section of the San Andreas Fault, *Geophys. J. Int.,* **203**, 48-62, doi: 10.1093/gji/gjis140783, 2015.



PETER SHEARER, DISTINGUISHED PROFESSOR OF GEOPHYSICS

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Research Interests: seismology, Earth structure, earthquake physics

My research uses seismology to learn about Earth structure and earthquakes, using data from the global seismic networks and local networks in California, Hawaii, and Japan. My work in crustal seismology has focused on improving earthquake locations using waveform cross-correlation and systematically estimating small-earthquake stress drops from P-wave spectra. Recently I collaborated with former IGPP Green Scholar Yoshihiro Kaneko (now at GNS New Zealand) to model simple yet dynamically self-consistent elliptical ruptures and test methods for estimating corner frequency and stress drop from far-field seismic records (Kaneko and Shearer, 2015). Our results show that asymmetric rupture models exhibit large variability in corner frequency and scaled energy over the focal sphere and that radiation efficiency estimates derived from seismic spectra alone are not reliable.

Foreshock sequences are important because they are one of the most commonly observed precursors to large earthquakes. Former graduate student Xiaowei Chen (now at the University of Oklahoma) systematically examined 64 California $M \geq 5$ earthquakes and found that about half have foreshock sequences (Chen and Shearer, 2015). The observed foreshock properties are not easily explained by standard statistical models of earthquake-to-earthquake triggering, favoring models of physical changes in the nucleation zone of large earthquakes.

The recent Mw 7.8 earthquake in Nepal was the focus of studies by graduate student Wenyuan Fan and Green Scholar postdoc Marine Denolle. Fan and Shearer (2015) implemented a global back-projection approach to image the Nepal rupture and identified a complex, frequency-dependent rupture process with three distinct stages (see Fig. 1). There was slow initial downdip rupture, followed by two faster updip ruptures that released most of the radiated energy northeast of Kathmandu. The observed relative lack of high-frequency radiation during the main moment release episode was confirmed by the spectral analysis of Denolle et al. (2015), which compared P-wave spectra of the mainshock with two large aftershocks. We found that surface reflections (depth phases) produce interference that severely biases spectral measurements unless corrections are applied. The beginning of the Nepal mainshock likely experienced a dynamic weakening mechanism immediately followed by an abrupt change in fault geometry.

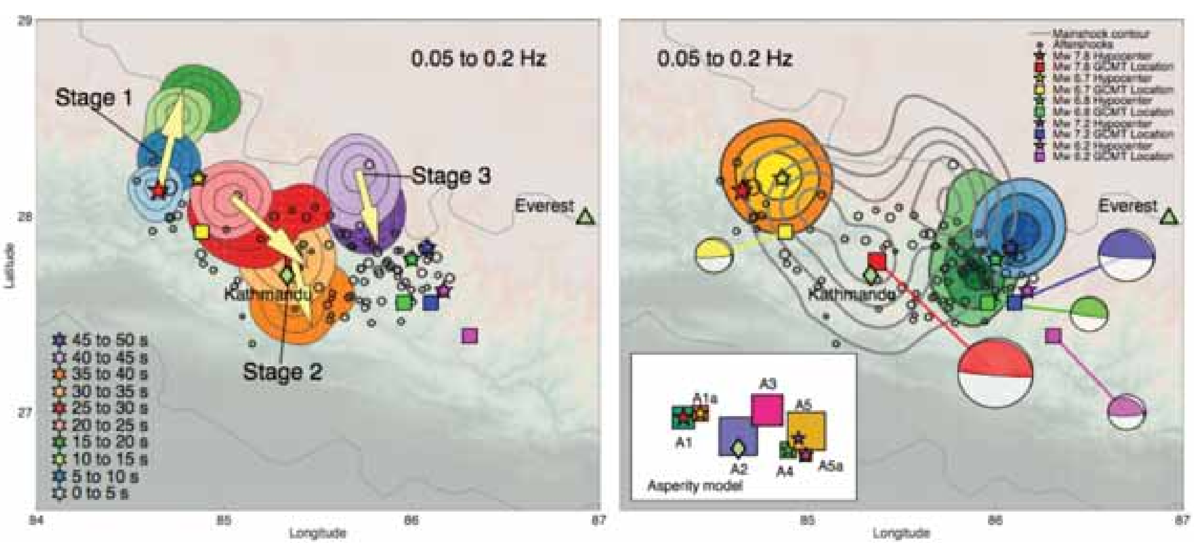

Figure 1. Rupture of the 2015 Nepal earthquake, as seen in time-integrated images of back-projected P waves. (left) High-frequency backprojection image over 60 s. (right) Low-frequency backprojection image over 60 s. Figure from Fan and Shearer (2013).

