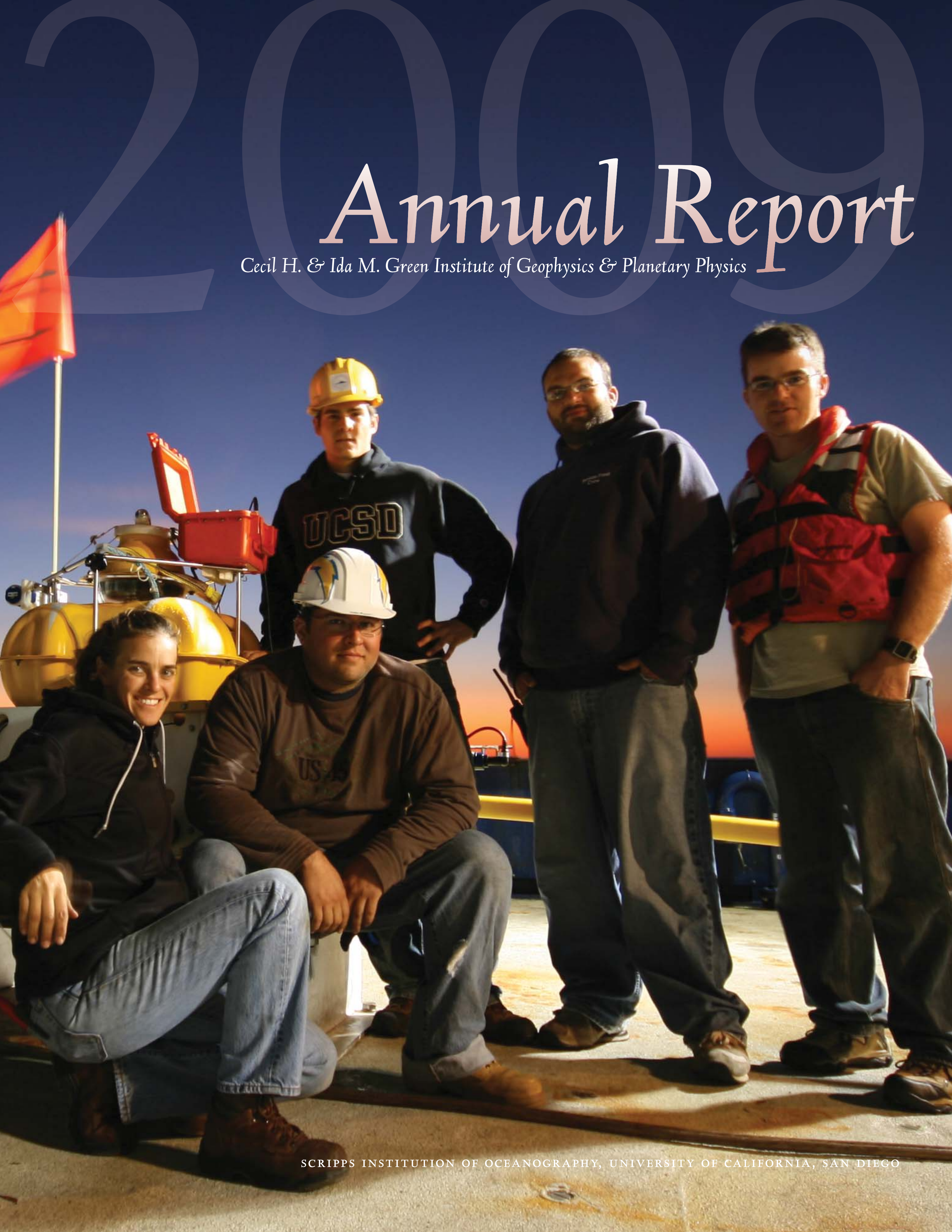
# 2009 Annual Report

Cecil H. & Ida M. Green Institute of Geophysics & Planetary Physics




SCRIPPS INSTITUTION OF OCEANOGRAPHY, UNIVERSITY OF CALIFORNIA, SAN DIEGO

# IGPP Annual Report

The 2009 Annual Report of the Cecil and Ida Green Institute of Geophysics and Planetary Physics is the fourth in a series begun in 2006 to present a comprehensive but brief account of the research going on at the Institute, concentrating on the past Academic Year. The objective is provide a description of our activities for prospective students and anyone else who has an interest in the Earth sciences, particularly geophysics.

