CECIL H. & IDA M. GREEN

INSTITUTE OF GEOPHYSICS & PLANETARY PHYSICS

2013 ANNUAL REPORT

SCRIPPS INSTITUTION OF OCEANOGRAPHY **UNIVERSITY OF CALIFORNIA, SAN DIEGO**

IGPP

This is the eighth Annual Report of the Cecil and Ida Green Institute of Geophysics and Planetary Physics. 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, developing earthquake early warning systems, understanding the behavior of ice sheets, improved methods of energy exploration, monitoring of carbon dioxide sequestration, and so on.

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

This year, two members of the IGPP faculty were recognized with honors. Bernard Minster was elected a fellow of the American Association for the Advancement of Science "for distinguished contributions in the areas of plate motion, crustal deformation, and satellite geodesy, as well as for community leadership and teaching the next generation of geophysicists." Cathy Constable received the William Gilbert award of the American Geophysical Union for "...her fundamental contributions to our understanding of secular variation of the geomagnetic field and exemplary service to the geomagnetism and paleomagnetism community."

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

Duncan Carr Agnew, *Professor*
Laurence Armi, *Professor**
Luciana Astiz, *Specialist**
Jeffrey Babcock, *Associate Project Scientist**
George Backus, *Professor Emeritus**
Jonathan Berger, *Research Scientist*†
Donna Blackman, *Research Scientist*
Yehuda Bock, *Research Scientist*
Adrian Borsa, *Assistant Research Geophysicist*
Catherine Constable, *Professor*
Steven Constable, *Professor*
J. Peter Davis, *Specialist*
Catherine deGroot-Hedlin, *Research Scientist*
Matthew Dzieciuch, *Project Scientist**
Peng Fang, *Specialist**
Yuri Fialko, *Professor*
Helen Fricker, *Associate Professor*
Freeman Gilbert, *Professor Emeritus**
Jennifer S. Haase, *Associate Research Geophysicist*
Alistair Harding, *Research Scientist*
Michael Hedlin, *Research Scientist*
Glenn Ierley, *Professor Emeritus**
Kerry Key, *Associate Professor*
Deborah Kilb, *Associate Project Scientist*
M. Gabriele Laske, *Professor in Residence*
T. Guy Masters, *Professor*
Jean-Bernard Minster, *Professor*
Walter Munk, *Research Professor*
Darcy E. Ogden, *Assistant Professor*
John Orcutt, *Professor**
Robert Parker, *Research Professor Emeritus*
David Sandwell, *Professor*
Peter Shearer, *Professor*
Lenord Srnka, *Professor of Practice**
Hubert Staudigel, *Research Scientist*
David Stegman, *Associate Professor*
Frank Vernon, *Research Scientist**
Kristoffer Walker, *Associate Research Scientist*
Bradley Werner, *Professor**
Peter Worcester, *Research Scientist*
Mark Zumberge, *Research Scientist*

* no annual report available

Emperor penguin on the Sea Ice near the Barnes Glacier, Ross Island, Antarctica. (Left to right) Anthony Rigoni, Laurie Connell and Forrest McCarthy. image courtesy of Hubert Staudigel

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

With support from Plate Boundary Observatory, the US Geological Survey, and the Southern California Earthquake Center, we operate ten longbase laser strainmeters (LSM's) at five locations in California: two instruments in Cholame, near the northwest end of the segment of the San Andreas fault that last ruptured in 1857; one instrument at the northern edge of the Los Angeles basin, near the San Gabriel mountains and in an area of possible NS compression; three instruments at Piñon Flat (**PFO**), 14 km from the San Jacinto fault; two instruments at Durmid Hill, 1.5 km from the trace of the San Andreas fault near the southern end; and two instruments 22 km from the Durmid Hill site, between the San Andreas and San Jacinto fault zones.

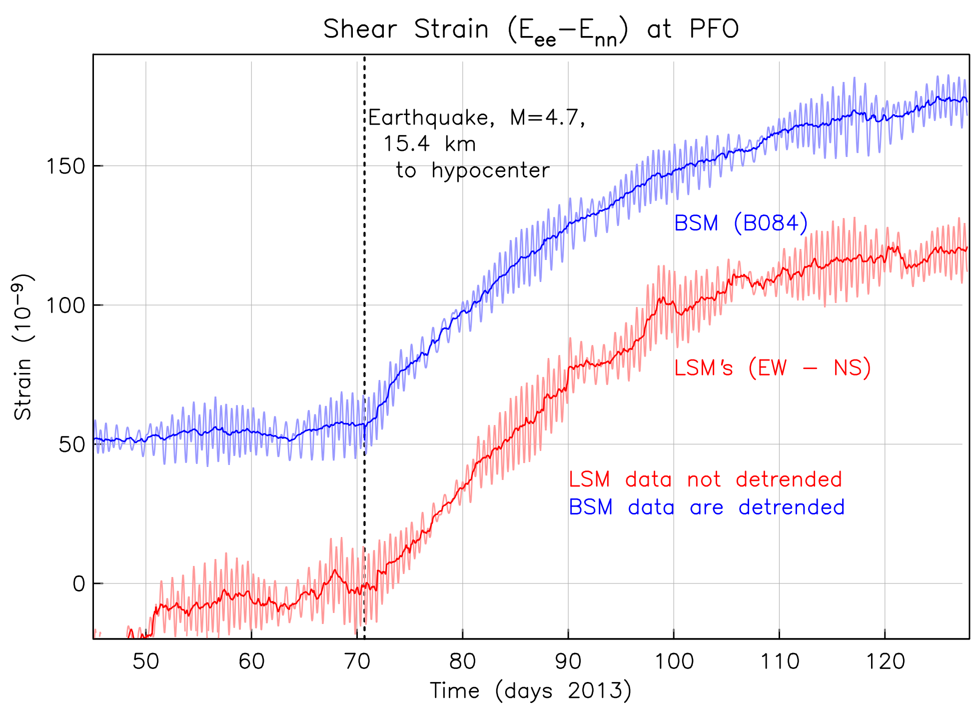

Figure 1: One component of shear at PFO, showing the similar postseismic behaviors of the LSM's and BSM.

The most interesting signal in the last year was observed at PFO. The nearby Anza segment of the San Jacinto Fault has not had a large earthquake in the last 200 years, longer than for any other part of this fault. From 1934 through 2000, there was only one earthquake of magnitude 5 or above in this region, in 1980; since 2001 there have been three (in 2001, 2005, and 2010). On March 11 (day 70) 2013, a magnitude 4.7 event occurred in this area. Immediately following this last earthquake, we observed changes in long-term strain rates on both the PBO borehole strainmeters (BSM's) that were installed in the region in 2006-2007, and on the longbase laser strainmeters (LSM's) that have operated at Piñon Flat Observatory (PFO) since well before the PBO.

At PFO the BSM (B084) is located inside the area enclosed by the LSM's. Both instruments show (**Figure 1**) a similar increase in the fault-parallel shear strain ($e_{EE} - e_{NN}$) following

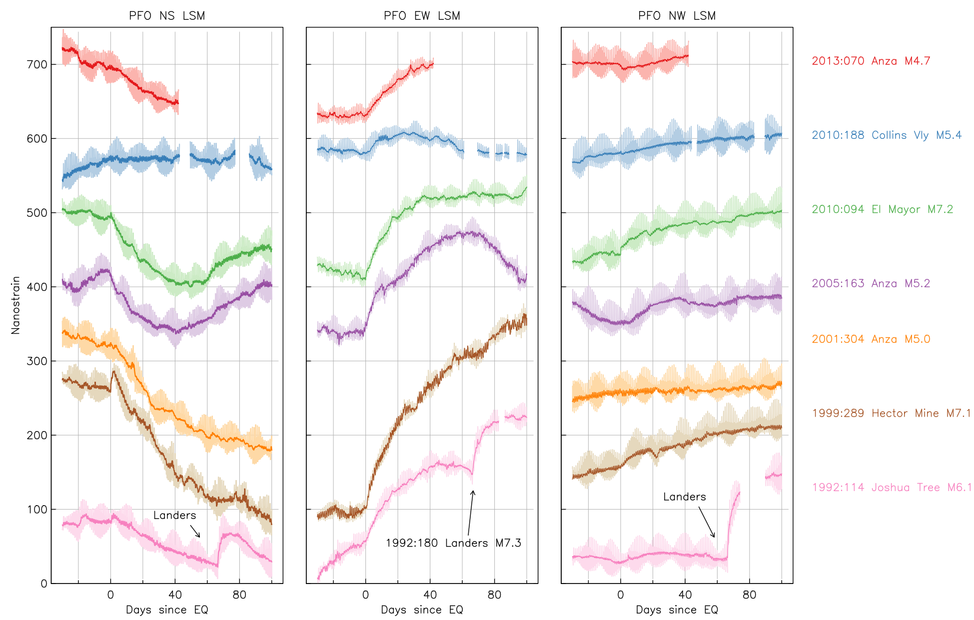

Figure 2 Responses of the three PFO LSM's to eight earthquakes, four local and four regional. Of these, all but the Landers event have produced similar responses.

the earthquake: note that the LSM result comes from combining results from two completely independent systems. The BSM and LSM shears also show several episodes of more rapid slip lasting for 1-2 hr. Agreement in other components is not as good; in particular, the NW-SE LSM shows little change, which is not the case for the fault-normal shear on the BSM. Postseismic strain changes were observed on other PBO BSM's in the Anza area, though in some cases with significantly different time behavior.

The LSM's at PFO have shown a similar response (**Figure 2**) following the El-Mayor Cucapah earthquake in 2010, and earlier Anza-area shocks in 2005 (mag 5.2) and 2001 (5.0) – though not following a magnitude 5.4 in 2010. The latter, and the El-Mayor Cucapah earthquake, also caused strain changes at many of the BSM's.

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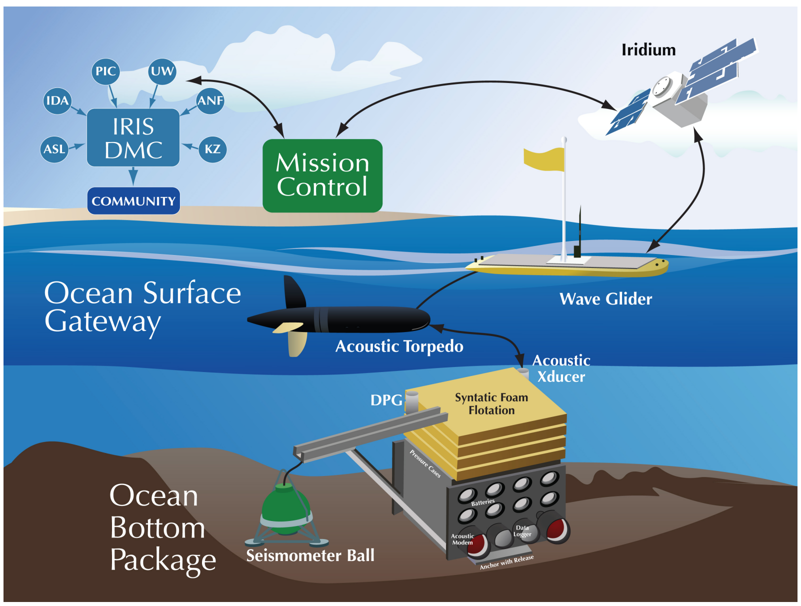
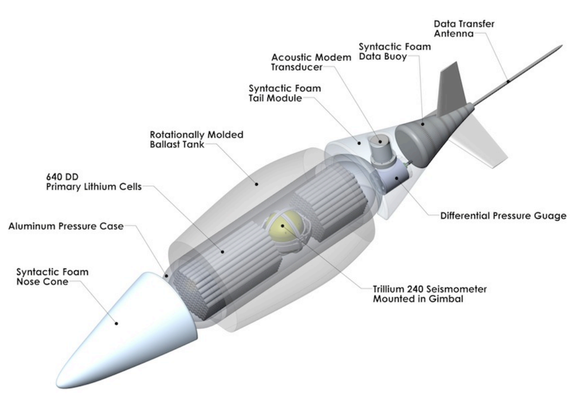
Research Interests: Global seismological observations, geophysical instrumentation, deep ocean observing platforms, global communications systems.

Under funding from an NSF Major Research Instrumentation (MRI) grant, my collaborators John Orcutt, Gabi Laske, and Jeff Babcock and I have developed 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 partnered with Liquid Robotics, which has developed an autonomous surface vehicle called the Wave Glider. This device harvests wave energy for propulsion and solar energy for electronics.



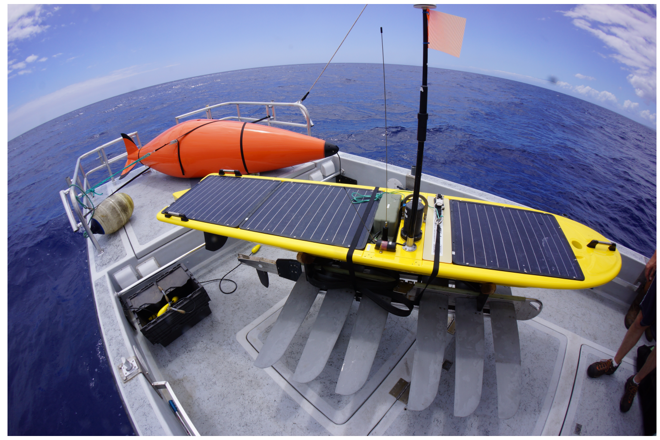
The overall concept is illustrated in the first figure. The wave-powered Wave Glider holds station over the ocean bottom package and acts as a surface gateway between acoustic transmissions through the ocean column and satellite transmissions to shore.

During this second year of our MRI grant we finished the implementation of this system and conducted two "wet" tests in the waters off La Jolla. Results of these tests demonstrated that the acoustic telemetry worked well with an overall efficiency of 262bits/J. This means that an ocean bottom platform with a 2-yr battery is practical. During our second deployment we made the first near real-time observations of an earthquake from an autonomous offshore observatory. Later this year we plan a three-month deployment off San Clemente Island in 4 km of water.



SHARC
Scripps Hybrid Autonomous Remote Capsule

A second major goal of this MRI grant was to design an ocean bottom package capable of being self deployed – that is being towed out to the deployment site by a wave glider. Martin Rapa designed a prototype package, which we call the SHARC (Scripps Hybrid Autonomous Remote Capsule). Designed for a two-year bottom life, the SHARC is nearly 3 m in length and will weight about 650 Kg in air but is predicted to have only 0.7 to 0.9 Kg drag at 2kts. A "break-away" pod at the stern provides a method of recovering the recorded data to the sea surface where it may be telemetered via radio to the wave glider.



We built a full-scale model of the SHARC and ballasted it with water to conduct tow tests off the island of Hawaii. The wave glider and mass model were deployed for a 24-hour period. The vehicle was run around a 1-km box to evaluate the wave glider's ability to navigate and tow the mass model. The wave glider had no problem navigating with the attached tow body and took approximately 2.7 hours to complete a 4-km circuit for an average of 0.8 knots. This is approximately 0.3-0.5 knots slower than an un-encumbered wave glider in this sea state. The wave glider used in this test was equipped with an auxiliary thruster. When the thruster was running there was approximately a 0.2-0.3 knot speed increase, which nearly compensated for the drag caused by the SHARC.

Relevant Publications

Jonathan Berger, John Orcutt, Gabi Laske, and Jeffrey Babcock (2013). ADDOSS Annual Report*, NSF, Sept 2013.*

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Research interests: Oceanic spreading centers- mantle flow and associated seismic anisotropy, effect of plate boundary geometry on flow and plate deformation, oceanic core complex structure and development. Hydroacoustics with application to nuclear test monitoring.

My research for 2012/2013 emphasized two projects: the effects of mineral alignment on deformation rates in the mantle beneath oceanic spreading centers; the extents to which an oceanic core complex becomes hydrated during exposure by detachment faulting.

A majority of my time this year was spent on program management for the Marine Geology and Geophysics program at the National Science Foundation, while I serve a couple-year rotation there. With successive continuing resolutions, sequestration, and a shutdown, it's been a challenging time to come up to speed on how NSF works.

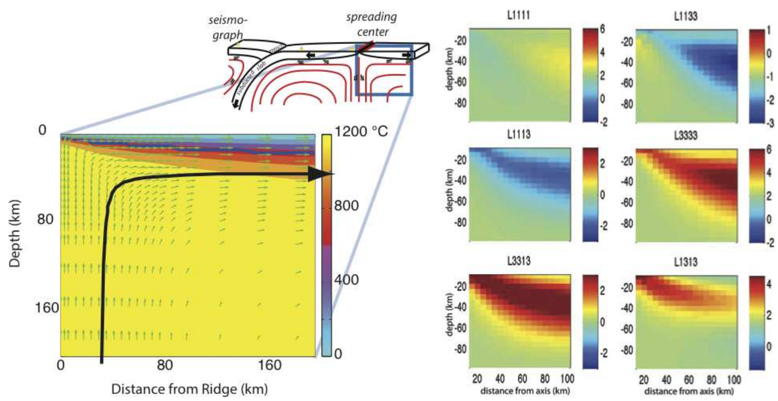

Figure 1: Numerical simulation of mantle flow beneath an oceanic spreading center. Mineral alignment and corresponding viscosity tensor are computed along flow lines. Tensor components are shown varying throughout the model space in the panels at right.

Seismic anisotropy measured near plate boundaries indicates that flow-induced mineral alignment and/or preferred orientations of embedded heterogeneities (composition, melt) occur in the mantle. Experimental results show that preferred mineral alignment can result in directional dependence of material properties, rheologic as well as seismic. Working with colleagues at Cornell and CNRS, Paris, we are trying to quantify how such rheologic effects might feedback into the pattern of mantle flow beneath an oceanic spreading center. A parallel finite element code is used to link microstructural behavior to an evolving macrostructural flow field. Our current 'soft' and 'intermediate' coupling tests start with isotropic viscosity. Flowlines are computed and mineral alignment is determined based on strain rate evolution along material paths. Updated local viscosity (in tensor form, allowed to be anisotropic if mineral orientation distributions dictate) is computed throughout the model space, using the flow line results. A next iteration of the flow solution is performed. Currently we are testing individual steps in the linked set of numerical simulations. Run times for cases where resolution tests indicate results are reliable are sufficiently low that we remain confident that fully-coupled cases can be viably solved.

Borehole logging at Atlantis Massif oceanic core complex shows that the deeper portion of the gabbroic domal core has had little contact with seawater, in contrast to the pervasively altered upper few hundred meters of the exposed core. Seismic velocity and resistivity along the wallrock of the 1.4 km deep IODP borehole are dominated by the extent of alteration measured by prior drill core analysis. Past zones of localized flow have seismic velocity that is 0.5-1 km/s slower than surrounding, less altered rock. Present, very narrow intervals of percolative flow are characterized by small dips in borehole fluid temperature. These narrow zones and the rapid downhole change in alteration record below a fault zone at ˜750 mbsf indicate that deformation and seawater circulation in the crust are localized, with significant regions unaffected by ongoing processes, even when kilometers of uplift and several tens of degrees of block rotation characterize the crustal evolution.

Recent publications

Blackman, D., A. Slagle, A. Harding, G. Guerin, A. McCaig (2013) IODP Expedition 340T: Borehole logging at Atlantis Massif Oceanic Core Complex. *Sci. Drilling*, **15** 31-33, 10.2204/iodp.sd.15.04.2013

Blackman, D.K., A. Slagle, G. Guerin, A. Harding (2013) Geophysical signatures of past and present hydration within a young oceanic core complex, *Geophys. Res. Lett.* in review

Marcuson, R. and D.K. Blackman (2013) Predictions of seismic anisotropy in the Lau back-arc basin using 2-D numerical models, *Phys. Earth Planet. Int.* submitted

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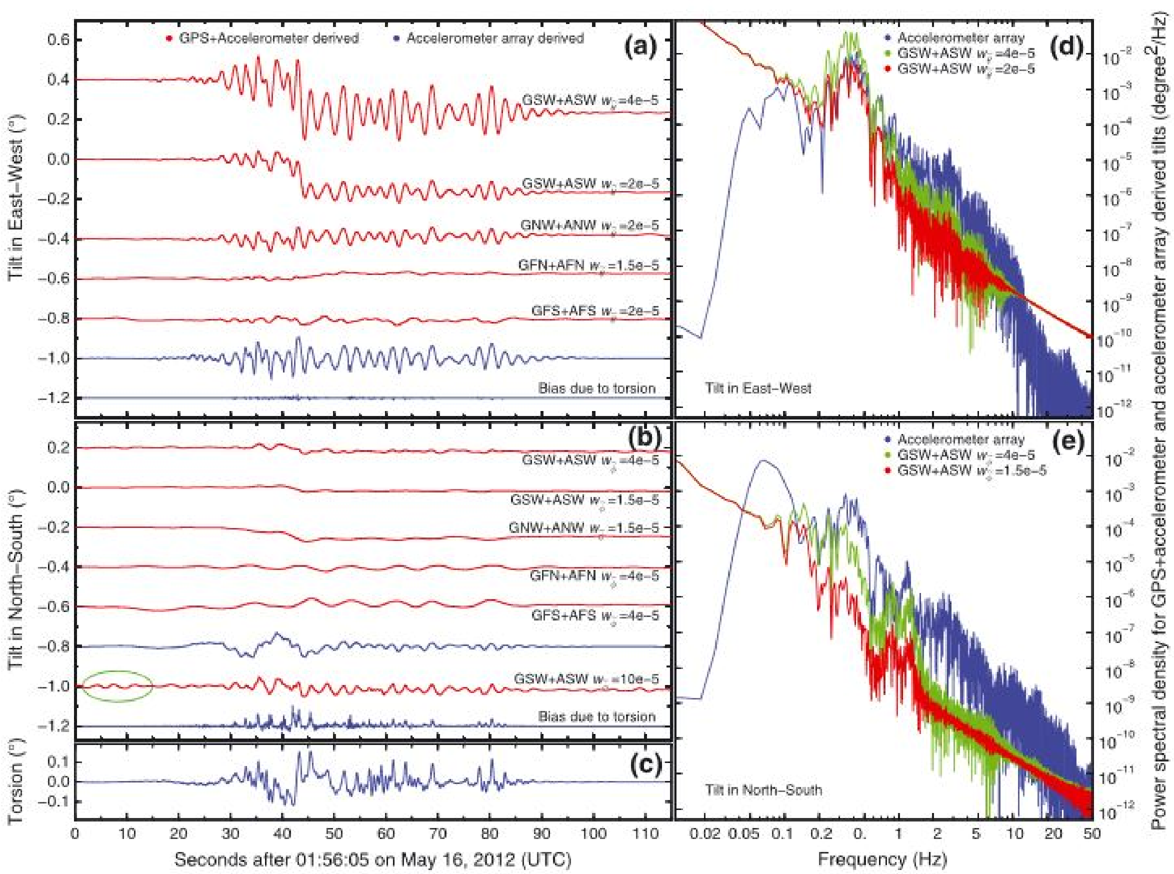
Research Interests: Space geodesy, crustal deformation, early warning systems for natural hazards, GPS seismology, GPS meteorology, GIS and Information Technology

Highlights of Yehuda Bock's research in 2013 with research geophysicist Jennifer Haase, postdoctoral scholar Jianghui Geng, graduate students Brendan Crowell and Diego Melgar, Scripps Orbit and Permanent Array Center (SOPAC) staff, include real-time integration of GPS and accelerometer measurements for the mitigation of earthquake hazards from seismogeodetic displacement, velocity and point tilt waveforms, rapid modeling of the Tohoku-oki earthquake, precise point positioning with ambiguity resolution tightly coupled with accelerometer data, and crustal deformation in the Salton Trough.