Postdoc Zhongwen Zhan (now at Caltech) recently discovered that large deep-focus earthquakes (M > 7, depth > 500 km) have exhibited strong seasonality in their occurrence times for over 100 years (Zhan and Shearer, 2015). Of 60 such events from 1900 to the present, 42 have occurred in the middle half of each year. The seasonality appears strongest in the northwest Pacific subduction zones and weakest in the Tonga region (see Fig. 2). This observation has no obvious physical interpretation and is difficult to test statistically, given that the observations have already been made. However, we make a testable prediction of seasonality for future quakes, which, if confirmed, would challenge our current understanding of deep earthquakes.

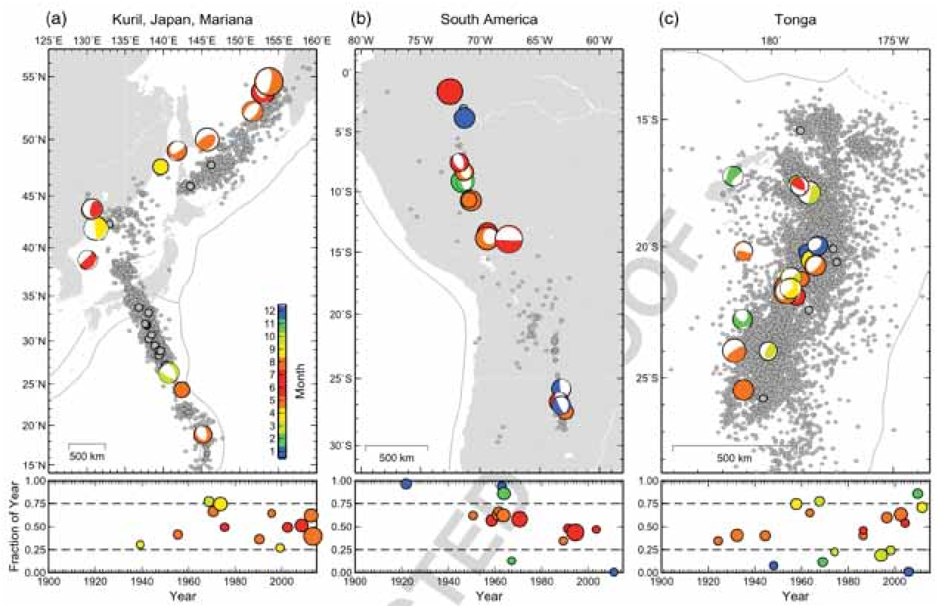

Figure 2. Regional plots of deep-focus earthquakes for the (a) NW Pacific, (b) South American, and (c) Tonga subduction zones. Events larger than M 7 are colored by month. Back-ground seismicity is shown as small grey dots. (bottom row) Event month versus year. Symbol sizes are proportional to magnitude.

Stacking of seismic data can sometimes reveal new or unexpected phases. Postdoc Janine Buehler recently stacked high-frequency waveforms from ~5200 earthquakes recorded by the Global Seismic Network and produced clear images of the seismic *T* phase, which propagates as acoustic energy in the ocean (Buehler and Shearer, 2015). This observation points the way toward more detailed studies of *T* phase propagation efficiency across major ocean basins.

Recent Publications

Buehler, J. S., and P. M. Shearer, T-phase observations in global seismogram stacks, *Geophys. Res. Lett.,* **42**, doi: 10.1002/2015GL064721, 2015.

Chen, X., and P. M. Shearer, Analysis of foreshock sequences in California and implications for earthquake triggering, *Pure Appl. Geophys.,* doi: 10.1007/s00024-015-1103-0, 2015.

Denolle, M. A., W. Fan, and P. M. Shearer, Dynamics of the 2015 M7.8 Nepal earthquake, *Geophys. Res. Lett.,* doi: 10.1002/2015GL065336, 2015.

Fan, W., and P. M. Shearer, Detailed rupture imaging of the 25 April 2015 Nepal earthquake using teleseismic P waves, *Geophys. Res. Lett.,* **42**, doi: 10.1002/2015GL064587, 2015.

Kaneko, Y., and P. M. Shearer, Variability of seismic source spectra, estimated stress drop and radiated energy, derived from cohesive-zone models of symmetrical and asymmetrical circular and elliptical ruptures, *J. Geophys. Res.,* **120**, doi: 10.1002/2014JB011642, 2015.