In past Academic Year we have been joined by two new members of the permanent staff: Professor David Stegman, and Dr. Kerry Key. Professor Stegman works in geodynamics and computer modeling of tectonic processes, and in planetary physics. Dr. Key's area is marine electromagnetic exploration with a special interest in inversion and forward modeling of conductivity structures.

Two members of the Institute received national recognition for their research contributions: Professor Peter Shearer was elected to the National Academy of Sciences, and yours truly was awarded the John Adam Fleming Medal of the American Geophysical Union.

IGPP continues to be one of the foremost research centers for geophysics in the nation.

Robert L. Parker
*Professor of Geophysics, Emeritus*

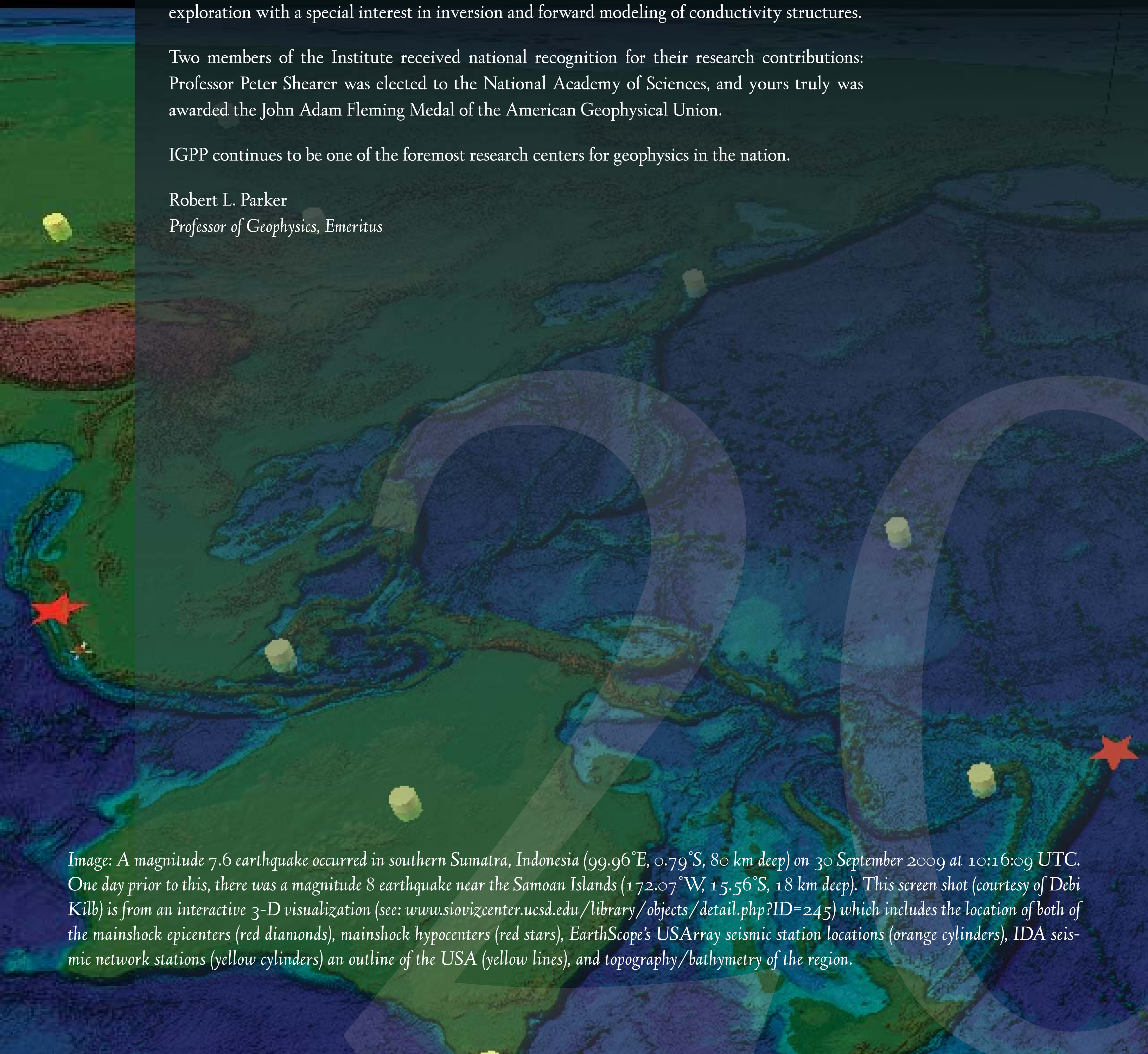


*Image: A magnitude 7.6 earthquake occurred in southern Sumatra, Indonesia (99.96˚E, 0.79˚S, 80 km deep) on 30 September 2009 at 10:16:09 UTC. One day prior to this, there was a magnitude 8 earthquake near the Samoan Islands (172.07˚W, 15.56˚S, 18 km deep). This screen shot (courtesy of Debi Kilb) is from an interactive 3-D visualization (see: www.siovizcenter.ucsd.edu/library/objects/detail.php?ID=245) which includes the location of both of the mainshock epicenters (red diamonds), mainshock hypocenters (red stars), EarthScope's USArray seismic station locations (orange cylinders), IDA seismic network stations (yellow cylinders) an outline of the USA (yellow lines), and topography/bathymetry of the region.*

acoustic thermometry, Dzieciuch, Worcester
acoustics, Blackman, Dzieciuch, Hedlin
Antarctic ice sheets, Fricker
complexity, Werner
crustal deformation, Agnew, Fialko, Sandwell