GENG ET AL.: RECOVER TILTS FROM GPS AND ACCELEROMETER

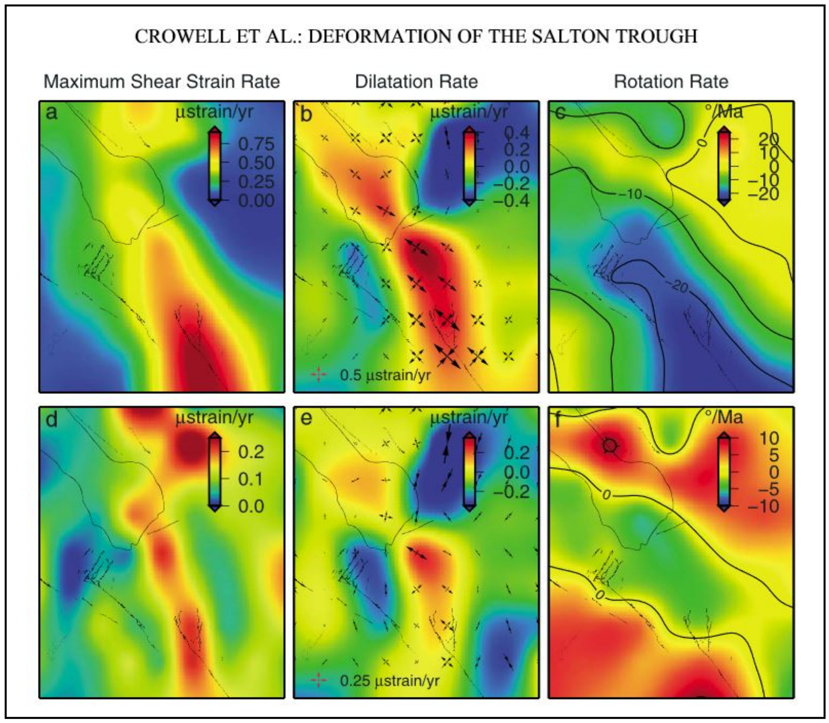


Seismogeodesy

Integration of GPS and accelerometer data at the observation level provides real-time estimates of seismic displacements, velocities, and point tilts that are more robust and informative than accelerometer or GPS data on their own (*Melgar et al.*, 2013a; *Geng et al.*, 2003a). Using data from the George E. Brown, Jr. Network for Earthquake Engineering Simulation Large High-Performance Outdoor Shake Table at UCSD, we demonstrate the estimation of coseismic point tilts on the roof of a five-story building subjected to accelerations recorded at the Trans-Alaska Pipeline System site PS09 during the 03 November 2002 Mw 7.9 Denali earthquake (figure above, panel a) (*Geng et al*., 2013b). Seismogeodetic data can be applied to enhanced earthquake early warning, rapid centroid moment tensor (CMT) solutions and finite fault slip models (*Crowell et al*., 2012) for near-source monitoring of large earthquakes with tsunamigenic potential such as the devastating 2011 Mw 9.0 Tohoku-oki earthquake in Japan (*Melgar et al*., 2013b). We've developed the SIO Geodetic Module and low-cost MEMS accelerometer package to economically upgrade existing GPS stations in southern California to seismogeodetic capability. Laboratory and field tests indicate that the instrument has the sensitivity to detect seismic motions in the near-field for ~magnitude 5 and greater earthquakes, and is particular useful for large earthquakes where accelerometer data saturate for earthquakes greater than M 7 to 8.

Current Deformation of the Salton Trough

Using a combination of campaign and continuous GPS measurements and a block model for regional tectonics constrained by the continuous GPS data (*Smith-Konter, B., and D. Sandwell (2009), Geophys. Res. Lett., 36*), *Crowell et al*. (2013) investigated deformation through the Brawley Seismic Zone from the Imperial Fault in the south to the San Andreas Fault in the north. Maximum shear strain, dilatation, and rotation rate changes are shown in the figure to the right using the total velocity field and the local velocity field. The most prominent feature in the strain rate fields is the large shear strain (0.9 µstrain/yr) in the total field associated with the strain localization on the Imperial Fault and a large dilatation (0.2 to 0.5 µstrain/yr) in the Central Brawley Seismic Zone. The strain becomes diffuse as it is partitioned between the San Andreas and San Jacinto Faults, down to between 0.25 and 0.5 µstrain/yr. Deformation south of the San Andreas Fault appears to be localized, leading to greater hazard and the possibility of sizeable earthquakes that might act as triggers for great earthquakes on the southern San Andreas Fault.



Recent Publications

Crowell, B. W., Y. Bock and D. Melgar (2012), Real-time inversion of GPS data for finite fault modeling and rapid hazard assessment, *Geophys. Res. Lett*., *39*, L09305, doi:10.1029/2012GL051318.

Crowell, B. W., Y. Bock, D. T. Sandwell, and Y. Fialko (2013), Geodetic investigation into the deformation of the Salton Trough, *J. Geophys. Res. Solid Earth*, 118, 5030–5039, doi:10.1002/jgrb.50347.

Geng, J., Y. Bock, D. Melgar, B. W. Crowell, and J. S. Haase (2013a), A new seismogeodetic approach applied to GPS and accelerometer observations of the 2012 Brawley seismic swarm: Implications for earthquake early warning, *Geochem. Geophys. Geosyst*., *14*, doi:10.1002/ggge.20144.

Geng, J., D. Melgar, Y. Bock, E. Pantoli, and J. Restrepo (2013b), Recovering coseismic point ground tilts from collocated high-rate GPS and accelerometers, *Geophys. Res. Lett*., *40*, doi:10.1002/grl.51001.

Melgar, D., Y. Bock, D. Sanchez and B. W. Crowell (2013a), On robust and reliable automated baseline corrections for strong motion seismology, *J. Geophys. Res*., 118, 1–11, doi:10.1002/jgrb.50135.

Melgar, D., B. W. Crowell, Y. Bock, and J. S. Haase (2013b), Rapid modeling of the 2011 Mw 9.0 Tohoku-oki earthquake with seismogeodesy, *Geophys. Res. Lett*., 40, 1-6, doi:10.1002/grl.50590.

Adrian Borsa

Assistant Research Geophysicist

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Research Interests: Airborne and space-based lidar imaging and system calibration/validation. Differential lidar techniques applied to problems in geomorphology and tectonic geodesy. Kinematic GPS for positioning, mapping, and recording transient deformation due to earthquakes, fault creep and short-period crustal loading. GPS multipath and other noise sources. Dry lake geomorphology.

My recent research in the area of tectonic geodesy has been directed toward the development of efficient algorithms to perform differential lidar analysis of pre- and post-earthquake airborne lidar datasets, with specific application to the 2009 M7.2 El Mayor-Cucapah rupture zone. In the case of the El Mayor event, airborne lidar differencing provided a map of surface deformation in the near-field of the rupture, which complemented the information provided by field mapping of visible surface rupture and the far-field deformation provided by InSAR and other imaging techniques.

In particular, differential lidar showed that vertical warping of the surface closely followed the shape expected from an elastic upper crust, except 1.) over dry lake sediments, where plastic deformation is observed, and 2.) nearby and between en-echelon fractures that are likely to be related to shallow structures. Important to the interpretation of field mapping, 50~90% of total vertical displacement took place as elastic/plastic distributed displacement off of mapped surface traces of the rupture. In addition, although the rupture follows or wraps around topographic features, the vertical displacements from this earthquake were antithetical to the motion expected given the topography on either side of the fault. Since repetitions of this event over time cannot create the visible topography of the El Mayor mountains, this earthquake is not characteristic for this fault system.

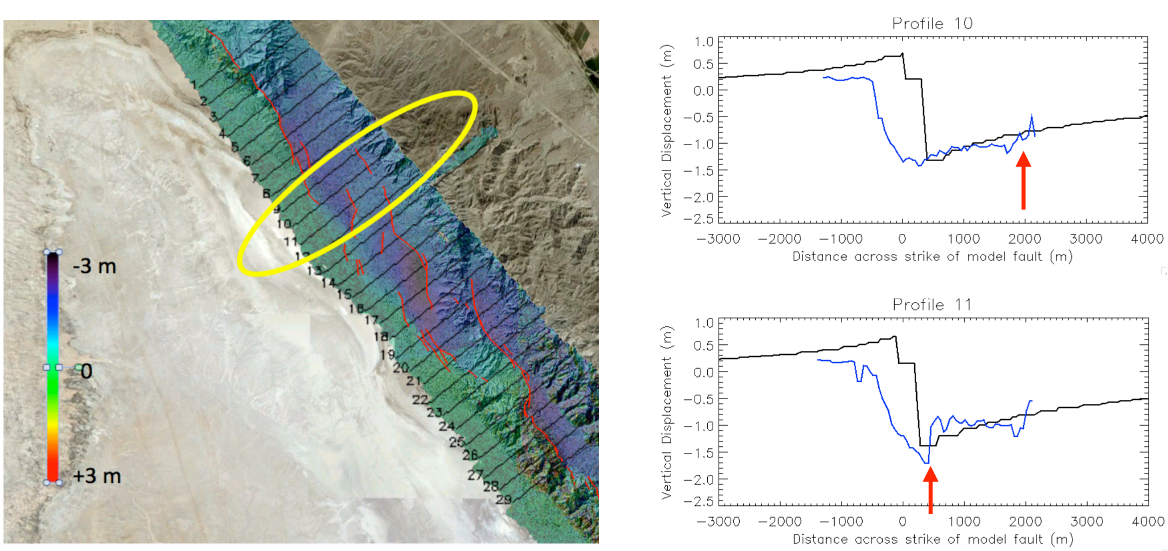

Figure 1: **Right**: Differential lidar vertical displacements from the M7.2 El Mayor-Cucapah earthquake in color, showing east-side down motion. Mapped traces of the rupture are in red. **Left**: Profiles 10 and 11 in the figure at right showing lidar results (blue) and elastic crustal model (black). The lidar results and model are similar in most profiles, but strongly diverge in areas of lake sediments to the east (x < 0) of the fault. Mapped surface ruptures (red arrows) do not always occur where the model indicates (Profile 10) or may face the opposite direction (Profile 11) as would be expected from the modeled vertical motion.

My other main area of current research has been the ongoing characterization of the salar de Uyuni in Bolivia, a high-elevation dry lakebed that is being used for the calibration and validation of satellite altimeter measurements. Our group has surveyed the salar three times with kinematic GPS (2002, 2009 and 2012) and established that the surface is both exceptionally flat (80 cm total relief over 50 km) and stable (< 3 cm RMS elevation change over a decade), while maintaining coherent geoid-referenced topography at wavelengths of tens of kilometers. We are using this knowledge to further our understanding of how a dynamic system like the salar maintains this surface equilibrium, as well as to improve geolocation algorithms and calibration parameters for use of ICESat-1 and Cryosat data for cryosphere mass balance studies.

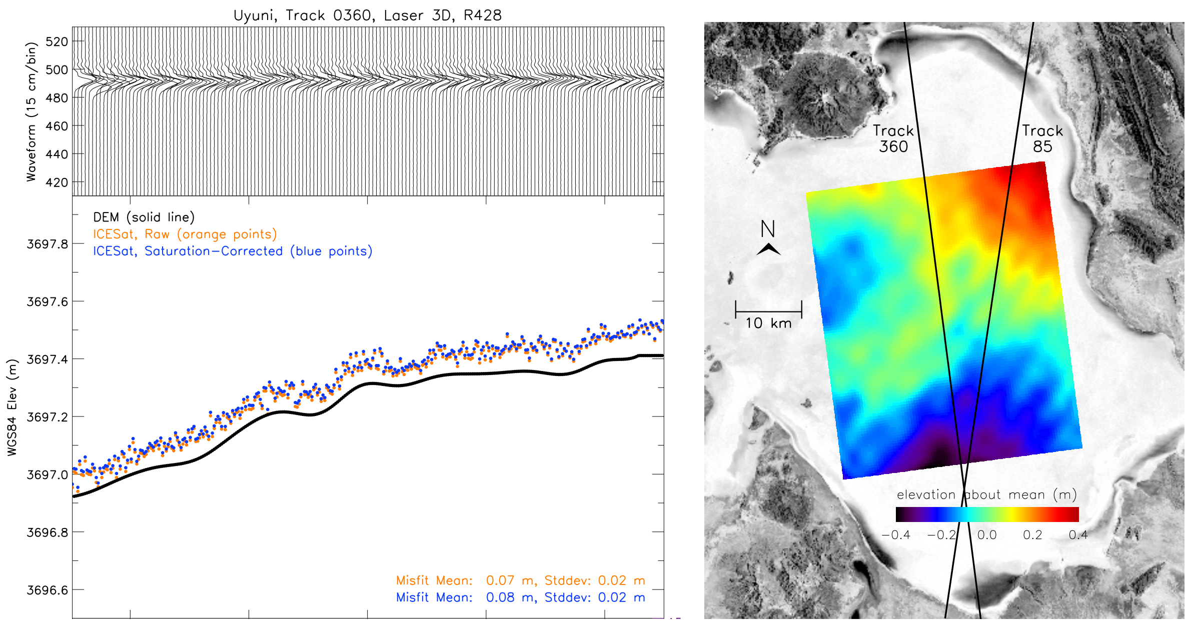

Figure 2: **Right**: DEM of the 45x54 km mapped region of the salar de Uyuni in Bolivia, showing 80 cm of total vertical relief over 50 km (possibly the flattest topography on Earth). Two tracks from the ICESat-1 mission cross the DEM and allow direct elevation comparisons for calibration/validation of range and other instrument parameters. **Left:** Elevations from ICESat-1 Track 360 (orange [raw] and blue [corrected] dots), compared with the DEM reference surface (black line), showing low scatter for this pass, but an apparent elevation bias. Waveforms for each geolocated elevation are shown at the top.

Relevant Publications

Borsa, A.A., G. Moholdt, H.A. Fricker, K.M. Brunt (2013). "A range correction for ICESat and its potential impact on ice sheet mass balance studies." The Cryosphere Discuss, **7**, pp. 4287-4319, doi:10.5194/tcd-7-4287-2013

Borsa, A.A. and J.-B. Minster (2012). "Rapid determination of near-fault earthquake deformation using LiDAR." *Bulletin of the Seismological Society of America*, **104**(4), pp. 1335-1347, doi: 10.1785/0120110159

Borsa, A.A., B.G. Bills, J.-B. Minster (2008). “Modeling the topography of the salar de Uyuni, Bolivia as an equipotential surface of Earth’s gravity field.” *Journal of Geophysical Research*, **113**, B10408

Borsa, A.A., H.A. Fricker, B.G. Bills, J-B. Minster, C.C. Carabajal, K. Quinn (2007). “Topography of the salar de Uyuni, Bolivia from kinematic GPS.” *Geophysics Journal International*, **172**(1)

Fricker, H.A., A.A. Borsa, C.C. Carabajal, K. Quinn, B.G. Bills and J.-B. Minster (2005). “Assessment of ICESat performance at the salar de Uyuni, Bolivia.” *Geophysical Research Letters*, **32**, L21S06

Hudnut, K.W., A.A. Borsa, C. Glennie and J.-B. Minster (2002). “High-resolution topography along surface rupture of the 16 October 1999 Hector Mine, California, earthquake from airborne laser swath mapping.” *Bulletin of the Seismological Society of America*, **92**(4)

Catherine Constable
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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.

Ongoing research projects over the past year have been concerned with (i) the behavior of the geomagnetic field on millennial timescales during the Holocene time period (in collaboration with Monika Korte of GeoForschungs Zentrum, Helmholtz Center, Potsdam), and back to 100 ka with postdoc Sanja Panovska; (ii) the magnetic field on million year time scales (with PhD student Geoff Cromwell, Catherine Johnson at University of British Columbia, Lisa Tauxe); (iii) application of modeling and data processing tools for global electromagnetic induction studies using magnetic field observations from low-Earth-orbiting satellites (PhD student, 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) work with PhD student Margaret Avery, postdoctoral researcher Christopher Davies (Leeds University, U.K.) and research associate David Gubbins on the compatibility of numerical geodynamo simulations with paleomagnetic results.

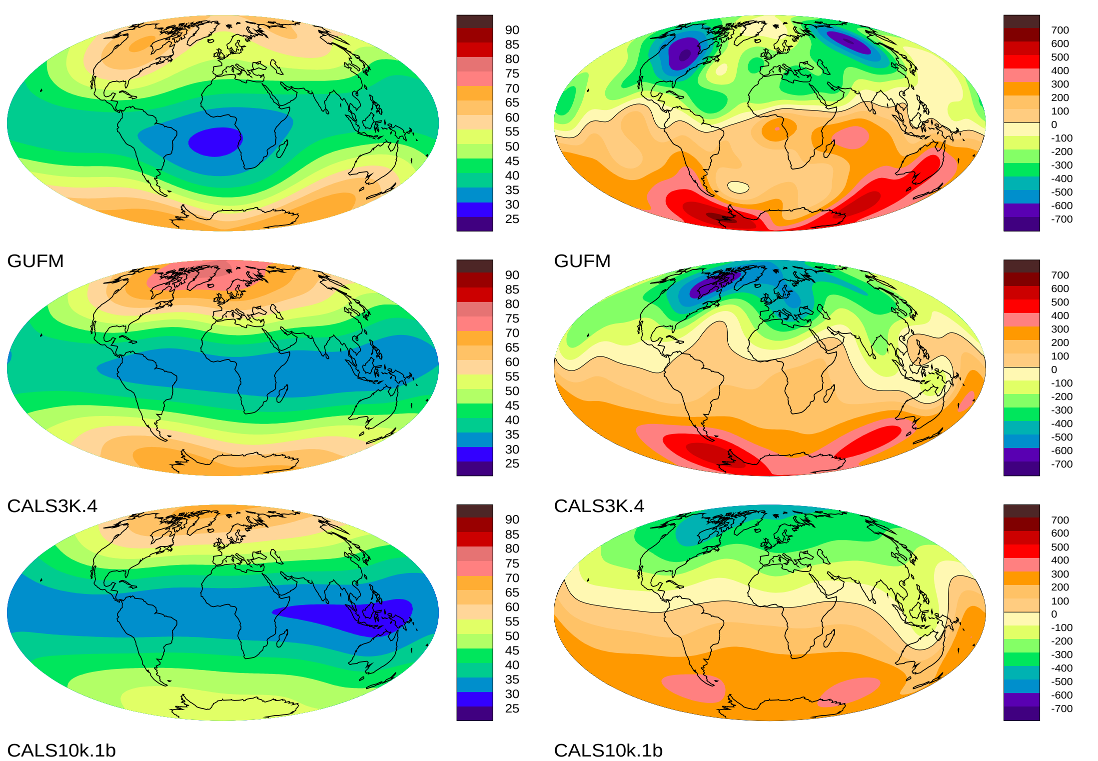

Figure 1: Strength of the magnetic field at Earth's surface (left) and radial field component downward continued to core-mantle boundary (right) for temporally averaged field models *gufm*, *CALS3k.4* and *CALS10k.1b*. Averaging times are 400, 3000 and 10 000 years respectively.

Figure 1 shows global reconstructions of surface geomagnetic field strength at Earth's surface and the radial magnetic field at the core-mantle boundary averaged over 400, 3000 and 10 000 years. Temporal averaging reduces, but does not eliminate, the structure. Work with Chris Davies has drawn on suitable numerical dynamo simulations to investigate three important questions about stability of the geodynamo process: is the present field representative of the past field; does a time-averaged field actually exist; and, supposing it exists, how long is needed to define such a field. The time needed to obtain a converged estimate of the time-averaged field was found to be comparable to the length of the simulation, even in non-reversing models, suggesting that periods of stable polarity spanning many magnetic diffusion times are needed to obtain robust estimates of the mean dipole field. Long term field variations are almost entirely attributable to the axial dipole, while non-zonal components converge to long-term average values on relatively short timescales (15 - 20 kyr). This suggests that average spatial characteristics of the field (but not average axial dipole strength, see Figure 2) should be recovered by the 100 ka model currently under construction.

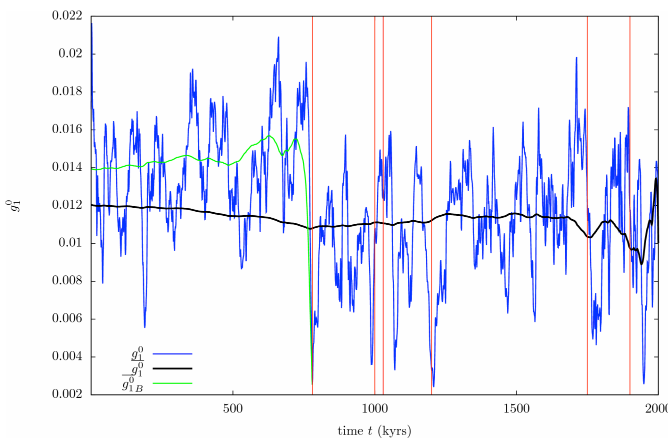

Figure 2: Time-series of the geomagnetic axial dipole coefficient g_1^0 (blue line) and the running average $\bar{g}_1^0$ (black line), for the time interval 0-2 Ma, (using model PADM2M of Ziegler et al., 2011). The green line shows $\bar{g}_1^0$ for the past 780 kyr with a running average started following the most recent field reversal. Reversals indicated by vertical red lines.

Relevant Publications

Ziegler, L.B., & C.G. Constable, Asymmetry in growth and decay of the geomagnetic dipole over the past 2 million years, *Earth Planet. Science 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, *Geophysical Journal International*, 184, 1069–1089, doi: 10.1111/j.1365-246X.2010.04905.x, 2011.

Buffett, B.A., L. Ziegler, & C.G. Constable, A stochastic model for palaeomagnetic field variations, *Geophysical Journal International*, 195, 86–97, doi: 10.1093/gji/ggt218, 2013.

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

Steven Constable directs the SIO Marine Electromagnetic Laboratory at IGPP, and along with Kerry Key oversees the Seafloor Electromagnetic Methods Consortium, an industry funding umbrella which helps support PhD students, postdocs, and research associates working in the group. The two main field techniques we use are controlled-source EM (CSEM), in which a deep-towed EM transmitter broadcasts energy to seafloor EM recorders, and magnetotelluric (MT) sounding, in which these same receivers record natural variations in Earth's magnetic field. This year we report on two marine MT projects.