Zhan, Z., and P. M. Shearer, Possible seasonality in large deep-focus earthquakes, *Geophys. Res. Lett.,* doi: 10.1002/2015GL065088, 2015.

LEONARD J. SRNKA, PROFESSOR OF PRACTICE

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Research Interests: Land and marine electromagnetic (EM) methods; integrated geophysical data analysis and interpretation; inverse theory; energy outlooks and global change

In the second year of my SIO appointment, I continued my research begun at ExxonMobil on earth-field (~2.2 kHz) nuclear magnetic resonance (NMR) as a technology for detecting contaminates in the shallow subsurface. This technology is particularly well suited for detecting oil under ice and snow, which is a crucial environmental need in the Arctic. The research led to a unique transmit/receiver antenna and signal protocol to detect oils of various properties in the presence of the huge water proton NMR signal. This approach demonstrated for the first time that such detection is feasible. Full-scale prototype testing using a helicopter-slung system has begun.

My research in seafloor electromagnetics turned to re-examining data acquired in the San Diego Trough in 2006 in about 900m water depth, where novel electric field gradient measurements were made using tandem long-wire electric (LEM) receivers pioneered by Professor Steve Constable and his laboratory at SIO. New techniques to suppress magnetotelluric (MT) and natural noises are being studied.

Responding to government and professional society interests in scoping better academic cooperation with the extensive marine industry, I participated in workshops at UC Irvine (NRC/OSB) and at the POGO-16 conference held at Tenerife, Spain, and summarized the opportunities and challenges of increased cooperation. One recommendation from POGO-16 is to form an industry-academic steering committee that would further explore cooperation options. Along the same lines, I began working with NSF on opportunities to use industry seismic vessels to augment or supplant the aging R/V Marcus G. Langseth.

Recent Publications

Chavez, L., Altobelli, S., Fukushima, E., Zhang, T., Nedwed, T., Palandro, D., Srnka, L., and Thomann, H., 2015, Using NMR to detect Arctic oil spills. *Near Surface Geophysics,* **13** (4), 409-416. DOI: 10.3997/1873-0604.2015023

DAVE STEGMAN, ASSOCIATE PROFESSOR

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Research Interests: Global tectonics, mantle dynamics, planetary geophysics, high-performance computing

Dr. Stegman researches dynamic processes within planetary interiors that shape their geologic, tectonic, magnetic and magmatic evolutions. My research group employs some of the nations fastest supercomputers to simulate these processes with the ultimate goal of developing a dynamical theory that explains how Earth and other planets evolve.

One of the questions I've recently investigated is what were the largest factors driving global sea level variations during Earth's 4.5 Billion year evolution? Earth's oceans have played an important role in the evolution of life and tectonics on Earth, yet our understanding of how long Earth's oceans have persisted, or how deep such oceans may have been, remains limited. Plate tectonics continuously alters the age-distribution of seafloor in the world's oceans, and seafloor subsides as it gets older, the volume of water that the ocean basins can hold is consequently changing as well. Over the past 140 Myr, global sea level may have varied 200m due to variations in the age-area distribution of oceanic plates as estimated from reconstructions of tectonic plates (Muller et al., 2008). The growth of continents over Earth history also influences the distribution of seafloor age, because as the amount of continent increases there is more opportunity for passive continental margins to develop, allowing ocean basins a stable tectonic environment to age.

