



2011

*Cecil H. & Ida M. Green Institute of Geophysics & Planetary Physics*  
SCRIPPS INSTITUTION OF OCEANOGRAPHY, UNIVERSITY OF CALIFORNIA, SAN DIEGO

# IGPP Annual Report

This is the sixth Annual Report of the Cecil and Ida Green Institute of Geophysics and Planetary. The objective is 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 and predicting the likely shaking from major earthquakes, 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.

Two members of IGPP received national or international recognition this year: David Sandwell was elected to the National Academy of Sciences, and Guy Masters received the Beno Gutenberg medal of the European Geophysical Union.

Thanks to Jennifer Matthews for her efforts in compiling and producing this report. 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*

WWMT

WIDC

SGPS

PSAP

DSSC

COTD

ROCH

AZRY

*Image: Mean line-of-sight (LOS) velocity map of the Southern San Andreas Fault system. For more information, please see Yuri Fialko's report contribution.*

ACOUSTIC THERMOMETRY, Dzieciuch,  
Worcester

ACOUSTICS, Blackman, Dzieciuch, Hedlin

ANTARCTIC ICE SHEETS, Fricker

COMPLEXITY, Werner

CRUSTAL DEFORMATION, Agnew, Bock,  
Fialko, Sandwell

CRUSTAL SEISMOLOGY, Fialko, Kilb, Shearer,  
Vernon

CYBERINFRASTRUCTURE, Bock, Constable,  
C., Orcutt, Staudigel

EARTH'S DEEP INTERIOR, Constable, S.,  
Masters

EARTHQUAKE MECHANISMS, de Groot-  
Hedlin, Fialko, Kilb, Minster, Shearer, Vernon

ELECTRICAL PROPERTIES, Constable, S.

ELECTROMAGNETIC INDUCTION, Constable,  
C., Constable S., Parker

FLUID MECHANICS, Ireley

GEODESY, Agnew, Bock, Fialko

GEODYNAMICS, Laske, Ogden, Sandwell,  
Stegman

GEODYNAMOS, Ireley

GEOMAGNETISM, Ireley, Constable, C., Parker

GEOPHYSICAL INSTRUMENTATION, Agnew,  
Bock, Berger, Constable, S., Davis, Vernon,  
Zumberge

GLOBAL SEISMOLOGY, Davis, Laske, Masters,  
Shearer

GPS, Agnew, Bock, Fialko, Minster

INFORMATION TECHNOLOGY, Bock,  
Orcutt, Vernon

INFRASOUND, de Groot-Hedlin, Hedlin

INVERSE THEORY, Key, Parker

LANDSCAPE SYSTEMS, Werner

MARINE ELECTROMAGNETIC INDUCTION,  
Constable, S., Key

MARINE GEOLOGY, Blackman, Harding, Laske,  
Staudigel

MARINE SEISMOLOGY, Harding, Laske, Orcutt

MID-OCEAN RIDGES, Constable, S., Blackman,  
Harding

NORMAL MODES, Davis, Masters, Laske

NUMERICAL METHODS, Constable, S.,  
Dzieciuch, de Groot-Hedlin, Parker

OBSERVATIONAL NETWORKS, Bock, Davis,  
Orcutt, Vernon

OCEAN ACOUSTICS, de Groot-Hedlin,  
Dzieciuch, Munk, Worcester

OCEANOGRAPHY, Munk, Worcester

OCEAN BATHYMETRY, Sandwell

PALEOMAGNETISM, Constable, C.

PLANETARY PHYSICS, Stegman

RADAR TECHNIQUES, Fialko, Fricker, Minster,  
Sandwell

REFLECTION SEISMOLOGY, Harding

SATELLITE LASER ALTIMETRY, Fricker

SEAMOUNTS, Staudigel

SEISMIC ANISOTROPY, Blackman

SEISMIC HAZARDS, Bock, Kent

SEISMOMETERS, Berger, Zumberge

SPECTRAL ANALYSIS, Dzieciuch, Parker,  
Shearer, Vernon

STRAINMETERS, Agnew, Zumberge

TIDES, Davis, Agnew

TURBULENCE, Ireley

VOLCANOS, Fialko, Hedlin, Ogden, Staudigel

ES

BEMT

CACT

HNPS

DHLG

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

As part of the Plate Boundary Observatory (PBO) project, we are operating six longbase laser strainmeters (LSM's) at four locations in California. From north to south these locations, and their instruments, are:

**Cholame:** Instruments CHL1 (NS, 439 m long) and CHL2 (EW, 380 m long). This location is near the northwest end of the segment of the San Andreas fault that last ruptured in 1857.

**Glendale:** Instrument GVS1 (N15°E, 559 m long). This instrument, originally constructed as part of the SCIGN network, is at the northern edge of the Los Angeles basin, near the San Gabriel mountains and in an area of possible NS compression. The instrument began operation in September 2002.

**Durmid Hill:** Instrument DHL2 (N94°E, 405 m long). This instrument was built to complement an existing LSM (DHL1, N4°E, 524 m long), that is operated with support from the US Geological Survey. The site is 1.5 km from the trace of the San Andreas fault in the Salton Trough, near the southern end of the fault segment with the most accumulated strain since its last rupture. DHL1 has been operating since December 1994.

**Salton City:** Instruments SCS1 (NS, 490 m long) and SCS2 (EW, 405 m long). This location is 22 km (at S40°W) from the Durmid Hill site, on the other side of the Salton Sea, and between the San Andreas and San Jacinto fault zones.

In addition the USGS and Southern California Earthquake Center support the operation of three non-PBO LSM's (PFO1, PFO2, and PFO3, all 720 m long) at **Piñon Flat Observatory**, in operation since 1972.

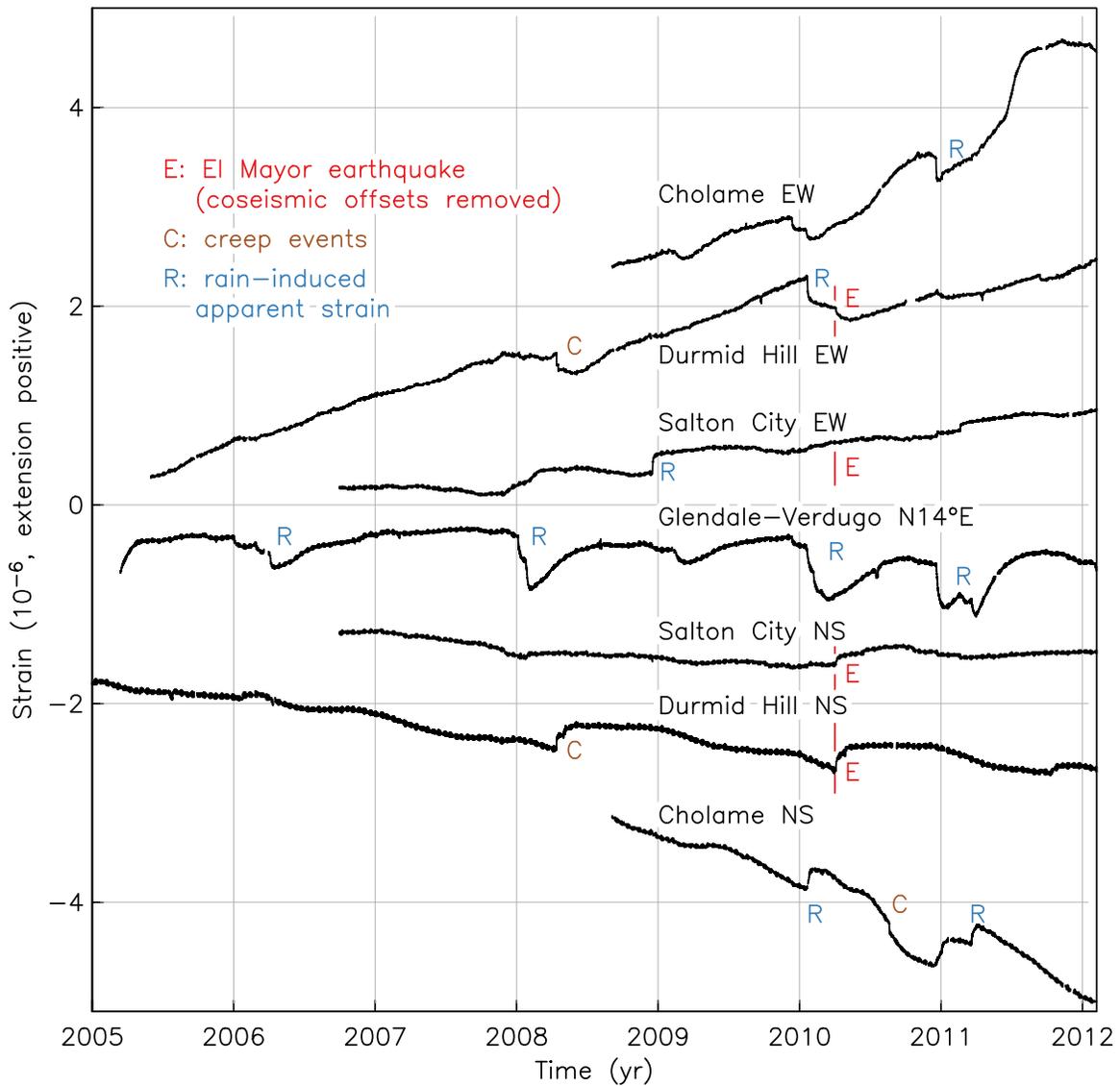
**Figure 1** shows all data from the PBO strainmeters, plus DHL1 (NS) for the same time. This is the most extensive and highest-quality dataset of strainmeter recordings in the world. By emphasizing the performance at the very longest periods, this plot shows how these instruments meet the most difficult challenge: recording secular strain accumulation; if an instrument can do this, tectonic variations at shorter periods will be recorded with even higher reliability. And we have seen these, both associated with earthquakes, and (at DHL and CHL) with creep events on the San Andreas fault.

The long-term strain-rates are:

Site	Strain Rates ( $10^{-6}/\text{yr}$ )			
	NS	EW	$\dot{\Delta}$	$\dot{\gamma}_1$
CHL	-0.52	0.69	0.17	-1.21
DHL	-0.20	0.29	0.09	-0.49
SCS	-0.03	0.16	0.13	-0.19
GVS	-0.06			

where  $\dot{\Delta}$  is the rate of dilatation, and  $\dot{\gamma}_1$  the rate of fault-parallel shear strain. These strain rates are in accord with the rates determined geodetically, and, unsurprisingly, high near fault zones, and lower farther from them. Though some instruments show transient signals from hydrologic changes, which we are working on modeling and removing, these sensors are providing the best available record of ground deformation over the broadest bandwidth: from seismic frequencies to periods of many months and longer.

## Long-term Strain Data from LSM's



**Figure 1**

### Publications

- Shen, Z.-K., R. W. King, D. C. Agnew, M. Wang, T. A. Herring, D. Dong, and P. Fang (2011). A unified analysis of crustal motion in Southern California, 1970-2004: The SCEC Crustal Motion Map, *J. Geophys. Res.*, **116**, B11402, doi:10.1029/2011JB008549
- Barbour, A. J., and D. C. Agnew (2011). Noise levels on Plate Boundary Observatory borehole strainmeters in Southern California, *Bull. Seismol. Soc. Am.*, **101**, 2453-2466, doi:10.1785/0120110062
- Barbour, A. J., and D. C. Agnew (2012). Detection of seismic signals using seismometers and strainmeters: Results from colocated borehole and surface instruments, *Bull. Seismol. Soc. Am.*, **102**, in press.

**Luciana Astiz**

**Specialist**

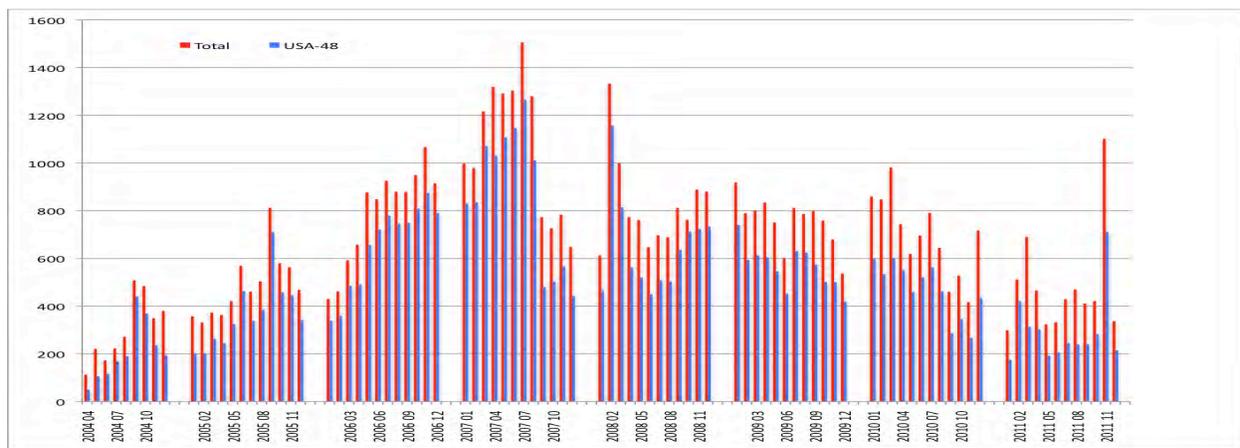
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Research Interest: Seismology and Tectonics, , time series analysis, earthquake physics

As part of the Array Network Facility (ANF) team at IGPP my main responsibility is help oversee and assess data quality issues with the transportable array (TA) stations of the USarray. The ANF is responsible for the acquisition of all data: seismic, environmental and equipment state of health of the USarray, which is forwarded to the IRIS Data Management Center (DMC) in Seattle for distribution to the scientific community. Automatic command and control to the stations, monitoring of state of health parameters and 'eyes on the data' by ANF analyst provides direction to service field engineer to maintain the remarkable > 95% data availability for TA data but also has helped improve data quality.

ANF uses the Antelope environmental monitoring software developed by Boulder Real Time Technologies (BRTT) to acquire and locate seismic events. The location algorithm uses the iasp91 velocity model for all automatic and analyst reviewed locations. These hypocenters are associated with the corresponding quick epicentral determinations (QED) solutions of the United States Geological Survey seismic bulletin as well as appropriate solutions from regional seismic networks if available. From April 2004 to December 2011 ANF analysts have located over 45,000 events in the continental US with over 1.7 million arrivals (most of them P phase arrivals). Although most events recorded are regional events (Figure 1), most of the picks (Figure 2) are generated by teleseismic events, such as the March 11, 2011 Japanese earthquake and its aftershocks as they are recorded at most USarray stations.



*Figure 1. Bar graph with the overall number of events recorded by USarray stations in red. The blue bars show the number of events recorded within the continental U.S.*

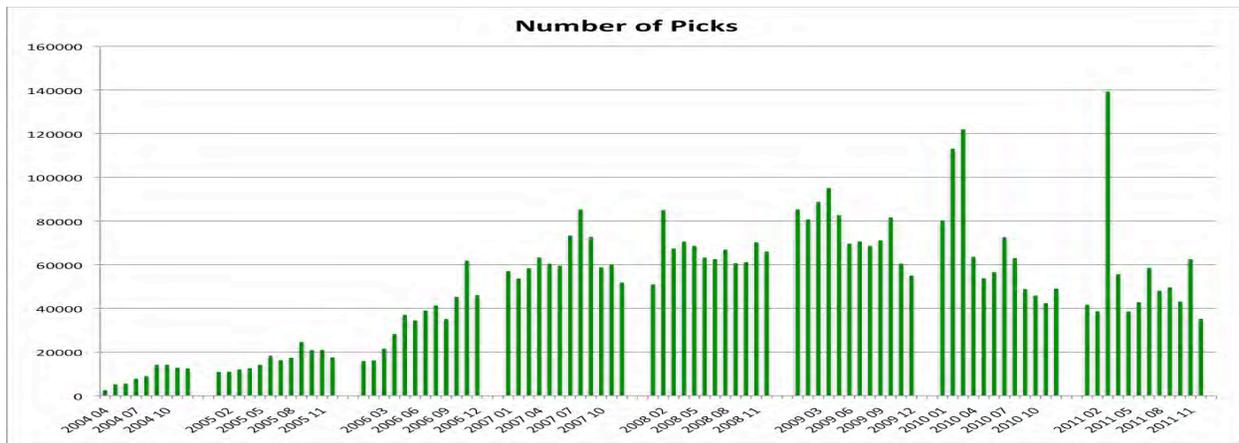


Figure 2. Bar graph with the overall number of revised picks recorded by USArray stations. Teleseismic picks have been used in tomographic models such as that of Burdick et al. (2012), [SRL, v83, p.23-27].

The USArray has provided for the first time, an integrated view of seismicity in the continental U.S., since at least 50% of events located by ANF have not been reported by other regional seismic networks (Figure 3). Note that ANF records and locates quarry blasts that are not included in regional seismic bulletins.

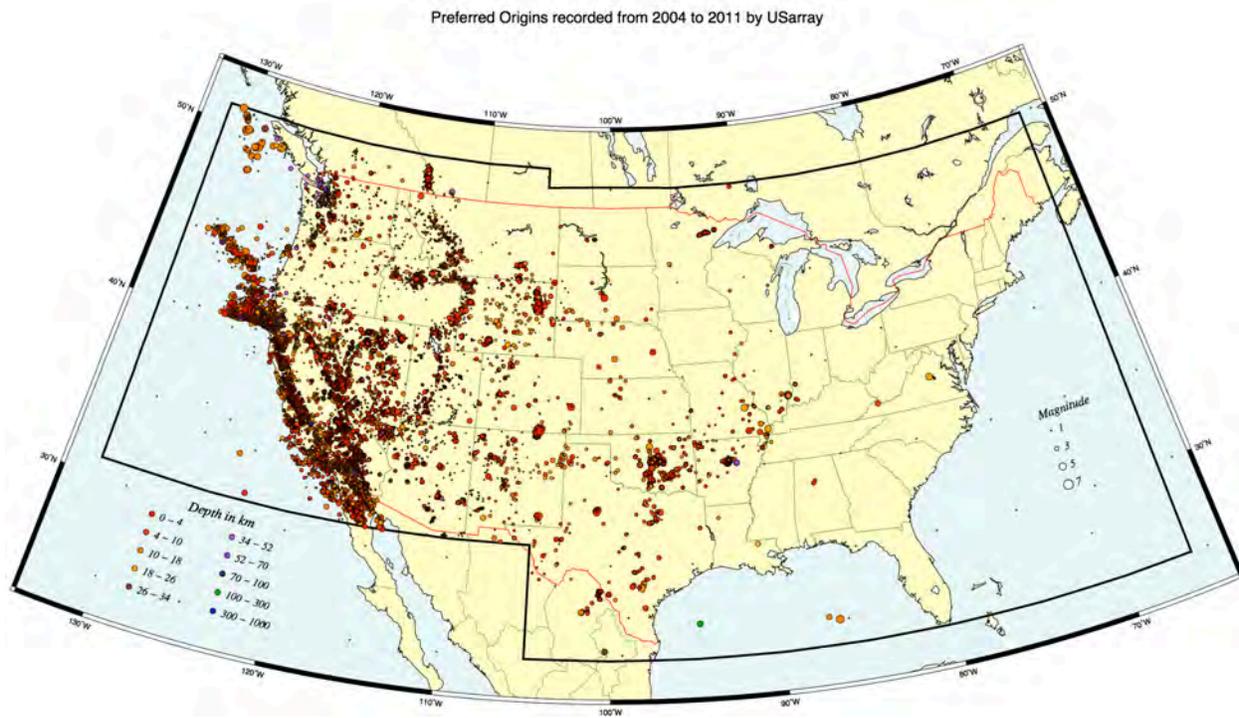


Figure 3. Seismicity distribution by depth for all events recorded within the bounding box.

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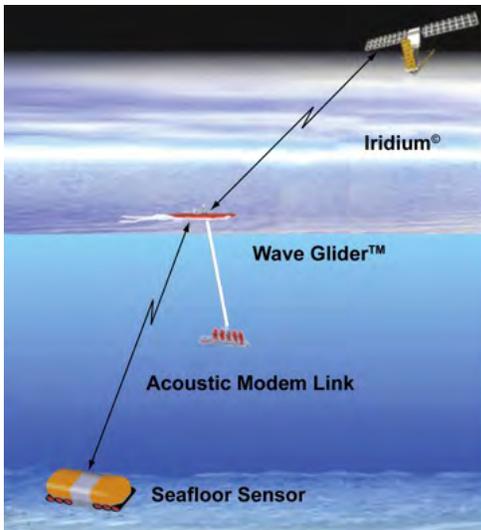
Phone: 42889

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

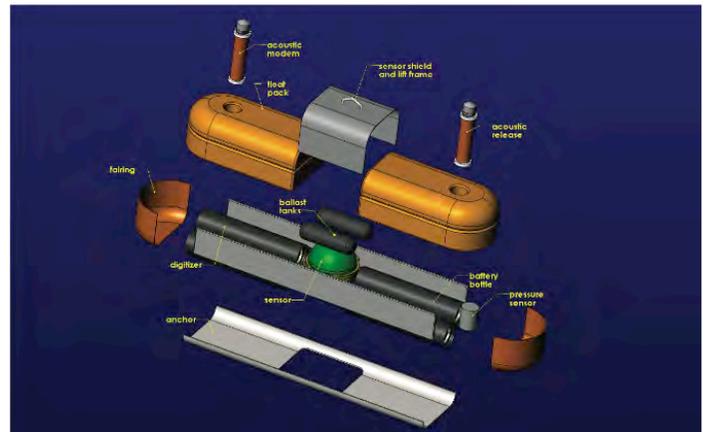
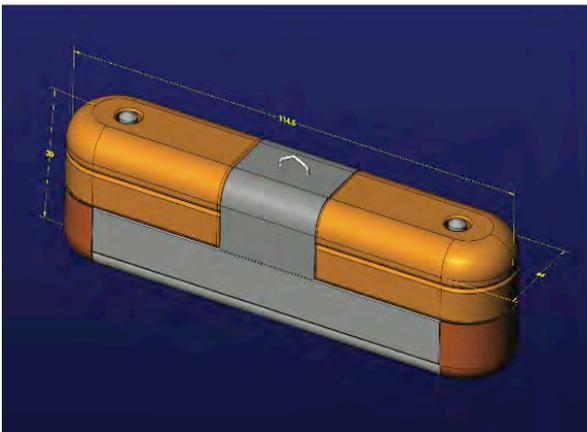
In collaboration with Mark Zumberge, I have been working on the development of new sensors to replace the obsolete and no longer available broadband sensors used in the Global Seismographic Network. We are funded to deploy a 3-component borehole model at the USGS Albuquerque Seismological Lab next year. The current prototype includes a new in-line vertical suspension which will not require leveling while the horizontal component sensors consist of a simple pendulum suspended by a monolithic, electrical discharge machined flexure.