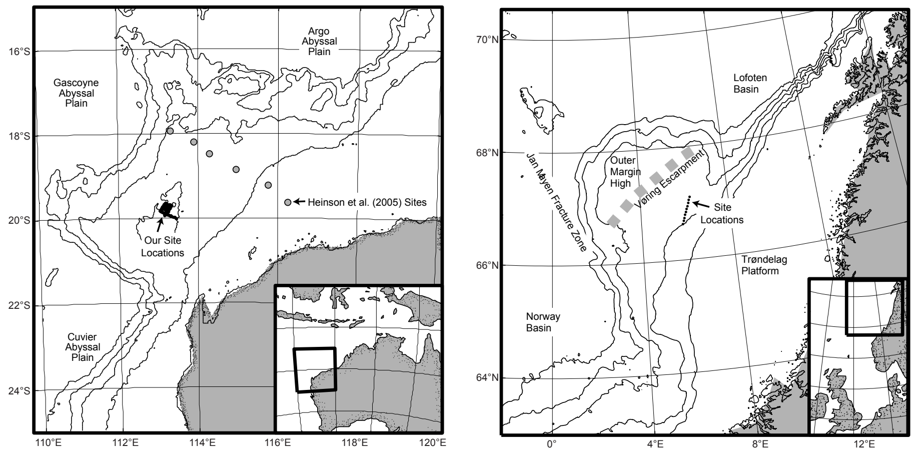

Figure 1. Maps showing the location of MT data collected over the Scarborough prospect on the Australian Northwest Shelf (left) and over the Vøring Plateau offshore Norway (right).

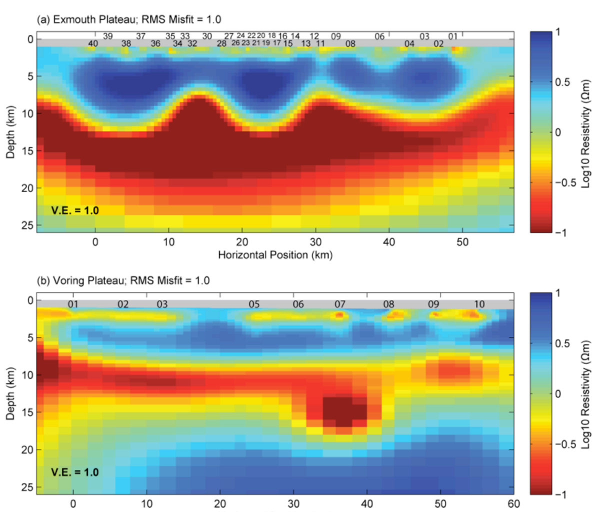

Figure 2. Inversions of MT data collected on the Northwest Shelf of Australia (top) and the Vøring Plateau offshore Norway (bottom). In both inversions a highly conductive (red) feature is seen in the mid-crust. We infer these to be related, and caused by cumulate layers of iron oxides in volcanic sills.

Often, serendipity plays an important role in scientific progress. For the SERPENT project, in our NSF proposal we promised to study water in lithosphere subducting beneath Nicaragua, but instead we discovered partial melting at the base of the lithosphere, the largest plate tectonic boundary on Earth (Naif *et al.*, 2013). Fortunately for our NSF reputation, we also imaged the water in the subducting slab (see Kerry Key's annual report entry).

In 2009, we were funded by an exploration company to collect marine both CSEM and MT data over the Scarborough gas field offshore NW Australia (Figure 1). The MT data were collected to help constrain the interpretation of the CSEM data, but we observed an unusually large conductor at a depth of about 10 km in the mid-crust, a feature that had been observed some years ago north of our array by a colleague. While we were pondering its significance, another company funded us to test

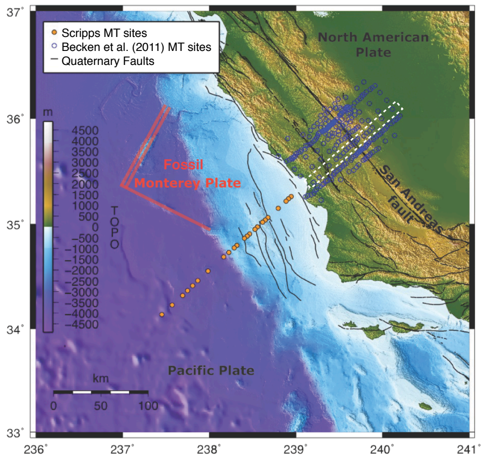

Figure 3. Map showing locations of offshore and land MT stations collected off Morro Bay, California.

the feasibility of collecting MT data during seismic operations offshore Norway, purely as a logistics exercise. When we processed the data we saw an almost identical conductor (Figure 2). These areas are both plateaus on passive rifted margins, and this connection led us to conclude that these unusual conductors were related to each other and to the geological processes associated with rifting. Our best guess at what causes these conductors is layers of cumulate magnetite (iron oxide) crystals inside sills. Layered intrusions require access to magma supplies for longer than conventional models for passive rifting would imply, so our results provide information on the timing of the rifting process (Myer *et al.*, 2013).

One of the great opportunities that Scripps offers graduate students is the chance to use institutional ship time for thesis projects. With a grant from UC Shipfunds, Brent Wheelock was able to extend a land MT survey carried out over the San Andreas fault by German colleagues into the adjoining ocean. The objective was to see if a conductor near the coast was being created by fluids migrating from the fossil subduction zone offshore. Inversion of the data does not show any evidence of an offshore conductor (Figure 4). However, in his thesis work, Brent showed how the effect of the coastlines can distort the MT response. When this was corrected for, the conductor moved inland and under the San Andreas Fault, suggesting that the fluids causing the conductor are associated with the San Andreas Fault zone.

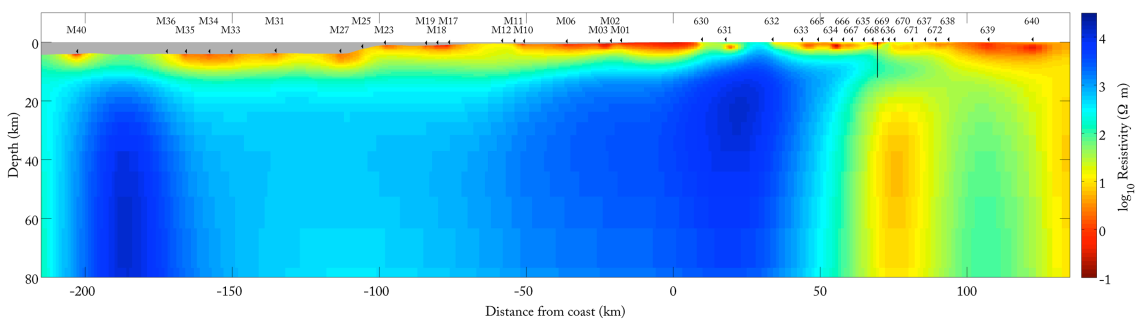

Figure 4. Inversion of onshore/offshore MT data collected over the San Andreas Fault (vertical black line) near Morro Bay, California.

Recent Publications

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Constable, S., Review paper: Instrumentation for marine magnetotelluric and controlled source electromagnetic sounding, *Geophysical Prospecting*, 61, 505–532, doi: 10.1111/j.1365-2478.2012.01117.x, 2013.

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

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

My research responsibilities at IGPP center upon managing the scientific performance of Project IDA's portion of the Global Seismographic Network (GSN), a collection of 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 funding provided by NSF via the IRIS Consortium. A map of the network showing upgraded systems denoted by orange triangles is shown in Figure 1. The upgrade effort is nearing its end – all legacy systems will have been replaced by the close of 2013.

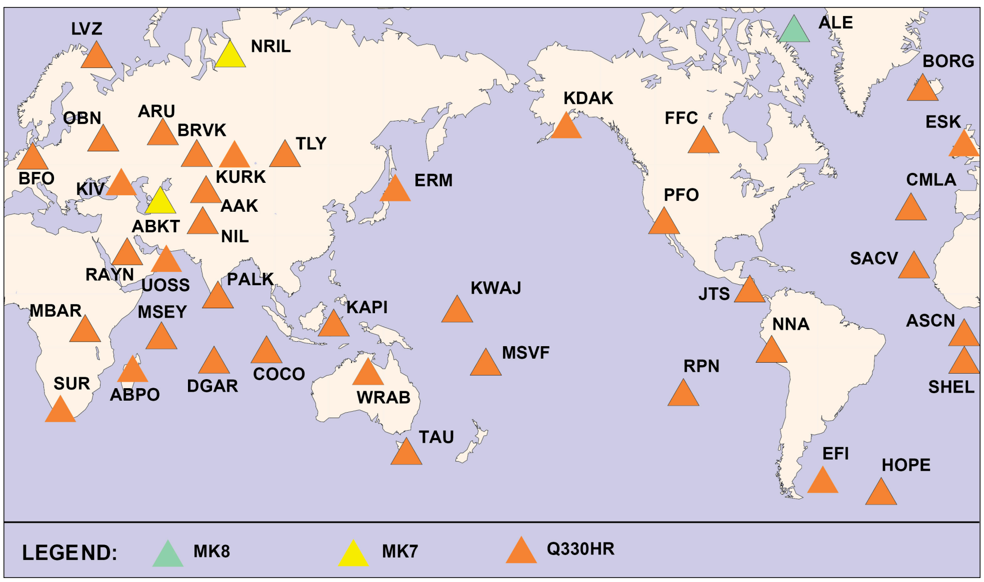

Figure 1. Current global seismic stations operated by Project IDA.

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

In coordination with our counterparts at the US Geological Survey, we are also engaged in a program to verify instrument responses using portable instruments. Figure 2 shows three-component seismograms recorded by two instruments at the IDA station NNA in Peru. The extent to which the recordings from these independent instruments match gives us confidence that our methods for verifying the accuracy of our published instrument responses are effective.

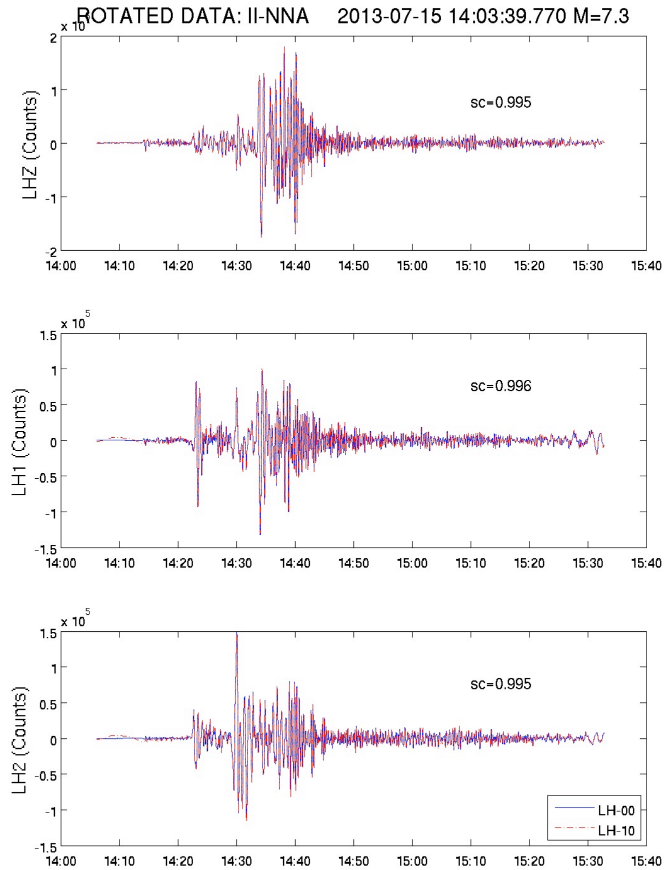

Figure 2. Seismograms from a large earthquake recorded on two instruments in Peru. The data from the three orthogonal components (vertical, north and east) nearly match, indicating the instrument responses are known precisely. The response's accuracy is verified with similar tests using Earth tides and normal modes of oscillation.

Relevant Publications

Davis, P., and J. Berger, Initial impact of the Global Seismographic Network quality initiative on metadata accuracy, *Seis. Res. Lett.,* **83(4)**, 697-703, 2012.

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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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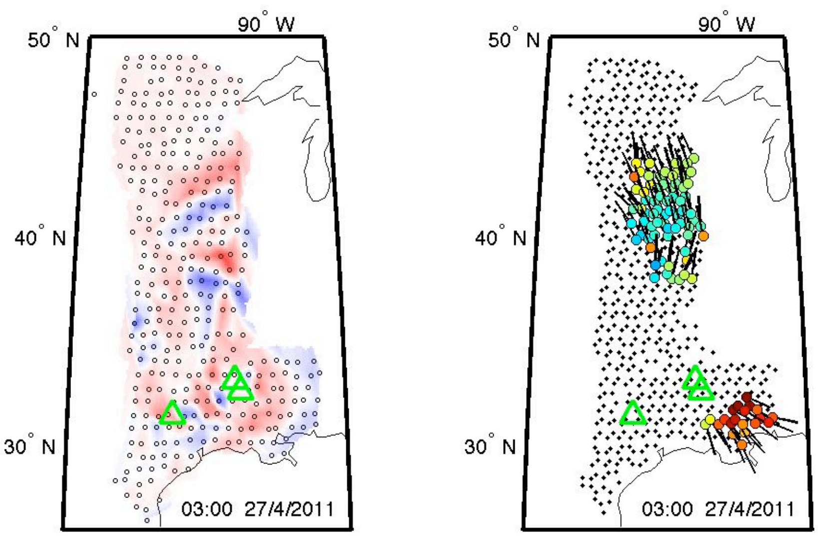
Research Interests: Infrasound and hydroacoustic propagation modeling; nuclear test-ban verification; analysis of infrasound and gravity waves at dense seismic networks.

Catherine de Groot-Hedlin's research makes use of seismic and infrasound data to study large-scale atmospheric phenomena. This involves the development of new analytic approaches to detect gravity wave signals at dense regional seismic and infrasound networks, and also involves the development of nonlinear numerical modeling techniques to understand the propagation of high amplitude pressure signals through the upper atmosphere.

In recent work done as part of the L2A (Laboratory for Atmospheric Acoustics) group, barometer data recorded at over 330 stations deployed with the USArray Transportable Array (TA) were analyzed to examine large amplitude (300 Pa peak-to-peak) gravity waves, or gust fronts, that originated near a severe tornadic storm system in the southern United States on April 27, 2011. The entire TA spans a region of approximately 2,000,000 square km. At this vast scale, even very large-scale arrivals are not coherent over the entire scale of the array, but do show coherence over the scale of at least the inter-station spacing. For this reason, the TA can be split up into a large number of small sub-arrays to track the propagation of long wavelength phenomena across large regions. We developed a new method in which the TA is divided over 500 3-station sub-arrays (triads), each of which is large enough to provide a robust estimate of the signal's direction and speed. The results from each triad were combined to follow the progress of gravity waves as they propagated across the TA over 2 days in late April, 2011. We observed a large, high-amplitude gravity wave, spanning a region over 200,000 km^2, progressing to the NNW away from the storm region.



Caption: (left) Interpolated pressure data from the USA Transportable array (TA), band-passed from T = 2 to 4 hours, for 03:00 UT, April 27, 2011. Circles mark station locations. The large green triangles denote tornado locations. (right) Gravity wave motion for the same time point. Dots indicate triads that did not register a gravity wave; circles mark triads where gravity waves were detected. The colors indicate the speed of the gravity waves and range from <10 m/s (deep blue) to 60 m/s (red). The black line attached to each circle indicates the direction of propagation.

Another research topic has involved the development of an accurate and efficient method to predict the nonlinear propagation of infrasound from large explosions in the atmosphere. This method is needed in order to predict infrasound propagation for diverse source types, including bolides, volcanic eruptions, and nuclear and chemical explosions. The solution also allows for the computation of other disturbances generated by explosions, including gravity waves (de Groot-Hedlin, 2012).

Relevant Publications

de Groot-Hedlin, C.D., Hedlin, M.A.H. 2013, Infrasound Detection of the Chelyabinsk Meteor at the USArray: A case study, Earth and Planetary Sciences Letters, in review.

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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, *Geop. J. Int.,* 176, 478-490 (2009)

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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 mechanics of mature strike-slip faults. In a recent study, Prof. Fialko and graduate student Eric Lindsey used high resolution Interferometric Synthetic Aperture Radar (InSAR) and GPS measurements of crustal motion across the Southern San Andreas Fault system to investigate the effects of elastic heterogeneity and fault geometry on inferred slip rates and locking depths. Geodetically measured strain rates are found to be asymmetric with respect to the mapped traces of both the Southern San Andreas and San Jacinto faults. Two possibilities have been proposed to explain this observation: large contrasts in crustal rigidity across the faults, or an alternate fault geometry such as a dipping San Andreas fault or a blind segment of the San Jacinto fault. Lindsey and Fialko evaluated these possibilities using a 2D elastic half space model accounting for heterogeneous elastic structure computed from the SCEC crustal velocity model CVM-H 6.3 and several fault geometries at depth suggested by seismic observations. The geodetic data were inverted using a Monte-Carlo sampling algorithm, which allowed to quantify uncertainties in the model parameters. The results demonstrate that variations in elastic properties of the crust constrained by seismic tomography have only a minor effect on the inferred slip rates in this area, and cannot explain the observed strain rate asymmetry. However, small changes in the position of faults at depth are shown to produce a significant asymmetry in the strain rate pattern. This effect may explain the large variability in slip rates reported by previous studies. The preferred model includes a Southern San Andreas fault dipping to the Northeast at 60 degrees, and two active branches of the Southern San Jacinto fault zone, the Coyote Creek fault and the Clark fault with a blind southern continuation into the Borrego badlands. The best-fitting models suggest a nearly equal partitioning of slip between the San Andreas and San Jacinto fault zones, with slip rates of 18±2 mm/yr for each. These slip rates are in good agreement with geologic measurements representing average slip rates over the last $10^4 - 10^6$ years.

In a related study, Prof. Fialko and a postdoctoral associate Yoshi Kaneko investigated interseismic deformation along the central section of the North Anatolian fault (NAF), a mature strike-slip fault in Turkey that shares a number of similarities with the San Andreas fault in California. Figure 1 shows a map of satellite line-of-sight (LOS) velocity derived from five ascending tracks of the ALOS satellite covering the NAF between 31.2°E and 34.3°E. The LOS velocity reveals discontinuities of up to ~5 mm/year across the Ismetpasa segment of the NAF, implying surface creep at a rate of ~9 mm/year; this is a large fraction of the inferred slip rate of the NAF (21-25 mm/year). The lateral extent of significant surface creep is about 75 km. The inferred surface velocity and shallow fault creep was further investigated using numerical simulations of spontaneous earthquake sequences that incorporate laboratory-derived rate and state friction. Results indicate that frictional behavior in the Ismetpasa segment is velocity strengthening at shallow depths, and transitions to velocity weakening at a depth of 4-6 km. The inferred depth extent of shallow fault creep is 5.5-7 km, suggesting that the deeper locked portion of the partially creeping segment is characterized by a higher stressing rate, smaller events, and shorter recurrence interval. The surface velocity in a locked segment of the NAF is well described by fault models with velocity-weakening conditions at shallow depth. These results imply that frictional behavior in a shallow portion of major active faults with little or no shallow creep is mostly velocity weakening.

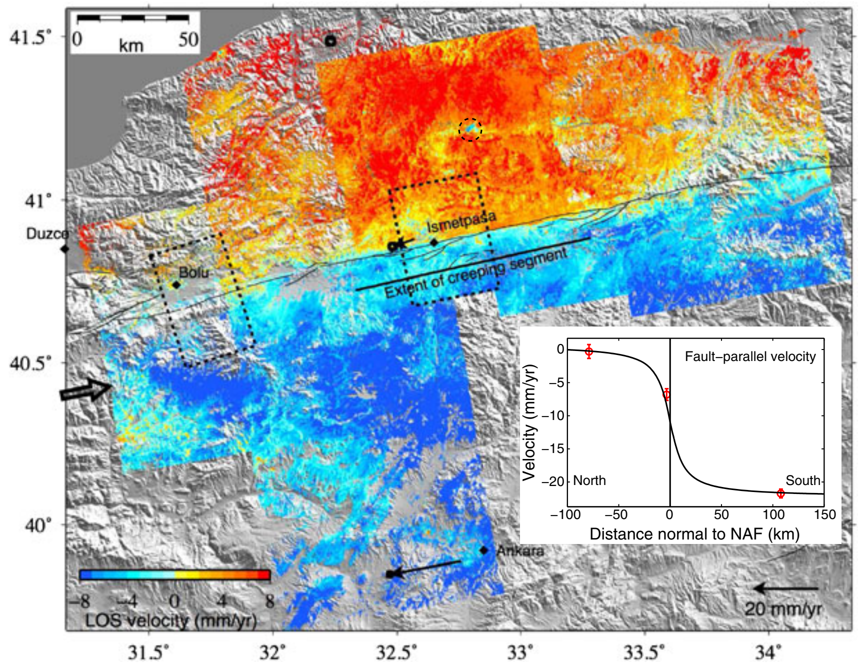

Figure 1: Line-of-sight (LOS) velocity of the Earth surface across the North Anatolian Fault in Turkey from a stack of ALOS radar interferograms spanning a time interval between 2007 and 2011. An arrow shows the radar look direction, and LOS velocities away from the satellite are assumed to be positive. A thick solid line shows the extent of significant surface creep. The inset shows the GPS data points and a model used for constraining the long-wavelength LOS velocity from the InSAR data.

Recent publications

Lindsey, E. and Y. Fialko (2013). Geodetic slip rates in the Southern San Andreas Fault System: Effects of elastic heterogeneity and fault geometry, *J. Geophys. Res.*, **118**, 689-697, `10.1029/2012JB009358`

Mitchell, E., Y. Fialko, and K. Brown (2013). Temperature dependence of frictional healing of Westerly granite: experimental observations and numerical simulations, *G-cubed*, **14**, 567-582, `10.1029/2012GC004241`

Kaneko, Y., Y. Fialko, D. Sandwell, X. Tong and M. Furuya (2013). Interseismic deformation and creep along the central section of the North Anatolian fault (Turkey): InSAR observations and implications for rate-and-state friction properties, J. Geophys. Res., **118**, 689-697, `10.1029/2012JB009661`

Crowell, B., Y. Bock, D. Sandwell, and Y. Fialko (2013). Geodetic investigation into the deformation of the Salton Trough, J. Geophys. Res., **118**, 5030-5039, `10.1002/jgrb.50347`

Takeuchi, C. and Y. Fialko, On the effects of thermally weakened ductile shear zones on postseismic deformation, *J. Geophys. Res.*, in press.

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

My research focuses on the Earth's **cryosphere**, in particular the **Antarctic ice sheet.** I lead the **Scripps Glaciology Group**, which currently has two postdocs (Sasha Carter and Geir Moholdt) and two graduate students (Fernando Paolo and Matthew Siegfried). One of the primary research questions concerning Antarctic Ice Sheet is whether its mass is changing due to climate change. The mass loss processes are iceberg calving and basal melting (see Figure 1).