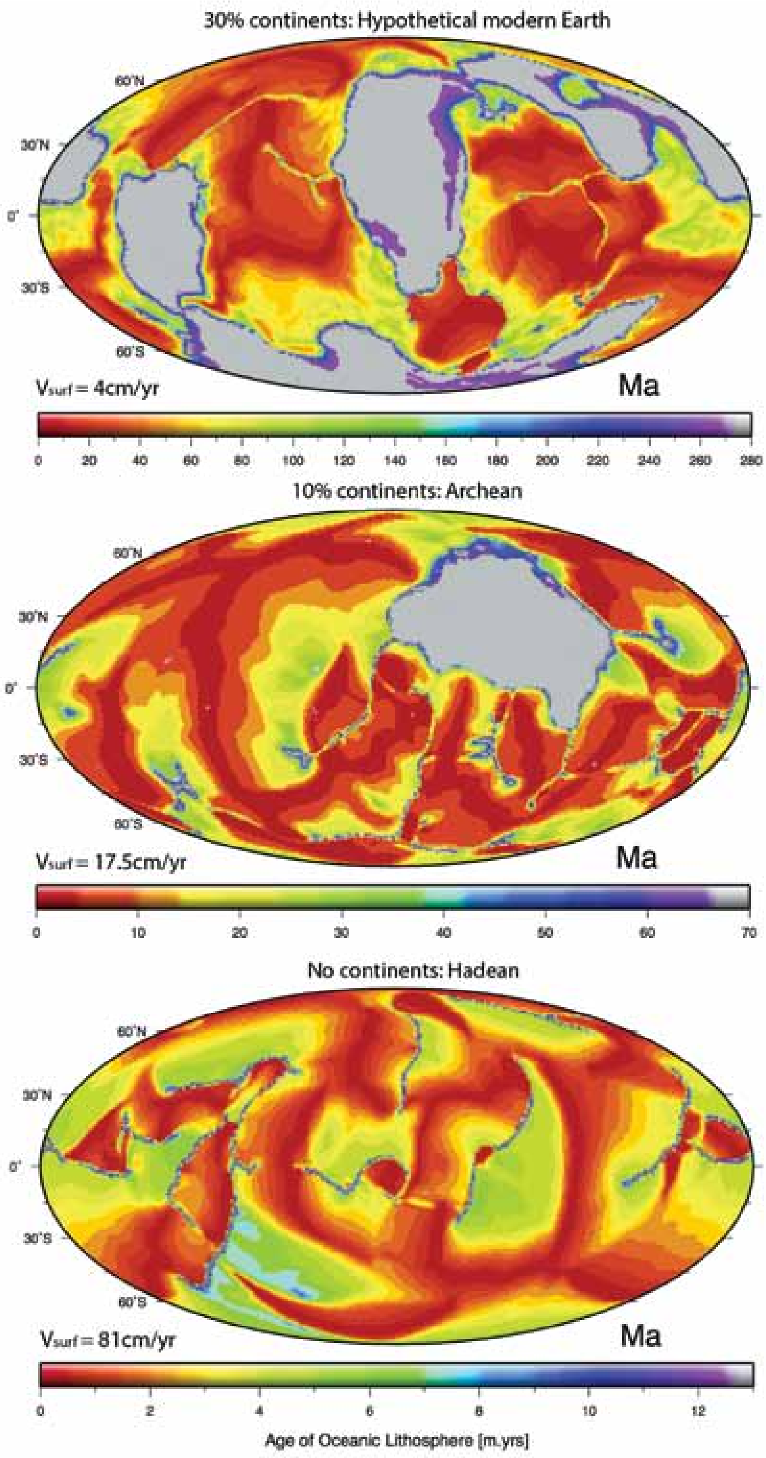

Figure 1. These are three oceanic plate age maps from our mantle convection models showing a representative time step for our 30% (top), 10% (middle) and 0% continents (bottom) models. The color contours shows the ages of the oceanic crust with the ages shown in each colorbar, which are different since each model is scaled to have surface velocity as shown on left bottom corner of each panel to represent the corresponding time period. The grey areas represent continents..

Working with PhD student Joyce Sim and collaborator Nicolas Coltice (ENS-Lyon), we used synthetic plate congurations derived from 3D spherical mantle convection models to estimate variations of global sea level under conditions appropriate for early Earth. By varying the amount of continents (0%, 10%, and 30%), we consider the competing effects of continental growth and seafloor age distribution leading to deepening ocean basins within the context of Earth's thermal evolution. The warmer, early Earth, is expected to have faster surface velocities and, on-average, younger seafloor as indicated in the scale bars for the different models (see Figure). Our main conclusion was that, according to these models, global sea level has remained fairly constant over geologic time, because the effect of continental growth approximately balances the effect of changes in average seafloor-age. As the continents on Earth grew, some of the surface became covered by continents, leading to an increase in global sea level which was nearly offset by the decrease associated with an older mean age of ocean basins.

Some other research activities during the year included working with PhD student Robert Petersen, building upon the models of subduction Petersen et al. (2015) and now considering the effects of damage rheologies in the slabs and effects of slab dehydration on rheology of the mantle wedge. I continued working with Green Scholar Chris Davies on a study related to gravitational coupling of the inner core, following up on our recent publication (Davies, Stegman, and Dumbery, GRL, 2014). Leah Ziegler and I worked with Chris to adapt his entropy-based parameterized inner core solidification model to the situation of a basal magma ocean dynamo, as was proposed by Stegman and Ziegler (2014).

Recent Publications

Petersen, R.I., D.R. Stegman, and P.J. Tackley (2015) A Regime Diagram of Mobile lid Convection with Plate-like Behaviour, *Physics of the Earth and Planetary Interiors* **241**, 65-76.