I have also been working with the OBSIP group at IGPP in developing a system that will allow us to deploy seismological observatories in the deep ocean and relay data to shore in near real-time. We have been successful in obtaining an NSF Major Research Instrumentation grant that will allow us to try out these ideas over the next two years.

We propose to develop an autonomously deployable, deep-ocean seismic system to provide long-term and near-real-time seismographic observations from sites far offshore. Building upon two proven technologies, autonomous wave-powered surface floats and ocean bottom seismometers, the proposed new generation instrument will, if successful, provide a means of increasing global coverage not only of seismic observations, but also of a variety of ocean bottom observables in an affordable, practical, and sustainable way. In this effort, we are teamed with a small company, Liquid Robotics, which has developed a new, breakthrough technology for deep ocean observations and telemetry. The Liquid Robotics Wave Glider technology comprises a surfboard-sized surface float tethered to a submerged glider, which converts wave motion into thrust and thereby propels itself. Equipped with acoustic and satellite telemetry systems, this platform will provide a communications gateway between an ocean bottom instrument and shore. Combining the Liquid Robotics technology with the technology developed for the US Ocean Bottom Seismograph Instrument Pool, the key features of this new instrument will be its capability to telemeter sensor data from the seafloor to shore without a cable or moored surface buoy, and to be deployable without a ship.



The overall concept is illustrated above. The Liquid Robotics Wave Glider surface float is equipped with solar panels, a satellite modem, GPS, and a small processor to provide commands to steer the system via a rudder on the glider. The Wave Glider has demonstrated the ability to “swim” thousands of kilometers across the open ocean and to hold station in a very small watch circle. Further, the Wave Glider has the capability to tow properly designed, low-drag loads with little loss of speed. Optimal speed performance will be reduced when towing objects, but persistent forward thrust will be maintained. Tests conducted by Liquid Robotics proved that towing an object 2 ft. in diameter and 11 ft. long behind a Wave Glider is practical. Leveraging the talents and strengths of Liquid Robotics and the SIO OBS team, we propose to develop the technology to tow a suitably designed ocean bottom seismic package to the desired site, deploy it, and then circle the launch site with the Wave Glider acting as a surface gateway between the acoustic transmission through the ocean column and the satellite transmissions to shore.



### Relevant Publications

- Mark Zumberge, Jonathan Berger, Jose Otero, and Erhard Wielandt., A Non-feedback Optical Seismometer. *Bulletin of the Seismological Society of America*, Vol. 100, No. 2, pp. 598–605.
- Zumberge, M. A., J. Berger, M. A. Dzieciuch, and R. L. Parker (2004). Resolving quadrature fringes in real time. *Applied Optics*, 43, 771-775.

**Donna Blackman**

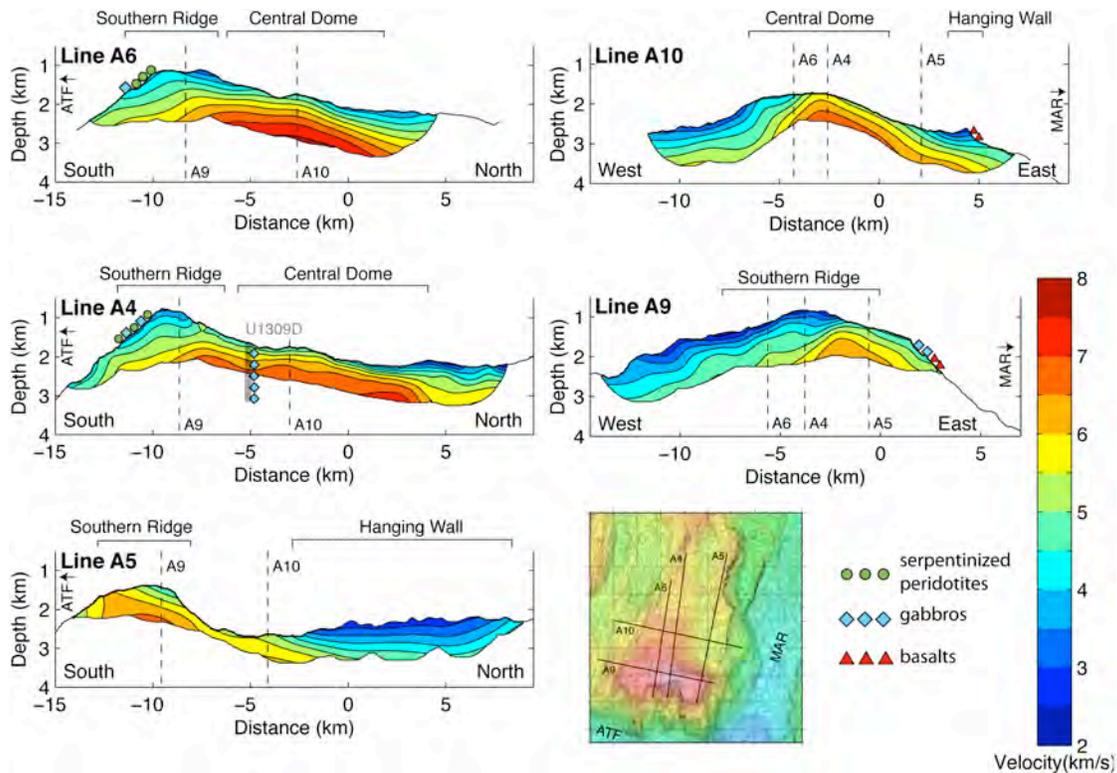
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*Research Interests:* tectonic and magmatic processes that occur along plate boundaries, with emphasis on oceanic spreading centers; deformation of minerals and the development of seismic anisotropy during upper mantle flow.

Geophysical investigations of oceanic spreading center processes remain a main focus of my research. In 2010/2011 my research followed three avenues at Atlantis Massif, an ocean core complex just west of the Mid-Atlantic Ridge axis, where detachment faulting has unroofed intrusive crustal rocks and at least lenses of mantle peridotite. The first avenue involved detailed refraction analysis of the top kilometer of the lithosphere. Grad student Ashlee Henig completed application of the Synthetic Ocean Bottom Experiment (SOBE) method to multi-channel seismic (MCS) data in this area and she refined models of magmatic intrusion and faulting as the core complex developed. Working with co-PI Alistair Harding who was instrumental in developing SOBE, we've been able to document the magnitude and scale of lateral heterogeneity throughout Atlantis Massif.



**Figure.** Seismic velocity structure of Atlantis Massif (from Henig et al. in prep). Map shows rift valley of the Mid-Atlantic Ridge (MAR, blue shades) at intersection with Atlantis transform fault (ATF). The Southern Ridge (red shades), Central Dome just to the north, and the hanging wall block, to the east, are shown with MCS lines overlain. Schematic illustration of drill/dredge/submersible sample locations uses symbols on/in seismic models (rock type in legend). Dashed lines indicate where MCS lines cross.

Secondly, synthesis of drill core analyses at the Central Dome IODP site and regional geophysical results were used in assessing the key factors in igneous, structural, and metamorphic evolution of Atlantis Massif, as reported in a JGR paper this year. Thirdly, looking ahead, Alistair and I will begin working with postdoc Adrien Arnulf to apply waveform inversion techniques to further refine knowledge of the seismic structure of the massif. A brief borehole study will be conducted at the Central Dome, to document local seismic properties that can anchor the regional seismic inversions.

In the Lau Basin, last November I helped recover an array of ocean bottom seismometers (OBS), that had been deployed for a year to record earthquakes generated during subduction of the Pacific plate at the Tonga trench. These data will be used to document seismic anisotropy in the mantle wedge between the trench and backarc spreading centers. While our colleagues on the project emphasize S-wave splitting measurements, we are moving ahead with linking models of mantle flow along 3 transects across the basin with quantitative predictions of anisotropy. Grad student Rachel Marcuson is in the process of conducting this initial numerical investigation. As analysis of the OBS data proceeds, we'll work with our collaborators to determine what flow parameters need to be adjusted so that model predictions match observed mantle anisotropy patterns.

A modest mapping project along four spreading segments that extend north from the Chile Triple Junction combined morphology data from two 2010 cruises. A systematic pattern of clockwise rotation of volcanic chain and fault scarp trends in the southern portion of 3 of the segments suggests that either regional tectonic forces or a persistent pattern of mantle upwelling may influence detailed axial morphology. We (Stegman and I with GRD colleagues Castillo, Day, & Cande) have designed additional mapping and lava sampling that could test between different models of plate-driven versus flow-driven evolution of the plate boundary and associated magma chemistry in this region.

Finally, I continued efforts in community planning for future drilling of the oceanic lithosphere and associated geophysical studies that could maximize the advances that deep core samples would provide. This was done mainly via participation in meetings for the ocean drilling (IODP) and ocean bottom seismic (OBSIP and R/V Langseth) programs.

Blackman, D.K., B. Ildefonse, B.E. John, Y. Ohara, D.J. Miller and Exp. 304/305 Science Party, Drilling Constraints on Lithospheric Accretion and Evolution at Atlantis Massif, Mid-Atlantic Ridge 30°N, *J. Geophys. Res.* 116, B07103, doi:10.1029/2010JB007931, 2011.

C. Berka, D. Blackman, B. Ildefonse, P. Kelemen, A. Mangum, J. Phipps Morgan, G. Myers, M. Schrenk, Y. Tatsumi, J. Warren, K. Suyehiro, Executive Summary: "Mantle Frontiers" Workshop, *Scientific Drilling* 11, 53-58, 2011.

Blackman, D.K. and O. Castelnau, Rheologic Anisotropy Associated with Flow-Induced Texturing of Earth's Mantle, presented at Polycrystal Modelling with Experimental Integration: A Symposium Honoring Carlos Tome, The Minerals, Metals & Materials Society Annual Mtg, San Diego, Feb. 2011.

## Yehuda Bock

### Research Geodesist and Senior Lecturer

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*Research Interests:* Space geodesy, crustal deformation, early warning systems for natural hazards, GPS seismology, GPS meteorology, GIS and Information Technology

Highlights of Yehuda Bock's research in 2011 with graduate students Brendan Crowell and Diego Melgar, Scripps Orbit and Permanent Array Center (SOPAC) staff, and collaborators at Caltech and JPL, includes real-time integration of geodetic, seismic and meteorological sensors for the mitigation of natural hazards. Integration of GPS and seismic sensors in real time (Figure 1) provides enhanced earthquake early warning

(Crowell *et al.*, 2009), rapid centroid moment tensor (CMT) solutions (Melgar *et al.*, 2012) and finite fault slip models (Figure 2) especially suited for near-source monitoring of large earthquakes with tsunamigenic potential such as the devastating 2011 Mw 9.0 Tohoku-oki earthquake in Japan. In Figure 1 we show 100 Hz displacement waveforms estimated

with a smoothed Kalman filter (Bock *et al.*, 2011), 1 Hz GPS displacements at station 0172 and 100 Hz accelerometer data at nearby site MYG001 on the western coast of Honshu and about 120 km from the earthquakes's epicenter. The displacements show about 2 m of permanent (coseismic) deformation in the north, 4 m in the east, and 0.6 m of subsidence in the vertical component. The Japanese Meteorological Agency (JMA) is responsible for earthquake characterization in Japan, but they severely underestimated the earthquake's magnitude as shown in Figure 1. It wasn't until 20 minutes after earthquake initiation and using teleseismic data that the National Earthquake Information Center (NEIC) determined that an Mw 9.0 earthquake had taken place. Using the 100 Hz displacement waveforms generated with the smoothed Kalman filter in a simulated real-time mode, we have demonstrated that one could have estimated an accurate CMT solution and finite fault slip model within about 3 minutes of earthquake initiation, almost an order of magnitude sooner than what occurred in practice. Knowing that an Mw 9.0 earthquake had occurred certainly would have improved the tsunami warning. Blowing up the vertical component in Figure 1 shows that the smoothed Kalman filter estimate clearly captures the P-wave arrival, which is the key for earthquake early warning systems. Once the P-wave has been detected then a prediction can be made when the destructive S-wave will be felt. This is important since existing seismic methods are unable to distinguish in real time between, for example, a magnitude 7 and magnitude 9 earthquake.

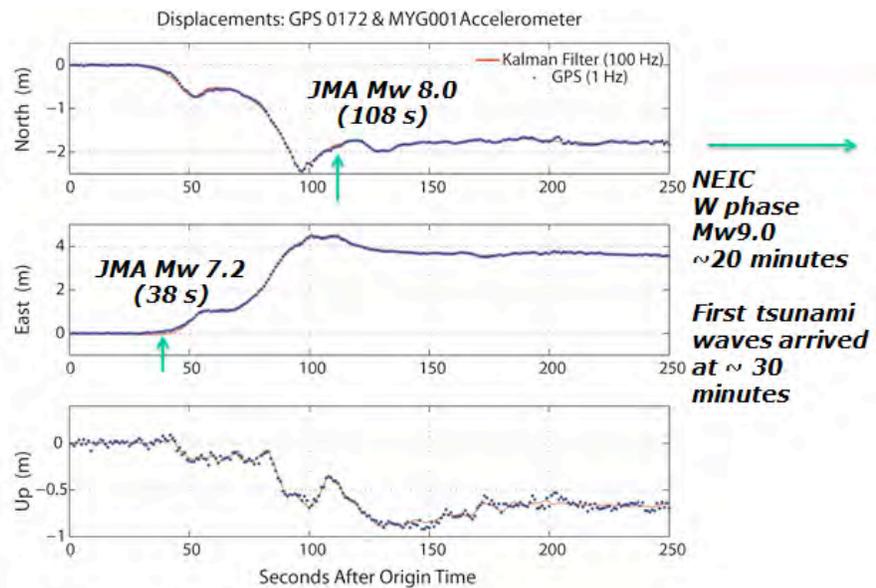


Figure 1

In Figure 2 we show a finite fault slip model generated in a simulated real-time mode from displacement waveforms estimated at 140 “collocated” GPS and accelerometer sensors in Japan, including the one shown in Figure 1, using the “rapid Okada” formulation described in *Crowell et al. (2012)*. It shows that after 3 minutes (the entire rupture process took about 2 minutes), we are able to produce a physically meaningful finite fault model for the event with an accurate magnitude estimate. The vertical displacements are shown in the figure for the 140 collocated stations.

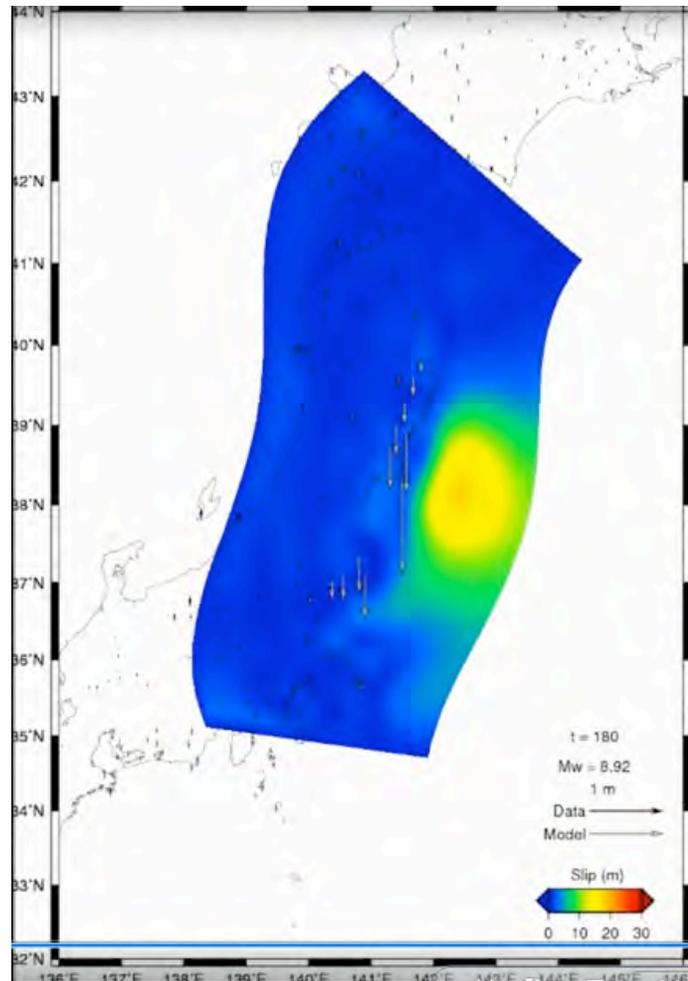
Integration of GPS and seismic sensors can also be applied to volcano hazards and monitoring of large engineered structures such as tall buildings, bridges, dams, and other critical infrastructure. Integration of GPS and meteorological sensors (with surface pressure and temperature readings) is useful for forecasting severe weather such as atmospheric rivers and monsoons, as precursors to flooding. Finally, GPS networks can

provide maps of the lower atmosphere that can be interpolated to calibrate satellite radar measurements and the technique of Interferometric Synthetic Aperture Radar (InSAR).

In 2011, we expanded the California Real Time Network (CRTN - <http://sopac.ucsd.edu/projects/realtime/>), now numbering more than 200 continuous GPS stations. We are working to upgrade existing real-time GPS stations throughout the Western U.S. with MEMS accelerometer and meteorological modules for natural hazards mitigation.

### Related Publications

- Crowell, B., Y. Bock, and M. Squibb (2009), Demonstration of earthquake early warning using total displacement waveforms from real time GPS networks, *Seismo. Res. Lett.*, *80*(5), 772-782, doi: 10.1785/gssrl.80.5.772.
- Bock, Y., D. Melgar, B. W. Crowell (2011), Real-Time Strong-Motion Broadband Displacements from Collocated GPS and Accelerometers, *Bull. Seismol. Soc. Am.*, *101*, doi: 10.1785/0120110007.
- Melgar, D., Y. Bock and B. Crowell (2012), Real-time centroid moment tensor determination for large earthquakes from local and regional displacement records, *Geophys. J. Int.*, doi: 10.1111/j.1365-246X.2011.05297.x.
- Crowell, B., Y. Bock and D. Melgar (2012), Real-time inversion of GPS data for finite fault modeling and rapid hazard assessment, *Geophys. Res. Lett.*, in revision.

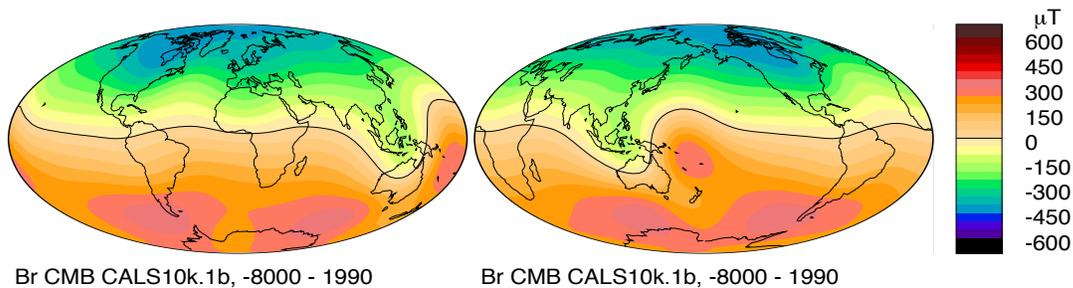


**Figure 2**

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*Research interests:* Paleomagnetism and geomagnetism, applied to study of long and short term variations of the geomagnetic field; linking paleomagnetic observations to numerical dynamo simulations; inverse problems; statistical techniques; electrical conductivity of the mantle; paleo and rock magnetic databases.

Major research interests over the past year have been (i) the behavior of the geomagnetic field behavior on millennial timescales during the Holocene time period (in collaboration with Monika Korte of GeoForschungs Zentrum, Helmholtz Center, Potsdam); (ii) the magnetic field on million year time scales (PhD student Leah Ziegler); (iii) development of modeling and data processing tools for global electromagnetic induction studies using magnetic field observations from low-Earth-orbiting satellites (PhD students, Joseph Ribaud and Lindsay Smith-Boughner); (iv) the development with Anthony Koppers (Oregon State University) and Lisa Tauxe of flexible digital data archives for magnetic observations of various kinds under the MagIC (Magnetics Information Consortium) database project. (v) continuing work with postdoctoral researcher Christopher Davies (now at Leeds University, U.K.) and research associate David Gubbins on the compatibility of numerical geodynamo simulations with paleomagnetic results.



**Figure 1** Time averages of CALS10k.1b for the radial component of the field at the core mantle boundary. Aitoff projection centred on 0 and 180°E.

(i) *Holocene Geomagnetic Field Behavior:* We have extended time-varying spherical harmonic geomagnetic field models to span the (0-10 ka) Holocene interval (see Figure 1). An updated global compilation of paleomagnetic records from rapidly accumulated sediments, archeological artifacts and young lava flows, allows the recovery of substantial structure in the southern hemisphere. For the past 400 years, twin magnetic flux lobes bordering the inner core tangent cylinder in both northern and southern hemispheres dominate the geomagnetic field and appear more or less fixed in location. In contrast, the millennial scale view shows that such features are quite mobile and subject to morphological changes on time scales of a few centuries to a thousand years, possibly reflecting large scale reorganization of core flow. The lobes rarely venture into the Pacific hemisphere, and average fields over various time scales generally reveal two or three sets of lobes, of diminished amplitude. Thus millennial scale models are suggestive of thermal core-mantle coupling generating a weak bias in the average field rather than a strong inhibition of large scale field changes. Persistent structure in the equatorial Pacific region is the subject of further study.

(ii) *Magnetic Field Variations on Million Year Time Scales:* The recovery of 0–2Ma variations in dipole moment (Ziegler *et al.*, 2011) allows frequency domain analysis to search for characteristic

time scales for core dynamics that might be associated with excursion and reversal rate, time taken for reversals, or any signs of control by Earth's orbital parameters. The spectrum is characteristically red for the time interval 0–160 Ma, suggesting non-stationarity associated with average reversal rate changes, probably reflecting the impact of superchrons and a continually evolving core. Distinct regimes of power law decay with frequency may reflect different physical processes contributing to the secular variation. Evidence for non-stationarity at shorter time-scales is present in dipole moment variations over 0–2 Ma with average growth rate faster than the decay process. Details can be found in Ziegler & Constable (2011).