crustal seismology, Fialko, Kilb, Shearer, Vernon
cyberinfrastraucture, Constable, C., Orcutt, Staudigel
Earth's deep interior, Constable, S., Masters
earthquake mechanisms, de Groot-Hedlin, Fialko, Kilb, Minster, Shearer, Vernon
electrical properties, Constable, S.
electrical properties, Constable, S.
electromagnetic induction, Constable, C., Constable S., Parker
fluid mechanics, Ireley
geodesy, Agnew, Fialko
geodynamics, Laske, Sandwell, Stegman
geodynamos, Ireley
geomagnetism, Ierley, Constable, C., Parker
geophysical instrumentation, Agnew, Berger, Constable, S., Davis, Vernon, Zumberge
global seismology, Davis, Laske, Masters, Shearer
GPS, Agnew, Fialko, Minster
observational networks, Davis, Orcutt, Vernon
ocean acoustics, de Groot-Hedlin, Dzieciuch, Munk, Worcester
oceanography, Munk, Worcester
ocean bathymetry, Sandwell
infrasound, de Groot-Hedlin, Hedlin
inverse theory, Key, Parker
landscape systems, Werner
marine electromagnetic induction, Constable, S., Key
marine geology, Blackman, Harding, Laske, Staudigel
marine seismology, Harding, Laske, Orcutt
mid-ocean ridges, Constable, S., Blackman, Harding
normal modes, Davis, Masters, Laske
numerical methods, Constable, S., Dzieciuch, de Groot-Hedlin, Parker
paleomagnetism, Constable, C.
planetary physics, Stegman
radar techniques, Fialko, Fricker, Minster,Sandwell
reflection seismology, Harding
satellite laser altimetry, Fricker
seamounts, Staudigel
seismic anisotropy, Blackman
seismic hazards, Kent
seismic networks, Davis, Vernon
seismometers, Berger, Zumberge
spectral analysis, Dzieciuch, Parker, Shearer, Vernon
strainmeters, Agnew, Zumberge
tides, Davis, Agnew
turbulence, Ierley
volcanos, Fialko, Hedlin, Staudigel