Sim, S., D.R. Stegman and N. Coltice (2015) The effect of continental growth on long-term global sea level, *submitted.*

PETER WORCESTER, RESEARCHER EMERITUS, RTAD

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Research Interests: Acoustical oceanography, ocean acoustic tomography, underwater acoustics.

My research is focused on the application of acoustic remote sensing techniques to the study of large-scale ocean structure and on improving our understanding of the propagation of sound in the ocean, including the effects of scattering from small-scale oceanographic variability.

Acoustic Propagation in the Philippine Sea. During 2009–2011 investigators from a number of oceanographic institutions worked together to conduct a series of experiments to investigate deep-water acoustic propagation and ambient noise in the oceanographically complex and highly dynamic Philippine Sea (Worcester et al., 2013). Two of the key goals were (i) to improve our understanding of the physics of scattering by internal waves and density-compensated temperature and salinity variations (see, e.g., Andrew et al., 2015) and (ii) to determine whether acoustic methods, together with other measurements and ocean modeling, can yield estimates of the time-evolving ocean state useful for making improved acoustic predictions and for understanding the local ocean dynamics.

The measured low-frequency travel-time series between the acoustic transceivers during the 2010–2011 Philippine Sea experiment compare well with time series computed from an ocean state estimate made using a high-resolution regional implementation of the MIT Ocean General Circulation Model (MITgcm) that was constrained by satellite sea surface height data, in situ temperature and salinity data, and other data. Significant (~ 30 ms) differences remained, however, including a bias. Ocean state estimates that incorporate the travel times in addition to the other data give improved temperature estimates at ~ 500–1500 depth and improved temperature forecasts at depth. The dynamically consistent ocean state estimates provided by the model can be used to quantify processes in a realistic ocean.

Canada Basin Acoustic Propagation Experiment (CANAPE). The Arctic Ocean is undergoing dramatic changes in both the ice cover and ocean structure. Changes in sea ice and the water column affect both acoustic propagation and ambient noise. The implication is that what has been previously learned about Arctic acoustics is now obsolete. Investigators at a

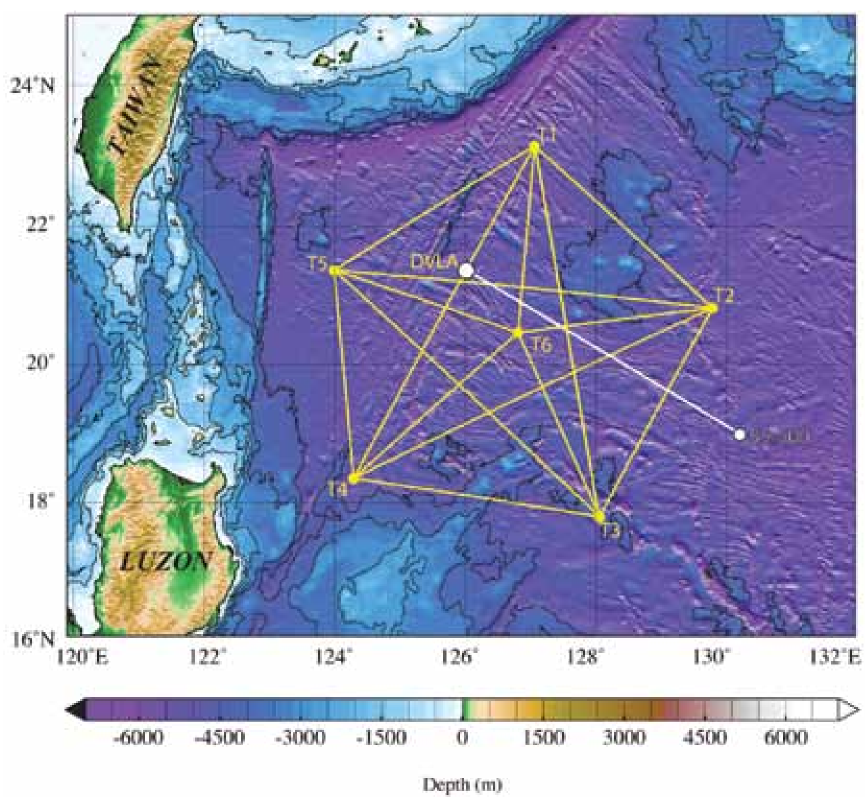


Figure 1. The 2010–2011 Philippine Sea experiment consisted of six broadband acoustic transceivers (T1, ... T6), a Distributed Vertical Line Array (DVLA) receiver, and ship-suspended sources, including one at SS-500.