(iii) *Global Electromagnetic Induction*: Satellite and observatory magnetic field measurements can be used for geomagnetic depth sounding to study electromagnetic induction and hence determine electrical conductivity variations in the deep mantle. Work is targeted to address three major challenges to acquiring reliable results: (1) accounting for the spatial structure of the external source field, (2) the impact of near surface heterogeneity on attempts to recover 1-D and 3-D structure, and (3) effective response estimation across the broadest possible frequency range with the length of continuous satellite and observatory time series available.

Items (1) and (2) above are studied using commercial software FlexPDE for flexible 3-dimensional forward modeling to accommodate arbitrary spatial and temporal variations in external source fields and 3D conductivity variations inside the earth (Ribaudo *et al.*, 2011). Forward modeling can be conducted in either the time or frequency domain: the former is particularly useful for satellite observations where motion of the satellite through a time-varying field can produce spatio-temporal aliasing, and the method can also accommodate the effects of Earth rotation, which are significant. Work continues on item (3), exploring the use of multi-taper spectral estimation explicitly designed to recover frequency-domain response function estimates from data series with inconvenient gaps. Current work involves the extension of the methods described in Smith-Boughner *et al.* (2011) to cross-spectral techniques for response function estimates.

### Relevant Publications

- Amit, H., M. Korte, J. Aubert, C. Constable, G. Hulot, The time-dependence of intense archeomagnetic flux patches, *J. Geophys. Res.*, , doi:10.1029/2011JB008538, 2011.
- Constable, C.G., Modelling the geomagnetic field from syntheses of paleomagnetic data, *Phys. Earth Planet. Int.*, 187, 109–117, doi:10.1016/j.pepi.2011.05.004, 2011.
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- Smith-Boughner, L., L.B. Ziegler, & C.G. Constable, Changing Spectrum of Geomagnetic Intensity Variations in a Fragmented 12 My Sediment Record from the Oligocene, *Phys. Earth Planet. Int.*, 188, 260-269, doi:10.1016/j.pepi.2011.07.011, 2011.
- Ziegler, L.B., & C.G. Constable, Asymmetry in growth and decay of the geomagnetic dipole over the past 2 million years, *Earth Planet. Sci. Lett.*, 312, 300-304, doi:10.1016/j.epsl.2011.10.019, 2011.
- Ziegler, L., C.G. Constable, C.L. Johnson & L. Tauxe, PADM2M: A penalized maximum likelihood model of the 0-2 Ma paleomagnetic axial dipole moment, *Geophys. J. Int.*, 184, 1069–1089, doi: 10.1111/j.1365-246X.2010.04905.x, 2011.

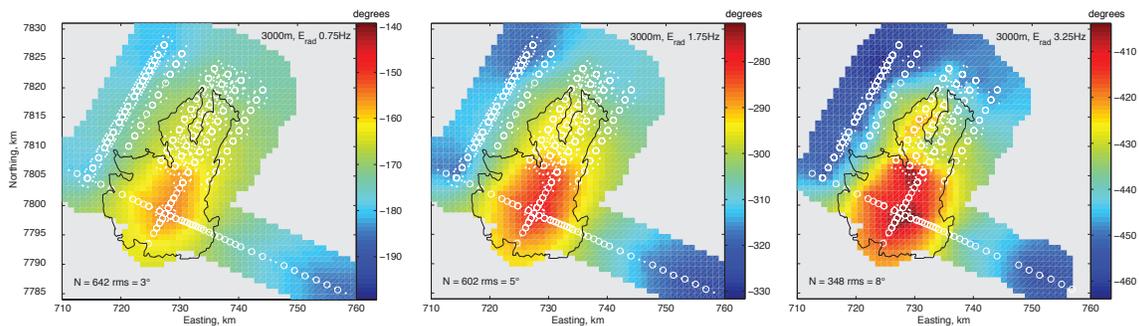
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*Research interests:* Marine EM methods, electrical conductivity of rocks.

Steven Constable directs the SIO Marine EM Laboratory along with assistant researcher Kerry Key. As the name suggests, much of the Lab's work is involved in developing and using marine EM methods. The two main techniques 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. We currently have 5 PhD students, a postdoc, a project scientist, and a research associate working in the group.



*Figure 1.* Phase of CSEM electric fields at three frequencies (0.75 Hz, 1.75 Hz, and 3.25 Hz) over the Scarborough gas field (outlined in black) at a fixed source–receiver offset of 3,000 m.

In 2009 we collected a large CSEM data set over the *Scarborough gas field*, on the Northwest Shelf of Australia, under sponsorship from BHP-Billiton. This project forms part of David Myer's PhD studies, and we are beginning to obtain results from the data analysis. One innovation we employed during this experiment was a new transmitter waveform that allows us to simultaneously collect a broad spectrum of frequencies, described in Myer *et al.* (2011). In Figure 1 we show the phase difference between the transmitter and seafloor receivers for three frequencies at a fixed source–receiver range of 3,000 m. Over the gas reservoir, which is slightly more resistive than the host rocks, the phase difference is less because EM fields propagate better in resistive rocks and so the apparent phase velocities are higher. The effect increases with increasing frequency because the skin depth, or EM propagation constant, gets shorter at higher frequencies, allowing a bigger difference in phase to accumulate at the fixed range. The data clearly illuminate the reservoir, and we are using geophysical inversion to recover the thickness and extent of the gas.

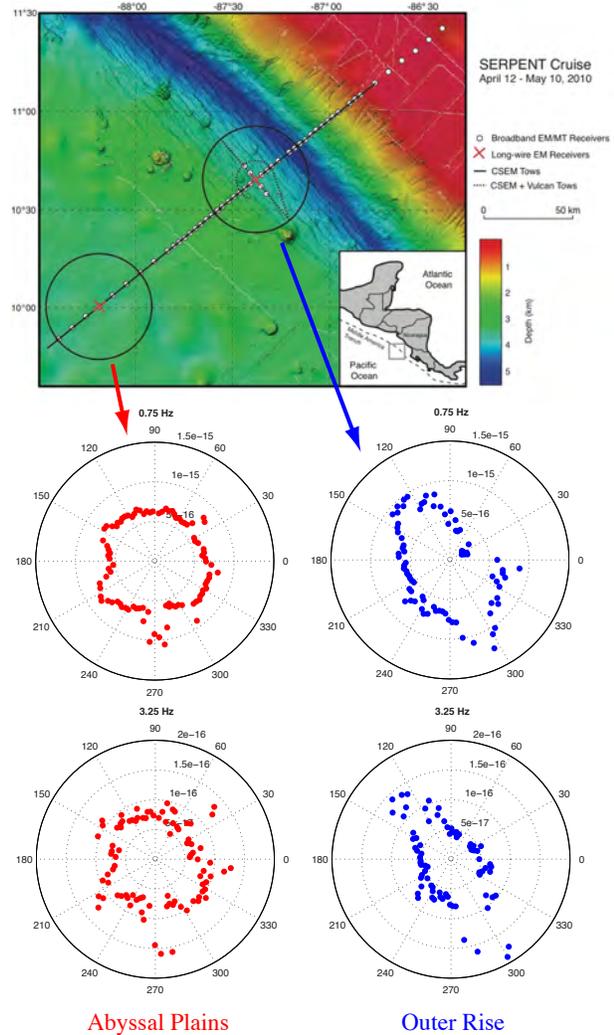
Last year we reported results from our efforts to map *marine gas hydrate* using CSEM methods. This year we have been working on measuring the electrical properties of methane hydrate in the laboratory. This is not a trivial task because the hydrate has to be kept under high pressure methane to be stable and to mimic the conditions in 1,000 m water depth, where it occurs naturally. We built a high pressure conductivity cell and made the first measurements of methane hydrate conductivity as a function of temperature. This work is reported in Du Frane *et al.* (2011) and described in Karen Weitemeyer's annual report entry, along with some comparisons between the Hydrate Ridge EM results and a seismic survey (Weitemeyer *et al.*, 2011).

This year we finally worked up and published a MT data set collected off Japan in May 2000 (Key and Constable, 2011). These data were some of the first collected on the modern generation of instruments, and to this day represent the deepest deployments we have made (up to 5,400 m). The analysis took advantage of recently developed modeling code which allowed us to understand more fully the effect of coastlines, which have a very large impact on data such as these. Kerry describes this work in his annual report entry.

In April and May last year we carried out the *SERPENT* experiment, collecting MT and CSEM data to study the geology of the Nicaraguan subduction zone. Kerry reports on the MT and CSEM data sets, but in Figure 2 we show the results of a novel experiment in which the EM transmitter is towed in a 30 km diameter circle around extra-sensitive instruments in order to study anisotropy, or changes in conductivity with direction. On the abyssal plain (red data) the size of the electric field does not vary very much with the direction to the transmitter. On the outer rise, however, there is a strong increase in fields when the transmitter is NW or SE of the receiver (blue data). Paradoxically, this means that the crust is more conductive in this direction, almost certainly because of the faulting associated with plate bending. Further work will quantify the amount and depth of the faults.

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

*Figure 2.* Polarization ellipse maxima as a function of transmitter–receiver direction for 30 km circular CSEM tows on the abyssal plain (red) and outer rise (blue) offshore Nicaragua.



## Recent Publications

- Constable, S., Ten years of marine CSEM for hydrocarbon exploration, *Geophysics*, 75, 75A67–75A81, 2010.
- Du Frane, W.L., L.A. Stern, K.A. Weitemeyer, S. Constable, J.C. Pinkston, and J.J. Roberts, Electrical properties of polycrystalline methane hydrate, *Geophysical Research Letters*, 38, doi:10.1029/2011GL047243, 2011.
- Key, K., and S. Constable, Coast effect distortion of marine magnetotelluric data: Insights from a pilot study offshore northeastern Japan, *Physics of the Earth and Planetary Interiors*, 184, 194–207, 2011.
- Myer, D., S. Constable, and K. Key, Broad-band waveforms and robust processing for marine CSEM surveys, *Geophysical Journal International*, 184, 689–698, 2011.
- Van Beusekop, A.E., R.L. Parker, R.E. Bank, P.E. Gill, and S. Constable, The 2-D magnetotelluric inverse problem solved with optimization, *Geophysical Journal International*, 184, 639–650, 2011.
- Weitemeyer, K.A., S. Constable, and A.M. Tréhu, A marine electromagnetic survey to detect gas hydrate at Hydrate Ridge, Oregon, *Geophysical Journal International*, 187, 45–62, 2011.
- Weitemeyer, K., G. Gao, S. Constable, and D. Alumbaugh, The practical application of 2D inversion to marine controlled-source electromagnetic sounding, *Geophysics*, 75, F199–F211, 2010.
- Zhdanov, M.S., L. Wan, A. Gribenko., M. Cuma, K. Key, and S. Constable, Large-scale 3D inversion of marine magnetotelluric data: Case study from the Gemini prospect, Gulf of Mexico, *Geophysics*, 76, F77–F87, 2011.

**J. Peter Davis**

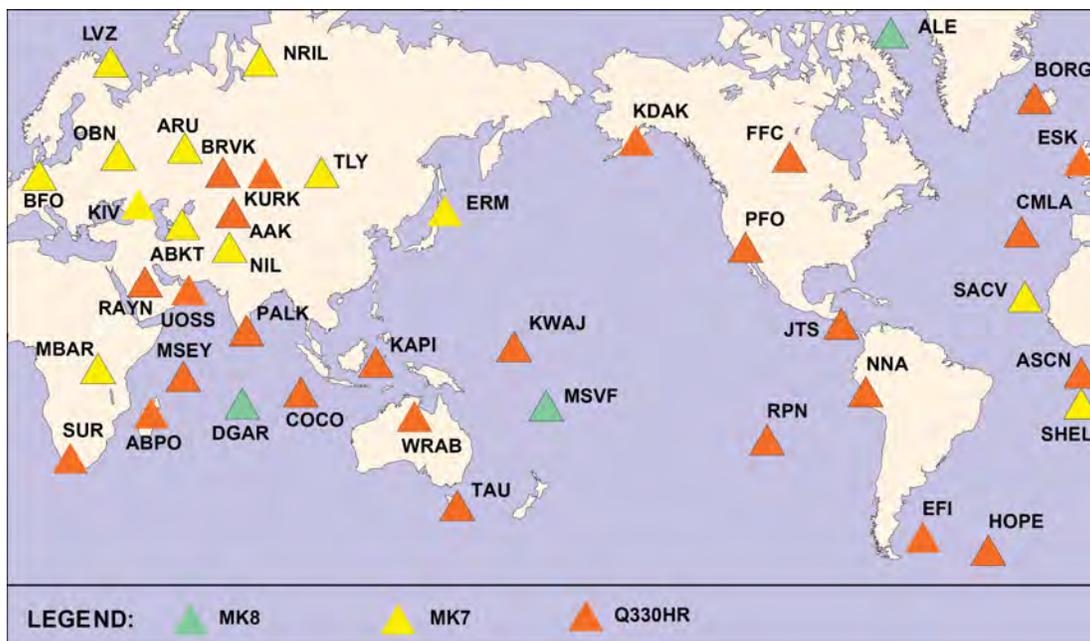
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*Research Interests:* seismology, time series analysis, geophysical data acquisition

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 42 seismographic and geophysical data collection stations distributed among 26 countries worldwide. IDA is currently upgrading the core data acquisition and power system equipment at all stations using stimulus funding provided by NSF through the IRIS Consortium. A map of the network showing upgraded systems denoted by orange triangles is shown in Figure 1.



*Figure 1.* Current global seismic stations operated by Project IDA.

The GSN has been fully deployed for only a short time: during this new phase of operation, IDA's staff is working to fine tune the network's performance. One method for accomplishing this tuning is comparing the GSN's recordings to those of instruments from other networks designed primarily for geodetic or tidal research. Key phenomena such as Earth tides and some normal modes should register the same on these fundamentally different geophysical tools. To the extent that measurements made with multiple instruments, which 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.

Although they occur infrequently, very large earthquakes like those that took place in Japan and Chile recently, afford scientists an excellent opportunity to verify the accuracy of instrument responses. Figure 2 shows a spectrum from two different instruments that recorded

the 2011 Tohoku quake. One is from the GSN seismometer at Sutherland, South Africa; the other, from a superconducting gravimeter in Germany. Prominent in both recordings are spectral peaks associated with the Earth's gravest normal modes. We expect the amplitudes of many of these modes to differ at the two locations, but one, the mode  $0S_0$ , should be excited to a uniform amplitude globally. The amplitude difference of  $0S_0$  here indicates inaccuracies in the instrument response of the seismometer that needs to be corrected.

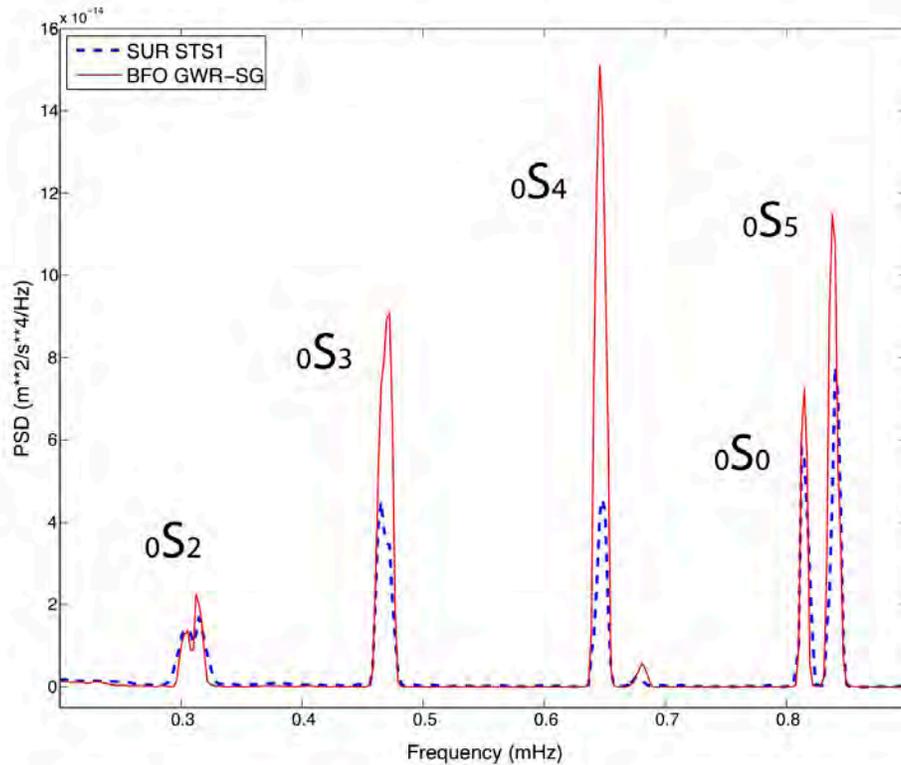


Figure 2. Spectrum of the 2011 Mw=9.0 Tohoku, Japan earthquake observed at IRIS/IDA station SUR (blue dashed line) and a superconducting gravimeter at Germany's Black Forest Observatory BFO (red line). The GSN produced spectacular data for this large event, including clear evidence of splitting of  $0S_2$  at single stations such as in these cases. Mode  $0S_0$  can be used to assess the quality of the network's published instrument responses.

### Relevant Publications

Davis, P., and J. Berger, Calibration of the Global Seismographic Network using tides, *Seis. Res. Lett.*, 78, 454-459, 2007.

Davis, P., M. Ishii and G. Masters, An assessment of the accuracy of GSN sensor response information, *Seis. Res. Lett.*, 76, 678-683, 2005.

Park, J., T.-R. Song, J. Tromp, E. Okal, S. Stein, G. Roult, E. Clevede, G. Laske, H. Kanamori, P. Davis, J. Berger, C. Braitenberg, M. Van Camp, X. Lei, H. Sun, H. Xu and S. Rosat, Earth's free oscillations excited by the 26 December 2004 Sumatra-Andaman earthquake, *Science*, 308, 1140-1144, 2005.

Berger, J., P. Davis, and G. Ekstrom, Ambient Earth Noise: a survey of the Global Seismic Network, *J. Geophys. Res.*, 109, B11307, 2004.

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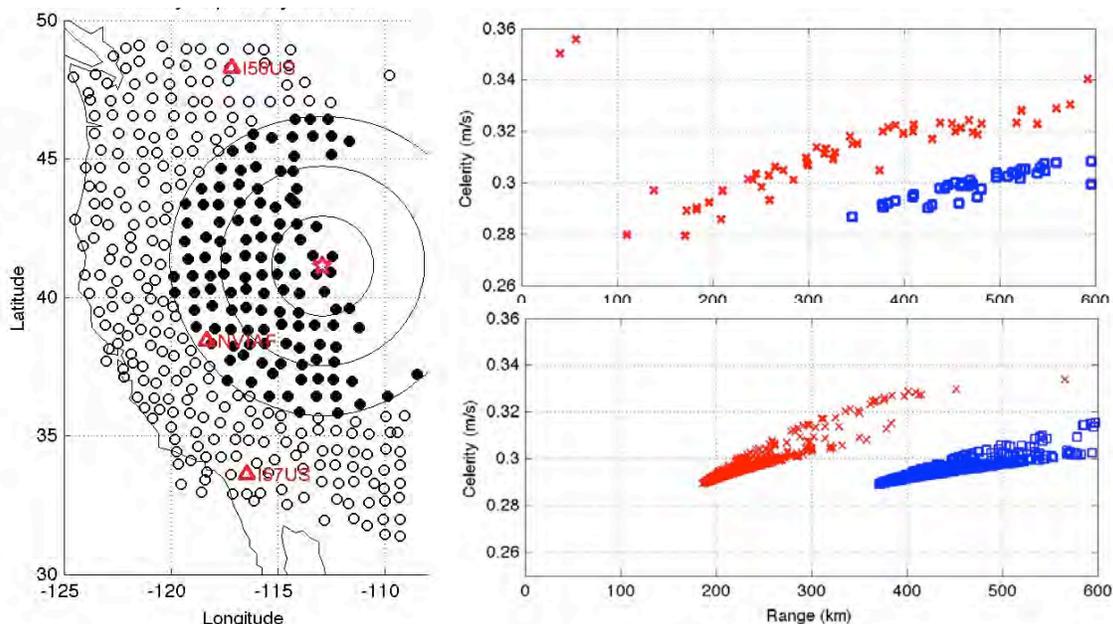
Phone extension: 223133

*Research Interests:* Acoustic propagation modeling with application to infrasound and hydroacoustics; application of hydroacoustics and infrasound to nuclear test-ban verification and hazard monitoring; use of dense seismic networks to analyze infrasound signals.

**Infrasound:** A primary goal in infrasound research is to understand the transmission of infrasound - sound at frequencies lower than human hearing - to distances of several hundreds to thousands of kilometers.

*Shockwaves:* de Groot-Hedlin is sole-PI on a project to develop numerical methods to compute 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 or man-made explosions.

*Infrasound observations at dense seismic networks:* de Groot-Hedlin is currently collaborating with other members of the Laboratory for Atmospheric Acoustics (L2A) at UCSD to analyze infrasound signals detected at a dense network of seismic stations operated by the USarray. An analysis of infrasound signals from the re-entry of the space shuttle Atlantis was presented in de Groot-Hedlin et al. (2008a). Currently, the L2A group is working on the analysis of infrasound signals at this network generated by explosions at the Utah Test and Training Range (UTTR), see Figure 1.



**Figure 1.** (left) A map of the configuration of the USarray seismic network in June 2007 (circles), also showing the source location (diamond) and sites of infrasound arrays (triangles). Signals at sites within 600 km of the source (dark circles) were analyzed. (right top) Observed celerities (=horizontal range/time). (right bottom) Predicted celerities.

The presence of the transportable USArray in this region provides this study with a much broader and denser array of sensors than would otherwise be available. Arrival times, predicted using standard atmospheric specifications that give variations in wind and sound speed with altitude, indicate that the arrivals are multi-pathed; the earlier arrivals are ducted within the thermosphere, later ones are refracted within the stratosphere. An unexplained observation is the presence of high frequency infrasound arrivals, near the acoustic frequency band. This suggests that propagation may be non-linear at upper altitudes, where non-linear steepening of the sound waves can take place to maintain the higher acoustic frequencies. Propagation algorithms to explain this phenomenon are under development.