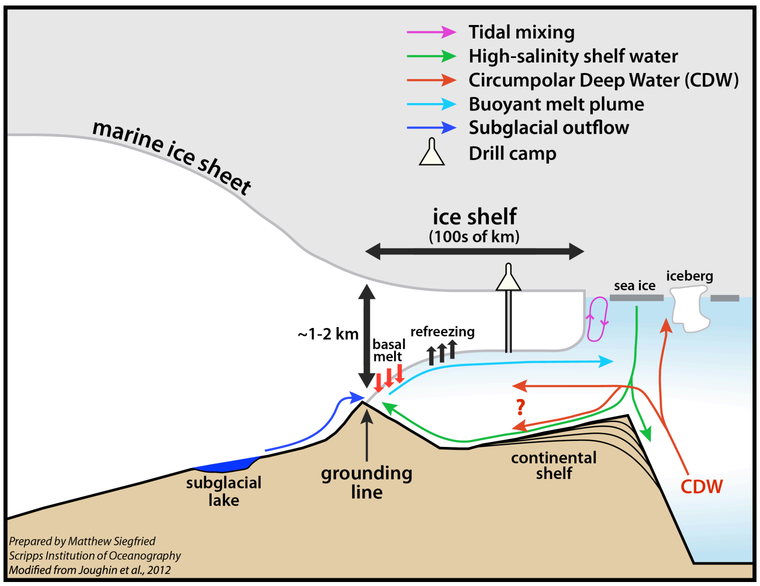

Figure 1: *Antarctic ice sheet mass loss processes*

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 surface change detection (*dh/dt*). 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, 2009 and 2012), led by IGPP Researcher Adrian Borsa. My group studies Antarctic ice sheet processes, as follows:

i) 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 speeds 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; Sasha Carter works with me on this aspect of the problem[4]. My team and our collaborators continue to monitor active lakes, and we have found 124 in total throughout Antarctica. To better understand the role of these types of lakes in the Antarctic system, I am a PI on the Whillans Ice Stream Subglacial Access Research Drilling (WISSARD) project, a large, interdisciplinary NSF project to drill into one of the subglacial lakes that I discovered – Subglacial Lake Whillans (SLW) on

Whillans Ice Stream. IGPP postdoc David Heeszel and IGPP student Matt Siegfried took part in the surface geophysics fieldwork in 2010-2011 and 2011-2012/2012-2013 respectively, and installed GPS on the lakes to monitor their activity. SLW was drilled in the 2012-2013 field season. Matt will revisit the region in 2013-2014.

ii) Ice shelf grounding zones: We use ICESat data to map the grounding zones (GZs) of the ice shelves - the transition zones between grounded and floating ice. 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. As part of the WISSARD project, we also acquired GPS data across the GZ in two different geometries, which is helping us understand how the local topography influences the ice shelf flexure and properties. IGPP student Matt Siegfried is currently working on this.

iii) Ice shelf stability and change: We analyze elevation changes on Antarctic ice shelves observed by satellite radar and laser altimetry[1,4,5]. In one recent study, we incorporated Seasat, ERS-1, ERS-2 and Envisat data (1978-2008) on the Antarctic Peninsula (AP) ice shelves[4] (see Figure 1). This was the first use of Seasat radar altimetry (RA) from 1978 to estimate ice shelf elevation trends prior to start of modern ESA RA era that began in 1992. IGPP student Fernando Paolo is improving on this initial work, and extending to all Antarctic ice shelves. IGPP postdoc Geir Moholdt is working on an innovative method to derive basal melt rates from ICESat data 2003-2008. We are also currently examining the causes in the differences in *dh/dt* signals between ICESat laser and Envisat radar altimetry for that time period.

iv) Glacio-seismology: I just completed 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. IGPP postdoc David Heeszel worked on this project until August 2013.

Publications 2012-2013

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6. MUELLER, R.D., L. PADMAN, M.S. DINNIMAN, **H.A. FRICKER** and M.A. KING (2012) Impact of tide-topography interactions on basal melting of Larsen C Ice Shelf, Antarctica, J. Geophys. Res.-Oceans, 117*,* C05005, doi:10.1029/2011JC007263.
7. WALTER, F., J. M. AMUNDSON, S. O'NEEL, M. TRUFFER, M. A. FAHNESTOCK and **H.A. FRICKER** (2012), Analysis of low-frequency seismic signals generated during a multiple-iceberg calving event at Jakobshavn Isbræ, Greenland, J. Geophys. Res., 117*, F01036,* doi:10.1029/2011JF002132*.*
8. **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.
9. 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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Research Interests: Development of new methods of atmospheric remote sensing using GPS signals, applied to targeted observations of tropical storms and improving numerical weather prediction in undersampled areas such as Antarctica. Precise GPS positioning applied to measurements of near field earthquake ground motions for earthquake early warning. Seismic wave propagation and amplification applied to seismic hazard analysis.

Most major Atlantic hurricanes form in cloud systems associated with African Easterly Waves, troughs of low pressure which move off the African continent and cross the Atlantic towards the Caribbean Sea and the southeastern United States. However, it is a challenge to forecast which of these tropical waves will develop, especially when they are passing over remote areas of the mid-Atlantic. New GPS technology was deployed on long-range research aircraft for the PRE-Depression Investigation of Cloud systems in the Tropics (PREDICT) experiment to attempt to understand the conditions that lead to the initial formation of tropical storms that may or may not develop into hurricanes at a later stage.

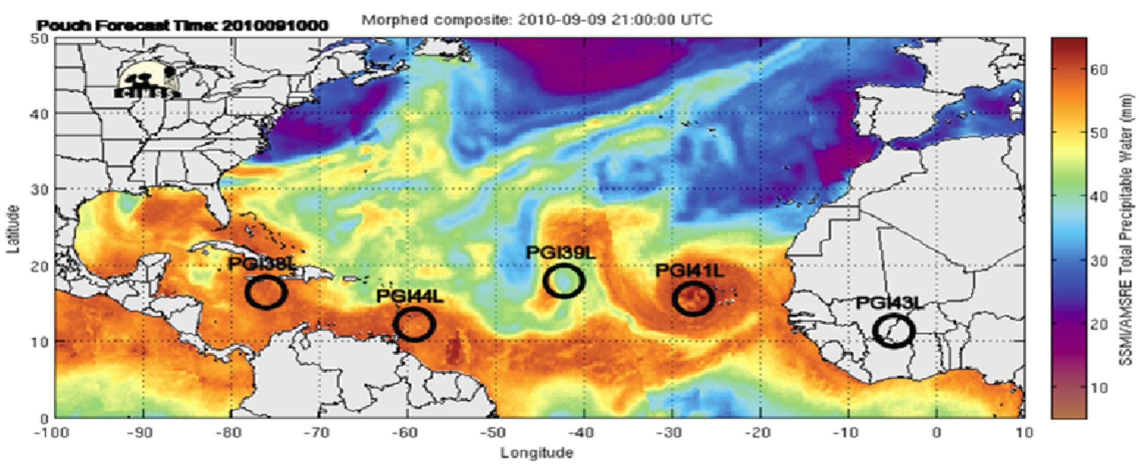

Figure 1. The orange areas indicate high moisture associated with African Easterly Waves as measured by satellites. However, the vertical structure that determines whether or not stored energy is released in tall convective clouds and rainbands is poorly known. Measuring the vertical structure is the objective of the GPS profiling technology (Image provided by the *Cooperative Institute for Meteorological Satellite Studies, and M. Montgomery, Naval Postgraduate School*)

The new GPS system was developed by Dr. Jennifer Haase at Scripps, and colleague Prof. James Garrison at Purdue University. Unlike meteorological satellite images, the signals from GPS satellites travel through heavy precipitation and clouds. By making precise measurements of the time delays in GPS signals received onboard a high altitude aircraft as the GPS satellite sets, it is possible to determine the properties of the atmosphere, information that is very useful in weather forecasting. The signals pass nearly horizontally through the atmosphere and are strongly affected by the pressure, temperature and moisture so it is possible to derive high-resolution vertical profiles of atmospheric properties within target areas within tropical storms during their development towards hurricane strength. Haase and her colleagues have shown that the new measurements are accurate and the group is now testing the ability to input the data into the weather forecast models. If the forecasts are shown to improve hurricane forecasts, then the system could eventually be deployed on hundreds of commercial and other aircraft to make real-time improvements in operational hurricane forecasting.

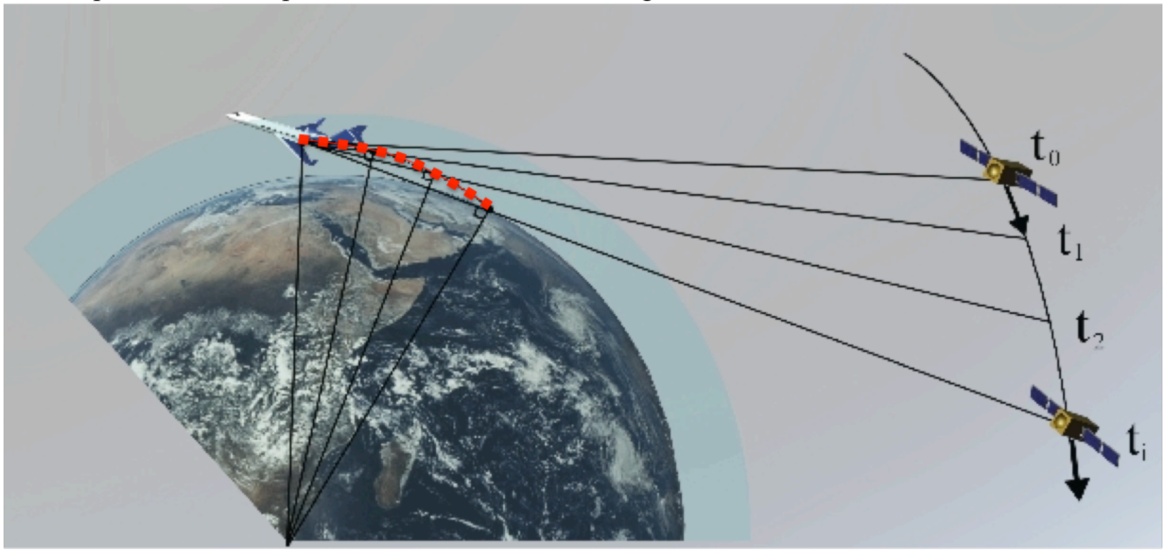

Figure 2 Airborne GPS measurement system. GPS signals are recorded on an aircraft as the GPS satellite sets or rises, with ray paths successively sampling deeper into the atmosphere. The measurements of the signal delay through the atmosphere are reduced to create a vertical profile of point measurements at the location of closest approach of the GPS signal path to the Earth's surface (red dots).

Recent Publications

Haase, J. S., B. J. Murphy, P. Muradyan, F. Nievinski, K. M. Larson, J. L. Garrison, and K.-N. Wang (2013), First Results from an Airborne GPS Radio Occultation System for Atmospheric Profiling, *Geophysical Research Letters*, *to be submitted*.

Wang, K.-N., P. Muradyan, J. L. Garrison, J. S. Haase, B. Murphy, U. Acikoz, and T. Lulich (2013), Open-loop tracking of rising and setting GNSS radio-occultation signals from an airborne platform: signal model and statistical analysis, paper presented at IEEE International Geoscience and Remote Sensing Symposium, Melbourne, Australia, 21-26 July 2013.

Symithe, S. J., E. Calais, J. S. Haase, A. M. Freed, and R. Douilly (2013), Coseismic slip distribution of the 2010 M7.0 Haiti earthquake and resulting stress changes on regional faults, *Bull. Seis. Soc. Am*, *103*(4), 2326-2343.

Melgar, D., B. W. Crowell, Y. Bock, and J. S. Haase (2013), Rapid modeling of the 2011 Mw 9.0 Tohoku-oki earthquake with seismogeodesy, *Geophysical Research Letters*, *40*(12), 2963-2968.

Geng, J., Y. Bock, D. Melgar, B. W. Crowell, and J. S. Haase (2013), A new seismogeodetic approach applied to GPS and accelerometer observations of the 2012 Brawley seismic swarm: Implications for earthquake early warning, *Geochemistry Geophysics Geosystems*, *14*(7), 2124-2142.

Douilly, R., J. S. Haase, W. L. Ellsworth, M.-P. Bouin, E. Calais, S. J. Symithe, J. G. Armbruster, B. F. de Lepinay, A. Deschamps, S.-L. Mildor, M. E. Meremonte, and S. E. Hough (2013), Crustal structure and fault geometry of the 2010 Haiti earthquake from temporary seismometer deployments *Bull. Seis. Soc. Am*, *103*(4), 2305-2325.

Bowling, T., E. Calais, and J. S. Haase (2013), Detection and modelling of the ionospheric perturbation caused by a Space Shuttle launch using a network of ground-based Global Positioning System stations, *Geophysical Journal International*, *192*(3), 1324-1331.

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

The southern California borderlands extends from the U.S.-Mexico border northwards to Los Angeles. Most of the borderlands are offshore, they are underlain by Catalina Schist and extend as far west as San Clemente and Santa Catalina islands. The Catalina Schist was exposed by extension and n during early Miocene as part of the process that transferred the majority of the Pacific-North America plate motion eastwards onto the San Andreas fault system and rifted Baja California away from mainland Mexico. The currently active offshore faults are usually mapped as a series of strike slip faults sub-parallel to the San Andreas fault, such as the Newport-Inglewood/Rose Canyon, Coronado Bank and San Diego Trough fault zones. However, there is disagreement as to whether the seismic hazard due to borderlands comes primarily from motion on these faults or from reactivation of detachment faults formed during the Miocene extension as a system of blind thrusts (*Rivero & Shaw*, 2011). These different views lead to different interpretations of structural features of the borderlands and to different patterns of expected deformation that can be investigated using seismic reflection methods. Existing reflection data for the borderlands are mostly conventional multichannel seismic data collected in 1970-1990's for the oil industry and the USGS, only some of which is available for interpretation. This summer, we collected a grid of high-resolution, sparker profiles using a 48 channel streamer with 6.25 m group spacing and a maximum offset of 320 m, as well as a more limited number of higher frequency

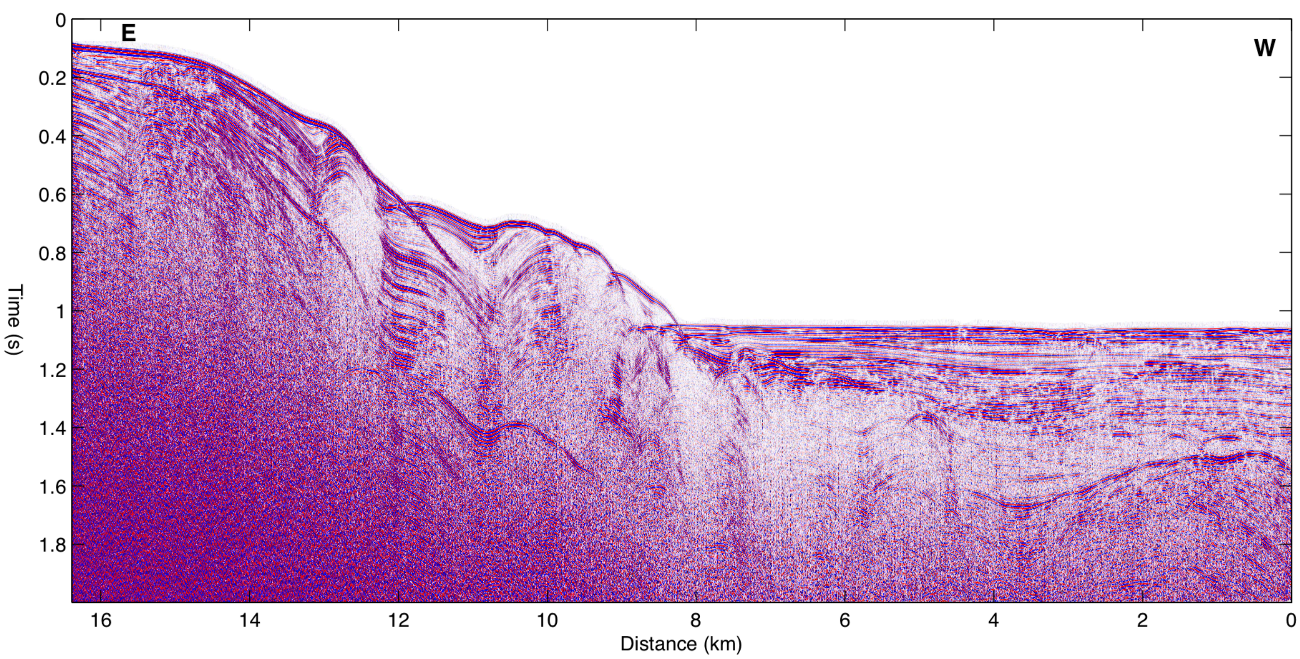

Figure 1: *Portion of a sparker dip line profile offshore of San Onofre, starting from ~5km offshore at its eastern end. Data is plotted with a fixed time-varying gain function starting at the seafloor reflection. In this presentation faster, older sediments tend to be more acoustically transparent. Recent deposition has taken place preferentially in the offshore basin and the sedimentary layers are for the most part flat-lying and undisturbed. At this latitude, the strike-slip Newport Inglewood fault zone is located on the shallow near-shore shelf.*

boomer profiles. The dominant frequency of the data is ~60 Hz, giving a vertical resolution of ~5-10 m, and allowing better resolution of current deformation. The sparker profiles provide coverage down to ~1 s or ~1 km below seafloor, and extend from the shallow, near-shore shelf out to approximately 30 km offshore and seafloor depths of ~800 m, Figure 1. Recent deposition on the near-shore shelf and slope is limited, but sediments in deeper water are, for the most part, flat-lying and undisturbed inconsistent with an active regional blind thrust system. Preliminary analysis of the data thus tends to support the idea that strike slip faults and the step overs between them are the dominant control on deformation, as inferred from recent interpretations of reprocessed older data (*Maloney*, *Ph. D. Thesis*, 2013).

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Research interests: Study of large atmospheric phenomena, study of long-range propagation of subaudible sound through the atmosphere, seismo-acoustics, 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 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 Laboratory for Atmospheric Acoustics (L2A) is the home of research in this field at IGPP. Several faculty, post-docs and PhD students work full or part time in L2A, supported by engineers and technicians in the lab and the field. More information about this lab can be found at l2a.ucsd.edu. Presently we study a broad suite of problems related to both natural and man-made sources.

Seismic network study of atmospheric events and infrasound propagation: The global infrasound network is unprecedented in scale however it is still very sparse, with ˜ 100 stations operating worldwide. To increase the density of sampling of the infrasonic wavefield we have used acoustic-to-seismic coupled signals recorded by dense seismic networks, such as the 400-station USArray Transportable Array (TA) and various PASSCAL deployments. We have used the TA 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 study the statistics of atmospheric activity. Large atmospheric events generate acoustic branches that are akin to seismic branches. The branches, which can only be studied in detail using dense network data, provide constraints on the large-scale structure of the atmosphere at altitudes that are not well constrained by instruments deployed on the ground or in space. Instantaneous sources commonly give rise to signals that last 10's to 100's of seconds. Recent research indicates that the infrasound wavefield is dispersed in time due to interaction with small-scale structure largely due to gravity waves. Dense seismic network data are now offering us an unprecedented opportunity to test statistical models of gravity waves.

Seismo-acoustic network studies: Our group was recently funded to upgrade the TA with infrasound microphones and barometers. Our sensor package is sensitive to air pressure variations from D.C. to 20 Hz, at the lower end of the audible range. The entire USArray TA has been retrofitted with these new sensors to create the first-ever semi-continental-scale seismo-acoustic network. The network spans ˜ 2,000,000 square km in the eastern United States and will eventually be redeployed in Alaska. We are currently using the upgraded TA to study the generation and long-range propagation of gravity waves. We are using the broadband seismic and barometric recordings to study the interaction of the atmosphere and Earth's crust.

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. 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.

Recent publications

de Groot-Hedlin, C.D., Hedlin, M.A.H. and Walker, K., 2011, Finite difference synthesis of infrasound propagation through a windy, viscous atmopshere: application to a bolide explosion detected by seismic networks, *Geophysical Journal International*, doi: 10.1111/j.1365-246X.2010.04925.x.

Drob, D.P., Broutman, D., Hedlin, M.A.H., Winslow, N.W. and Gibson, R.G., 2012, A method for specifying atmospheric gravity-wave fields for long-range infrasound propagation calculations, *J. Geophys. Res.*, doi:10.1029/2012JD018077.

Hedlin, M.A.H., Walker, K., Drob, D. and de Groot-Hedlin, C.D., 2011, Infrasound: Connecting the Solid Earth, Oceans and Atmosphere, *Annual Review of Earth and Planetary Sciences*, 40, 327-354

Hedlin, M.A.H., de Groot-Hedlin, C.D. and Drob, D., 2012, A study of infrasound propagation using dense seismic network recordings of surface explosions, *Bulletin of the Seismological Society of America*, **102**, 1927-1937, doi: 10.1785/0120110300

Hedlin, M.A.H. and Walker, K., 2012, A study of infrasonic anisotropy and multipathing in the atmosphere using seismic networks, *Phil. Trans. Roy. Soc. A* 371:20110542; doi:10.1098/rsta.2011.0542.

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

Electromagnetic (EM) imaging of the oceanic crust and mantle: Despite nearly 50 years since the plate tectonics paradigm became widely accepted, we continue to make new discoveries about how this fundamental process works. Graduate student Samer Naif's analysis of data from the SERPENT project has led to the discovery of a melt rich channel beneath the oceanic lithosphere-asthenosphere boundary, which we infer to be a low viscosity layer that acts to decouple the overlying brittle lithosphere from the deeper convecting mantle (Naif et al, 2013). Figure 1 presents an image of mantle upwelling beneath the fast-spreading Northern East Pacific Rise that is consistent with passive rather than active upwelling. Our result requires the presence of mantle volatiles (water and carbon dioxide) to explain melting observed at depths much greater than the dry solidus (Key et al., 2013). My colleague Steven Constable's entry discusses our serendipitous discovery of layered mafic intrusions beneath the rifted margins offshore Northwest Australia and Norway (Myer et al., 2013). We are grateful for over a decade of sponsorship from the oil and gas exploration industry, which has enabled us to build a fleet of 60 seafloor EM receivers, two deep-towed EM transmitter systems and the numerical modeling codes that our recent tectonic studies have relied upon. Since there have only been a handful of marine EM array deployments across oceanic plate boundaries, future surveys hold promise for more discoveries.