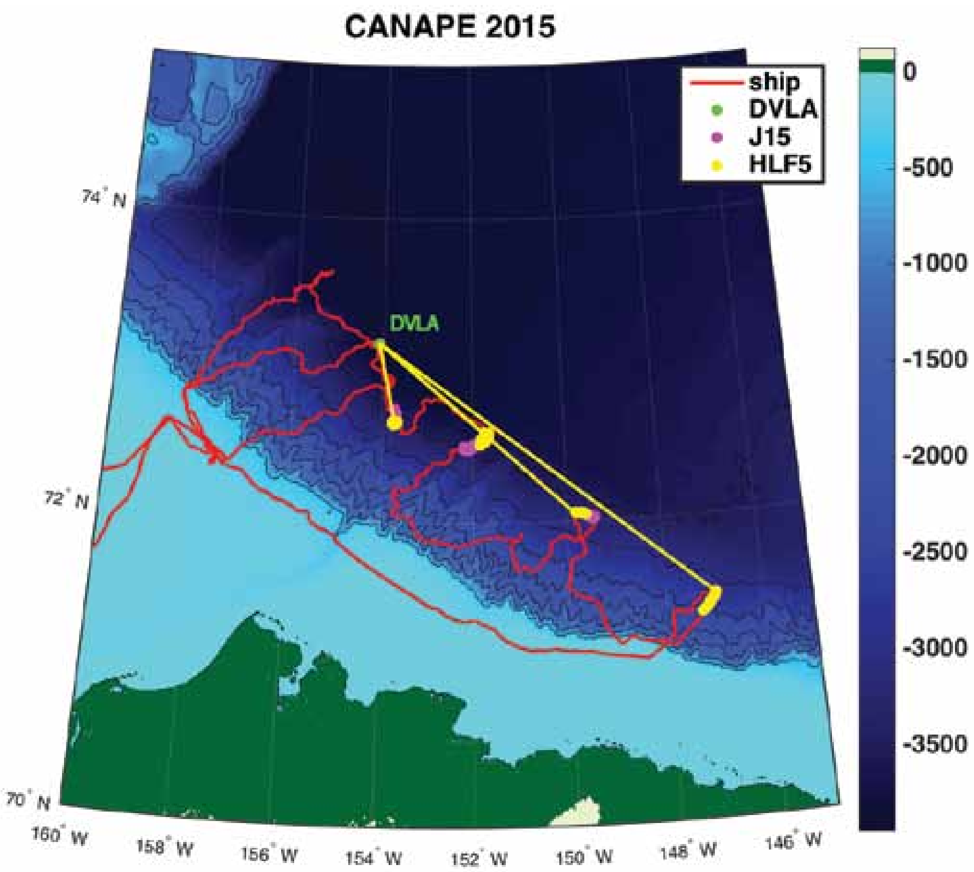


Figure 2. CANAPE 2015 pilot study geometry showing the DVLA receiver and the acoustic paths.

number of institutions are working together to conduct a yearlong experiment in the Canada Basin north of Alaska during 2016–2017 to study the effects of changing Arctic conditions on Arctic acoustics. The 2016–2017 experiment was preceded by a pilot study during summer 2015 in which HLF-5 (250 Hz) and J15-3 (75 and 125 Hz) acoustic sources suspended from shipboard transmitted to a moored DVLA receiver at ranges of ~ 50, 100, 200, and 300 km. All of the acoustic paths were covered by a combination of multiyear and first year ice.