**Hydroacoustics:** Work is continuing on the analysis of hydroacoustic data recorded on hydrophones that comprise part of the global International Monitoring System (IMS) network. In the past, data from IMS hydrophones has been used to investigate the generation of ocean-borne sound waves by submarine earthquakes (de Groot-Hedlin and Orcutt, 1999 and 2001), the rupture of the 2004 Great Sumatran rupture, that released a devastating tsunami (de Groot-Hedlin, 2005), as well as a series of investigation into long-range acoustic propagation in the Indian Ocean (Blackman et.al., 2004) and through the Antarctic Circumpolar Current (de Groot-Hedlin et.al., 2009).

### Relevant Publications

- de Groot-Hedlin, C., M. Hedlin, K. Walker, 2010, "Finite difference synthesis of infrasound propagation through a windy, viscous atmosphere: Application to a bolide explosion detected by seismic networks", *Geophys. J. Int.*, doi: 10.1111/j.1365-246X.2010.04925.x
- Walker, K, M. Hedlin, C de Groot-Hedlin, J. Vergoz, A. Le Pichon, D. Drob, 2010, The Source location of the 19 February 2008 Oregon Bolide using Seismic Networks and Infrasound Arrays, *J. Geophys. Res.*, 115, B12329, doi:10.1029/2010JB007863
- Hedlin, M.A.H., D. Drob, K. Walker, C. de Groot-Hedlin, , 2010, "A study of acoustic propagation from a large bolide in the atmosphere with a dense seismic network", *Journal of Geophysical Research (Solid Earth)*, 115, B11312, doi:10.1029/2010JB007669
- Matoza, R.S., M.A. Garces, B.A. Chouet, L., D'Auria, M.A.H. Hedlin, C. de Groot-Hedlin, and G.P. Waite, 2009, "The source of infrasound associated with long-period events at Mount St. Helens", accepted by *Journal of Geophysical Research (Solid Earth)*, 114, B04305, doi:10.1029/2008JB006128.
- de Groot-Hedlin, C.D., D.K. Blackman, and C.S. Jenkins, 2009, "Effects of variability associated with the Antarctic Circumpolar Current on sound propagation in the ocean", *Geophys. J. Int.*, 176, 478-490 (2009)
- de Groot-Hedlin, C.D., M.A.H. Hedlin, K.T. Walker, D. D. Drob, and M.A. Zumberge, Evaluation of infrasound signals from the shuttle Atlantis using a large seismic network, *J. Acoust. Soc. Am.*, 124, 1442-1451, (2008a)
- de Groot-Hedlin, C.D., Finite-difference synthesis of infrasound propagation through an absorbing atmosphere, *J. Acoust. Soc. Am.*, 124, 1430-1441, (2008b)

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

Yuri 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, including the ERS and ENVISAT satellites of the European Space Agency, and the ALOS satellite of the Japanese Space Agency, as well as the Global Positioning System, to investigate the response of the Earth's crust to seismic and magmatic loading.

A particular area of Prof. Fialko interests is the Southern San Andreas Fault system. The San Andreas Fault (SAF) is a mature continental transform fault that accommodates much of the relative motion between the North American and Pacific plates. The southernmost section of the SAF has not produced major earthquakes in historic time (over more than 300 years), as it is currently believed to be late in the interseismic phase of the earthquake cycle. Estimates of seismic hazard on the SAF as well as on other major faults in Southern California critically depend on the present-day strain rates and the degree of fault locking in the seismogenic crust (i.e., the presence and extent of fault creep). Both factors can in principle be evaluated with help of precise spatially dense measurements of surface deformation. In collaboration with colleagues from IREA (Italy), Prof. Fialko used a large set of ERS-1 and ERS-2 acquisitions spanning the southern part of San Andreas Fault system (Figure 1). The new results are an improvement on previously published velocity data (Fialko, 2006, *Nature*, vol. 441, pp. 968-971) due to better temporal and spatial coverage. In particular, the new data extend to the central and northern sections of the San Jacinto fault (Figure 1). One can clearly see a regional deformation pattern due to interseismic strain accumulation on major faults (in particular, the San Andreas and San Jacinto faults). Prof. Fialko and his students are combining these data with sophisticated models of interseismic deformation to place robust constraints on slip rates and locking depths of major active faults in the area. This work may ultimately result in better understanding of seismic hazards in Southern California.

On April 4, 2010, a major earthquake hit Southern California near the US-Mexico border. The  $M_w$ 7.2 El Mayor-Cucapah earthquake was the largest earthquake to strike the region in the last 18 years. In collaboration with colleagues from SIO and CICESE (Mexico), Prof. Fialko is studying the aftermath of this event. The El Mayor-Cucapah earthquake was well imaged by several space-borne InSAR missions, including ENVISAT and ALOS. Among the initial results of this research is evidence for surface slip on multiple faults in the Imperial Valley triggered by the main shock (Wei et al., 2011). Analysis of InSAR data showed small (centimeter-scale) co-seismic offsets on the San Andreas, Superstition Hills, Imperial, Elmore Ranch, Wienert, Coyote Creek, Elsinore, Yuha, and several minor faults near the town of Ocotillo at the northern end of the mainshock rupture. Field measurements of slip on the Superstition Hills Fault were shown to agree with InSAR and creepmeter measurements to within a few millimeters. Dislocation models of the InSAR data from the Superstition Hills Fault confirmed that creep in this sequence, as in previous slip events, is confined to shallow depths (less than 3 km).

Another area of interest of Prof. Fialko is the origin, evolution and extent of damage around major crustal faults. Over the last year Prof. Fialko worked with Postdoctoral Scholar Yoshi Kaneko on a problem of inelastic yielding of the host rocks during dynamic rupture, and the effects of yielding on surface deformation. Evidence for such yielding

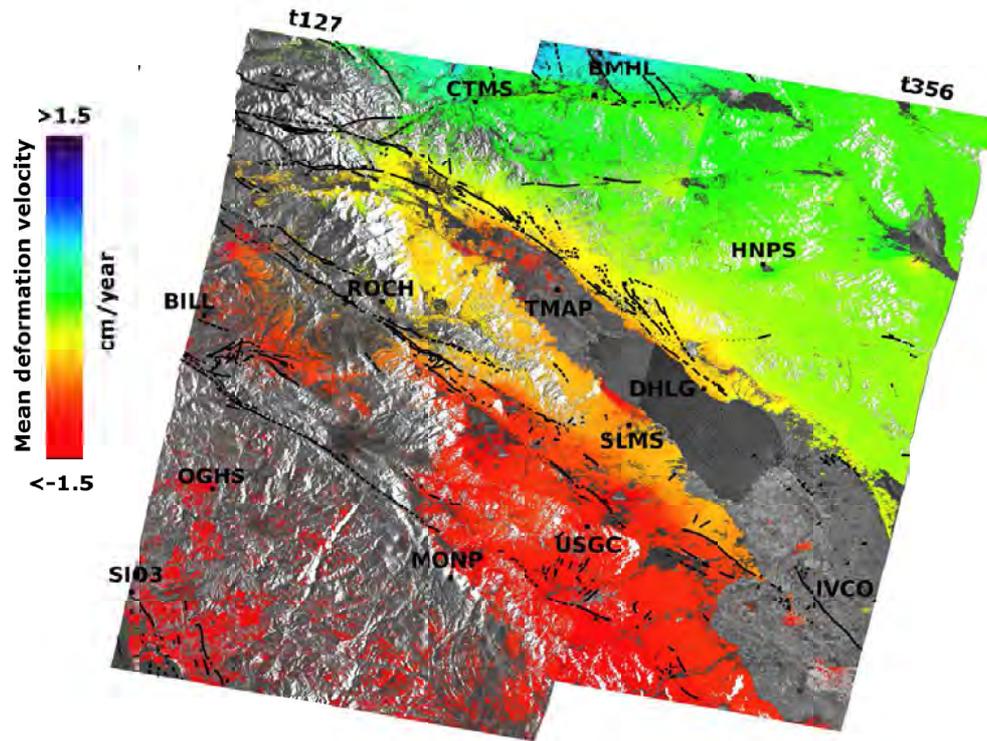


Figure 1: Mean line-of-sight (LOS) velocity map of the Southern San Andreas Fault system. The map is a mosaic of two ERS-1 and 2 tracks. Traces of active faults and locations of several continuous GPS sites used in this study are indicated by the black lines and squares, respectively.

is emerging from geologic, seismic and geodetic observations. This work showed that the amount of shallow slip deficit (that is, coseismic slip appears to decrease towards the Earth surface) is proportional to the amount of inelastic deformation near the Earth surface. The largest magnitude of slip deficit in models accounting for off-fault yielding is 2-4 times smaller than that inferred from kinematic inversions of geodetic data. However, assumptions implicit in the kinematic inversions may bias the inferred slip distributions. Inelastic deformation in the shallow crust reduces coseismic strain near the fault, introducing an additional “artificial” deficit of up to 10 per cent of the maximum slip in inversions of geodetic data that are based on purely elastic models. The largest magnitude of slip deficit in elasto-plastic rupture models combined with the bias in inversions accounts for up to 25 per cent of shallow slip deficit, which is on the low end of deficit inferred from kinematic inversions.

#### Recent publications:

Manzo, M., Y. Fialko, F. Casu, A. Pepe and R. Lanari (2011), A quantitative assessment of DInSAR measurements of interseismic deformation: the Southern San Andreas Fault case study, *Pure Appl. Geophys.*, 168, doi:10.1007/s00024-011-0403-2.

Kaneko, Y. and Y. Fialko (2011), Shallow slip deficit due to large strike-slip earthquakes in dynamic rupture simulations with elasto-plastic off-fault response, *Geophys. J. Int.*, 186, 1389-1403.

Meng, W., D. Sandwell, and Y. Fialko (2011), Slip on faults in the Imperial Valley triggered by the 4 April 2010 Mw 7.2 El Mayor-Cucapah earthquake revealed by InSAR, *Geophys. Res. Lett.*, 38, L01308.

**Helen Amanda Fricker**

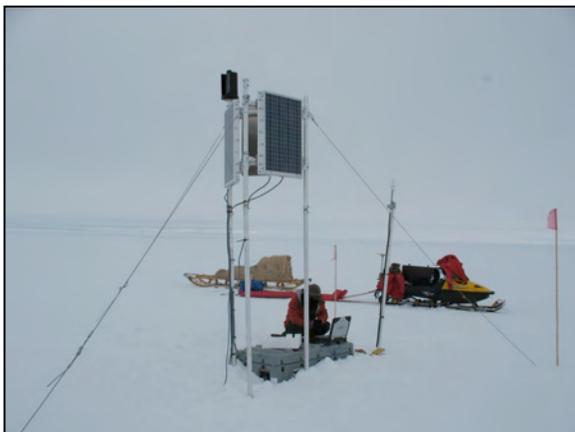
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*Research Interests:* cryosphere, Antarctic ice sheet, subglacial lakes, ice shelves, remote sensing

My research focuses on the Earth's **cryosphere**, in particular the **Antarctic ice sheet**. I lead the Scripps Glaciology Group, which currently has three postdocs (Sasha Carter, Geir Moholdt and David Heeszel) and two graduate students (Fernando Paolo and Matthew Siegfried). One of the primary research questions in Antarctica is whether its mass is changing due to climate change. 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. For much of my recent work I have used laser altimetry data from NASA's Ice, Cloud & land Elevation Satellite (ICESat). ICESat operated between January 2003 and December 2009, and provided accurate elevation data along repeated ground-tracks for ice sheet change detection. I was a member of the ICESat Science Team and I am a member of ICESat-2 Science Definition Team. As well as analyzing ICESat data for various scientific purposes mentioned below, my group is also involved in the validation of the ICESat elevation data, using "ground-truth" from our repeated GPS surveys of the salar de Uyuni in Bolivia (in 2002 and 2009). Our main science projects are as follows:

***j) Antarctic subglacial water:*** 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 elevation change signals in repeat-track ICESat data (up to 10m in some places), which corresponded to draining and filling of subglacial lakes beneath 1-2 km of ice. Changing the basal conditions of an ice sheet, particularly beneath fast flowing ice streams and outlet glaciers, is one possible mechanism to increase its contribution to sea level rise, through increased ice flow rates in the ice streams. With the current interest in Antarctic ice sheet mass balance and its potential impact on sea-level rise, it is important to understand the subglacial water process so that it can become incorporated into models; IGPP postdoc Sasha Carter works with me on this aspect of the problem<sup>4</sup>. My team and our collaborators continue to monitor active lakes, and we have found 124 in total throughout Antarctica. I am a PI on a large, interdisciplinary 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; Plate 1). Jeff Severinghaus is also a PI on this proposal. IGPP postdoc David Heeszel and graduate student Matt Siegfried took part in the surface geophysics fieldwork in 2010-2011 and 2011-2012 respectively.



*Plate 1: IGPP graduate student Matt Siegfried downloading data from a GPS receiver installed on Subglacial Lake Whillans, part of a 12-site network designed to monitor lake activity in the region and investigate the link between lake drainage and ice dynamics (December 2011).*

**ii) Ice shelf grounding zones:** My group uses ICESat data to map the grounding zones (GZs) of the ice shelves - the transition zones between grounded and floating ice. GZs are important because they are the gateway through which ice flows off the grounded ice sheet into the ice shelves and ultimately to the ocean, and monitoring them is an important part of ice sheet change detection. ICESat can detect the tide-forced flexure zone in the GZ because repeated tracks are sampled at different phases of the ocean tide; this has provided accurate GZ location and width information for each track. Working with former IGPP postdoc Kelly Brunt (now at NASA-GSFC) we used this technique to map the GZ for all of Antarctica. The data were used in a continent-wide grounding line mapping effort<sup>3</sup>; this combined with surface elevation at the grounding lines will contribute to improved calculations of the ice sheet's mass balance. The work also included an investigation of ice flexure and topography across various ice plains<sup>5</sup>.

**iii) Ice shelf stability and change:** My group also works on observing elevation changes on Antarctic ice shelves with satellite radar altimetry<sup>1,2</sup>. In one recent study, we incorporated Seasat, ERS-1, ERS-2 and Envisat data (1978-2008) on the Antarctic Peninsula ice shelves<sup>1</sup>. IGPP graduate student Fernando Paolo will expand and improve on this initial work for his PhD. I also work with Hamish Pritchard of British Antarctic Survey, who visited IGPP in November/December 2009, on analysis of changes in the ice shelves from ICESat; this paper has just been accepted by *Nature*.

**iv) Glacio-seismology:** I have an NSF project with Jeremy Bassis and Shad O'Neel (both former IGPP postdocs) investigating the source processes for seismic signals recorded in three different glaciological environments: Amery Ice Shelf; Ross Ice Shelf; and Columbia Glacier, Alaska. Former IGPP postdoc Fabian Walter worked on this project, and we also worked with IGPP student Xiaowei Chen and Peter Shearer on an Antarctic seismic paper<sup>6</sup>. IGPP postdoc David Heeszel now works on this project.

#### **Publications 2011 to early 2012 (in reverse chronological order)**

1. **FRICKER, H. A.** and L. PADMAN (2012) Thirty years of elevation change on Antarctic Peninsula ice shelves from multi-mission satellite radar altimetry, *J. Geophys. Res.-Oceans*, 117, C02026, doi:10.1029/2011JC007126.
2. PADMAN, L., D. P. COSTA, M. S. DINNIMAN, **H. A. FRICKER**, M. E. GOEBEL, L. A. HUCKSTADT, A. HUMBERT, I. JOUGHIN, J. T. M. LENAERTS, S. LIGTENBERG, T. A. SCAMBOS, and M. van den BROEKE (2012) Oceanic controls on the mass balance of Wilkins Ice Shelf, Antarctica, *J. Geophys. Res.-Oceans*, 117, C01010, doi:10.1029/2011JC007301.
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4. CARTER, S. P., **H. A. FRICKER**, D. D. BLANKENSHIP, D. A. YOUNG, J. V. JOHNSON, S. F. PRICE and W. LIPSCOMB (2011) Modeling five years of subglacial lake activity in the MacAyeal Ice Stream catchment through assimilation of ICESat laser altimetry, *J. Glaciol.*, 57(206), 1098-1112.
5. BRUNT, K. M., **H. A. FRICKER**, L. PADMAN (2011) Analysis of ice plains of Filchner/Ronne Ice Shelf, Antarctica, using ICESat laser altimetry, *J. Glaciol.*, 57(205), 965-975.
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*Research Interests:* Analysis of acoustic signals from large-scale atmospheric phenomena; study of seismo-acoustic phenomena, nuclear test-ban verification.

*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 ostensibly 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.

*Research at L2A:* The new 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. Presently we study a broad suite of problems related to both natural and man-made sources.

**Seismic network observations of atmospheric events:** The global infrasound network is unprecedented in scale however it is still very sparse, with on the order of 100 stations operating worldwide. To increase the density of sampling of the infrasonic wavefield to study atmospheric phenomena and propagation of infrasound through the atmosphere we have used acoustic-to-seismic coupled signals recorded by dense regional seismic networks, such as the 400-station USArray. We have studied propagation from large bolides and other events, such as large explosions. The seismic network is allowing us to study in detail acoustic branches from large atmospheric events that are akin to seismic branches. We are using the network to create a catalog of atmospheric events in the 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 identify regions where large atmospheric events are prevalent.

**USArray upgrade:** We were recently funded to upgrade the USArray with infrasound microphones and barometers. Our sensor package will be sensitive to air pressure variations from D.C. to 20 Hz, at the lower end of the audible range. We expect that over the coming year the entire USArray will be retrofitted with these new sensors to create the first-ever semi-continental-scale seismo-acoustic network. The network will span  $\sim 2,000,000$  square km in the eastern United States before being redeployed in Alaska.

**Miscellaneous studies: 1) Ocean noise:** Using data from our permanent array in the Anza-Borrego desert and two more arrays near San Diego we detect surf noise from along the coast of California. Infrasonic waves from the crashing surf propagate through the stratosphere to our stations up to 200 km away. We see further avenues for research in this area in that lower frequency signals, known as microbaroms, are known to propagate 1000's of km and can be used to probe atmospheric structure. **2) Natural hazards:** Our group is using infrasound energy to detect and monitor emerging hazards (such as volcanic eruptions, major storms at sea, tornadoes).

We are particularly interested in the use of infrasound sensors to monitor volcanoes, such as Mount Saint Helens, that have a history of releasing ash into the stratosphere. **3) Study of seismo-acoustic phenomena:** The Earth's free-surface is rich in sources that generate both downgoing seismic and upgoing acoustic energy. We believe to properly characterize such sources it is necessary to study the entire seismo-acoustic wavefield. We have recently completed a study of Mount Saint Helens using both types of sensors (Robin Matoza, PhD thesis). Studies of other seismo-acoustic sources (such as shallow earthquakes) are currently underway.

*Field operations:* Our group has built two permanent infrasound arrays in the US and one in Africa. In recent years we have deployed infrasound arrays across the southwestern US to record signals from high-altitude explosions and natural phenomena. We currently operate research arrays located near San Diego with another to be deployed near Chico, California in late 2010. A typical temporary array comprises 4 to 8 aneroid microbarometers or fiber-optic sensors spanning an area 100 to 300 meters across, with data recorded using 24-bit Reftek digitizers and telemetered in realtime to our lab in La Jolla. We use Sun workstations and a suite of Macintosh G5 computers. All data from the field is archived on a multi-TB RAID. All computers, and supporting peripherals such as printers, are linked via a broadband communications network.

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**Kerry Key**

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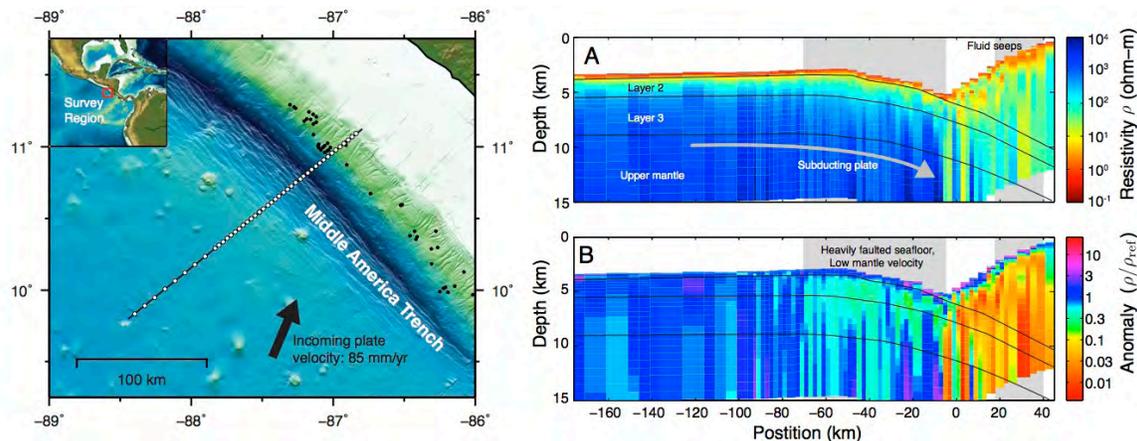
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*Research Interests:* Marine electromagnetic exploration, subduction zones, mid-ocean ridge, margins, hydrocarbon exploration, numerical methods, marine geophysical instrumentation.

*SERPENT: Serpentinite, Extension and Regional Porosity Experiment across the Nicaraguan Trench:* In last year's annual report I described our research cruise to characterize the electrical structure of the subduction zone offshore Nicaragua (Figure 1); this year we share some preliminary results. The controlled-source EM (CSEM) data reveal that when the seafloor bends and fractures at the trench due to subduction, it is accompanied by a significant decrease in electrical resistivity at crustal depths; this is likely due to conductive seawater penetrating into the porous extensional faults (Figure 1). My collaborator Steven Constable shows in his annual report entry another EM data set that constrains the conductivity increase to be anisotropic in a fault parallel geometry, furthering our evidence that it is due a porosity increase from faulting. Graduate student Samer Naif is analyzing the magnetotelluric (MT) data to see how this influx of seawater affects deeper conductivity in the upper mantle and the subsequent generation of partial melts after the hydrated plate has been subducted.