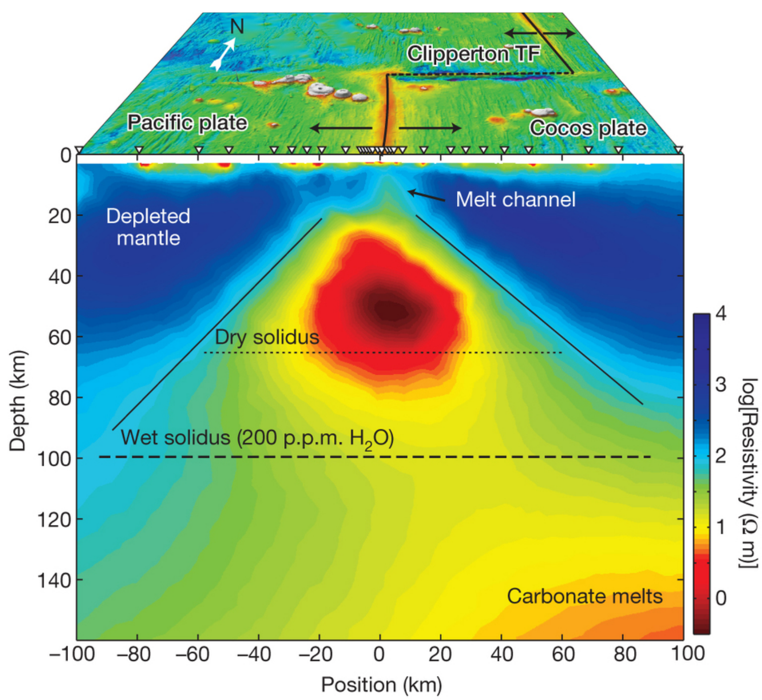

Figure 1. Image of mantle upwelling and melting beneath the East Pacific Rise mid-ocean spreading ridge. The top panel shows the seafloor topography. Colors in the underlying model denote log[resistivity (Ω m)] obtained from nonlinear inversion of data from the sea-floor magnetotelluric stations (inverted triangles). Green to red colors indicate high conductivity (low resistivity) due to partial melts generated in the upwelling mantle. Solidus (melting) depths for upwelling dry and wet peridotite are shown as horizontal lines. From Key et al. (2013).

Bayesian Inversion of Marine EM Data: Graduate student Anandaroop Ray continued his quest to apply Bayesian inversion methods to quantify the non-uniqueness and resolution of EM geophysical data (Figure 2). This year he extended the reversible jump Markov chain Monte

Carlo method with a parallel tempering approach that is more robust to the effects of local probability maxima and thus is able to search the model space for likely structure more efficiently (Ray et al, 2013). Ongoing work shows great promise for extending this computationally demanding approach to practically relevant 2D and 3D model geometries.

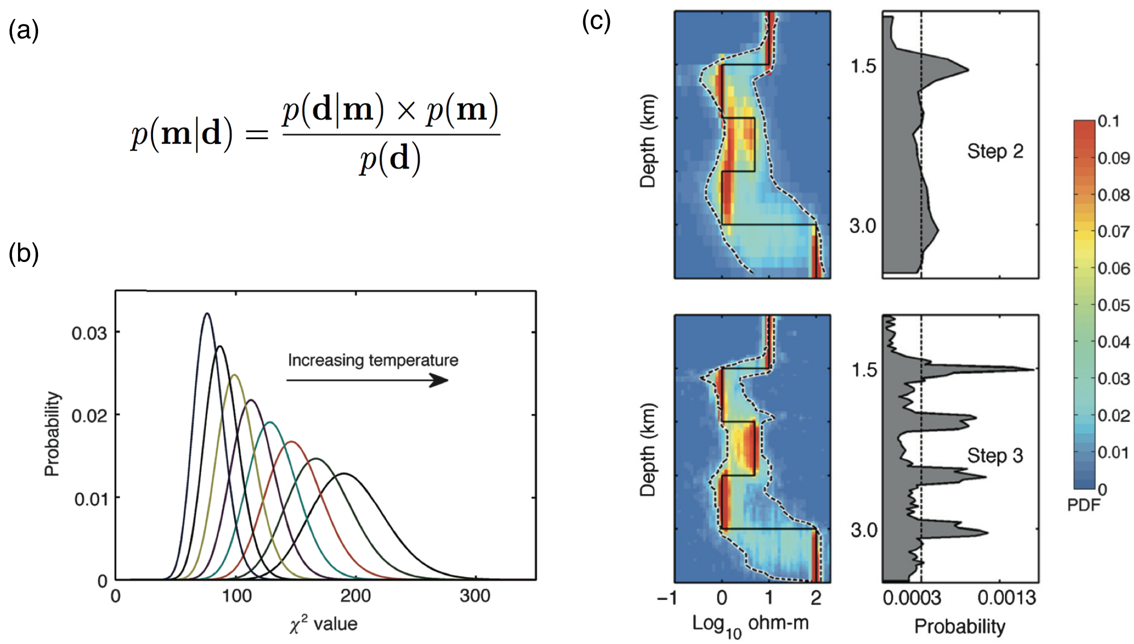

Figure 2. Robust Bayesian inversion of marine electromagnetic data using parallel tempering. (a) The inverse problem is formulated using Bayes' Theorem to estimate $p(\mathbf{m}|\mathbf{d})$, the probability of the model **m** given the data **d**. (b) Parallel, interacting Markov chains with "tempered" likelihoods sample the model likelihood $p(\mathbf{d}|\mathbf{m})$, enabling the system of chains to effectively escape local probability maxima. (c) Example synthetic application to a five-layer model (black line) shows a high likelihood of resolving the true model structure (top). Even better results are possible when available geologic evidence (e.g. from well logs or seismic stratigraphy) is used to extract the distribution of models containing layer boundaries near the true locations (bottom).

Recent Publications

Key, K., S. Constable, L. Liu, and A. Pommier, 2013, Electrical image of passive mantle upwelling beneath the northern East Pacific Rise, *Nature*, 495, 499-502.

Myer, D., S. Constable and K. Key, 2013, Magnetotelluric evidence for layered mafic intrusions beneath the Vøring and Exmouth rifted margins, *Physics of the Earth and Planetary Interiors*, 220, 1-10.

Naif, S., K. Key, S. Constable, and R. Evans, 2013, Melt-rich channel observed at the lithosphere-asthenosphere boundary, *Nature*, 495, 356-359.

Pommier, A., R.L. Evans, K. Key, J.A. Tyburczy, S. Mackwell and J. Elsenbeck, 2013, Prediction of silicate melts viscosity from electrical conductivity: A model and its geophysical implications, *Geochemistry Geophysics Geosystems*, 14, 1685–1692, doi:10.1002/ggge.20103.

Ray, A., D. Alumbaugh, G.M. Hoversten and K. Key, 2013, Robust and accelerated Bayesian inversion of marine controlled-source electromagnetic data using parallel tempering, *Geophysics*, 78(6), E271–E280. doi: 10.1190/geo2013-0128.1

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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.

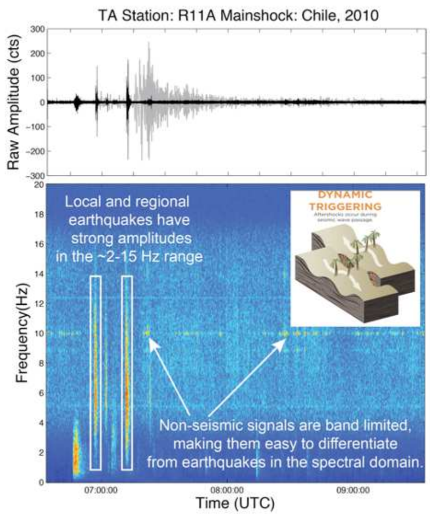

Figure 1. Data from the magnitude 8.8 Chile earthquake on 27 February 2010 recorded at TA station R11A. (top) On the unfiltered trace (light gray) showing the large amplitude mainshock coda, we juxtapose the filtered time series (black line; 5 Hz high pass). (bottom) Spectragrams enable rapid visual distinction between events of interests and noise signals. Cartoon inset depicts remote aftershocks (orange bursts) triggered by the passage of seismic waves from a remote large earthquake.

Dynamic triggering potential of large earthquakes using a frequency domain detection method. A growing body of studies documents that the dynamic stresses associated with the passage of transient seismic signals from earthquakes thousands of kilometers away can trigger local earthquakes (Inset, Figure 1). We use data from the EarthScope U.S. Transportable Array (TA) for distant earthquakes with $M > 8$ to understand some of the parameters driving this triggering. We initially located triggered earthquakes in the time domain by comparing a short-term to long-term average (STA/LTA) of the variance. Because of site sensitivities and noise this gave too many false detections. So we developed a frequency-domain detector that pre-whitens each seismogram and computes a frequency stack using three hours of data after the origin time of the mainshock. This method is successful because of the broadband nature of earthquake signals, differing from more band-limited non-seismic signals (Figure 1). Of the 15 mainshocks we studied, 12 show evidence of clusters of local earthquakes during the mainshock coda. We see the most activity in the Western US, including Northwest Wyoming, West Texas, Southern New Mexico and Western Montana. TA stations available for two or more mainshocks are few, and exclusively in California and Nevada. Our results suggest that remote triggering in the US is likely a complicated interplay between parameters (e.g., amplitude threshold, wave orientation, tectonic environment, etc.) and cannot be explained by a single dominant driver.

Selecting Empirical Green's Functions in Regions of Fault Complexity: A Study of Data From the San Jacinto Fault Zone, Southern California (Kane et al., 2013) To constrain the source properties of an earthquake, path- and site-effect contributions to the seismic waveform can be approximated using another earthquake as an empirical Green's function (EGF). An ideal EGF earthquake is smaller than the mainshock and shares a similar focal mechanism and hypocenter. We quantify how to optimally select EGF events using data from the spatially complex San Jacinto Fault Zone (SJFZ) in southern California. The SJFZ's high seismicity rate allows us to use a range of EGF's > 200 for each mainshock to test the EGF method for 51 target M>3 events. We include a large population of inappropriate EGFs so we can identify thresholds and restrictions to define optimal EGF selection criteria. For each mainshock/EGF pair we compute the spectral ratio, fit the mainshock corner frequency, and measure the variability of these corner frequencies across the network. We assume a suitable EGF event will produce similar corner frequency estimates at every station. Surprisingly, we find separation distances of 2-14 km produce negligible changes in corner frequency variability, suggesting that EGF events at 2 km distance may be as poor a choice as EGF events at much greater distances. When no EGF events within 1 km are available, we conclude that limiting selection to EGF events with highly similar waveforms to the mainshock waveforms is critical to ensuring source similarity.

A Comparison of Spectral Parameter Kappa from Small and Moderate Earthquakes Using Southern California ANZA Seismic Network Data (Kilb et al., 2012a): Kappa is a one-parameter estimator of a seismogram's spectral amplitude decay with frequency. Low values ($\approx$ 5ms) indicate limited attenuation of high frequency energy whereas values of $\approx$ 40ms substantial attentuation. Kappa is often assumed to be a site term and used in seismic designs. We address two key questions about kappa: (1) How to identify source, path, and site contributions to it; and (2) can kappa estimates from smaller earthquakes, with weak-motion recordings, be extrapolated to estimate kappa for larger earthquakes? We estimated kappa for seismograms from 1,137 small earthquakes ($M < 1$) recorded by the ANZA seismic network in southern California, and compared these to results from 43 earthquakes with $M \geq 3.5$ inside the network. We found that kappa from small earthquakes predicts the relative values of kappa at different stations for larger earthquakes, though at some sites kappa values from small earthquakes over-predict those from moderate and large earthquakes. Although site effects are most important to kappa estimates, the scatter of kappa estimates at a given site is likely caused by near-source effects, perhaps scattering.

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

Recent publications

Kane, D.L., **D. Kilb,** F.L. Vernon (2013) Selecting Empirical Green's Functions in Regions of Fault Complexity: A Study of Data from the San Jacinto Fault Zone, Southern California *Bull. Seism. Soc. Am.*, **103** 10.1785/0120120189 2013.

Kilb, D., G. Biasi, J. Anderson, J. Brune, Z. Peng, and F. L. Vernon (2012) A Comparison of Spectral Parameter Kappa from Small and Moderate Earthquakes Using Southern California ANZA Seismic Network Data, *Bull. Seism. Soc. Am.*, 284-300 10.1785/0120100309

Kilb, D., Z. Peng, D. Simpson, A. Michael, M. Fisher and D. Rohrlick (2012) Listen, Watch, Learn: SeisSound Video products, *Seis. Res. Lett*, 281-286, 10.1785/gssrl.83.2.281

Peng, Z., C. Aiken, **D. Kilb,** D. R. Shelly, and B. Enescu (2012) Listening to the 2011 magnitude 9.0 Tohoku-Oki, Japan earthquake, *Seis. Res. Lett.* 287-293 10.1785/gssrl.83.2.287

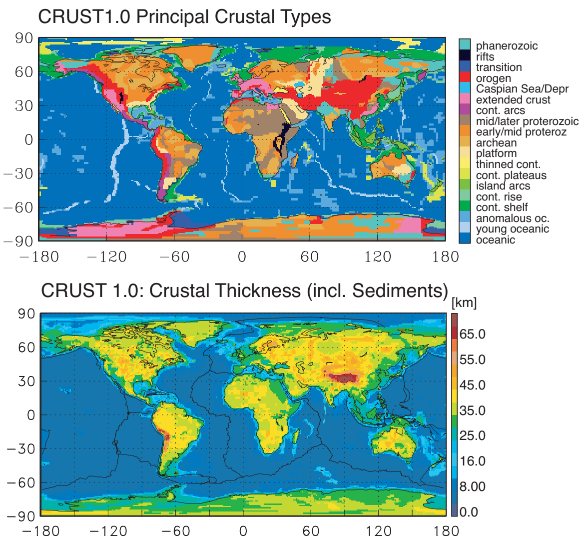

Figure 1: The prototype crustal model CRUST1.0. Top: updated crustal types; Bottom: thickness of the crystalline crust including sediment cover. The input crustal thickness was compiled using existing active source data as we as receiver functions and some gravity data.

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

Gabi Laske's main research area is the analysis of seismic surface waves and free oscillations, and the assembly of global and regional seismic models.

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.

Global reference models: With CRUST5.1 and CRUST2.0, Laske and collaborators Masters and Mooney produced the most widely used models of global crustal structure. Applications relying on CRUST2.0 are found across multiple disciplines in academia and industry, and sometimes reach into quite unexpected fields such as the search for Geoneutrinos. Laske collaborates with Masters, graduate student Zhitu Ma and Michael Pasyanos at LLNL to compile a new lithosphere model, LITHO1.0. A prototype 1-degree crustal model, CRUST1.0 has been released this summer for initial testing (Figure 1).

The PLUME project: Laske has been 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, U. Hawaii, DTM and Yale Univ.. During two 1-year deployments in 2005 through 2007, the team collected a continuous broadband seismic dataset from the world's largest network of ocean bottom seismometers (OBS).

Results from body wave tomography strongly suggest that Hawaii's volcanism is indeed fed by a deep-reaching mantle plume rather than from passive magmatism originating in the Pacific plate. The surface wave study imaged a relatively narrow low-velocity feature

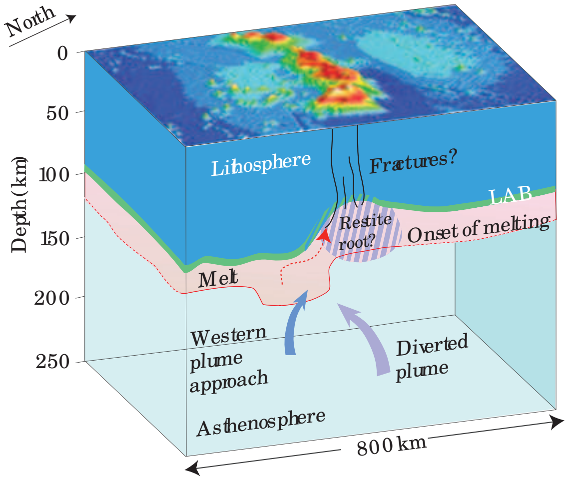

Figure 2: Interpretative schematic of plume-plate interaction. A thermal plume impinges on the LAB (green line) 100 km west of Hawaii, depressing the onset of melting (red). The plume either naturally approaches from the west or approaches from the east but is diverted to the west by a restite root. Melt travels toward Hawaii (red dashed arrow), directed by a gently sloping permeability barrier at the LAB and/or pre-existing lithospheric fractures.

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 (Figure 2). Laske has collaborated with Kate Rychert who identified two anti-correlated upper-mantle boundaries that align with the anomalies for in the surface wave study. The upper boundary is likely the lithosphere-asthenosphere boundary while the lower one indicates the initiation of melting within the asthenosphere. Our images suggest a restite root beneath the Island of Hawaii around which ascending plume material has to flow, providing a possible cause for the low-velocity anomaly to the west of Hawaii.

Laske and students currently analyze frequency-dependent azimuthal anisotropy to ultimately obtain 3-D images of mantle flow beneath Hawaii. Most recently Laske has collaborated with Christine Thomas to search for new and unmapped D" precursors in the PLUME database.

Laske recently participated in a collaboration to locate and investigate the nature of the 15 February 2013 Chelyabinsk, Russia meteor event that manifest itself in strong Rayleigh wave signals. We have been able to constrain the altitude of the major flare as well as the yield of the explosion.

Recent publications:

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.*, 187, 1725-1742, 2011.

Rychert, C.A., Laske, G., Harmon, N. and Shearer, P.M., Seismic imaging of melt in a displaced Hawaiian plume, *Nature Geoscience*, 6, 657-660, 2013.

Thomas, C. and Laske, G., Observation of D" reflections in the Pacific using PLUME OBS data, *Geophysical Research Abstracts*, 15, EGU2013-3941, 2013.

Brown, P.G. and 32 co-authors, The Chelyabinsk airburst: Implications for the Impact Hazard, *Nature*, in press, 2013.

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Research interests: Global seismology, mineral physics

During the past year, we have developed a new efficient data analysis technique to measure surface wave phase velocity. This process resulted in nearly 600,000globally distributed measurements for low frequency Rayleigh waves and 200,000 for Love waves. Measurements at high frequency are harder to make, but we still have 280,000 measurements for Rayleigh waves at 35mHz and 100,000 for Love waves at 30mHz.

This large dataset of phase delay measurements is combined with our previous group velocity dataset to produce high quality 2D surface wave tomography maps for the globe. A b-spline model is used to give internally consistent model of both phase and group velocities. A subset of the resulting maps for Rayleigh waves is shown in Figure 1.

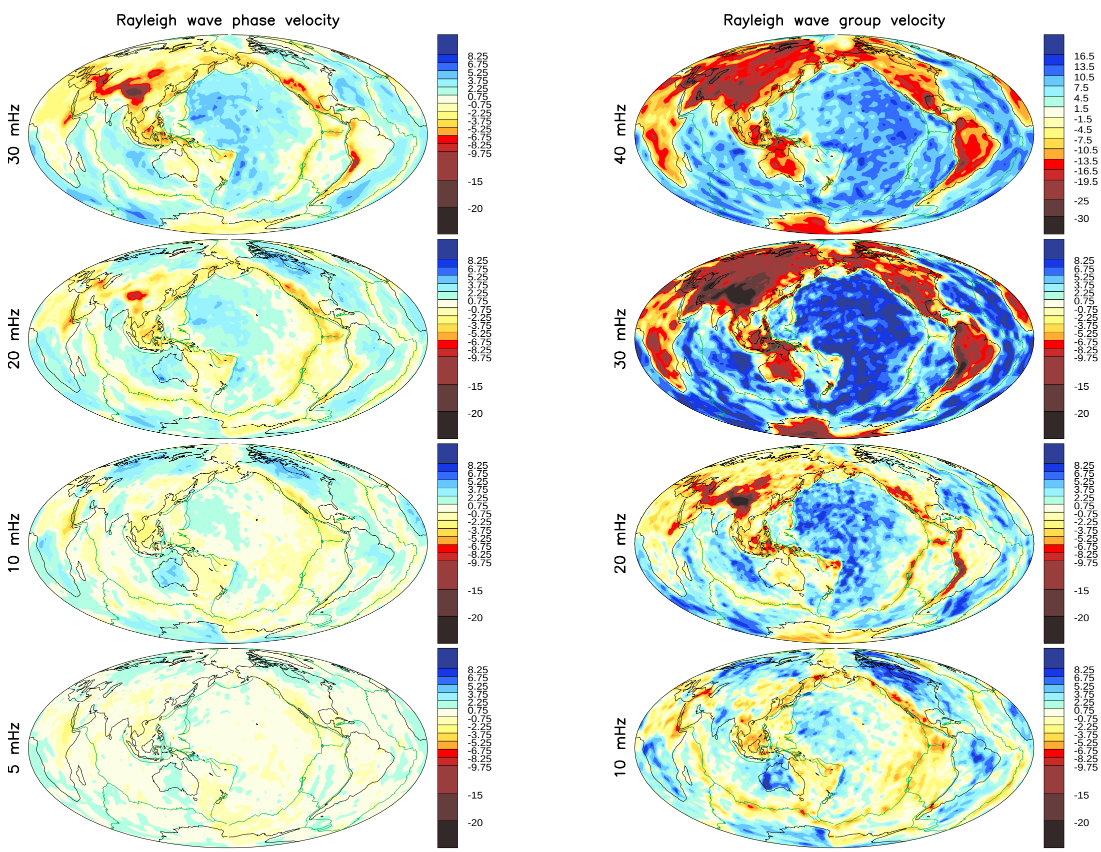

Figure 1 Rayleigh wave phase and group velocity from the spline model.

An age-progression trend of both phase and group velocities in the ocean basins can be clearly seen in the maps and a detailed analysis shows significant departures from the simple half-space cooling model. Adding such seismic constraints to seafloor topography and heat flow measurements will give us a more complete understanding of oceanic lithospheric evolution.

We also find that including azimuthal anisotropy is essential to obtain reliable isotropic perturbation maps. Because the amplitude of azimuthal anisotropy is rather small, uncertainties in earthquake locations cannot be ignored and must be incorporated in the inversions. Figure 2 shows some preliminary results for Rayleigh waves. The strongest signals from azimuthal anisotropy come from the oceans, especially in the Eastern Pacific where fast directions follow the plate motions.