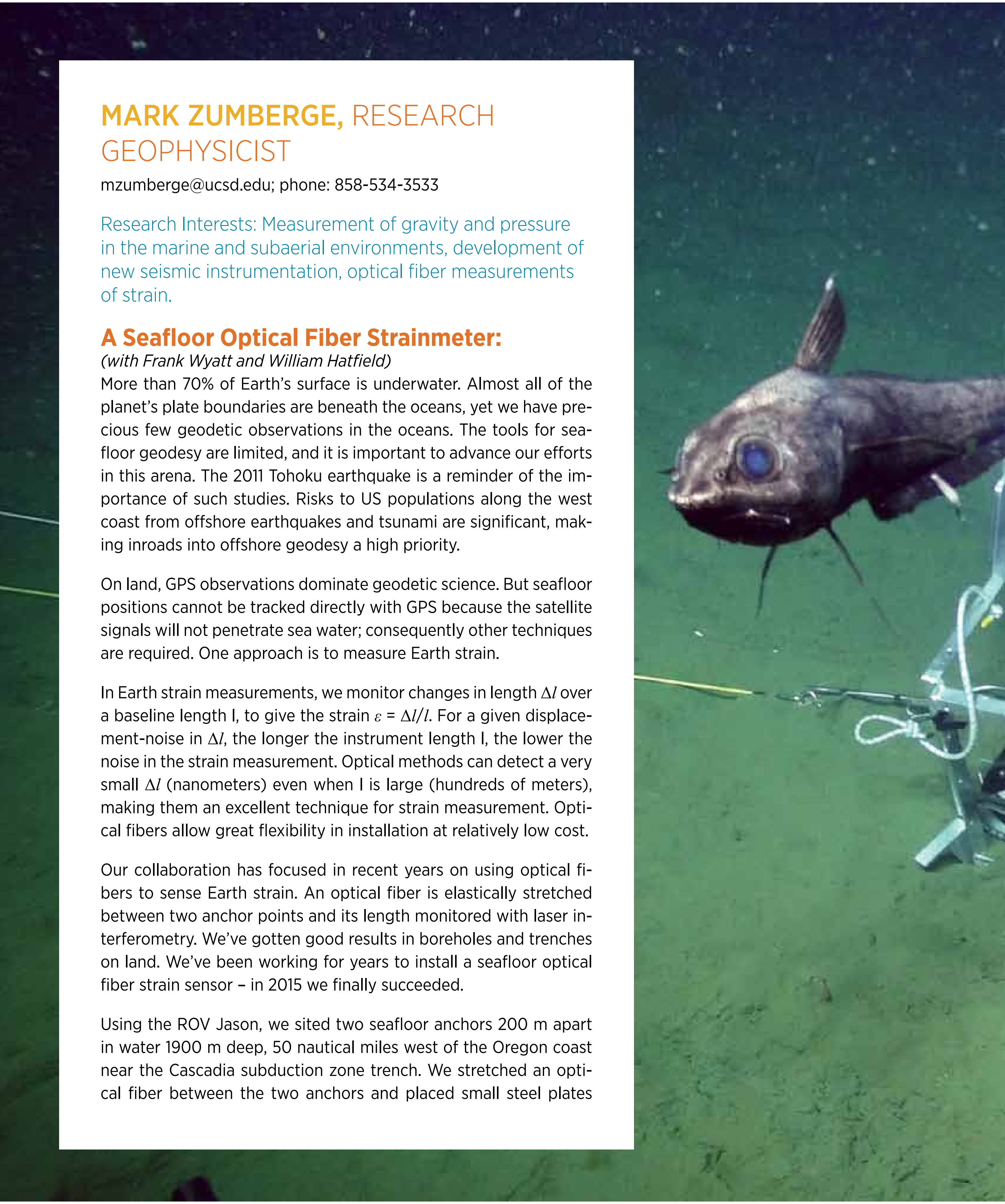
The hope is that these first steps will lead to a permanent acoustic monitoring, navigation, and communications network in the Arctic Ocean (Mikhalevsky et al., 2015).

Recent Publications

Andrew, R. K., A. W. White, J. A. Mercer, M. A. Dzieciuch, P. F. Worcester, and J. A. Colosi (2015), A test of deep water Rytov theory at 284 Hz and 107 km in the Philippine Sea, *J. Acoust. Soc. Am.*, **138**(4), 2015–2023, http://dx.doi.org/10.1121/1.4929900.

Mikhalevsky, P. N., et al. (2015), Multipurpose acoustic networks in the Integrated Arctic Ocean Observing System, *Arctic,* **68**(5), 11–27, http://dx.doi.org/10.14430/arctic4449.

Worcester, P. F., et al. (2013), The North Pacific Acoustic Laboratory deep-water acoustic propagation experiments in the Philippine Sea, *J. Acoust. Soc. Am.,* **134**(4), 3359–3375, http://dx.doi.org/10.1121/1.4818887.



MARK ZUMBERGE, RESEARCH GEOPHYSICIST

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Research Interests: Measurement of gravity and pressure in the marine and subaerial environments, development of new seismic instrumentation, optical fiber measurements of strain.

A Seafloor Optical Fiber Strainmeter:

(with Frank Wyatt and William Hatfield)

More than 70% of Earth's surface is underwater. Almost all of the planet's plate boundaries are beneath the oceans, yet we have precious few geodetic observations in the oceans. The tools for seafloor geodesy are limited, and it is important to advance our efforts in this arena. The 2011 Tohoku earthquake is a reminder of the importance of such studies. Risks to US populations along the west coast from offshore earthquakes and tsunami are significant, making inroads into offshore geodesy a high priority.