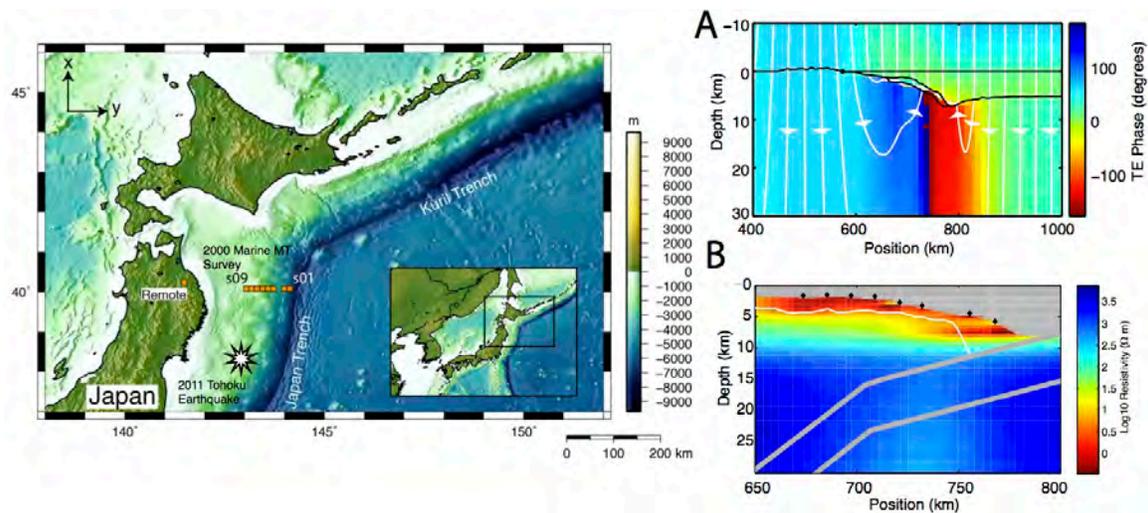


*Figure 1.* Marine EM survey of bending faults in the subduction zone offshore Nicaragua (left). Seafloor EM receivers (white dots) deployed across the Middle America Trench recorded EM transmissions from an electric dipole deep-towed across the array (black line). (A) Electrical resistivity model obtained from inversion of the CSEM data. The lateral variation of resistivity is more readily seen after normalization by an average vertical profile (B).

*Adaptive Finite Element Modeling:* In Key and Ovall (2011) we developed a 2.5D electromagnetic modeling code (2D model with a 3D source) that automatically generates and refines an unstructured modeling grid until the solution achieves the desired accuracy, thereby enabling even novices to obtain reliable modeling results for complicated electrical conductivity models with dipole or plane-wave EM sources. Our parallel implementation allowed us to run this code on a cluster computer using 1000 CPUs, where results were computed in only a few seconds to tens of seconds instead of the minutes to hours required when using only a single CPU.

*MT Survey offshore Japan:* In Key and Constable (2011) we finally published an analysis of some very unusual magnetotelluric data we acquired back in 2000 when I was a PhD student (Figure 2). This pilot experiment was carried out to study the electrical structure of the seismic zone

offshore Japan using our then newly developed broadband MT receiver. The data exhibited unusual cusps and extreme phase variations that our new modeling 2D code (Key and Owall, 2011) revealed to be due to strong inductive coupling at the edge of the conductive ocean, leading to the normally downward diffusing MT plane-wave instead diffusing back up beneath the margin slope (Figure 2A). 2D inversion of this data constrains the thickness of conductive forearc sediments and the underlying high resistivity associated with the mantle wedge and subducting oceanic lithosphere (Figure 2B). Although we only interpreted a 2D subset of this data due to 3D complexities at long periods, pending analysis of the entire data set will help us constrain the distribution of fluids along the plate boundary and how these may be related to nearby source region of the great 2011 Tohoku earthquake.



*Figure 2.* Marine MT survey of the subduction zone offshore northeastern Japan where the Pacific plate subducts beneath the island arc. Eight seafloor MT stations (orange squares) were acquired in June 2000 along the margin slope about 200 km north of the location of the 2011 Tohoku earthquake (star). (A) EM Poynting vectors (white lines) showing the direction of diffusion for the MT plane wave and colors show the corresponding TE mode phase. (B) Electrical resistivity model obtained from 2D MT inversion.

### Recent Publications

Key, K. (2011), Marine electromagnetic studies of seafloor resources and tectonics, *Surveys In Geophysics*, doi:10.1007/s10712-011-9139-x.

Zhdanov, M.S., L. Wan, A. Gribenko, M. Cuma, K. Key, and S. Constable (2011), Large-scale 3D inversion of marine magnetotelluric data: Case study from the Gemini Prospect, Gulf of Mexico, *Geophysics*, 76, F77–F87.

Myer, D., S. Constable, and K. Key (2011), Broad-band waveforms and robust processing for marine CSEM surveys, *Geophysical Journal International*, 184, 689–698.

Key, K. and S. Constable (2011), Coast effect distortion of marine magnetotelluric data: Insights from a pilot study offshore northeastern Japan, *Physics of the Earth and Planetary Interiors*, 184, 194–207.

Key, K. and J. Owall (2011), A parallel goal-oriented adaptive finite element method for 2.5D electromagnetic modeling, *Geophysical Journal International*, 186, 137–154.

**Deborah Lyman Kilb**

**Associate Project Scientist**

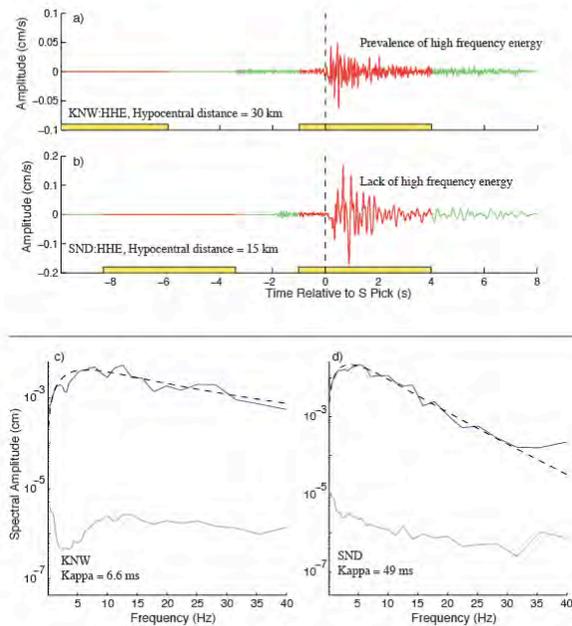
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*Research Interests:* Crustal seismology, earthquake triggering, earthquake source physics.

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

***A Comparison of Spectral Parameter Kappa from Small and Moderate Earthquakes Using Southern California ANZA Seismic Network Data:*** Kappa is a one-parameter estimator of a seismogram's spectral amplitude decay with frequency (Kilb *et al.*, 2011a). Low values (~5ms) indicate limited attenuation of high frequency energy whereas higher values (~40ms) indicate high frequency energy has been removed (Figure 1). Kappa is often assumed to be a site



**Figure 1:** Data from a magnitude 3.6 earthquake. (a) Seismogram recorded at ANZA station KNW (located on hard rock). Elongated rectangles identify the time windows of the noise window (left) and S-wave signal (right). (b) As in (a) for a seismogram recorded at the ANZA station SND (located within the San Jacinto Fault Zone). (c) Velocity spectra (blue line) and model fit (black dashed line) for station KNW and noise spectra (green line). (d) As in (c) but for data recorded at station SND. Note the enriched high frequency energy at the more distant station KNW (hypocentral distance: 30 km; kappa=6.6), in comparison with that of station SND (hypocentral distance: 15 km; kappa=49), which is counter to what is expected.

term and used in seismic designs. Kilb and her co-authors address two key questions about kappa: (1) How to identify source, path, and site contributions to kappa; and (2) Can kappa estimates from smaller earthquakes, and more readily accessible weak-motion recordings, be reasonably extrapolated to estimate kappa of larger earthquakes? The use of small earthquakes (magnitudes < 1) presents many challenges and requires new approaches. Kilb and her team developed estimates of kappa for seismograms from 1,137 small earthquakes recorded by the ANZA seismic network in southern California, and they compare these to results from the stronger recorded shaking generated by 43 earthquakes of magnitude 3.5 or greater inside the network. They found kappa from small earthquakes predicts the relative values of kappa for larger earthquakes (e.g., measurements at stations PFO and KNW are small compared with those at stations TRO and SND). For SND and TRO data, however, kappa values from small earthquakes over-predict those from moderate and large earthquakes. Although site effects are most important to kappa estimates, the scatter within kappa measurements at a given station is likely caused by a significant contribution from near the source, perhaps related to near source scattering. Because of this source-side variability, care is recommended in

using individual small events as Green's functions to study source-time effects of moderate and large events.

**Potential triggers for large ruptures along the southern San Andreas Fault:** In a collaborative project with past SIO graduate students Daniel Brothers and Karen Luttrell, in addition to professors Neal Driscoll and Graham Kent, Kilb explores why the southern San Andreas Fault (SSAF) in California has not had a large earthquake in approximately 300 years, yet the average recurrence for the previous five ruptures is about 180 years. Key in this work is the observation that a 60 km section of the SSAF has periodically been submerged during high lake levels of the large late-Holocene Lake Cahuilla (LC), and emerging evidence indicates coincident timing between LC flooding and fault displacement. As a large SSAF earthquake appears imminent, it is important to understand how crustal stress perturbations can promote or inhibit fault failure(s) in this region. In this work, Kilb and co-workers assess the potential for LC to act as a catalyst in triggering a sequence of large earthquakes. They find calculated static stress perturbations from LC flooding and/or rupture of secondary faults beneath LC are sufficient (*i.e.*, reaching levels above an assumed triggering threshold of 0.1 MPa) to potentially trigger large earthquakes on the SSAF. Since the current lake level is relatively stable, any future interaction between the faults under today's Salton Sea and the SSAF will depend solely on tectonic loading, without any perturbing stresses from lake level changes. In general, these results highlight the importance of including lake loading and secondary fault ruptures in seismic hazard assessments, as both have the potential to modulate earthquake cycles on major plate boundary faults such as the SSAF (Brothers *et al.*, 2011).

**Listen, Watch, Learn:** The increased popularity of YouTube videos has changed the format of how information is distributed and assimilated, highlighting the importance of including auditory information in videos. Videos that include sound are also permeating the research community as evidenced by their recent increase within on-line supplements to journal articles. Tapping into this new approach of information exchange, Kilb and her co-workers are creating a seismic data video repository. These videos augment visual imagery (seismograms and associated spectrograms) with the associated auditory counterparts (Kilb *et al.*, 2011b; Peng *et al.*, 2011). We term these 'SeisSound' video products, which are presented in movie format to indicate how the data evolves with time. Concepts that can be more easily discussed and investigated by incorporating sound include: categorizing seismic wave attenuation with distance from the source, identifying aftershock rates and recognizing site effects including reverberation in basins. *SeisSound* products can also be useful in discriminating complicated seismic signals from multiple sources, such as aftershocks within the coda of large earthquakes, remote triggering of earthquakes and tremor.

See <http://eqinfo.ucsd.edu/~dkilb/current.html> for an expanded description of these projects.

### Recent Publications

Brothers, D., D. Kilb, K. Luttrell, N. Driscoll and G. Kent, 'Loading of the San Andreas fault by flood-induced rupture of faults beneath the Salton Sea', *Nature Geoscience*, 4, pp: 486-492  
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Kilb, D., G. Biasi, J. Anderson, J. Brune, Z. Peng, and F. L. Vernon, 'A Comparison of Spectral Parameter Kappa from Small and Moderate Earthquakes Using Southern California ANZA Seismic Network Data', *Bull. Seism. Soc. Am.*, in Press, 2011a.

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Peng, Z., C. Aiken, D. Kilb, D. R. Shelly, and B. Enescu, 'Listening to the 2011 magnitude 9.0 Tohoku-Oki, Japan earthquake', *Seis. Res. Lett.*, in Press 2011.

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*Research interests:* regional and global surface wave seismology; 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.

*Global and regional tomography:* 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. Laske has collaborated with Guust Nolet at GeoAzur, U. Nice, France and his students to image upper mantle structure beneath North America and to compile and analyze a new set of free oscillation splitting matrices.

*Global reference models:* With CRUST5.1 and CRUST2.0, Laske and collaborators Masters and Mooney produced the most widely used global crustal models that found application in a wide range of disciplines in academia and industry, and sometimes reached into quite unexpected fields such as the search for Neutrinos. Laske collaborates with Masters, graduate student Zhitu Ma and Michael Pasyanos at LLNL to compile a new global crustal and lithosphere model, LITHO1.0. A prototype 1-degree crustal model, CRUST1.0 is close to public release for initial testing (Figure 1). The new model is based on most recent models of topography and ice cover, an improved version of Laske and Masters' global sediment map as well as an updated compilation of Moho depths. Initial adjustments have been made to improve the fit to Ma's new group velocity dataset. Collaborating with Masters, she currently works on refining estimates of Earth's inner core differential rotation.

*The PLUME project:* Laske is the lead-PI of the Hawaiian PLUME project (Plume–Lithosphere–Undersea–Mantle Experiment) to study the plumbing system of the Hawaiian hotspot. The project aims at resolving the fundamental question whether a deep-reaching mantle plume or other mechanisms feed Hawaii's extensive volcanism. The PLUME team includes co-PIs from SIO (Laske, Orcutt), WHOI (Collins, Detrick), U. Hawaii (Wolfe), DTM (Solomon, Hauri) and Yale Univ. (Bercovici). During two 1-year deployments in 2005 through 2007, the team collected a unique large seismic dataset from the world's largest network of broadband ocean bottom seismometers (OBS).

The body wave study provided conclusive evidence that Hawaii's volcanism is indeed fed by a deep-reaching mantle plume rather than from passive magmatism resulting from a cracking plate. A surprisingly thick and large body of anomalous mantle material appears to pond at depths below 200 km. The surface wave study, on the other hand, imaged a relatively narrow low-velocity feature in the asthenosphere to the west of the island of Hawaii which likely provides the pathway for plume material to reach Hawaii's magma chambers (Figures 2 and 3). The Hawaiian lithosphere has undergone a thermal rejuvenation process with no extensive mechanical erosion. The group found no evidence for a broad and thin pancake spreading beneath the lithosphere as is predicted by some geodynamical models. The seismic low-velocity anomalies are consistent with a marked temperature anomaly of roughly 250°C and perhaps 1-2% of partial melt. The PLUME crustal receiver function study (Leahy et al., 2010) found extensive crustal underplating beneath the Hawaiian Swell, thereby supporting the anomalies imaged by the surface waves. Graduate student Paula Chojnacki currently conducts a detailed study of surface wave azimuthal anisotropy to con-

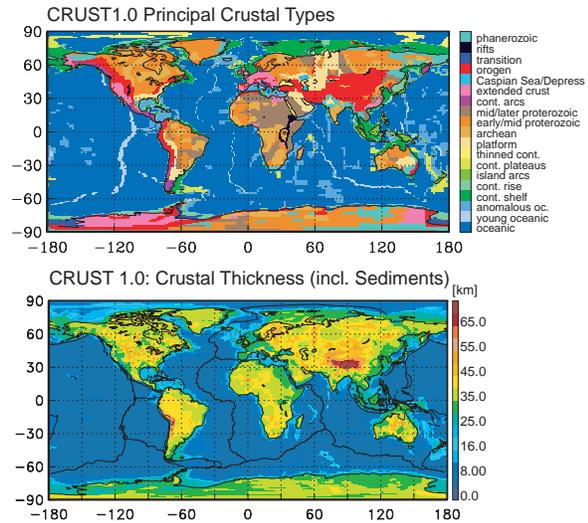


Figure 1: The prototype crustal model CRUST1.0. Top: updated crustal types; Bottom: thickness of the crystalline crust including sediment cover. The input crustal thickness was compiled using existing active source data as well as receiver functions and some gravity data.

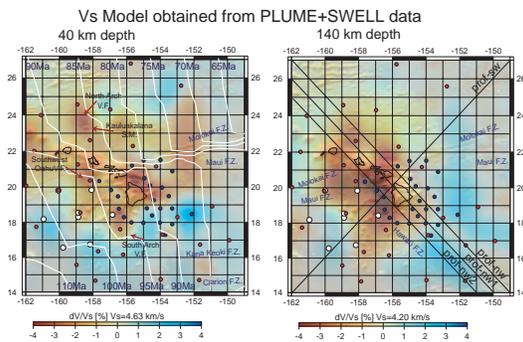


Figure 2: Two depth maps of the 17-layer shear-velocity model obtained from inverting two-station Rayleigh wave phase velocity curves collected from the SWELL and PLUME deployments. Also shown are crustal ages (white lines), the grey-shaded bathymetric relief and the location of the cross sections of Figure 2.

strain patterns of mantle flow and fabric.

### Recent publications:

- Laske, G., Collins, J.A., Wolfe, C.J., Solomon, S.C., Detrick, R.S., Orcutt, J.A., Bercovici, D. and Hauri, E.H., Probing the Hawaiian hot spot with new broadband ocean bottom instruments, *EOS Trans. AGU*, 90, 362-363, 2009.
- Leahy, G.M., Collins, J.A., Wolfe, C.J., Laske, G., Solomon, S.C. Underplating of the Hawaiian Swell: evidence from teleseismic receiver functions, *Geophys. J. Int.*, 183, 313–329, DOI: 10.1111/j.1365-246X.2010.04720.x, 2010.
- Wolfe, C.J., Solomon, S.C., Laske, G., Collins, J.A., Detrick, R.S., Orcutt, J.A., Bercovici, D., Hauri, E.H., Mantle *P*-wave velocity structure beneath the Hawaiian hotspot, *Earth Planet. Sci. Lett.*, 303, 267–280, 2011.
- Laske, G., Markee, A., Orcutt, J.A., Wolfe, C.J., Collins, J.A., Solomon, S.C., Detrick, R.S., Bercovici, D. and Hauri, E.H.. Asymmetric Shallow Mantle Structure beneath the Hawaiian Swell - Evidence from Rayleigh Waves Recorded by the PLUME Network, *Geophys. J. Int.*, in press, 2011.

## Guy Masters

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*Research interests:* global seismology, 3D earth models, interfacing mineral physics with seismology

During 2011, Guy Master's research focused on developing efficient techniques to measure extremely large data sets of surface wave phase and group velocity and surface wave amplitudes. The former measurements are being used to improve global crustal models while the latter are being used to develop models of 3D attenuation in the upper mantle. This work is being done with graduate student Zhitu Ma.

Compared with the numerous 3D velocity models of the mantle, there have been relatively few attempts to estimate 3D attenuation globally. The fundamental problem is that surface wave amplitudes are impacted by many things and intrinsic attenuation is a relatively minor contributor. The observed surface wave amplitude anomaly can be expressed as

$$A(\omega) = A_S(\omega)A_I(\omega)A_F(\omega)A_Q(\omega) \quad (1)$$

where  $A_S$  and  $A_I$  are due to uncertainties in earthquake size and instrument responses,  $A_F$  is due to focusing-defocusing effects and  $A_Q$  is due to attenuation structure. The first two effects are relatively easy to deal with, but the method of dealing with  $A_F$  can be important. It is common to use ray theory to model  $A_F$  but ray theory gives undue weight to short wavelength structure and its successful use requires careful filtering of the model. We find that finite frequency kernels seem able to give a more objective treatment of the focusing effects. An example of such a kernel is shown in figure 1. Note that all the terms must be included in equation 1 if the contribution to the amplitudes of intrinsic attenuation is to be reliably recovered.

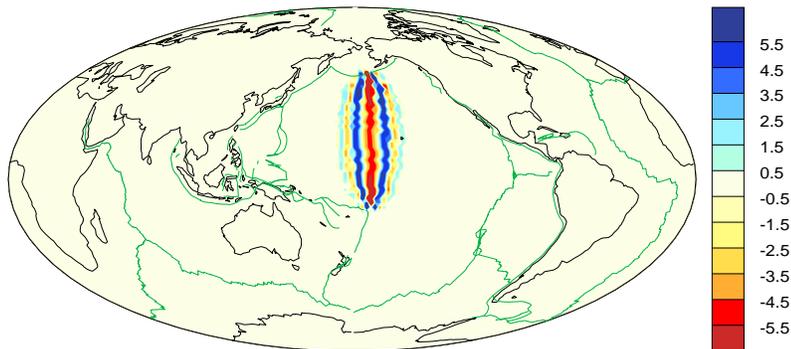


Figure 1 Finite frequency focusing kernel, calculated at 10mHz for an event in Aleutians (01/08/1990) and recorded at station AFI in Samoa. This example parameterizes the phase velocity in 2 degree equal-area pixels

Joint inversion of extremely large datasets of Rayleigh wave phase and amplitude data at a variety of frequencies give the preliminary results shown in figure 2 for the global distribution of phase velocity and attenuation. The attenuation maps make good physical sense with high attenuation regions associated with ocean ridges and back arc basins while low attenuation regions tend to be associated with continental cratons. Because of the effects of physical dispersion, large changes in attenuation can lead to measurable changes in phase velocity so it is important to include attenuation effects when interpreting phase velocity data.

The ultimate goal of this work is to generate a global 3D model of attenuation in the upper mantle. Joint interpretation with velocity models allows the discrimination between thermal and chemical anomalies.