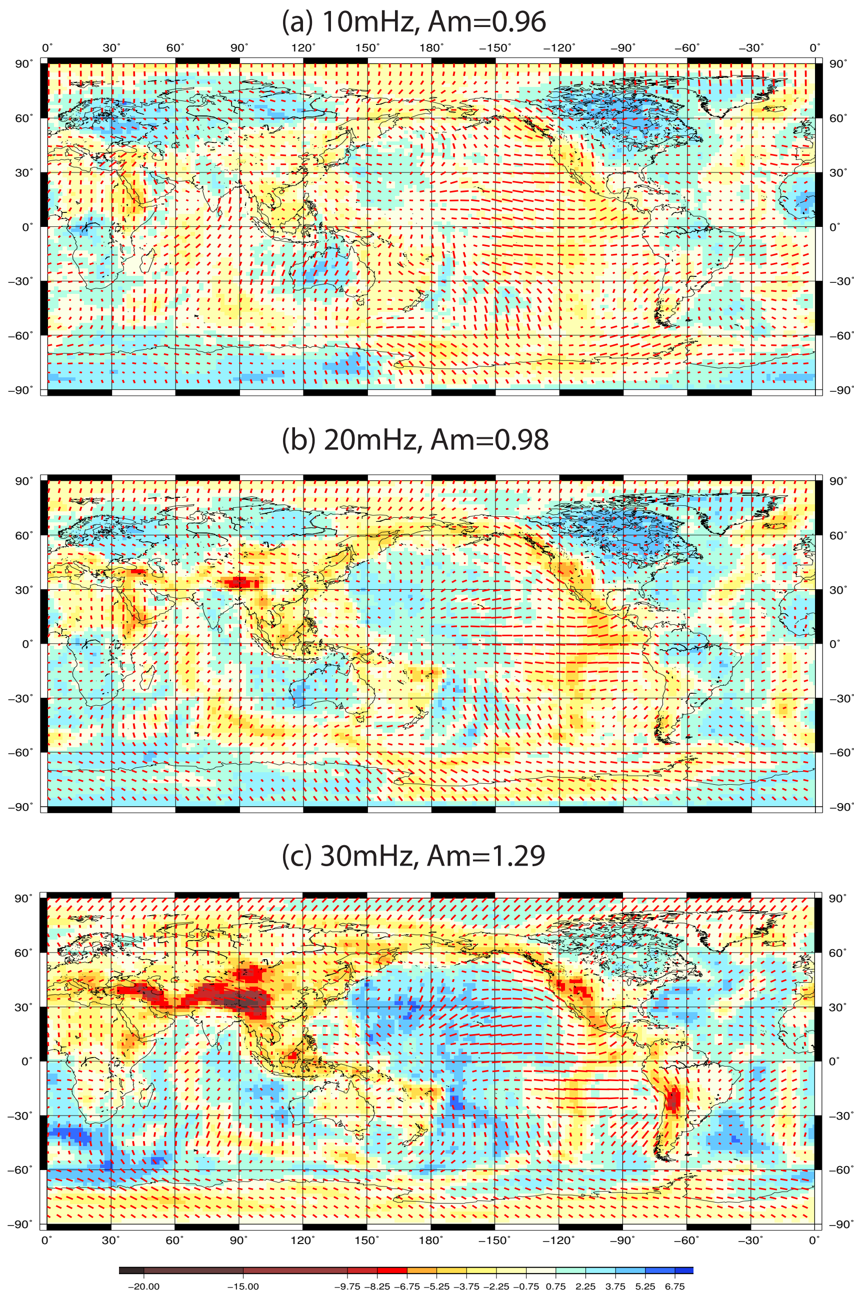

Figure 2 Inversion results for 10, 20 and 30mHz Rayleigh wave. Background colors indicate the perturbations of isotropic phase velocity with respect to the global average value for each frequency. Lengths of the red bars indicate the amplitude of azimuthal anisotropy. Directions of the bars show the fast directions. Maximum amplitude of azimuthal anisotropy, which corresponds to the length of the longest bar for each frequency, is shown in the title of each plot.

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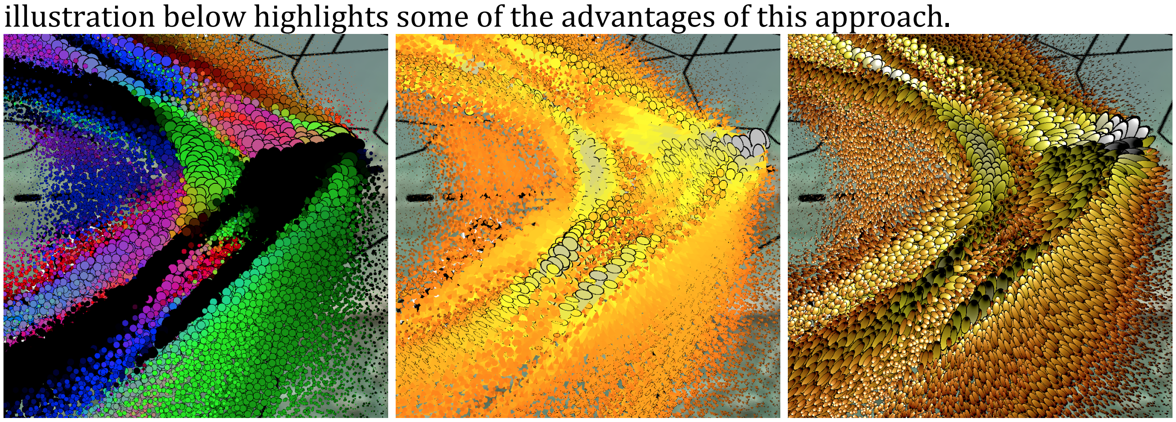
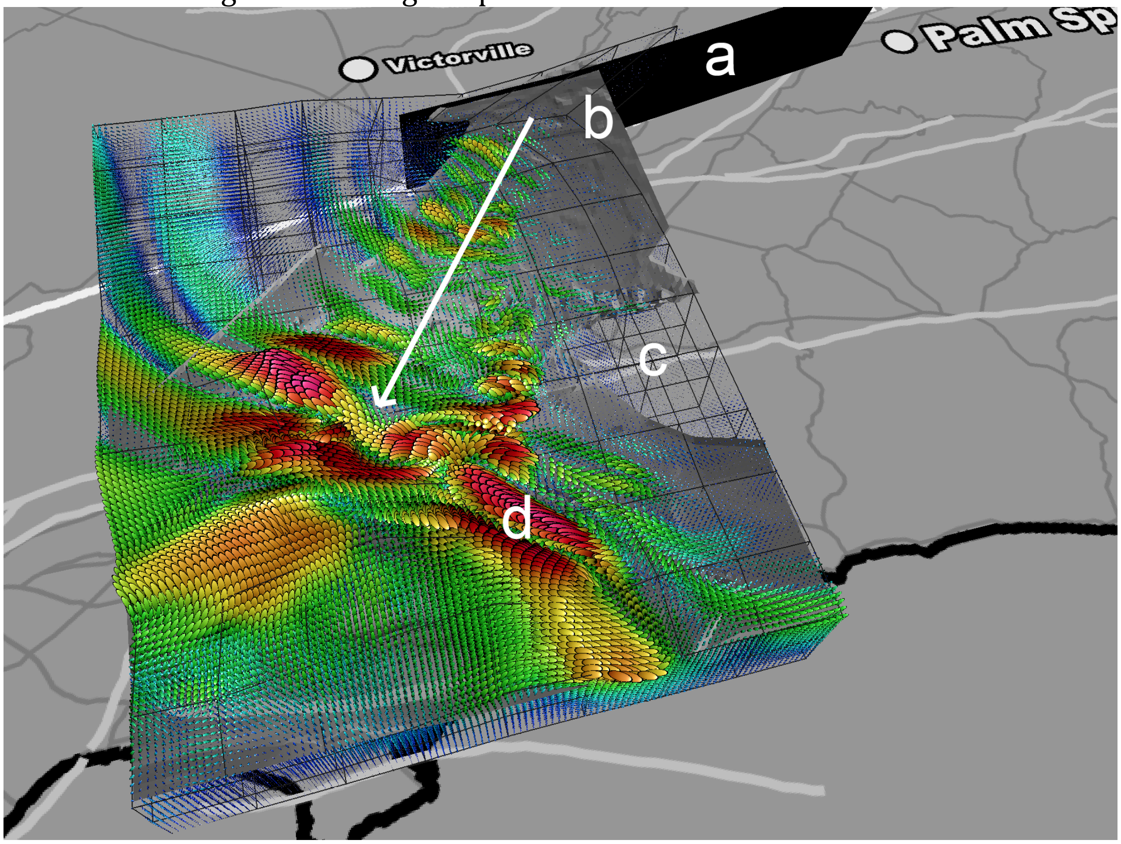
Research Interests: **Plate tectonics and plate deformation; Application of space-geodetic techniques to study crustal dynamics; Satellite laser altimetry and Satellite Synthetic Aperture Radar applications to Earth studies; Earthquake source physics and large-scale supercomputer earthquake simulations; Earthquake prediction, pattern recognition; Multiscale modeling in geophysics & applications of 4D visualizations to earthquake modeling; Verification of nuclear Test Ban Treaties by geophysical means (seismic, imaging, ionosphere). Application of hyperspectral imaging to paleoseismology. Chair, ICSU-WDS Scientific Committee.**

Recent research:
Large-scale simulations of three-dimensional dynamic phenomena, such as seismic events, on super-computers typically generate an enormous volume of digital data, (potentially reaching petabytes, should one desire to save the entire output). Except to answer very limited, narrow questions where the answer can be expressed in terms of a few numbers, it is impractical to study such material by means other than visualization. This has been used very successfully at the Southern California Earthquake Center and San Diego Supercomputer Center to highlight the results of the *TeraShake, PetaShake, and CyberShake* series of simulations. Other applications include large scale astrophysical magneto-hydrodynamic (MHD) simulations. However, the movies generated have typically been restricted to the illustration of fileds along two-dimensional subsets fields. Visualizing the interior of a three-dimensional volume during a dynamic phenomenon has proved a very difficult task. Research over the past few years focused on visualizing dynamic vector fields was conducted with Emmett McQuinn (IBM-Research Almaden), in collaboration with Amit Chourasia (San Diego SuperComputer Center) and Jürgen Schulze (Calit2). This led to the development of an interactive visualization package called GlyphSea. The illustration below highlights some of the advantages of this approach.



Glyph visualization of the formation of a Mach cone in the ground velocity field, caused by supersonic rupture in a Magnitude 8.0 earthquake simulation. Glyph sizes are proportional to the velocity. The vector field is visualized using (a) color

(RGB) coding (b) Conical glyphs with flat shading (c) Ellipsoidal glyphs with dipole texture. The latter highlights the near field ground motion, where white tipped ellipsoids indicate motion towards the viewer while black tipped ellipsoids motion away from the viewer. This technique enables an intuitive and extensible method to visualize vector fields. The following visualization shows how several sources of data can be merged into a single representation



This is a snapshot of the dynamic velocity field in the Los Anglees Basin, computed in the *TeraShake* simulation of an earthquake on the southern San Andreas Fault.. The background is a contextual map showing freeways dark gray), fault lines (light gray) and geographical labels. Label (a) marks the San Andreas vertical rupture fault plane, (b) is an isosurface of three-dimensional seismic velocity in gray color, (c) shows a deformed lattice illustrating exaggerated ground displacements, (d) shows wave amplification in sedimentary basins bordering the San Gabriel range, which constitute a wave guide for strong ground shaking (white arrow).

Reference:

E. McQuinn, E., A. Chourasia, J. P. Schulze, and J. B. Minster, GlyphSea: Visualizing Vector Fields, *SPIE Visualization and Data Analysis* 2014, 9017-20. 2013.

Web-accessible 4D vizualizations (courtesy Amit Chourasia, SDSC):

http://visservices.sdsc.edu/projects/scec/hh/movies/hh.mp4
http://visservices.sdsc.edu/projects/scec/hh/movies/hh-2k.mp4
http://visservices.sdsc.edu/projects/scec/hh/movies/hh-snapshots.zip
http://visservices.sdsc.edu/projects/scec/hh/movies/hh-with.mp4
http://visservices.sdsc.edu/projects/scec/hh/movies/hh-without.mp4
http://visservices.sdsc.edu/projects/scec/hh/movies/hh-2d.mp4

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William Farrell and I have continued our work on ultra-gravity (ug) waves, typical length scale is 10 cm. The ug spectrum icontributes roughly 2/3 of the mean-square slope at the sea surface, and plays an important role in wind drag over a rough sea surface. The ambient abyssal noise is probably associated with the ug spectrum. The generation of ug waves is NOT understood.

I continue my work on the generation of distant swell, with the aim of understanding the arrival of drogue waves on special beaches at rare (decadal) intervals.

Recent publications

W.E.Farrell and W.H.Munk (2013) Surface gravity waves and their acoustic signatures, 1-30 Hz, on the mid-Pacific sea floor. *J. Acoust. Soc. Am.* **134** 3134-3143 10.1121/1.4818780

Munk, W., G. Miller, F. Snodgrass, and N. Barber (2013) Directional recording of swell from distant storms (correction) *Phil. Trans. Roy. Soc. A* **371**, 10.1098/rsta.2013.0039; see *Phil. Trans. Roy. Soc. A* **255**,505-584 10.1098/rsta.1963.0011

W. Munk (2013) The perfect storm, *Proc. Am. Phil. Soc.* (in press).

Darcy E. Ogden

Assistant Professor of Geophysics

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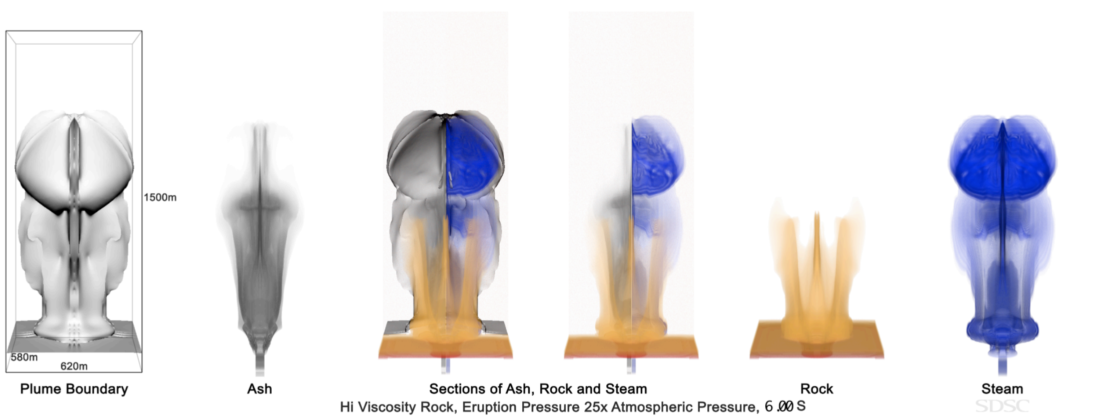
Research Interests: Application of computational fluid dynamics models to explosive volcanic eruptions. Volcano infrasound. Formation of volcanic vents.

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[1] and laboratory experiments of volcanic jet analogs[2].

Eruptive conduits feeding volcanic jets and plumes are connected to the atmosphere through volcanic vents that, depending on their size and 3D shape, can alter the dynamics and structure of these eruptions. The host rock comprising the vent, in turn, can collapse, fracture, and erode in response to the eruptive flow field. With collaborators at Los Alamos National Laboratory, I run fully coupled numerical simulations of high speed, multiphase volcanic mixtures erupting through erodible, visco-plastic host rocks. This work explores the influence of different host rock rheologies and eruptive conditions on the development of simulated volcanic jets.



Numerical simulation of high pressure volcanic eruption and crater formation by Darcy Ogden and Ken Wohletz (Los Alamos National Laboratory). Visualization by Amit Chourasia (San Diego Supercomputing Center).

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.

Relevant Publications

1. Dunham, E. M. & D. E. Ogden, 2012. Guided waves along fluid-filled cracks in elastic solids and instability at high flow rates, J. Applied Mechanics, 79(3), doi:10.1115/1.4005961.

2. Ogden, D.E. & N.H. Sleep, 2012. Explosive eruption of coal and basalt and the End Permian mass extinction. Proceedings of the National Academy of Sciences, 109, 59-62.

3. Ogden, D.E., 2011. Fluid dynamics in explosive volcanic vents and craters. Earth & Planetary Science Letters. 312, 401-410.

4. Saffaraval, F., Solovitz, S. A., Ogden, D. E., & Mastin, L. G., 2012. Impact of Reduced Near-Field Entrainment of Overpressured Volcanic Jets on Plume Development. J. Geophysical Research, 117, doi:10.1029/2011JB008862.

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Research interests: Inverse theory, geomagnetism, spectral analysis, electromagnetic induction.

Spectral analysis has been at the heart of many classical investigations in geophysics, from the work of Walter Munk on tides, to the analysis of the normal modes of oscillation of the Earth by Freeman Gilbert and his collaborators. Recent applications include marine electromagnetic sounding, exemplified by the work of Steve Constable and Kerry Key reported in these pages. In the last two decades David Thomson has established multitapers as the optimal technique for the estimation of the power spectrum, yet the wider geophysical community (outside I) has been surprisingly reluctant to adopt the new ideas. Thomson concentrated on the prolate spheroidal family of tapers. When the very long records ($> 100,000$ terms, say) of modern geophysical series are considered, the prolate tapers are difficult to calculate in sufficient numbers to achieve the very large variance reduction available from the data, but an alternative family of tapers, the sine functions can be employed to advantage. As Riedel and Sidorenko showed, spectra based on sine tapers can be computed rapidly and accurately, and the estimation can be made adaptive, which means that the accuracy and frequency resolution varies across the spectrum, adjusted to the spectral shape.

All these ideas appear in the literature, but none of the popular software packages for time-series analysis currently embody this practice. Andrew Barbour, a student, and Bob Parker, have written and documented a sine multitaper power spectrum estimation program in `R`, and published a paper explaining the theory and illustrating the code. All references to the theory in the first paragraph are listed in the paper cited below.

Geophysical signals are often associated with "mixed" processes, which means the spectra may combine strong peaks, broader peaks with smooth or even flat portions. Spectra like this cannot be properly estimated with traditional techniques which demand a single resolution at every frequency. The adaptive facility that can be built into the sine multitaper approach is perfectly suited to this kind of record. However, we show in Barbour and Parker that Riedel and Sidorenko's criterion based on the minimization of (an approximation to) mean the square error, must be modified to suppress runaway averaging.

By way of an illustration, consider Figure 1, which shows a rich power spectrum, full of information. The time series comprises 300,000 terms sampled at 62.5 Hz of the north channel of a seafloor magnetometer deployed by the Constable group. At the time of recording a strong tidal current is flowing over the instrument causing it to vibrate. Small tilting motions couple the Earth's constant magnetic field into the north component giving rise to both the continuum on the left and the many peaks, which correspond to mechanical resonances of the capsule and its antennas. Observe that several of the resonances exhibit harmonics. Between 12 and 25 Hz, except for two sharp lines, the spectrum is flat, indicating the noise floor of the magnetometer. The precipitous fall-off just above 25 Hz is the effect of powerful anti-aliasing filters in the recording system. Notice the two lines at 12.5 and 25 Hz, quite different in character from the broad peaks of lower frequency. These are due to stray magnetic fields generated by the instrument's clock; they are precise spectral lines.

This power spectrum was computed with the default settings in the code. In the smoother segments, several thousand tapered periodograms contribute to the final estimate, producing a stable,

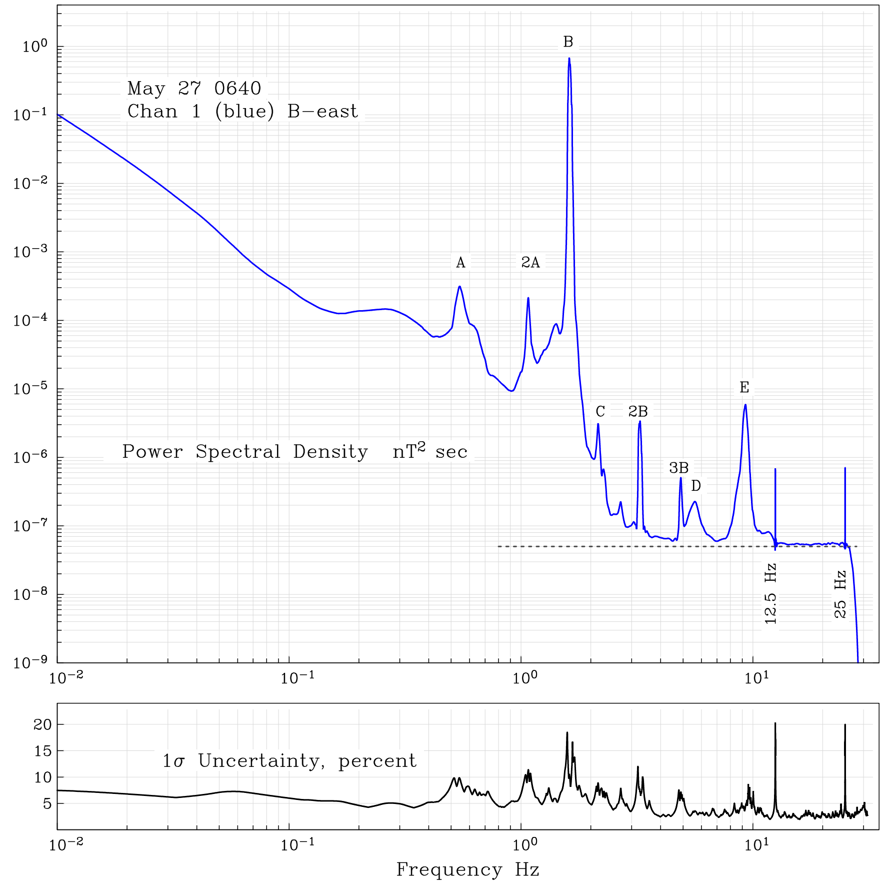

Figure 1: Figure 1: Power spectrum of the magnetic field measured by a seafloor magnetometer.

low-variance result. Where the spectrum varies rapidly, far fewer components are averaged, permitting a much higher resolution. No intervention or experimentation was required of the user.

Recent publications

Barbour, A. J., and Parker, R. L. (2013). PSD: Adaptive, sine multitaper power spectral density estimation for R, *Computers and Geosciences*, in press, `10.1016/j.cageo.2013.09.015`

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Research Interests: Geodynamics, global bathymetry, crustal motion modeling

Students and Funding - Research for the 2012-13 academic year was focused on understanding the dynamics of the crust and lithosphere. Our group comprises three graduate students Soli Garcia, Eric Xu, and John Desanto, one postdoc Xiaopeng Tong and two undergraduate students Chris Olson and Amber Jackson. Our research on improvement in the marine gravity field is co-funded by the National Science Foundation (NSF) the Office of Naval Research, and the National Geospatial Agency. In addition we are funded by NSF and Google to improve the accuracy and coverage of the global bathymetry. The NSF EarthScope Program funds our investigation of the strain rate and moment accumulation rate along the San Andreas Fault System from InSAR and GPS.

Global Gravity and Bathymetry – We are improving the accuracy and spatial resolution of the marine gravity field using data from three new satellite radar altimeters (CryoSat-2, Jason-1, and Envisat). This is resulting in a factor of 2-4 improvement in the global marine gravity field. Most of the improvement is in the 12 to 40 km wavelength band, which is of interest for investigation of seafloor structures as small as 6 km. The current version of the altimeter-derived gravity field has an accuracy of 1.7 mGal in the Gulf of Mexico and 2.4 mGal in the Canadian Arctic (*Sandwell et al.,* 2013). The improved marine gravity is important for exploring unknown tectonics in the deep oceans as well as revealing thousands of uncharted seamounts (Figure 1).

Integration of Radar Interferometry and GPS - We are developing methods to combine the high accuracy of point GPS measurements with the high spatial resolution from radar interferometry to measure interseismic velocity along the San Andreas Fault system (*Tong et al.,* 2013a). We analyzed InSAR observations, initially from ALOS ascending data, spanning from the middle of 2006 to the end of 2010, and totaling more than 1100 interferograms. The final InSAR line-of-sight data match the point GPS observations with a mean absolute deviation of 1.3 mm/yr. These combined GPS/InSAR data are critical for understanding the along-strike variations in stress accumulation rate and associated earthquake hazard. The InSAR processing was performed with new software called GMTSAR developed at SIO (http://topex.ucsd.edu/gmtsar).