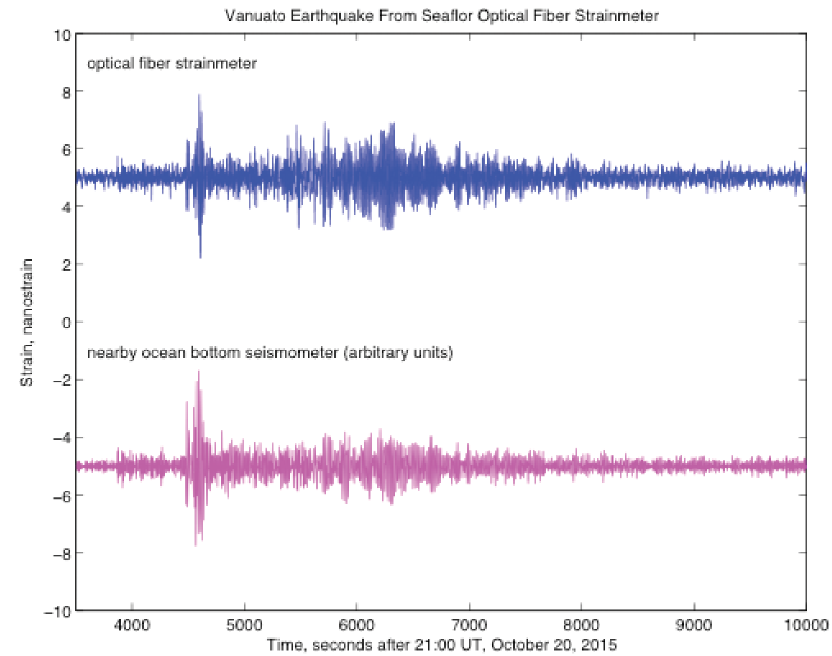
On land, GPS observations dominate geodetic science. But seafloor positions cannot be tracked directly with GPS because the satellite signals will not penetrate sea water; consequently other techniques are required. One approach is to measure Earth strain.

In Earth strain measurements, we monitor changes in length Δl over a baseline length l, to give the strain $\varepsilon = \Delta l/l$. For a given displacement-noise in Δl, the longer the instrument length l, the lower the noise in the strain measurement. Optical methods can detect a very small Δl (nanometers) even when l is large (hundreds of meters), making them an excellent technique for strain measurement. Optical fibers allow great flexibility in installation at relatively low cost.

Our collaboration has focused in recent years on using optical fibers to sense Earth strain. An optical fiber is elastically stretched between two anchor points and its length monitored with laser interferometry. We've gotten good results in boreholes and trenches on land. We've been working for years to install a seafloor optical fiber strain sensor – in 2015 we finally succeeded.

Using the ROV Jason, we sited two seafloor anchors 200 m apart in water 1900 m deep, 50 nautical miles west of the Oregon coast near the Cascadia subduction zone trench. We stretched an optical fiber between the two anchors and placed small steel plates

on top of it to keep it settled into the seafloor sediment. An infrared diode laser illuminates an interferometer formed by the stretched optical fiber (the strain sensing fiber) and a second fiber of approximately the same length wound onto a silica mandrel. The nearly equal path Michelson interferometer is less sensitive to small fluctuations in laser wavelength which would otherwise be misinterpreted as Earth strains.



Soon after the installation of the seafloor optical fiber strainmeter, a magnitude 7.1 earthquake occurred 9500 km away. The part per billion (nanostrain) strain signals were clearly observed. A long strain time series awaits recovery of the instrument next year.

One important difficulty with optical fibers in sensing strain is their inherent sensitivity to temperature. A standard fiber's index of refraction varies 10 ppm per °C, yielding a significant apparent strain effect as the temperature along the sensing fiber changes. Even on the seafloor, where daily temperature excursions may be 0.1°C or less, the microstrain effect is significant when nanostrain signals are the ones of interest. To combat this problem, we observe the interferometric length changes of two different types of fiber—one having a different temperature coefficient—in the same sensing cable. This allows us to separate the temperature effect from the strain effect and compensate for thermal signals.

Recent Publications

Zumberge, M.A., DeWolf, S., Wyatt, F.K., Agnew, D.C., Elliott, D., Hatfield, W., Results from a Borehole Optical Fiber Interferometer for Recording Earth Strain, *Proc. SPIE 8794, Fifth European Workshop on Optical Fibre Sensors*, 87940Q (May 20, 2013); doi:10.1117/12.2025896

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