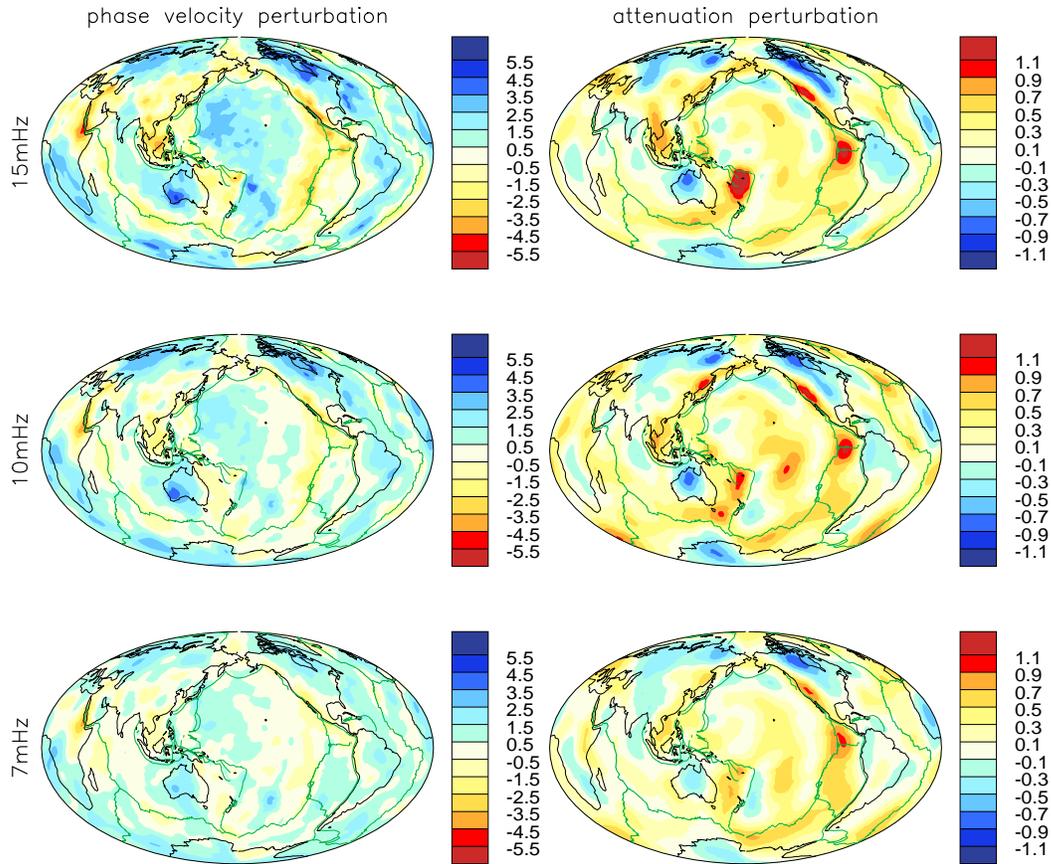


Figure 2. Phase velocity perturbation and attenuation maps for 7mHz, 10mHz and 15mHz. Note that the phase velocity perturbation is in  $\delta c/c(\%)$  and attenuation is in  $\delta Q^{-1}/Q^{-1}$ .

**Darcy E. Ogden**

**Assistant Professor of Geophysics**

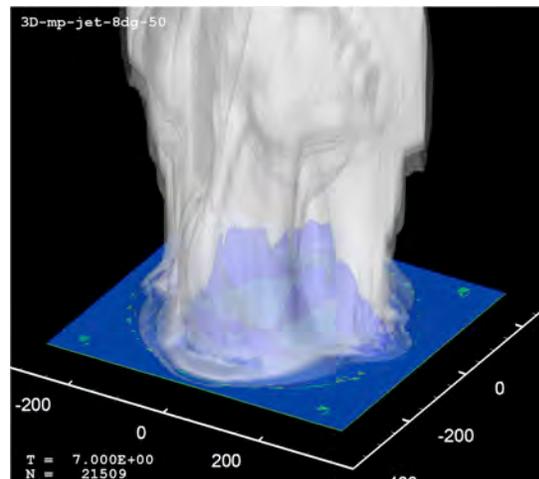
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*Research Interests:* Application of computational fluid dynamics models to explosive volcanic eruptions. Volcano infrasound. Formation and evolution of volcanic vents. Fluid-Structure Interaction problems in Geosciences.

I specialize in adapting cutting edge computational models to address research problems in geosciences. My interests are process oriented with a focus on fluid dynamics. I primarily apply this work toward explosive volcanic eruptions. The two major themes of my current work are linking acoustic signals generated by eruptions to physical processes in the eruption column and the interaction of eruptions with the surrounding rock. I am also involved in projects related to volcano seismicity, laboratory experiments of volcanic jet analogs, and connecting volcanic processes to mass extinction.

In explosive volcanic eruptions, rapidly expanding particulate-laden gases decompress through erodible and brittle vents. The shape of the vent can change in response to the stresses applied by the fast-moving expanding gas, which, in turn, is controlled by the vent shape. In particular, the degree of curvature undergone by fluid in the vent has a strong influence on the pressures and velocities of the eruptive fluid, which can have dramatic effects on eruption dynamics (Ogden, 2011). With collaborators at Los Alamos National Laboratory (LANL), I use computational simulations to determine the effect of vent formation on the evolution of an eruption column through time. These projects include



**Numerical simulation of volcanic vent formation**

both the theoretical aim of more fully understanding the dynamics of supersonic turbulent flow at volcanic scales and the practical goal of quantifying these effects for application to volcanic hazards analysis. Our simulations indicate that vent shape is more strongly dependent on eruptive dynamics than the rheology of the surrounding rock. However, higher resolution and longer simulations are required to test this theory.

Infrasound (acoustic signals with frequencies below that of human hearing) provides a means to detect the atmospheric oscillations from volcanoes at distances of meters to thousands of kilometers from the source. Recent infrasound recordings of volcanic jets have frequency spectra similar to the acoustic signal produced by man-made jets (jet noise). For the past 60 years, aeroacoustics has studied the relationship between the flow properties of man-made jets and the acoustic signal produced. Our long-term objective is to reverse this concept by determining the flow properties of volcanic jets based on the infrasound signal produced by the eruption. As a first step toward that goal, my research group is using a combination of analytical and

computational models to adapt empirical man-made jet noise results from aeroacoustics to the more complex volcanic jet system.

This past year saw expansion of my research into exotic volcanism, i.e., eruptions that are not common on the Earth's surface in the present day. In collaboration with Norm Sleep at Stanford University, I explored the feasibility of explosive interaction of coal and basalt as a mechanism for the End Permian mass extinction (Ogden & Sleep, 2011). Around the time of this extinction, large amounts of basaltic volcanism occurred in Siberia, forming what is now known as the Siberian Traps. However, there was no robust physical mechanism linking this relatively local volcanism to mass, global extinction. Basaltic volcanism is not capable of injecting matter high enough into the atmosphere to produce global climate change and ocean acidification. We proposed that the basalt may have interacted explosively with local coal beds, which would produce enough thermal and kinetic energy to drive large amounts of particulates and green house gasses high into the atmosphere. This injection would result in rapid climate change, ocean acidification and loss of biota on land and in the ocean.

### **Relevant Publications**

Dunham, E. M. and D. E. Ogden (2011) Guided waves along fluid-filled cracks in elastic solids and instability at high flow rates. *J. App. Mech.*, submitted.

Ogden, D.E. (2011). Fluid dynamics in volcanic vents and craters. *Earth Planet. Sci. Let.*, submitted.

Ogden, D.E. and N.H. Sleep (2011). Explosive Eruption of Coal and Basalt and the End Permian Mass Extinction. *Proc. Nat. Acad. Sci.*, submitted.

Saffaraval, F., S.A. Solovitz, D.E. Ogden, L.G. Mastin, (2011). Impact of Reduced Near-Field Entrainment of Overpressured Volcanic Jets on Plume Development. *J. Geophys. Res.*, submitted.

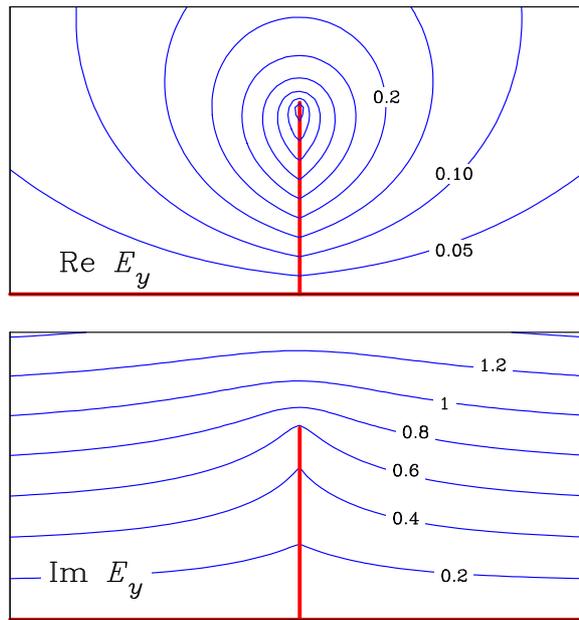
**Robert L. Parker**  
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*Research Interests:* Inverse theory, geomagnetism, spectral analysis, electromagnetic induction.

Bob Parker has continued to study theoretical problems in electromagnetic induction. After the horizontally or radially layered systems, the simplest electrical structures to understand are 2-dimensional. Then the magnetotelluric (MT) induction problem naturally decomposes into two modes, one in which the driving magnetic field is parallel to the lineation, Transverse Magnetic (TM) induction, the other where the field is perpendicular to it, Transverse Electric (TE) induction. In his recent work (ref 1 below), Parker investigates TE in a degenerate structure comprising conductors that are extremely thin compared to their width, a model often used for representing the oceans in large-scale modeling, or for fluid-filled cracks and rifts. He discovers a large class of such conductors with a strange property: the electromagnetic response possess a single (imaginary) resonant frequency. The response, defined as the  $E_x/i\omega B_y$ , of every known 2-dimensional system until now, exhibited infinitely many such resonances.

In the well-understood 1-dimensional inverse problem for MT, conductivity profiles with finitely many resonances play a central role, and they too consist of thin layers embedded in an insulator. Although mathematical analysis the 2-dimensional inverse problem is almost completely lacking, there is reason to believe that best-fitting models may also be built from thin conductors with a finite number of resonances, so that the new class of solutions to the TE induction problem could play a part in a fully-developed 2-dimensional inverse theory.

Another role for these models is in validating numerical codes, which are at present almost our sole means of exploring induction in dimensions higher than one. Thin layers represent a considerable challenge to finite difference and (to a lesser extent) finite element programs. Exact solutions for the new models are readily found using analytic functions of complex variables.



The diagram above gives contours of  $E$ , where the electric field into the page is  $E_y(x, z, t) = E(x, z) e^{i\omega t}$ , around a simple 2-dimensional system of conductors, shown in red. The base is a perfect conductor and the thin vertical conductor has a specially designed conductance profile,  $\tau(z) = a\tau_0/(a^2 - z^2)^{1/2}$  that yields a single resonance for this geometry. The contours are also lines of magnetic force.

### Recent Publications

Parker, R. L., New analytic solutions for the 2-D TE mode MT problem, *Geophys. J. Internat.*, doi:10.1111/j.1365-246X.2011.05091.x 186, pp 980-6, 2011.

Van Beuskom, A. E., Parker, R. L., Bank, R. E., Gill, P., E., and Constable, S. The 2-D magnetotelluric inverse problem solved with optimization, *Geophys. J. Internat.*, doi:10.1111/j.1365-246X.2010.04895.x 184, pp 626-38, 2010.

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*Research Interests:* Geodynamics, global bathymetry, crustal motion modeling

During the 2011 academic year, Dave Sandwell's research was focused on solid Earth Geophysics with an emphasis on understanding the dynamics of the crust and lithosphere. Our group comprises three graduate students Karen Luttrell, Meng Wei, and Xiaopeng Tong. Our research is mostly supported by three grants; two are from the National Science Foundation with titles Observations and Modeling of Shallow Fault Creep Along the San Andreas Fault Zone and High-Resolution Gravity, Topography, and Seafloor Roughness while the third is from NASA to perform Geodetic Imaging and Modeling of the San Andreas Fault System.

*Radar Interferometry* - After five years in orbit, the L-Band synthetic aperture radar (SAR) aboard the Japanese ALOS spacecraft is performing beautifully and is providing global interferometric crustal motion measurements. Xiaopeng Tong, David Sandwell and co-investigators, are using these data to investigate the coseismic deformation associated with the 2010 M8.8 Maule, Chile earthquake (Figure 1). We are developing new methods for mosaicking the numerous interferograms covering the 800 km by 300 km zone of deformation. This involves the development of new ScanSAR interferometry methods and code (<http://topex.ucsd.edu/gmtsar>).

*Global Bathymetry* - David Sandwell and Walter Smith (NOAA - Silver Spring Maryland) continued their collaboration on retracking the raw radar altimeter waveforms from ERS-1 and Geosat to further improve the accuracy and resolution of the global marine gravity field (Sandwell and Smith, 2009). J.J. Becker has used ship soundings to estimate the slope of the ocean floor in relation to the critical slope needed to convert tidal energy into internal waves (Becker and Sandwell, 2008). This research helps to resolve the issue of, where and how, deep-ocean mixing occurs. The global bathymetry grid is used to search for uncharted seamounts (Sandwell and Wessel, 2010)

*Crustal Motion Modeling* - Bridget Konter-Smith (now at the University of Texas, El Paso) continued her development of a semi-analytic model for the deformation of western North America that is consistent with the growing array of continuous GPS and InSAR measurements (Smith and Sandwell, 2009). This model was used to predict the crustal stress at seismogenic depth and at various times in the past. Karen Luttrell performed a series of GPS measurements in the Salton Trough area of California in order to measure the viscoelastic rebound of the lithosphere in response to unloading of Lake Cahuilla 300 years ago. Cyclic loading from Lake Cahuilla changes the stress field along the San Andreas Fault and could perhaps trigger a major rupture (Luttrell et al., 2007).

More information is provided at <http://topex.ucsd.edu>.

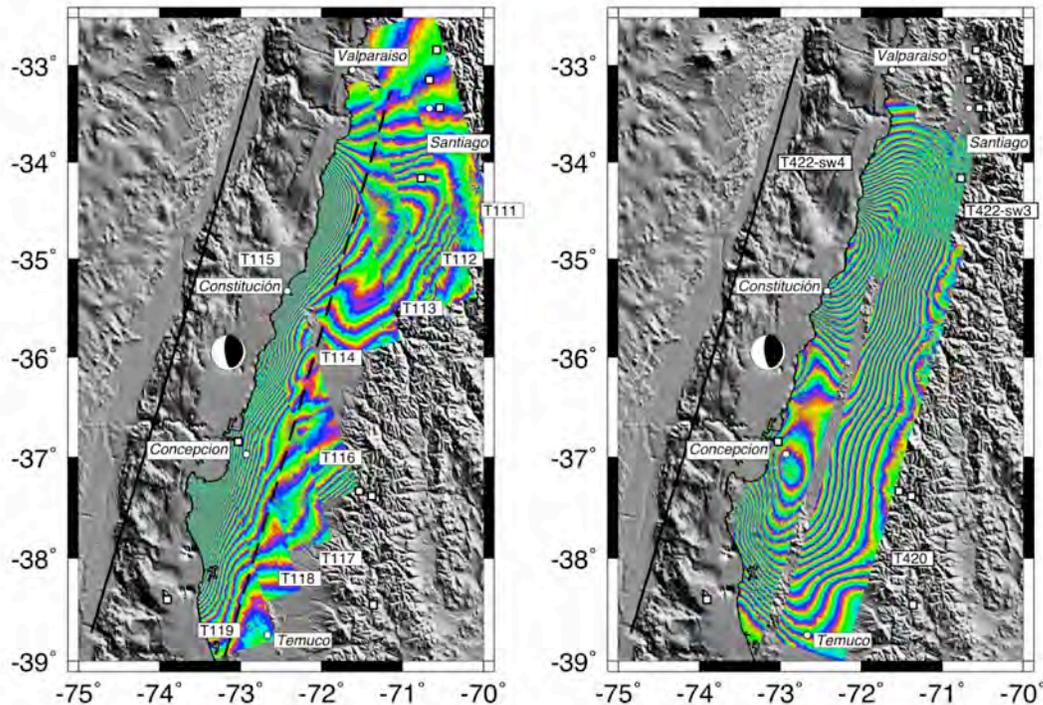


Figure 1. Radar interferometry of the 2010 M8.8 Maule, Chile Earthquake. Nine tracks of ALOS ascending interferograms and two tracks of ALOS descending interferograms cover a wide area from the coastline of central Chile to the foothills of the southern Andes.

### Relevant Publications

- Becker, J. J., D. T. Sandwell, (2008) Global estimates of seafloor slope from single-beam ship soundings, *J. Geophys. Res.*, 113, C05028, doi:10.1029/2006JC003878.
- Luttrell, K., D. Sandwell, B. Smith-Konter, B. Bills, and Y. Bock, (2007) Modulation of the earthquake cycle at the southern San Andreas fault by lake loading, *J. Geophys. Res.*, 112, B08411, doi:10.1029/2006JB004752.
- Luttrell, K., and D. Sandwell (2010), Ocean loading effects on stress at near shore plate boundary fault systems, *J. Geophys. Res.*, 115, B08411, doi:10.1029/2009JB006541.
- Sandwell, D. T., D. Myer, R. Mellors, M. Shimada, B. Brooks, and J. Foster, (2008) Accuracy and resolution of ALOS interferometry: Vector deformation maps of the Father's Day Intrusion at Kilauea, *IEEE Trans. Geosciences and Remote Sensing*, 46, no. 11, p. 3524-3534.
- Sandwell, D. T., and W. H. F. Smith, (2009) Global marine gravity from retracked Geosat and ERS-1 altimetry: Ridge segmentation versus spreading rate, *J. Geophys. Res.*, 114, B01411, doi:10.1029/2008JB006008.
- Smith, B., and D. T. Sandwell, (2009) Stress evolution of the San Andreas fault system: Recurrence interval versus locking depth, *Geophys. Res. Lett.*, 36, L13304, doi:10.1029/2009GL037235.
- Sandwell, D. T., and P. Wessel, (2010) Seamount discovery tool aids navigation to uncharted seafloor features, *Oceanography*, 23:1, p. 24-26.
- Tong, X., D. T. Sandwell, and Y. Fialko, (2009) Coseismic Slip Model of the 2008 Wenchuan Earthquake Derived From Joint Inversion of InSAR, GPS and Field Data, *J. Geophys. Res.*, 115, B04314, doi:10.1029/2009JB006625.

**Peter Shearer**

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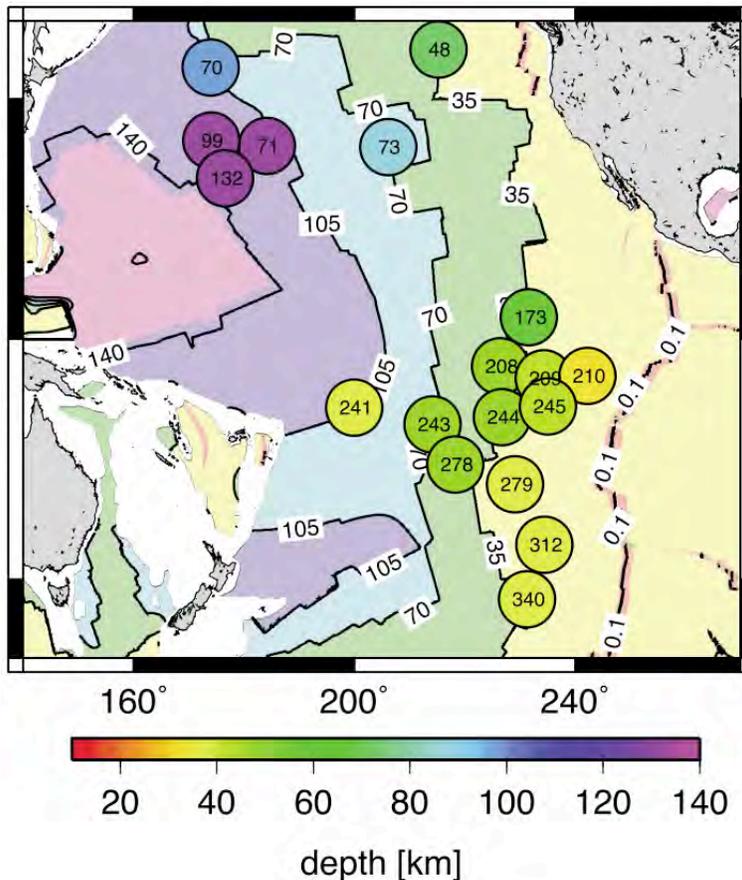
Phone extension: 42260

*Research Interests:* seismology, Earth structure, earthquake physics

Peter Shearer's research uses seismology to learn about Earth structure and earthquakes, both globally and in California, and has involved the development of new analysis approaches to handle efficiently the large digital data sets that are now emerging from the global and regional seismic networks. Recent work with former postdoc Catherine Rychert (now at the University of Bristol, U.K.) applied seismic receiver function analysis in a comprehensive study of the lithosphere-asthenosphere boundary (LAB), showing that it is a globally pervasive feature that varies in depth depending upon the tectonic environment. Receiver functions provide information only near seismic stations, limiting studies to continents and excluding most of the oceanic crust and lithosphere. *SS* precursor studies provide more complete global coverage, but traditionally have been used only to image interfaces deeper than the LAB, such as the 410 and 660-km discontinuities, which appear as distinct *SS* precursor phases. *Rychert and Shearer (2011)* show that subtle differences in *SS* waveform stacks can be used to resolve the LAB under the Pacific. The depth to the discontinuity varies from 25 to 130 km and correlates with distance from the ridge along mantle flow lines. This implies that the depth of the oceanic lithosphere-asthenosphere boundary depends on the temperature of the underlying asthenosphere.

A wealth of new seismic data is available from the USArray project, enabling increased resolution for studies of the lithospheric and deeper structure of the North American continent. Graduate student Janine Buehler analyzed *Pn* arrival times from the transportable stations of USArray to resolve crustal thickness and uppermost mantle structure (*Buehler and Shearer, 2010*). Her crustal thickness map generally agrees with previous results but differs in some details. High upper-mantle seismic velocities are found beneath eastern Washington and northern Idaho, and lower velocities near the California-Mexico border, the Sierra Nevada, the northern coastal California region, and the greater Yellowstone area. These results should complement other seismic studies (e.g., body- and surface-wave tomography and shear-wave splitting) to provide information about composition, temperature, and tectonic processes in the western United States.

Shearer's southern California work has focused on improving earthquake locations using robust methods, waveform cross-correlation, and the development of new crustal tomography models to account for 3D velocity variations. Work with former student Guoqing Lin (now at the University of Miami) developed a relocated catalog of southern California seismicity from 1981 to 2005 (the LSH catalog) that is now being widely used by other researchers. *Smith-Konter, Sandwell and Shearer (2011)* used this catalog to estimate locking depths along major faults from the maximum depth of seismicity and compared these results to geodetic constraints on locking depths. The methods agree in most areas, with the notable exception of the Imperial, Coyote Creek and Borrego fault segments. These differences have important implications for the accuracy to which future major earthquake magnitudes can be estimated. Graduate student Xiaowei Chen examined seismicity in the Salton Trough, in particular the behavior of the numerous seismic swarms that are common in this region. She found that all of the swarms exhibited spatial migration of seismicity, with migration velocities characteristic of hydraulic diffusion for swarms near geothermal sites (*Chen and Shearer, 2011*). Swarms with faster migration velocities cannot be explained by the diffusion curve, rather, their velocity is consistent with the propagation velocity of creep and slow slip events. Thus, these variations in migration behavior allow us to distinguish among different swarm driving processes.