Crustal Motion Modeling – Xiaopeng Tong and Bridget Konter-Smith (at the University of Texas, El Paso) are refining a semi-analytic earthquake cycle model for the deformation of western North America using crustal velocity measurements from the growing array of continuous GPS stations and InSAR acquisitions (*Tong et al.,* 2013b). This model is used to estimate the seismic moment accumulation rates along the fault system.

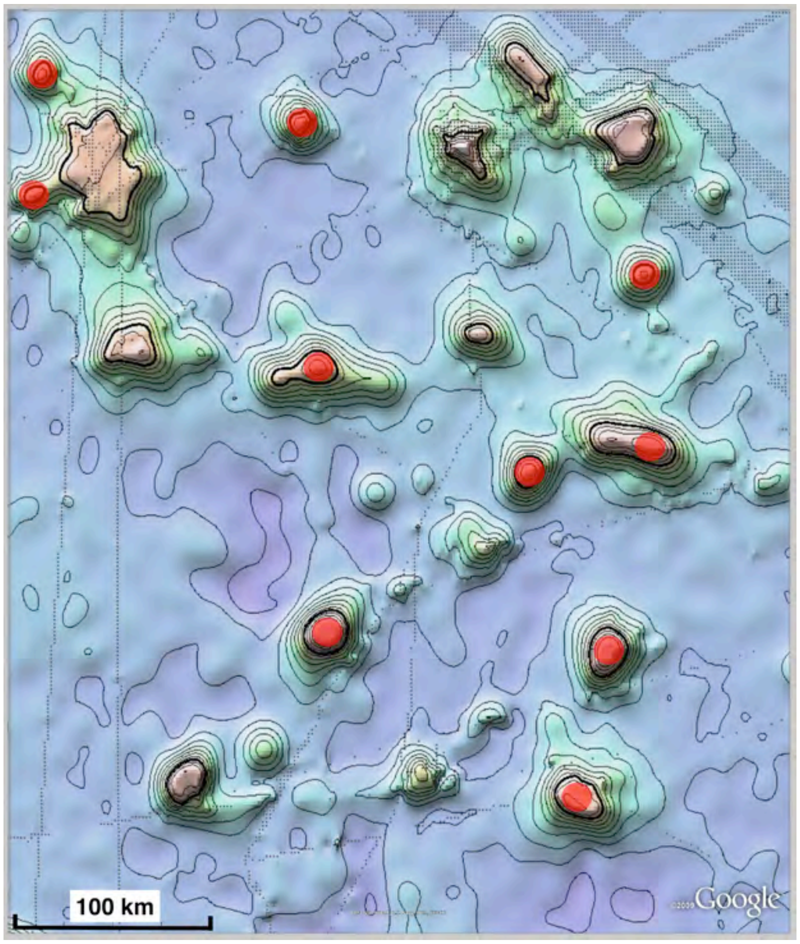

Figure 1. Seafloor depth for a large region of the western Pacific based on satellite gravity and ship soundings (grey dots). Large red dots show 10 uncharted seamounts more than 3-km tall. The overlays were made using new capabilities of the Generic Mapping Tools and are available at ftp://topex.ucsd.edu/pub/srtm30_plus/SRTM30_PLUS_V8.kmz

Relevant Publications

Meyer, F.J., Sandwell, D.T., SAR interferometry at Venus for topography and change detection. *Planetary and Space Science*, http://dx.doi.org/10.1016/j.pss.2012.10.006, 2012.

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

Kaneko, Y., Y. Fialko, D. T. Sandwell, X. Tong, and M. Furuya, Interseismic deformation and creep along the central section of the North Anatolian Fault (Turkey): InSAR observations and implications for rate-and-state friction properties, *J. Geophys. Res. Solid Earth, 118*, doi:10.1029/2012JB009661, 2013.

Garcia, E., D. T. Sandwell, W. H. F. Smith. Retracking CryoSat-2, Envisat, and Jason-1 Radar Altimetry Waveforms for Improved Gravity Field Recovery, Revised: *Geophysical Journal International,* June 15, 2013.

Crowell, B. W., Y. Bock, D. T. Sandwell, and Y. Fialko, Geodetic Investigation into the Deformational Makeup of the Salton Trough, *J. Geophys. Res.*, in press, September, 2013.

Sandwell, D. T., E. Garcia, K. Soofi, P. Wessel, and W. H. F. Smith, Towards 1 mGal Global Marine Gravity from CryoSat-2, Envisat, and Jason-1, *The Leading Edge*, August, 2013.

Tong, X., B. Smith-Konter, D. Sandwell, Is there a descrepabcy between geological and geodetic slip rates along the San Andreas Fault System?, submitted to *J. Geophys. Res.,* October, 2013b.

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Phone: x42260

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. His southern California work has focused on improving earthquake locations using waveform cross-correlation and systematically computing small-earthquake stress drops. Recently graduate student Xiaowei Chen analyzed foreshocks from the three largest recent southern California earthquakes and found that they all exhibit spatial migration (*Chen and Shearer*, 2013). Moreover, their estimated stress drops are significantly less, on average, than those of aftershocks in the epicentral region (see Fig. 1). These results suggest that the foreshock sequences resemble swarms, rather than earthquake-to-earthquake triggering, and most likely result from aseismic transients, which have promoted the occurrence of both the foreshocks and the eventual mainshocks.

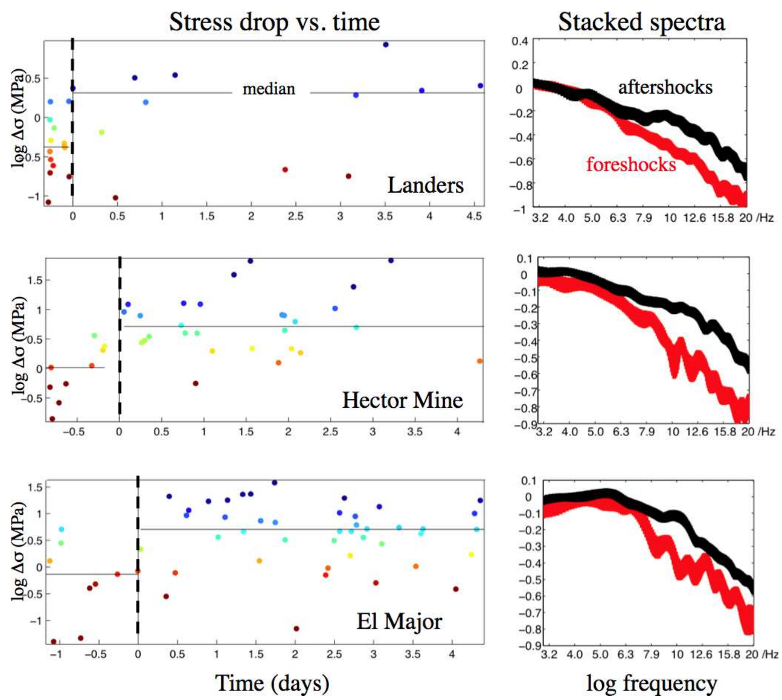

Figure 1: (left) Estimated event stress drops versus time for foreshocks and aftershocks of the Landers, Hector Mine, and El Mayor-Cucapah earthquakes. Note the lower median stress drops for the foreshock sequences. (right) Stacked source spectra for the foreshocks (red) versus aftershocks (black), normalized for moment differences, confirming the lower frequency content of the foreshocks.

Recently Shearer began applying the earthquake relocation methods developed for southern California to analysis of seismicity recorded on the Island of Hawaii by the Hawaii Volcano Observatory (HVO). Postdoc Robin Matoza has taken the lead in this research and Matoza *et al.* (2013) presents a relocated catalog of over 100,000 earthquakes from 1992 to 2009. The results show a dramatic sharpening of earthquake clustering along faults, streaks, and magmatic features, permitting a more detailed understanding of fault geometries and volcanic and tectonic processes.

Shearer has also pioneered new approaches to imaging large earthquake ruptures, including the waveform back-projection method that is now widely applied by different groups following major earthquakes. Work with postdocs Takahiko Uchide and Huajian Yao constrained the rupture history of the 2010 El Mayor–Cucapah earthquake just south of the Mexican border using both local strong motion data and back-projection of high-frequency data from the Japanese Hi-Net array (Uchide *et al.* 2013). The results show that bursts of high-frequency radiation often occur near the edges of major slip patches, consistent with theoretical models of rupture propagation. Work with Huajian Yao and Peter Gerstoft used seismic arrays in the United States and Japan to image four recent giant subduction zone earthquakes. Yao *et al.* (2013) show that these earthquakes have frequency-dependent seismic radiation, with the lower frequencies coming mainly from the shallow part of the fault and the higher frequencies coming mainly from the deeper part of the fault. This appears to be a general property of megathrust ruptures (Figure 2).

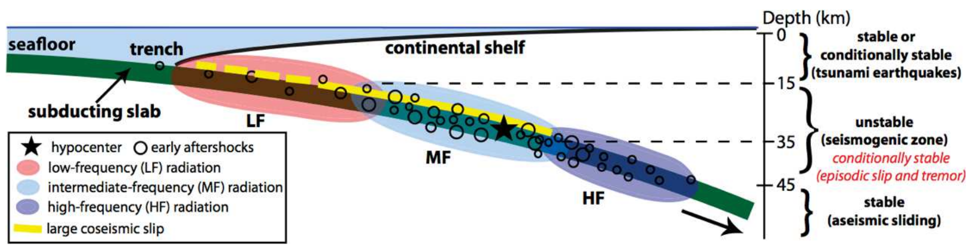

Figure 2: Seismic observations of subduction zone megathrust earthquakes and frictional stability regimes of the subducting plate interface. The yellow dashed line suggests possible large coseismic slip in the shallow portion of the slab interface in the case of tsunami earthquakes. From Yao *et al.* (2013).

In global seismology, graduate student Nicholas Mancinelli recently stacked over 10,000 high-frequency seismograms to image precursors to the core phase PKP and constrain the strength of scattering in the lowermost mantle (Mancinelli *et al.* 2013). Using an energy-conserving multiple-scattering algorithm, he found that he could fit the data data reasonably well with an rms velocity perturbation of 0.1% in the lower mantle. These results resolve a long-standing discrepancy in the amplitude of these scatterers, but may be hard to reconcile with other proposed scattering models.

Recent publications

Chen, X., and P. M. Shearer (2013) California foreshock sequences suggest aseismic triggering process, *Geophys. Res. Lett.*, **40**, `10.1002/grl.50444`

Mancinelli, N. J., and P. M. Shearer (2013) Reconciling discrepancies among estimates of small-scale mantle heterogeneity from PKP precursors, *Geophys. J. Int.*, `10.1093/gji/ggt319`

Matoza, R. S., P. M. Shearer, G. Lin, C. J. Wolfe, and P. G. Okubo (2013) Systematic relocation of seismicity on Hawaii Island from 1992 to 2009 using waveform cross correlation and cluster analysis, *J. Geophys. Res.*, **118** `10.1002/jgrb.50189`

Uchide, T., H. Yao, and P. M. Shearer (2013) Spatio-temporal distribution of fault slip and high-frequency radiation of the 2010 El Mayor-Cucapah, Mexico earthquake, *J. Geophys. Res.*, **118**, `10.1002/jgrb.50144`

Yao, H., P. M. Shearer, and P. Gerstoft (2013) Compressive sensing of frequency-dependent seismic radiation from subduction zone megathrust ruptures, *Proc. Nat. Acad. Sci.*, **110**, `10.1073/pnas.1212790110`

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http://earthref.org/whoswho/ER/hstaudigel/index.html

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, the lithosphere and biosphere. My most recent focus aims at the biogeosciences of volcanic systems in particular seamounts and in the extreme environments of McMurdo/Antarctica. 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.

Microbes in Volcanoes: I study the bio- geosciences of volcanoes using geological and microbiological approaches. In the geological record we study trace fossils of microbes drilling into volcanic glass and explore specific morphological features of these trace fossils might give us some leads on the physiological traits of the microbes that cause them. This work demonstrated that microbes are active in any ocean crust section studied to date 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. While we are still in the dark about the actual microbes involved, I am working with microbiologists to explore microbe – rock interaction inside volcanoes and their hydrothermal systems. We studied Vailulu'u seamounts in the Samoan archipelago and Loihi Seamount off the Big Island on Hawaii. There we characterized and isolated microbes from natural rock surfaces and exposure experiments for future experiments. My current field 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. Most of our 2012/13 field season was spent on Ice caves on Erebus and sub- sea-ice diving.

Details can be found on our expedition website; (earthref.org/ERESE/projects/GOLF439/2012/) in a lecture I gave at Birch Aquarium www.uctv.tv/search-details.aspx?showID=16074 and in a Youtube movie on our diving: www.youtube.com/watch?v=CSlHYlbVh1c (footage by Henry Kaiser, famed Antarctic diver and movie director).

Seamounts: Most recent field work focused on Loihi Seamount and seamounts in the Samoan Chain including Vailulu'u seamount. I coordinated a Seamount Biogeoscience Network and co-edited and wrote papers in a special volume of Oceanography on "Mountains in the Sea": see www.tos.org/oceanography/archive/23-1.html. My papers include in particular contributions regarding the geological history and structure of seamounts their role in subduction systems and the associated deep-sea metal deposits. Other recent papers on seamounts include the description of microbial consortia in their hydrothermal systems and the discovery that fungi are common in these submarine systems, not unlike in terrestrial soils.

Teaching: In collaboration with Cheryl Peach, I am running a NSF educational program for graduate students to work with K-12 students ("GK-12"), the "Scripps Classroom Connection" (earthref.org/SCC/) which offers nine 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 one-third effort, 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

Connell, L., Staudigel, H. (2013) Fungal Diversity in a Dark Oligotrophic Volcanic Ecosystem (DOVE) on Mount Erebus, Antarctica. Biology 2, 798-809.

Koppers Anthony A. P., Russell, J. A., Roberts, J., Jackson, M. G., Konter, J. G., Wright, D. J., Staudigel, H., and Hart, S.R. (2011) Age systematics of two young en echelon Samoan volcanic trails. Geochemistry Geophysics Geosystems, **12**, Q12009 `10.1029/2010gc003232`

Knowles, E., Staudigel, H., Templeton, A. (2013) Geochemical characterization of tubular alteration features in subseafloor basalt glass, *Earth Planet. Sci. Lett.* **374** 239-250 `10.1016/j.epsl.2013.05.012`

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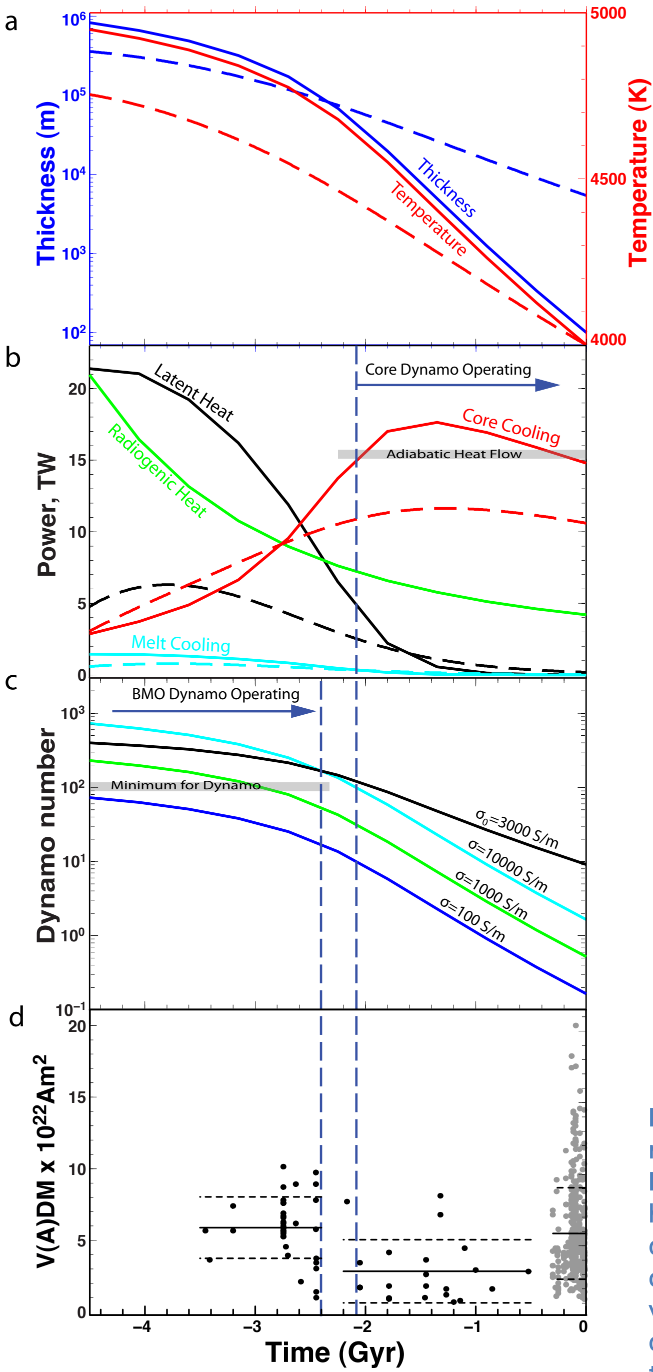
Research Interests: Global tectonics, mantle dynamics, planetary geophysics, applying high-performance computing and 4-D visualization to geodynamics

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



This past year I worked with Dr. Leah Ziegler, a recent IGPP graduate, to propose a new model for the Earth's magnetic history in that its ancient magnetic field (from 4500-2500 Myrs ago) was actually generated by dynamo action within a molten region of Earth's mantle above the core. Presently, Earth's inner core plays a pivotal role in supplying an energy source for this motion, however recent findings suggest Earth's inner core is likely not more than 500 Myrs old. In contrast, geologic evidence supports the continuous existence of a magnetic field since 3500 Myrs ago. The energetics of generating a field without the help of an inner core pose difficulty because given present knowledge, Earth's mantle and core would have to cool at much faster rates than what is indicated from geologic constraints on past temperatures. Consequently, there are currently no viable models for the thermal evolution of the mantle and core that can account for maintaining a magnetic field for so long. We show the thermal evolution of a basal magma ocean (Fig 1a,b) in which the upwardly revised adiabatic heat flow of 15 TW must be exceeded to produce a magnetic field from purely thermal convection in the core without the aid of inner core solidification. We also compute

Figure 1: a) thermal evolution of 'basal magma ocean' (solid lines); Model of Labrosse et al., [2007] (dashed lines).b) heat budget for evolution (solid and dashed as in a) c) Dynamo number of BMO-core region using constant and time-varying electrical conductivities (labeled) d) Paleomagnetic field intensity data older than 0.5 Gyr ago (black) and 10-500 Gyr ago (gray)

the Dynamo number for this layer of silicate melt, and based on its evolution (Fig 1c) we propose it may be capable of producing Earth's ancient magnetic field for certain values of electrical conductivities. We also show that a hiatus may have occurred between when magnetic field generation transitioned from within the basal magma ocean to inside the core and this is something that can be tested with paleomagnetic observations (Fig 1d).

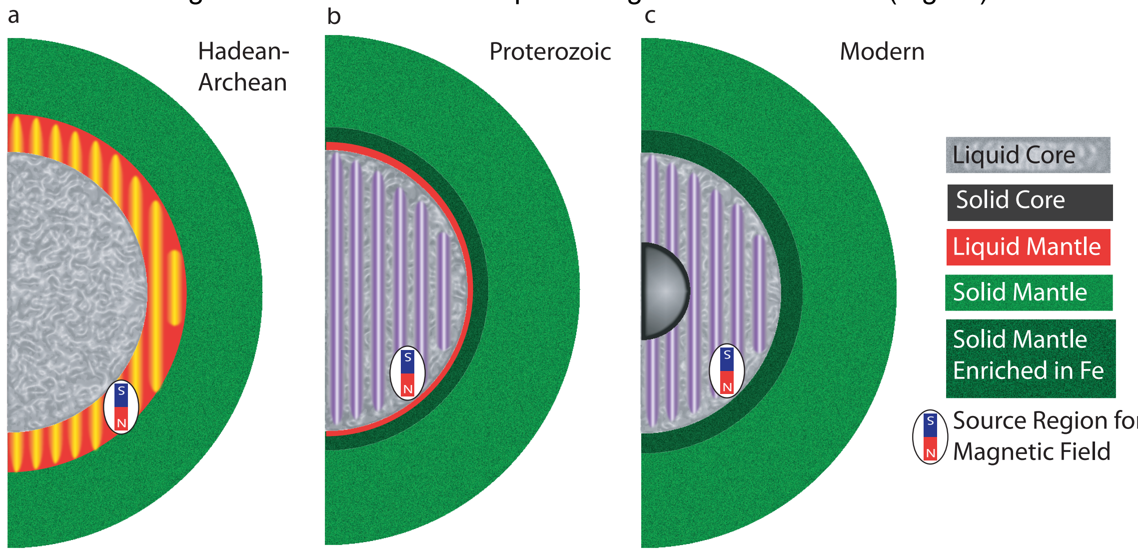


Figure 2: Illustration of a newly proposed geomagnetic history for Earth in which generation of the magnetic field occurred during three regimes: a) from 4.5-2.5 Ga within a molten layer of the non-metallic material above the core, b) from 2.5-0.5 Ga within the Earth's core which is completely fluid in the absence of a solid inner core, and c) from 0.5 Ga to present, within the fluid outer core that surrounds a growing solid inner core.

In another study with Chris Davies, a former IGPP Green Scholar, I investigated how Earth's inner core is gravitationally coupled with Earth's mantle. This research is important because the inner core plays such an influential role in generating Earth's magnetic field now. The magnetic field lines permeate into the inner core, allowing spatial-temporal variations in the magnetic field to perturb the inner core out of the equilibrium state as prescribed by the gravitational field of the mantle. This then provides a mechanism through which angular momentum can be exchanged between the core and the mantle, as the oscillations of the inner core generate corresponding motions within the fluid outer core known as torsional oscillations. These small changes in angular momentum, ultimately arising from the fluctuations in the magnetic field, can be observed as very minute changes in the length of Earth's day.

Publications for 2012-2013

Ziegler, L.B. and **D.R. Stegman**. "Implications of a long-lived basal magma ocean in generating Earth's ancient magnetic field", *Geochem. Geophysics Geosystems*, (in press), 2013.

Davies, C., **D.R. Stegman**., and M. Dumberry "The Strength of Gravitational Core-Mantle Coupling," *Geophys. Res. Lett*, (in review), 2013.

Jackson, C., Ziegler, L. B., Zhang, H., Jackson, M., **Stegman, D. R.,** 2013. A geochemical evaluation of potential magma ocean dynamics using a parameterized model for perovskite crystallization. *Earth Planet. Sci. Lett.,* (in review) 2013.

Kincaid, C, Druken K. A, Griffiths R. W., **Stegman D. R**. "Bifurcation of the Yellowstone plume driven by subduction-induced mantle flow." *Nature Geoscience*. 6:395-399, 2013.

Druken, K. A., Kincaid, C., Griffiths, R. W., **Stegman, D. R.** and Hart, S. "Plume-slab interaction: Laboratory modeling of the Samoa-Tonga system" *Physics of the Earth and Planetary Interiors*, (in revision) 2013.

Druken, K. A., **Stegman, D. R.,** Kincaid, C. R., and Griffiths, R. W. "Regimes of plume-slab interaction and consequences for hotspot volcanism." *Physics of the Earth and Planetary Interiors* (in prep) 2013.

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Research interests:

Seismology, infrasound, seismo-acoustics, nuclear explosion monitoring, advanced array processing, and waveform imaging techniques.

Infrasound from ocean waves: I recently published a study in which I evaluated the opposing-wave interaction hypothesis for the generation of microbaroms in the eastern North Pacific (Walker, 2012). I led a UCSD team in the deployment of two microphone arrays in California during 2010 to record "microbaroms", quasi-continuous atmospheric pressure oscillations with a period of 5 s. I developed a time-progressive, frequency domain beamforming method called "FTBeam" to detect and analyze microbaroms recorded by these and 10 other infrasonic arrays along the North Pacific rim. Common pelagic microbarom sources that move around the North Pacific are observed during the boreal winter. Summertime North Pacific sources are only observed by western Pacific arrays, presumably a result of weaker microbarom radiation and westward stratospheric winds. A well-defined source is resolved ~2000 km off the coast of California in January 2011 that moves closer to land over several days. I developed an acoustic ray tracer for an advective medium called "ART2D". The source locations were corrected for deflection by horizontal winds using ART2D with range-dependent atmospheric specifications provided by ground-to-space models. The observed source locations do not correlate with anomalies in NOAA Wave Watch 3 (NWW3) ocean wave model data. However, application of the opposing wave, microbarom source physics model of Waxler and Gilbert (2006) to the NWW3 directional wave height spectra output at buoy locations within 1100 km of the western North America coastline predicts microbarom radiation in locations that correlate with observed locations. These results suggest that pelagic North Pacific microbarom radiation detected by infrasonic arrays during the boreal winter could be routinely used to validate NWW3 results in regions with poor sensor coverage.

Improved infrasonic sensors: I also collaborated with Ph.D. graduate student Scott DeWolf and his advisor, Mark Zumberge, on a study of the efficacy of spatial averaging of infrasonic pressure in varying wind speeds (DeWolf et al., 2013). Wind noise reduction (WNR) is a critical part in the detection of infrasound. Spatial averaging theory led to the development of rosette pipe arrays. The efficacy of rosettes decreases with increasing wind speed and only provides a maximum of 20dB WNR due to a maximum size limitation. An Optical Fiber Infrasound Sensor (OFIS), which UCSD has been developing for the last 15 years, reduces wind noise by instantaneously averaging infrasound along the sensor's length. In this study two experiments quantify the WNR achieved by rosettes and OFISs of various sizes and configurations. Specifically, we show that linear OFISs ranging in length from 30 to 270m provide a WNR of up to ~30dB in winds up to 5m/s. The measured WNR was found to be a logarithmic function of the OFIS length and depends on the orientation of the OFIS with respect to wind direction. OFISs oriented parallel to the wind direction achieve ~4dB greater WNR than those oriented perpendicular to the wind. Analytical models for the rosette and OFIS are developed that predict these observations.

Earthquake infrasound: I led an international team of six researchers in the study of the 2011 Mw 9.0 Tohoku earthquake, which generated infrasound that was recorded by nine infrasonic arrays (Walker et al., in press). Most arrays recorded a back azimuth variation with time due to the expanse of the source region. We use ray tracing to predict the infrasonic observations and define back azimuth wind corrections. The K-NET accelerometer network recorded Japan ground shaking in unprecedented spatial resolution. We back projected infrasound from arrays IS44 (Kamchatka) and IS30 (Tokyo) to the source region and compare these results with K-NET acceleration data. IS44 illuminates well the complex geometry of land areas that experienced shaking. IS30 illuminates two volcanoes and a flat area around the city of Sendai, where the maximum accelerations occurred. The locations of the arrays and epicentral region define three source-receiver profiles. The observed transmission loss (TL) of infrasound in stratospheric and thermospheric waveguides follows an exponential decay law with decay constants being directly proportional to the maximum ratio of the effective sound speed in the stratosphere to that at the ground. A model is developed that yields 65% variance reduction relative to predictions from a traditional stratospheric arrival TL relationship. This model is a simplified version of the model of Le Pichon et al. (2012), which yields an 83% variance reduction, implying fine-scale atmospheric structure is required to explain the TL for stratospheric upwind propagation. Our results show that infrasonic arrays are sensitive to ground acceleration in the source region of megathrust earthquakes. The TL results may improve infrasonic amplitude scaling laws for explosive yield.

Investigation of atmospheric phenemona: I was also involved in two studies of the generation of gravity waves that propagated across the U.S. and originated from atmospheric weather events. The first study was published earlier this year (de Groot-Hedlin et al., 2013). This is a case study introducing a method for detecting and tracking gravity wave propagation across the USArray pressure sensors. The method was successfully applied to the tracking of gravity waves generated by a series of tornadoes in the central U.S. The second study is the analysis and modeling of a tsunami generated by a rare combination of atmospheric events over the western North Atlantic ocean. The tsunani generated gravity waves that propagated across the eastern part of the USArray (Knight et al., 2013). This interesting event was also an important test of the Tsunami Warning Center's detection system along the eastern U.S. coastline.

Recent publications

de Groot-Hedlin, C., Hedlin, M., and Walker, K. T., 2013, Detection of gravity waves across the USArray: A case study, *Earth Planet. Sci. Lett.*, `10.1016/j.epsl.2013.06.042`

DeWolf, S., Walker, K. T., Zumberge, M. A., and Denis, S., 2013, Efficacy of spatial averaging of infrasonic pressure in varying wind speeds, *J. Acoust. Soc. Am.*, **133**, 3739-3750, `10.1121/1.4803891`

Walker, K. T., 2012, Evaluating the opposing-wave interaction hypothesis for the generation of microbaroms in the eastern North Pacific, *J. Geophys. Res,*, **117**, C12016, `10.1029/2012JC008409`

Walker, K. T., Le Pichon, A., Kim, T. S., de Groot-Hedlin, C., Che, I.-Y., and Garces, M., An analysis of ground shaking and transmission loss from infrasound generated by the 2011 Tohoku earthquake, *J. Geophys. Res. Atmo.*, in press. `10.1002/2013JD020187`

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

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

Acoustic Propagation in the Philippine Sea. During 2009–2011 the Acoustical Oceanography Group at Scripps Institution of Oceanography worked with investigators from other oceanographic institutions to conduct a series of experiments to investigate deep-water acoustic propagation and ambient noise in the oceanographically and geologically complex Philippine Sea: (i) 2009 NPAL Pilot Study/Engineering Test (PhilSea09), (ii) 2010–2011 NPAL Philippine Sea Experiment (PhilSea10), and (iii) Ocean Bottom Seismometer Augmentation of the 2010–2011 NPAL Philippine Sea Experiment (OBSAPS). Worcester *et al*. (2013) provides an overview of the three experiments. Initial results are given in Colosi *et al*. (2013), Freeman *et al*. (2013), Van Uffelen *et al*. (2013), and White *et al*. (2013).

The goals of the Philippine Sea experiments included (i) understanding the impacts of fronts, eddies, and internal tides on acoustic propagation, (ii) determining whether acoustic methods, together with other measurements and ocean modeling, can yield estimates of the time-evolving ocean state useful for making improved acoustic predictions and for understanding the local ocean dynamics, (iii) improving our understanding of the physics of scattering by internal waves and spice (density-compensated temperature and salinity variations), (iv) characterizing the depth dependence and temporal variability of the ambient noise field, and (v) understanding the relationship between the acoustic field in the water column and the seismic field in the seafloor for both ambient noise and signals.

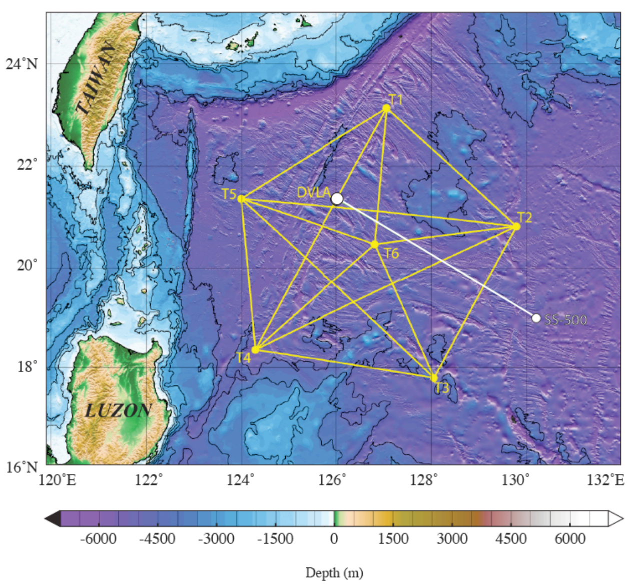

Fig. 1. The PhilSea10 experiment consisted of six broadband acoustic transceivers (T1, … T6), a Distributed Vertical Line Array (DVLA) receiver, and ship-suspended sources that transmitted to the DVLA.

Thin-ice Arctic Acoustic Window (THAAW). The Arctic Ocean is currently undergoing dramatic changes, including reductions in the extent and thickness of the ice cover and extensive warming of the intermediate layers. The multiyear ice is melting. Ice keels are getting smaller. With more open water, the internal wave energy level is likely increasing, at least during summer. The long-term objectives of this research program are to understand the effects of changing Arctic conditions on low-frequency, deep-water propagation and on the low-frequency ambient noise field. The hope is that these first few steps will lead to a larger, permanent acoustic monitoring, communications, and navigation network in the Arctic Ocean.

A DVLA receiver was deployed through the ice near the North Pole at Russian ice camp Barneo during 12–15 April 2013. On 3 May 2013 we began receiving ALARM messages from the Iridium-GPS beacon located on top of the subsurface float, indicating that the mooring had prematurely surfaced. The mooring drifted slowly south toward Fram Strait after surfacing. The mooring was recovered on 20 September 2013 at approximately 84º 02.1'N, 003º 03.5'W, far north of the ice edge, from a Norwegian Coast Guard icebreaker. Analysis of the ambient noise, temperature, and salinity data collected as the THAAW mooring drifted from the North Pole toward Fram Stait will occur during the coming year.

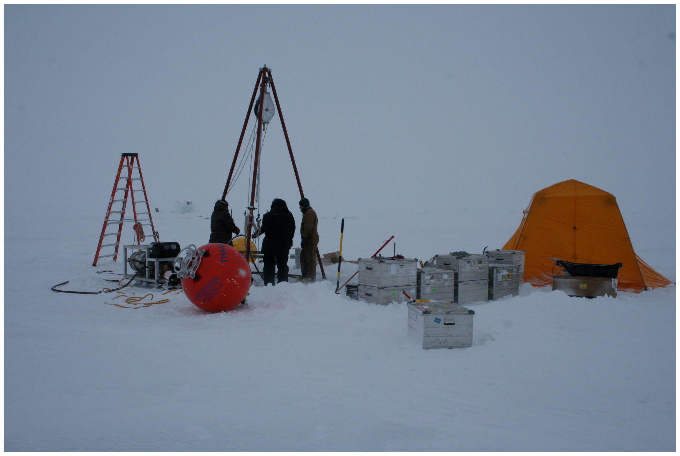

Fig. 2. Deployment of the THAAW mooring near the North Pole. (Photo: P. Worcester)

Bottom Interacting Acoustics in the North Pacific. A near-seafloor DVLA receiver and an array of ocean bottom seismometers (OBS) were deployed in the Northeast Pacific during June–July 2013 in an experiment conducted jointly by the Acoustical Oceanography Group at Scripps and Woods Hole Oceanographic Institution to study the relationship between the acoustic field in the water column and the seismic field in the seafloor for both ambient noise and signals transmitted by a low-frequency source. The experiment was motivated in part by unexpected arrivals observed on OBSs at the same location from signals transmitted during the 2004 Long-range Ocean Acoustic Propagation Experiment (LOAPEX) (Stephen *et al*., 2009, 2013). Analysis of these data is just beginning.

Relevant Publications

Colosi, J. A., Van Uffelen, L. J., Cornuelle, B. D., Dzieciuch, M. A., Worcester, P. F., Dushaw, B. D., and Ramp, S. R. (**2013**). "Observations of sound-speed fluctuations in the western Philippine Sea in the spring of 2009," J. Acoust. Soc. Am. **134**, 3185–3200.

Freeman, S. E., D'Spain, G. L., Lynch, S. D., Stephen, R. A., Heaney, K. D., Murray, J. J., Baggeroer, A. B., Worcester, P. F., Dzieciuch, M. A., and Mercer, J. A. (**2013**). "Estimating the horizontal and vertical direction-of-arrival of water-borne seismic signals in the northern Philippine Sea," J. Acoust. Soc. Am. **134**, 3282–3298.

Stephen, R. A., Bolmer, S. T., Dzieciuch, M. A., Worcester, P. F., Andrew, R. K., Buck, L. J., Mercer, J. A., Colosi, J. A., and Howe, B. M. (**2009**). "Deep seafloor arrivals: An unexplained set of arrivals in long-range ocean acoustic propagation," J. Acoust. Soc. Am. **126**, 599–606.

Stephen, R. A., Bolmer, S. T., Udovydchenkov, I. A., Worcester, P. F., Dzieciuch, M. A., Andrew, R. K., Mercer, J. A., Colosi, J. A., and Howe, B. M. (**2013**). "Deep seafloor arrivals in long range ocean acoustic propagation," J. Acoust. Soc. Am. **134**, 3307–3317.

Van Uffelen, L. J., Nosal, E.-M., Howe, B. M., Carter, G. S., Worcester, P. F., Dzieciuch, M. A., Heaney, K. D., Campbell, R. L., and Cross, P. S. (**2013**). "Estimating uncertainty in subsurface glider position using transmissions from fixed acoustic tomography sources," J. Acoust. Soc. Am. **134**, 3260–3271.

White, A. W., Andrew, R. K., Mercer, J. A., Worcester, P. F., Dzieciuch, M. A., and Colosi, J. A. (**2013**). "Wavefront intensity statistics for 284-Hz broadband transmissions to 107-km range in the Philippine Sea: Observations and modeling," J. Acoust. Soc. Am. **134**, 3347–3358.

Worcester, P. F., Dzieciuch, M. A., Mercer, J. A., Andrew, R. K., Dushaw, B. D., Baggeroer, A. B., Heaney, K. D., D'Spain, G. L., Colosi, J. A., Stephen, R. A., Kemp, J. N., Howe, B. M., Van Uffelen, L. J., and Wage, K. E. (**2013**). "The North Pacific Acoustic Laboratory deep-water acoustic propagation experiments in the Philippine Sea," J. Acoust. Soc. Am. **134**, 3359–3375.

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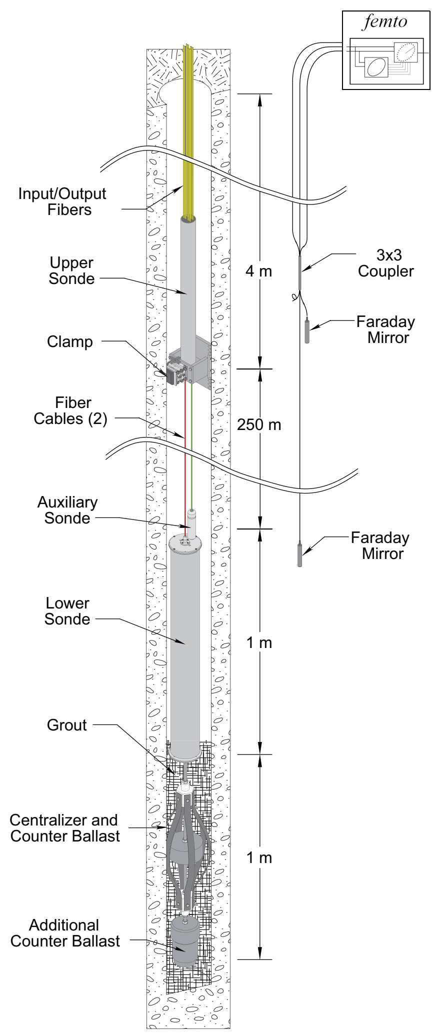
Research Interests: Measurement of gravity and pressure in the marine and subaerial environments, development of new seismic instrumentation, optical fiber measurements of strain and pressure

A Borehole Optical Fiber Strainmeter
(In collaboration with Scott Dewolf and Frank Wyatt)

Measurements of Earth strain can provide information about many geophysical processes, including the deformations associated with earthquakes, volcanoes, ocean ridge spreading, and subduction. Strain measurements can also be used for geotechnical purposes such as hydrocarbon reservoir monitoring and studies of seafloor sediment movements.



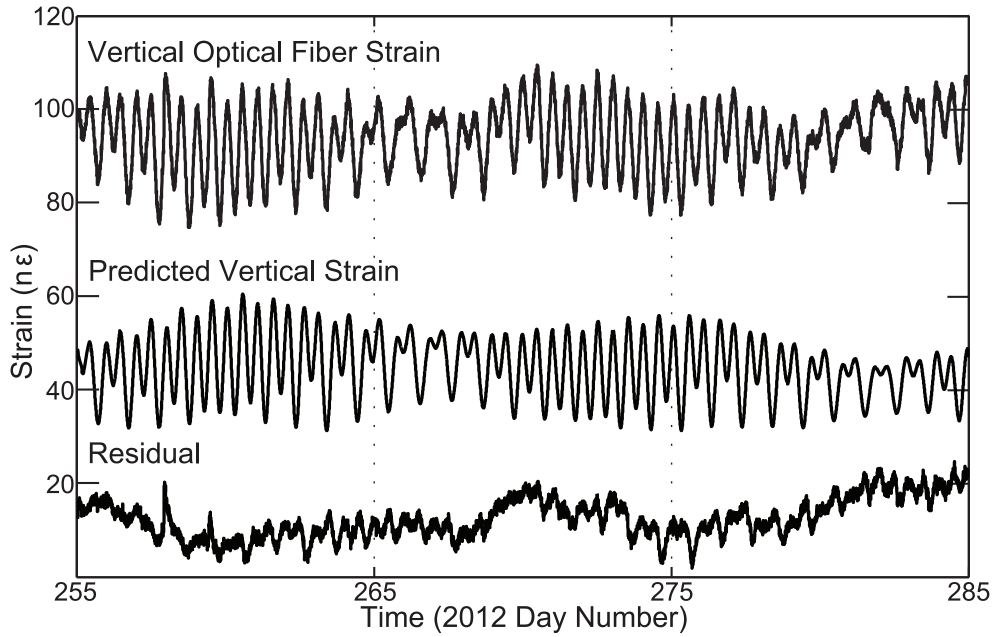
Schematic diagram of an optical fiber borehole strainmeter (graphic by Scott Dewolf).

In Earth strain measurements, we monitor changes in length Δl over a baseline length l, to give the strain $\varepsilon = \Delta l/l$. For a given displacement-noise in Δl, the longer the instrument length l, the lower the noise in the strain measurement. For many geophysical applications, noise in Δl comes from imperfect coupling to the ground, which is ameliorated by longer baselines. Optical methods can detect a very small Δl even when l is large (hundreds of meters), making them an excellent technique for strain measurement. Optical fibers allow great flexibility in installation at relatively low cost; their main drawback is the temperature coefficient of the index of refraction (about 10^{-5} $°C^{-1}$); and, for the very longest time periods of interest, possible long-term drift of this index.

Long baseline vertical strain in a borehole can be recorded by measuring the length of an optical fiber stretched between two points in the borehole at depths separated by tens to thousands of meters. We have installed a new optical fiber borehole strainmeter in a 260-m deep borehole at our test site, Piñon Flat Observatory (PFO). In this new instrument, we have incorporated a range of improvements developed as part of installing more than a dozen optical fiber borehole strainmeters in the past two decades. A special signal processing scheme called “femto” allows us to detect displacements of a few picometers with a range up to many tens of mm.

Optically, the instrument consists of a Michelson interferometer formed by a 3×3 coupler and Faraday mirrors at the ends of the two arms. The reference arm is a short segment of fiber (approximately 0.1 m long) terminated in a Faraday mirror and held in a shallow borehole sonde along with the 3×3 coupler. The strain-sensing arm extends from the shallow sonde to a deep sonde that houses a second Faraday mirror. The tensioned fiber along the length of the borehole is encased in a 1 mm diameter stainless steel tube jacketed with plastic. The lower sonde is anchored with cement into the bottom of the uncased borehole; the upper sonde is held inside the borehole using a scissors-jack-clamp activated with a 5 m long tool operated from the surface. Pre-tensioning of the fiber is done from the surface by pulling on the upper sonde before engaging the scissors-jack-clamp.

Standard single mode communication fiber (SMF28) is used throughout the setup. Laser light is injected into one of the inputs of a 3×3 coupler; the two interferometer sensing-arms (one to full depth) are spliced to a pair of the three output fibers. Two fringe signals, phase shifted by 120˚ (owing to the nature of the 3×3 coupler), emerge from two of the coupler inputs. Faraday mirrors prevent varying birefringence from affecting the fringe contrast.



Displayed above is a month of data from the optical fiber borehole strainmeter. The solid Earth tides are clearly discernable (having a maximum peak-to-peak amplitude of approximately 30 nε). Also located at PFO is an array of three 730 m-long horizontal laser strainmeters that operate through vacuum pipes. These highly stable reference instruments provide us with calibration signals, making the site an ideal test-bed. At a free surface, two orthogonal horizontal strain components can be combined to predict the vertical strain seen by a borehole instrument. Modeling the Earth as an elastic solid, the vertical strain ε_z can be predicted from the horizontal areal strain ε_A.

In a previous installation of an optical fiber strainmeter at the SAFOD observatory, we were unable to see the tidal signal because of noise from temperature variations. In this new sensor, owing to its length and isolation from surface temperature variation, we observe the tides clearly. This bodes well for future applications of this new technology in the detection of strain signals from a variety of sources.

Images (from the top) 1) SIO Pier at sunset captured by Kerry Key; 2) Global ocean and land topography. The ocean topography is based on sparse ship soundings and dense satellite gravity measurements. Ocean data were compiled at IGPP. Image courtesy of David Sandwell; 3) Kinematic GPS survey of the salar de Uyuni in Bolivia—courtesy of Adrian Borsa; 4) Snapshot from a 3D interactive visualization of seismic data from the Anza region of southern California. Data include seismic station locations (green cylinders), background seismicity (small blue orbs), the largest earthquakes in the region (red diamonds), aftershocks of the 2010 magnitude 4.9 mainshock (pink cubes), aftershocks of the 2005 magnitude 5.2 mainshock (orange cubes), aftershocks of the 2001 magnitude 5.1 mainshock (green cubes) and known surface fault traces (brown lines). Image courtesy of Debi Kilb

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