**Figure 1.** Pacific bouncepoint caps with well-resolved depths to the lithosphere-asthenosphere boundary (LAB). Circle colors correspond to the depth of the discontinuity. Background pastel colors show sea floor age from young (0–35 Myr in yellow) to old (140–175 Myr in magenta). Note the generally shallower LAB under young regions. From *Rychert and Shearer (2011)*.

### Recent Publications

- Buehler, J. S., and P. M. Shearer, Pn tomography of the western United States using USArray, *J. Geophys. Res.*, 115, doi: 10.1029/2009JB006874, 2010.
- Yang, Z., A. Sheehan, and P. Shearer, Stress-induced upper crustal anisotropy in southern California, *J. Geophys. Res.*, 116, doi: 10.1029/2010JB007655, 2011.
- Shearer, P. M., C. A. Rychert, and Q. Liu, On the visibility of the inner-core shear wave phase PKJKP at long periods, *Geophys. J. Int.*, 185, 1379–1383, doi: 10.1111/j.1365-246X.2011.05011.x, 2011.
- Smith-Konter, B. R., D. T. Sandwell, and P. Shearer, Locking depths estimated from geodesy and seismology along the San Andreas Fault System: Implications for seismic moment release, *J. Geophys. Res.*, 116, doi: 10.1029/2010JB008117, 2011.
- Chen, X., P. M. Shearer, F. Walter, and H. A. Fricker, Seventeen Antarctic seismic events detected by global surface waves and a possible link to calving events from satellite images, *J. Geophys. Res.*, 116, doi: 10.1029/2011JB008262, 2011.
- Kiser, E., M. Ishii, C. H. Langmuir, P. M. Shearer, and H. Hirose, Insights into the mechanism of intermediate-depth earthquakes from source properties as imaged by back projection of multiple seismic phases, *J. Geophys. Res.*, 116, doi: 10.1029/2010JB007831, 2011.
- Rychert, C. A., and P. M. Shearer, Imaging the lithosphere–asthenosphere boundary beneath the Pacific using SS waveform modeling, *J. Geophys. Res.*, 116, doi: 10.1029/2010JB008070, 2011.
- Chen, X., and P. M. Shearer, Comprehensive analysis of earthquake source spectra and swarms in the Salton Trough, California, *J. Geophys. Res.*, 116, B09309, doi:10.1029/2011JB008263, 2011.

## **Hubert Staudigel**

### **Research Geologist, Lecturer**

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*Research Interests:* Seamounts, Mid-ocean Ridges, Water-Rock Interaction, Low Temperature geochemical fluxes, Volcanology, Biogeoscience, Science Education (K-16)

My long-term scientific interests aim broadly at volcanoes, how they work, exploring their impact on the geochemistry of the hydrosphere, and the mantle – crust evolution, and the role they play in biogeosciences. My recent work is described below focusing on two themes, the biogeosciences of seamounts and on the interaction of microbes with volcanoes. My teaching includes a field class in volcanology and I run a NSF funded (GK-12) educational program that brings graduate students into in Middle and High School classrooms in the San Diego Unified School District. References to my broader research interests and other prior work can be found in the bibliography at my website (<http://earthref.org/whoswho/ER/hstaudigel/index.html>)

*Seamounts:* Most of my recent field work focused on Loihi Seamount and seamounts in the Samoan Chain including Vailulu'u seamount. I am expecting to dive on Vailulu'u in 2012 using the Pisces submersibles. Over the last three years I coordinated a Seamount Biogeoscience Network and co-edited and wrote papers in a special volume of Oceanography on of "Mountains in the Sea". All of the articles in this volume are freely available from the website of The Oceanographic Society (<http://www.tos.org/oceanography/archive/23-1.html>). My papers include in particular contributions regarding the geological history and structure of seamounts (Staudigel and Clague, 2010), their role in subduction systems (Staudigel et al., 2010) and the associated deep-sea metal deposits (Hein et al., 2010). Other recent papers on seamounts include the description of microbial consortia in their hydrothermal systems (Sudek et al., 2009) and the discovery that fungi are common in these submarine systems, not unlike in terrestrial soils (Connell et al., 2009).

*Microbes in Volcanoes:* I study the biogeosciences of volcanoes using geological and microbiological approaches. In the geological record we study trace fossils of microbes drilling into volcanic glass. This demonstrated that microbes are active in any ocean crust section studied so far and that these fossils can be trace back in time to the time period of the origin of life on earth 3.5 Ga ago (e.g. Staudigel et al., 2008; McLoughlin et al., 2010). Our microbiological work continues at Vailulu'u and Loihi Seamounts with the characterization and isolation of microbes from these settings (Sudek et al, 2009; Bailey et al., 2009) as well as studies of how they colonize rock surfaces and how they may dissolve volcanic glass (Templeton et al, 2010). My work on microbe-basalt interaction now focuses on extreme environments of the McMurdo area in Antarctica, including volcanic terrains in the Royal Society Range, the Dry Valleys, and in particular on Mt Erebus on Ross Island. Details of this work can be found on in an on-line lecture I gave at the Birch Aquarium <http://www.uctv.tv/search-details.aspx?showID=16074> and our Antarctica Expedition website (<http://earthref.org/ERESE/projects/GOLF439/index.html>).

*Teaching:* Jointly with colleagues from Scripps and UC Davis, I am offering a two-week volcanology field class in Hawaii. In collaboration with Cheryl Peach I am also running a NSF educational program for graduate students to work with K-12 students ("GK-12"). This

program, the “Scripps Classroom Connection” (“SCC”; <http://earthref.org/SCC/> ) offers nine graduate fellowships to Scripps graduate students each year to improve their communication skills by teaching in middle and high school classrooms. Fellows receive full support for an overall 1/3<sup>rd</sup> effort in SCC, including a four week Summer Institute and the teaching in classrooms during the school year. Fellows are chosen from all science sections at Scripps.

### **Recent Publications**

- Bailey B, A. Templeton, H. Staudigel, B. M. Tebo, (2009) Potential utilization of substrate components during basaltic glass colonization by *Pseudomonas* and *Shewanella* isolates, *Geomicrobiology Journal*, Volume 26, 648-656.
- Connell, L., A. Templeton, A. Barrett, and H. Staudigel (2009) Diverse fungal consortia associated with an active deep sea volcano: Vailulu’u Seamount, Samoa. *Geomicrobiology Journal*, Volume 26, 597-605.
- Hein, J.R., T.A. Conrad, and H. Staudigel, 2010, Seamount Mineral Deposits: A Source of Rare Metals for High-Technology Industries *Oceanography* 23-1, 184-189,
- McLoughlin, N., H. Staudigel, H. Furnes. B. Eickmann and M. Ivarsson (2010) Mechanisms of microtunneling in rock substrates: distinguishing endolithic biosignatures from abiotic microtunnels, *Geobiology*, 8, 245–255 DOI: 10.1111/j.1472-4669.2010.00243.x
- Sudek, L.A. , Alexis S. Templeton, Bradley M. Tebo and Hubert Staudigel (2009) Microbial Ecology of Fe (hydr)oxide Mats and Basaltic Rock from Vailulu’u Seamount, American Samoa, *Geomicrobiology Journal*, Volume 26, 581-596
- Staudigel H., and D.A. Clague, 2010, The Geological History of Deep-Sea Volcanoes: Biosphere, Hydrosphere, and Lithosphere Interactions., *Oceanography* 23-1, 58-71.
- Staudigel, H., A.A.P. Koppers, J.W. Lavelle, T.J. Pitcher and T.M. Shank (eds. 2010). Mountains in the Sea. *Oceanography* 23(1): 16-227
- Staudigel, H., A.A.P. Koppers, T.A. Plank, and B.B. Hanan, 2010, 176-181. Seamounts in the Subduction Factory *Oceanography* 23-1, 176-181
- Templeton, A. S., E. J. Knowles, D. L. Eldridge, B. W. Arey, A. C. Dohnalkova, S. M. Webb, B. E. Bailey, B. M. Tebo and H. Staudigel, 2009, A seafloor microbial biome hosted within incipient ferromanganese crusts., *Nature Geoscience*, 2, 872-876.

**Dave Stegman**

**Assistant Professor**

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*Research Interests:* Global tectonics, mantle dynamics, planetary geophysics, applying high-performance computing and 4-D visualization to geodynamics

My field, geodynamics, aspires to develop a dynamical theory that provides a physical explanation for both the motions of tectonic plates as well as motion of plate boundaries. While I routinely employ some of the nation's fastest supercomputers to run numerical models that simulate the motions of tectonic plates, this past year afforded me an opportunity to work with Prof Steve Cande on analyzing and interpreting a diverse suite of tectonic observations.

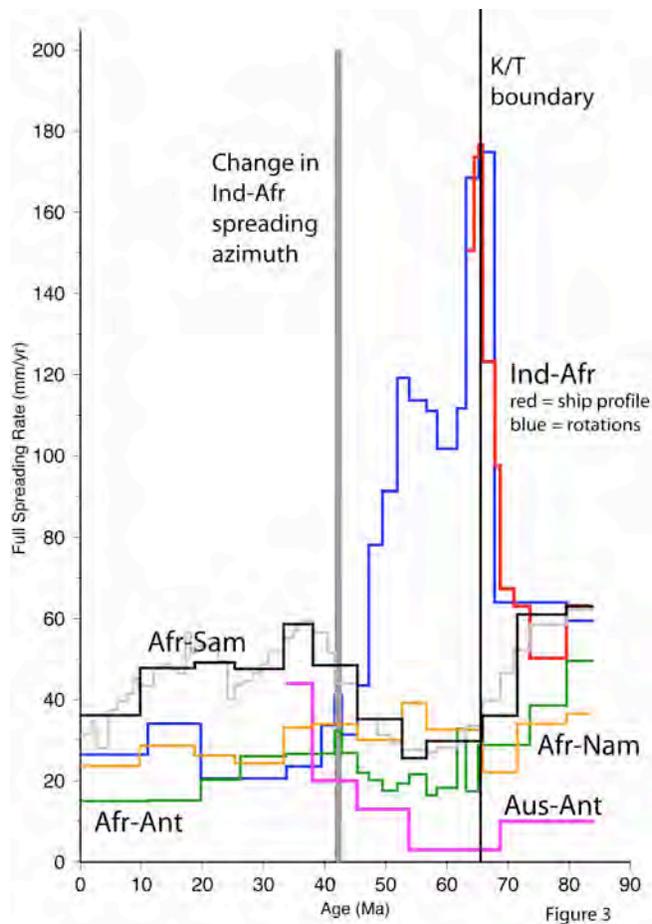
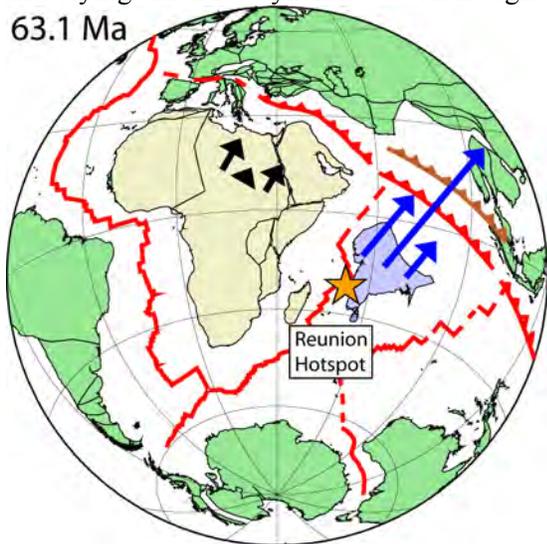


Figure 1

It is well-documented that during the Cenozoic, the Indian plate traveled towards Asia at speeds reaching 18 cm/yr. We have recently attempted to better constrain the details of this extraordinary event and discovered something quite remarkable. The onset of this motion is coincident with the arrival of the Deccan plume head just slightly before 65 Ma as seen in Figure 1. India's motion prior to 70 Ma is a typical value for a plate that is attached to a subducting slab. However, the superfast speeds that India recorded (18 cm/yr) were only for a very short (1 Myr) burst, followed by sustained plate speeds >11 cm/yr until 55 Ma, before finally fading down to more typical plate speeds by 43 Ma. Yet, even more interesting is that the slow northward motion of Africa appears to have become hindered over the same time period, shown in Figure 1 as dips in the spreading rate. This hinderance is seen in Africa's spreading histories with South America, North America, and Australia-Antarctica and recorded as S-shaped bends, shown in Figure 2 in the otherwise linear-trending magnetic anomaly patterns in the corresponding South Atlantic, Central Atlantic, and Southwest Indian ocean basins, respectively.

This suggests the Deccan plume head played a major role in both providing the driving force for the sudden onset and sustained plate speeds of India as well as providing a force to temporarily slow Africa's motion. Because the Deccan plume head was positioned in between India and Africa during this time, straddling their common spreading center, the picture that immediately emerges is that Deccan pushed in all directions, driving India faster away and slowing Africa coming towards it (Figure 3).

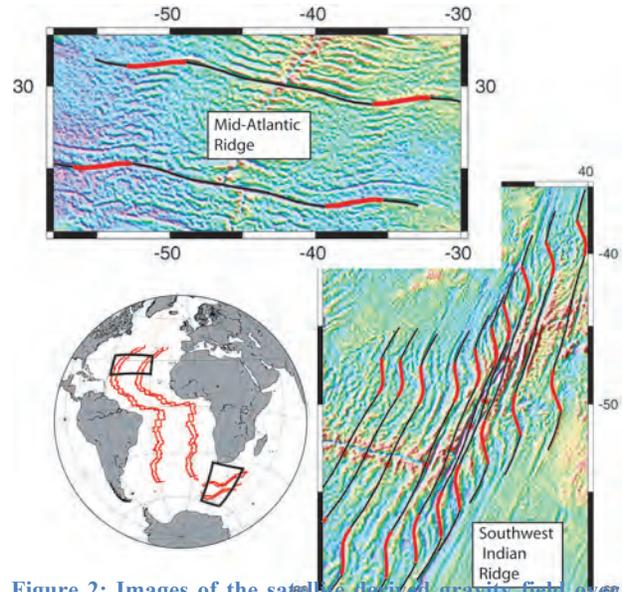
Our work thus far provides compelling evidence for the existence of this plume-push force, which if indeed is a new driving force for plate tectonics, has significant importance for reconciling reconstructed plate motions with the underlying mantle dynamics. Although the



**Figure 3: Reconstruction of the Indo-Atlantic Ocean at 63 million years, during the time of the superfast motion of India which we attribute to the force of the Reunion plume head. The arrows show the relative convergence rate of Africa (black arrows) and India (dark blue) relative to Eurasia before, during and after (from left to right) the period of maximum plume head force. The jagged red and brown lines northeast of India show two possible positions of the trench (the subduction zone) between India and Eurasia depending on whether the India-Eurasia collision occurred at 52 million years or 43 million years.**

### Publications for 2010-2011

Cande, S.C. and D.R. Stegman. "Indian and African plate motions driven by the push force of the Reunion plume head," *Nature*, 475, 7354, 47-52, 2011.



**Figure 2: Images of the satellite derived gravity field over the Central Atlantic (top) and Southwest Indian Ridge (right) showing the zones of rough topography and sharp bends in the fracture zones which were caused by the slowing of Africa's motion as the Reunion plume head reached its maximum force. The inset globe shows the location of the gravity maps as well as the extent of the parallel zones of rough topography (outlined in red) on the flanks of the Mid-Atlantic and Southwest Indian ridges caused by the change in Africa's motion.**

plume-push force appears to be ephemeral by nature, the new findings (Cande and Stegman, 2010) suggest it can significantly influence global plate motions over 5-20 Myr time-intervals. If the superfast motion of India is caused by the plume-push force, the slowdown of India starting from 55 Ma can be reinterpreted simply as the weakening influence of the plume head as India moves further away from the source in addition to diminishing strength of the plume head over time. Figure 1 shows the implication if the slowdown at 55 Ma was not due to the India-Asia collision, but rather, due to fading of the plume-push force. It is interesting to note that no change in spreading azimuth is recorded until 43 Ma. Such a change in the direction of Indian plate motion almost certainly reflects an India-Asia collision.

**Kristoffer T. Walker**

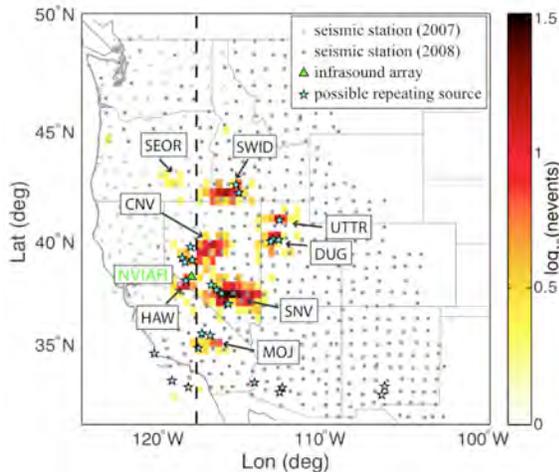
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*Research Interests:* Atmospheric infrasound, earthquakes, tectonics, array processing, ray tracing

I've been working on several projects in atmospheric infrasound. The most mature of these projects is the creation of the Western U.S. Infrasonic Catalog, ver. 1 (WUSIC-1; Walker et al., in press). The USArray is in an excellent position to discover sources of infrasound in the U.S. as well as investigate problems in infrasonic propagation and atmospheric dynamics using these events in the same way that seismologists use earthquakes to tackle problems in seismology and geodynamics. A key interest is in studying atmospheric phenomena with infrasound. But before this can be done well, we need to validate recent advances in the creation of time-varying atmospheric sound speed models. Arguably the best approach for this is a statistical analysis of hundreds to thousands of events recorded over many months. Toward that goal, undergraduate student Richard Shelby and I used reverse time migration of envelope functions of 1 to 5 Hz acoustic-to-seismic coupled signals recorded by USArray to detect and locate 901 infrasonic sources in the western U.S. (Figure 1). We are now conducting a similar study using the Southern California Seismic Network.



*Figure 1. Two-dimensional histogram showing imaged source locations for 901 events detected by the USArray in 2007-08. Warm areas illuminate repeating sources of infrasound, or “infrasonic hotspots.” The hotspots spatially correlate with areas of military activity (stars). From Walker et al. (in press).*

I'm also leading a study of the imaging of the source location of microbaroms. Microbaroms are hypothesized to be the acoustic equivalent of microseisms; pressure signals with frequencies of about 0.2 Hz generated from the interaction of anti-parallel ocean waves. However, there has yet to be a study combining observations and theoretical modeling that has definitely tested this hypothesis. In 2010 I led the installation of two infrasonic arrays in Southern California and Northern California. There are now six infrasonic arrays in the western U.S. states as well as several tens of microphones at USArray sites in Cascadia, all of which are in a good position to record infrasound from microbarom sources in the eastern Pacific during the 2011-12 winter season. Preliminary results from the 2010-11 season suggest that the arrays detect the same source of infrasound quite often, when either the source is in the deep Pacific basin or when the source is close to the coast. Modeling of the microbarom source strength using NOAA Wave Watch 3 model data shows a predicted microbarom source near the coast, in general agreement with the array observations (Figure 2), but more work needs to be done

I'm also analyzing the infrasonic and strong-motion seismic recordings of the Mw 9.1 Tohoku earthquake, which has presented to date the best opportunity to study global infrasonic emissions from a very large earthquake. An array near Tokyo provided the first infrasonic recordings in the near field (<

500 km) for such a large event. High-frequency infrasound that originated from surface shaking in the epicentral region (the Earth is a speaker) was detected to 5700 km range. A clear relationship exists between amplitude and range for both stratospheric and thermospheric arrivals. Lastly, infrasound recorded by the Tokyo array as well as an array in Kamchatka has been back projected to the source region to illuminate the areas that experienced the greatest intensity of surface shaking. These results correlate with the spatial distribution of maximum shaking defined by the strong-motion network..

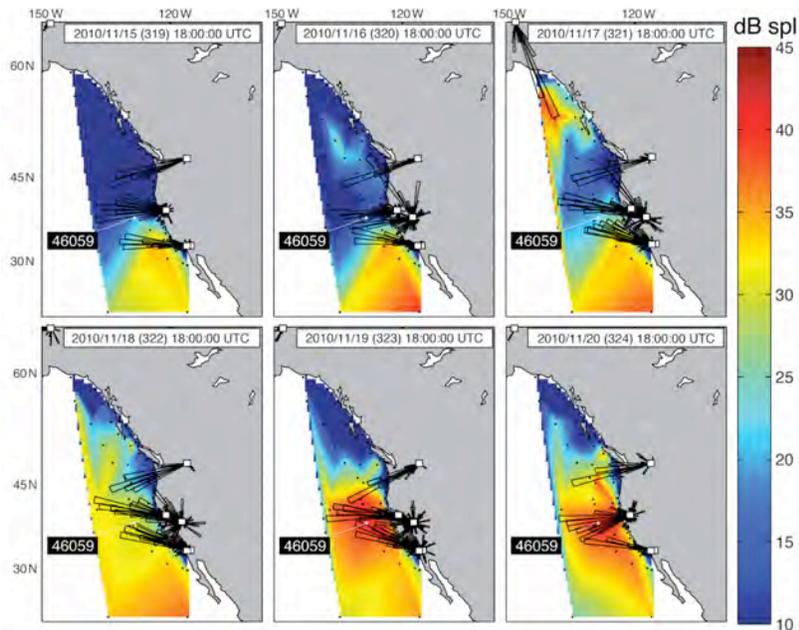


Figure 2. Prediction of microbarom source strength squared from NOAA WW3 model output at buoy locations compared to observations. The concentration of buoys near the coast limits the comparison to the first several hundred kilometers from coast. Nonetheless, a source clearly moves from farther out in the Pacific toward the California coastline over a few days. Back azimuth wind corrections were not applied. Buoy #46059 is labeled for reference.

I'm working with AOS graduate student Scott DeWolf in the quantification of the self-similarity of outdoor wind turbulence using Optical Fiber Infrasound Sensors (OFISs). Measurements of wind turbulence were made with OFISs of different lengths in 2009-10. These measurements provide the needed information to develop a quantitative approach for designing the optimum OFIS array for windy locations where the expected signal strength is known a priori (such as in the case of nuclear monitoring).

## Relevant Publications

- de Groot-Hedlin, C., Hedlin, M., and Walker, K., 2011, Finite difference synthesis of infrasound propagation through a windy, viscous atmosphere: application to a bolide explosion detected by seismic networks, *Geophys. J. Int.*, doi: 10.1111/j.1365-246X.2010.04925.x
- Hedlin, M.A.H., D. Drob, K.T. Walker, and C. de Groot-Hedlin, 2010, A study of acoustic propagation from a large bolide in the atmosphere with a dense seismic network, *J. Geophys. Res.*, 115, B11312, doi:10.1029/2010JB007669.
- Walker, K.T., and Hedlin, M.A.H., 2010, A review of wind noise reduction methodologies, in: *Infrasound Monitoring for Atmospheric Studies*, ed. by A. Le Pichon, E. Blanc, and A. Hauchecorne, Springer, p. 141-182, doi:10.1007/978-1-4020-9508-5.
- Walker, K.T., Hedlin, M.A.H., de Groot-Hedlin, C., Vergoz, J., Le Pichon, A., and Drob, D.P., 2010, Source location of the 19 February 2008 Oregon bolide using seismic networks and infrasound arrays, *J. Geophys. Res.*, 115, B12329, doi:10.1029/2010JB007863.
- Walker, K.T., Shelby, R., Hedlin, M., de Groot-Hedlin, C., and Vernon, F., Western U.S. Infrasonic Catalog: Illuminating infrasonic hotspots with the USArray, *J. Geophys. Res.*, in press.
- Hedlin, M.A.H., Walker, K., Drob, D.P., and de Groot-Hedlin, C.D., Infrasound: Connecting the Solid Earth, Oceans, and Atmosphere, *Annual Review of Earth and Planetary Sciences*, in review.

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*Research interests:* Marine EM methods, gas hydrates

Karen Weitemeyer is apart of the SIO Marine EM Laboratory run by Professor Steven Constable along with assistant researcher Kerry Key. Much of Karen's work is involved in developing and using marine electromagnetic methods for mapping gas hydrates. Gas hydrate, a frozen mixture of water and gas (mostly methane), is extremely important for a variety of reasons. It may be an economically viable source of natural gas, it is a hazard for deepwater drilling, and may be involved in slope failure and rapid climate change, yet we know little about its distribution in seafloor sediments.

Last year's annual report from Steven Constable described a controlled source electromagnetic (CSEM) data collection cruise to the Gulf of Mexico aimed at mapping gas hydrate deposits. The report also discussed the initial results from Mississippi Canyon block 118 (MC 118) and demonstrated the sensitivity of electromagnetic methods to gas hydrate concentration and distribution. To fully utilize the CSEM field data we have also expanded our knowledge of the electrical properties of gas hydrates by undertaking laboratory electrical conductivity measurements on methane hydrate and methane hydrate sediment mixtures. The success of this has drawn on the expertise of postdoc Wyatt DuFrane (LLNL), Laura Stern (USGS), Jeff Roberts (LLNL), and Steven Constable (SIO). We developed a pressure cell to synthesize gas hydrate while simultaneously measuring the in-situ frequency dependent electrical conductivity. Initial findings were published this year in *Geophysical Research Letters* which shows that pure methane hydrate is resistive as expected, about 20,000  $\Omega\text{m}$  at 0°C and has an activation energy of 30.6kJ/mol (-15 to 15° C ). These results give a conductivity-temperature relationship of pure methane hydrate that provide a basis for future work on hydrate-sediment mixtures in order to understand mixing relationships. This research will eventually allow us to convert the field electrical resistivity measurements into a hydrate concentration.

A collaboration with Anne Tréhu at Oregon State University allowed us to incorporate a 3D seismic tomography inversion with our 2D CSEM inversion result from Hydrate Ridge. Figure 1 shows the usefulness of examining both seismic and EM data jointly. The seismic inversion shows a low velocity zone that coincides exactly with a high resistive region in the CSEM inversion, suggestive of a free gas zone, likely associated with seismic horizon A, a conduit that carries free gas to the gas hydrate stability zone. There is also agreement between the EM and the seismic inversions in the pattern of the high velocity and the high resistivity associated with the folding of the accretionary complex sediments. The comparison of the 3D seismic tomography inversion to the CSEM inversion as well as comparisons to magnetotelluric data and resistivity well logs were published this summer in *Geophysical Journal International*.

**Relevant Publications**

Du Frane, W. L., L. A. Stern, K. A. Weitemeyer, S. Constable, J. C. Pinkston, and J. J. Roberts, Electrical properties of polycrystalline methane hydrate, *Geophysical Research Letters*, 38, L09313, 2011.

Weitemeyer, K. A., S. Constable, and A. M. Tréhu, A marine electromagnetic survey to detect gas hydrate at Hydrate Ridge, Oregon, *Geophysical Journal International*, 187, 45–62, 2011.

Weitemeyer, K., G. Guozhong, S. Constable, and D. Alumbaugh, The practical application of 2D inversion to marine controlled source electromagnetic data, *Geophysics*, 75, F199-F211, 2010.

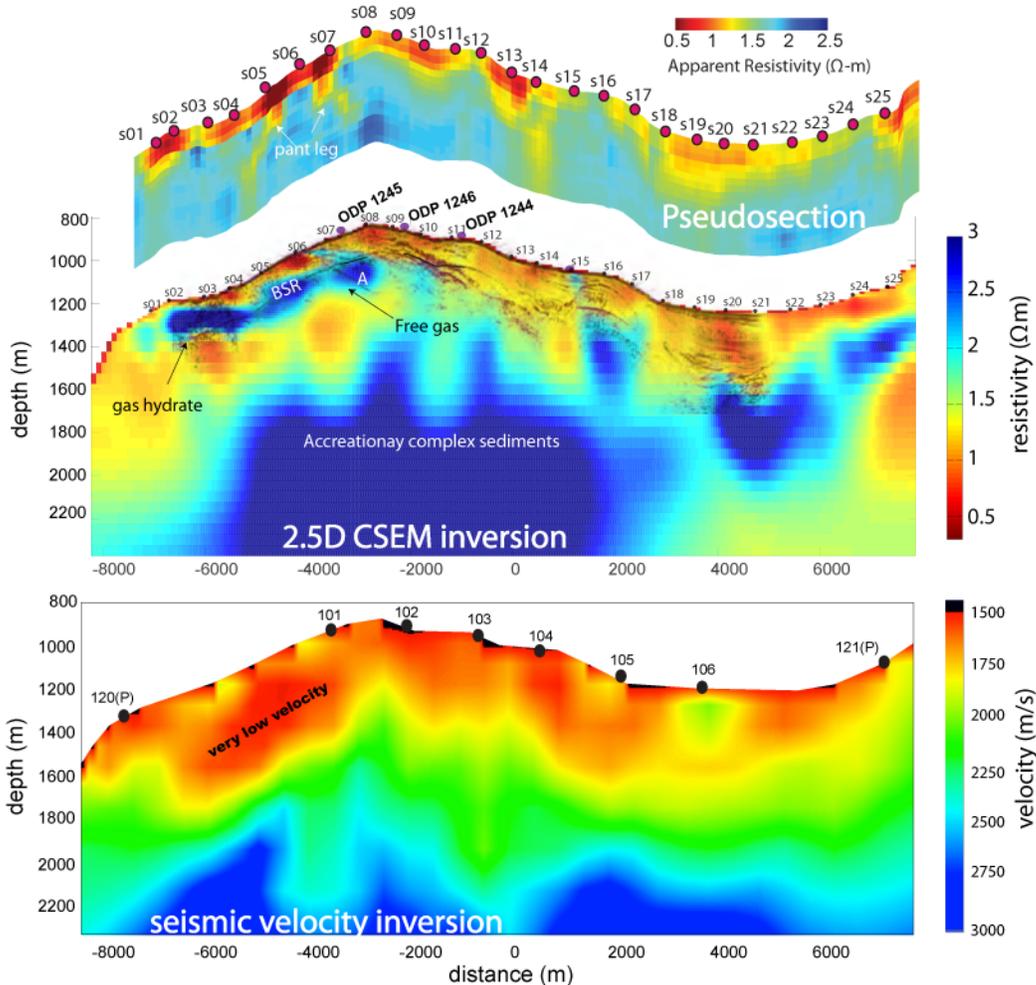


Figure 1. Apparent resistivity pseudosection section for 5 Hz CSEM data collected at Hydrate Ridge shows a pant leg feature associated with a surface conductor, such as brines (top); the 2D CSEM inversion is overlain on seismic line 230 (middle) and has collapsed the pant leg feature into a surface conductor. There is a resistive region hovering above and below the seismic bottom simulating reflector (BSR) suggestive of hydrate above and free gas below. Seismic horizon A is a conduit carrying free gas into the gas hydrate stability zone and is highly resistive. The bottom panel is a slice through a 3-D seismic P-wave velocity model, for which velocities were constrained to be above 1.5 km/s beneath the seafloor. Without this constraint, the low velocity zone beneath the western flank is more compact and the minimum velocity within it decreases. This anomaly is interpreted to indicate the presence of free gas associated with horizon A. Higher velocities are associated with folded accretionary complex sediments. These apparent folds in the velocity model correlate well with high resistivity zone in the CSEM model. Seismic line 230 is from Teuhu and Bangs (2001); the 2D CSEM inversion was done in collaboration with G. Guozhong and D. Alumbaugh at EMI-Schlumberger; and seismic inversion is from Arsenault et al. (2001).

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

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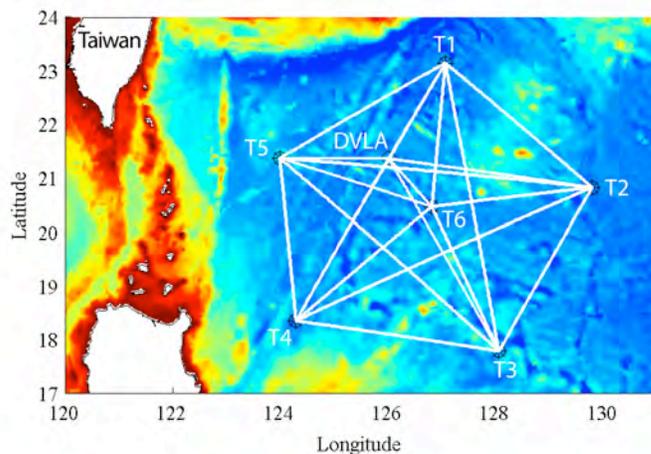
Phone: 44688

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

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

**Acoustic Propagation in the Philippine Sea.** Over the last twenty years, long-range, deep-water acoustic propagation experiments have been performed almost entirely in the oceanographically benign northeast and north central Pacific Ocean [e.g., Colosi *et al.*, 2010; Van Uffelen *et al.*, 2009, 2010]. The North Pacific Acoustic Laboratory (NPAL) Group recently conducted a series of acoustic experiments in the northern Philippine Sea to study deep-water propagation in a much more oceanographically energetic and variable region. A short-term Pilot Study/Engineering Test was conducted during April-May 2009 (PhilSea09). The 2010–2011 NPAL Philippine Sea Experiment, consisting of six acoustic transceivers and a new water-column spanning Distributed Vertical Line Array (DVLA) receiver, was deployed during April 2010 and recovered one year later, during March-April 2011 (PhilSea10).

The goals are to (i) understand the impacts of fronts, eddies, and internal tides on acoustic propagation in this complex region, (ii) determine whether acoustic methods, together with satellite, glider and other measurements and coupled with ocean modeling, can yield estimates of the time-evolving ocean state useful for making improved acoustic predictions and for understanding the local ocean dynamics, (iii) improve our understanding of the basic physics of scattering by small-scale oceanographic variability due to internal waves and density-compensated variability (spice), and (iv) characterize the ambient noise field, particularly its variation over the year and its depth dependence. The ultimate goal is to determine the fundamental limits to signal processing in deep water imposed by ocean processes, enabling advanced signal processing techniques to capitalize on the three-dimensional character of the sound and noise fields.

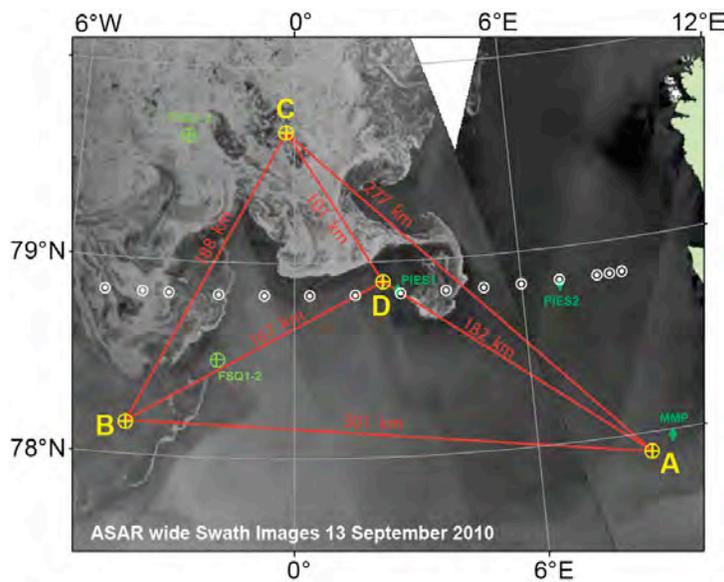


*Figure 1.* Overall mooring geometry of the 2010–2011 Philippine Sea Experiment, consisting of six 250-Hz acoustic transceivers (T1, T2, ... T6) and a new DVLA receiver. The array radius is approximately 330 km.

Finally, the one-month Ocean Bottom Seismometer Augmentation of the 2010–2011 NPAL Philippine Sea Experiment (OBSAPS) was conducted during April-May 2011, immediately following the PhilSea10 mooring recovery cruise. For this experiment, a low-frequency acoustic source

suspended from shipboard transmitted to six Ocean Bottom Seismometers (OBS) and a Near-seafloor DVLA. The OBSAPS experiment was motivated by similar observations made during the 2004–2005 NPAL Experiment in the central North Pacific, during which four OBS were deployed around a Deep Vertical Line Array receiver. Broadband transmissions with a center frequency of about 75 Hz from a ship-suspended source revealed a new class of arrivals in long-range ocean acoustic propagation that were named Deep Seafloor Arrivals (DSA), because they were the dominant arrivals observed on the OBS, but were either undetected or very weak on the deepest Deep VLA hydrophone (Stephen *et al.*, 2010).

**Fram Strait Tomography Experiment.** The Fram Strait, with a sill depth of 2600 m and a width of nearly 400 km, is the only deep connection where exchanges of intermediate and deep waters take



place between the North Atlantic and Arctic Oceans. It is therefore a key location to study the impact of the Arctic Ocean on global climate change. The Nansen Environmental and Remote Sensing Center (NERSC) in Bergen, Norway, with assistance from Worcester's group, installed an ocean acoustic tomography array in Fram Strait during summer 2010, with final recovery planned for summer 2012. The goal is to improve the accuracy of estimates of the heat, mass, and freshwater transports through Fram Strait by combining the acoustic measurements with data from gliders and oceanographic moorings and a high-resolution ice-ocean model through data assimilation.

*Figure 2.* Overall mooring geometry of the 2010–2012 Fram Strait Tomography Experiment, consisting of three 250-Hz acoustic transceivers (A, B, C) and a small vertical receiving array (D), superimposed on an Advanced Synthetic Aperture Radar (ASAR) satellite image. The gray/white areas correspond to sea ice; the darker areas are open water.

### Relevant Publications

- Colosi, J. A., J. Xu, P. F. Worcester, M. A. Dzieciuch, B. M. Howe, and J. A. Mercer, 2009: Temporal and vertical scales of acoustic fluctuations for 75-Hz, broadband transmissions to 87-km range in the eastern North Pacific Ocean. *Journal of the Acoustical Society of America*, 126, 1069–1083.
- Stephen, R. A., S. T. Bolmer, M. A. Dzieciuch, P. F. Worcester, R. K. Andrew, L. J. Buck, J. A. Mercer, J. A. Colosi, and B. M. Howe, 2009: Deep seafloor arrivals: An unexplained set of arrivals in long-range ocean acoustic propagation. *Journal of the Acoustical Society of America*, 126, 599–606.
- Van Uffelen, L. J., P. F. Worcester, M. A. Dzieciuch, and D. L. Rudnick, 2009: The vertical structure of shadow-zone arrivals at long range in the ocean. *Journal of the Acoustical Society of America*, 125, 3569–3588.
- Van Uffelen, L. J., P. F. Worcester, M. A. Dzieciuch, D. L. Rudnick, and J. A. Colosi, 2010: Effects of upper ocean sound-speed structure on deep acoustic shadow-zone arrivals at 500- and 1000-km range. *Journal of the Acoustical Society of America*, 127, 2169–2181.

**Mark A. Zumberge**

**Research Geophysicist**

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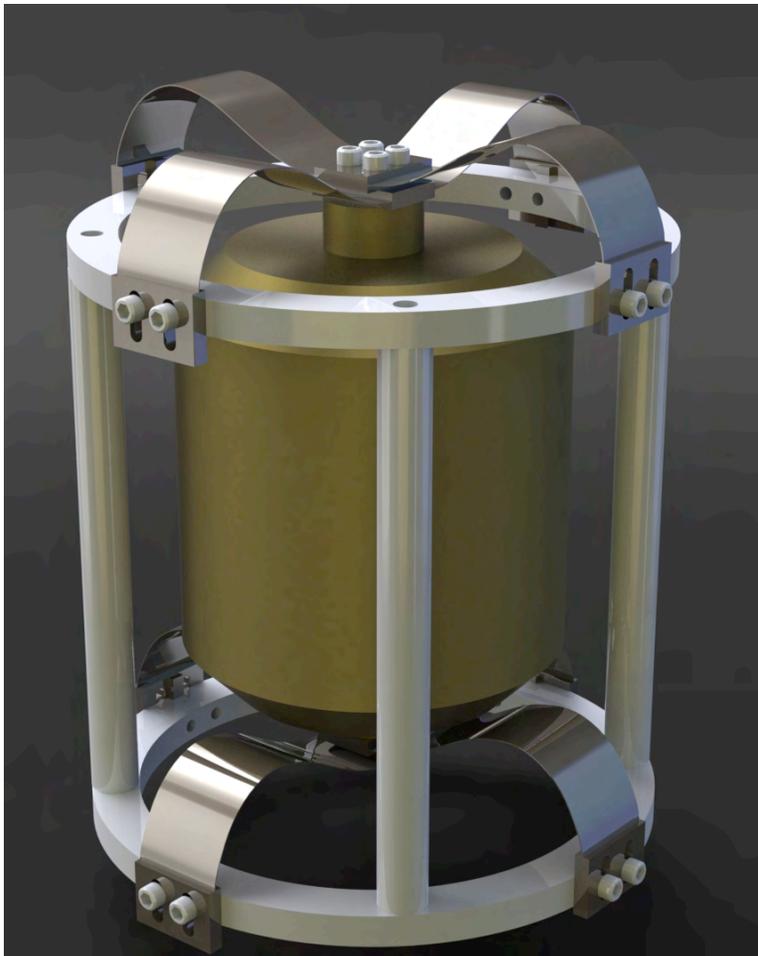
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*Research Interests:* Measurement of gravity and pressure in the marine and subaerial environments, development of new seismic instrumentation, optical fiber measurements of strain and pressure

**A new suspension for a vertical optical seismometer**

(In collaboration with Jon Berger)

Technologies for seismology, geothermal energy research, and nuclear test monitoring require advancements in seismometers capable of achieving the resolutions of existing sensors which operate in underground vaults but with the capability to operate in boreholes and, in some instances, at high temperature. Electronics-based sensors are problematic when installed in boreholes, especially very deep ones because normal silicon-based electronics encounter problems above 150 °C, a temperature reached in boreholes a few km deep or in shallower ones in geothermal regions.



*Figure 1:* Most modern vertical seismometers use a leaf spring design in which a mass is attached to a horizontal beam that rotates around a hinge. A leaf spring connecting the pivoted mass to the frame provides a restoring force to center the beam. Careful design of the spring geometry leads to a long free period and hence high sensitivity as a seismic sensor. Such suspensions, however, are very sensitive to alignment with the local vertical. If the sensor becomes slightly tilted, the geometry is spoiled and the seismometer no longer operates properly. We have adopted a design first invented by Erhard Wielandt at the University of Stuttgart which uses leaf springs to provide a long free period while the mass moves in a straight line rather than an arc. The resulting sensor makes adaptation to a borehole much simpler.

We are pursuing an alternative to electronics for acquiring downhole seismic records. The emergence of new optical fibers with metal and/or advanced polymer coatings which can withstand temperatures up to 600 °C, and the success we have achieved using optical fiber sensors in seismometers and tiltmeters in vaults, enables complete elimination of electronics from the downhole sondes without loss of sensitivity. Such devices will allow precise observation of geophysical parameters in high temperature boreholes encountered in geothermal monitoring environments.

The in-line geometry of the sensor depicted in Figure 1, when adapted to a borehole, will operate even when tilted. Our optical displacement transducer's wide dynamic range will accommodate the shift in vertical position of the mass that will accompany small tilts. Elimination of leveling motors in the borehole sonde will be a significant simplification.



*Figure 2.* Installation of the first in-line optical seismometer at our test vault at Piñon Flat Observatory.

#### **Relevant Publications**

Zumberge, M., Berger, J., Otero, J., Wielandt, E., “An Optical Seismometer without Force Feedback.”  
*Bul. Seis. Soc. Am.* 100 No. 2 (2010): 598-605.

*Cover: IGPP doctoral student, Matthew Siegfried prepares for a 110 kilometer snowmobile traverse to Subglacial Lake Whillans while on his six week research expedition in West Antarctica. Below: A pair of LC-130s sit at the Pegasus Airfield on the Ross Ice Shelf, West Antarctica. Both images are courtesy of Matthew Siegfried.*



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