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

**Crustal Deformation (Strainmeters)**

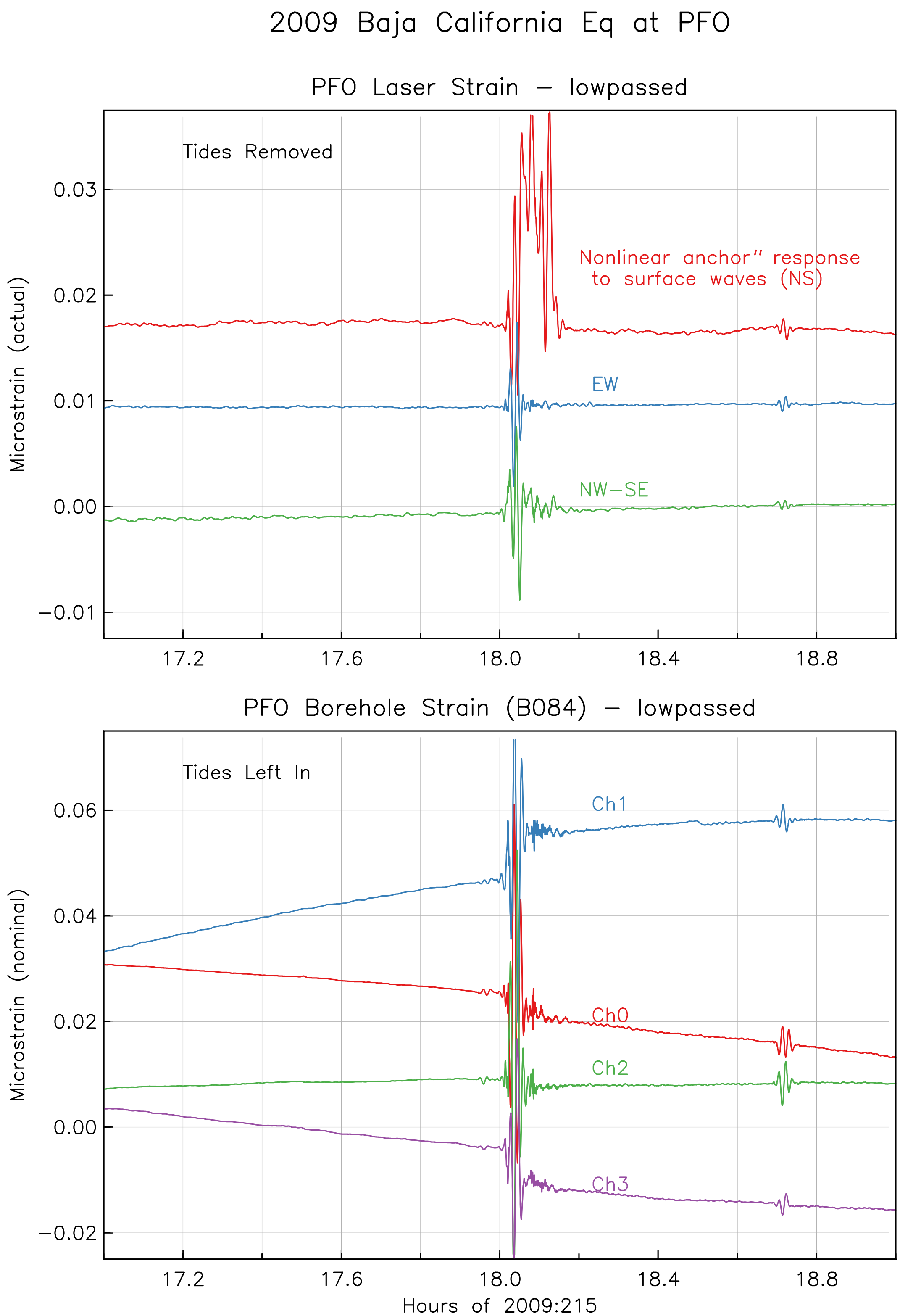
A major activity this year has been operating longbase laser strainmeters, both those supported by the Plate Boundary Observatory, and others: an activity led by Wyatt and supported by staff members Don Elliott and Billy Hatfield.

One particularly interesting result for the last year came as a result of a magnitude 6.9 earthquake in the Gulf of California on August 3, 2009 (day 215). The size, proximity, and radiation pattern of this event meant that the dynamic strains from the surface waves were the largest seen since the magnitude 7.2 earthquake off the coast of northern California on June 15, 2005 (day 166); before that, comparably large surface waves came from the Sumatra-Andaman earthquake (magnitude 9.3) of December 21, 2004 (day 356) and from the Denali earthquake (magnitude 7.8) of November 3, 2002 (day 307). The distances from PFO of these earthquakes were 610, 1190, 14700, and 3970 km respectively.

The surface waves from the 2009 earthquake were thus the first large dynamic strains (over $10^{-6}$ peak-to-peak observed since the installation of borehole strainmeters (BSM's) by the PBO. Most components of most of the BSM's in the Anza area showed significant offsets at the time of this earthquake. The expected static strains from this event at this distance are well below what was observed, but these offsets might be thought caused by triggered slip on more local faults if it were not for the results from the borehole strainmeters (BSM) and laser strainmeters (LSM) at Piñon Flat Observatory (PFO). Figure 1 shows the BSM and LSM data around the time of the earthquake, lowpassed to reduce the larger surface waves. Both the mainshock and a smaller (magnitude 6.2) aftershock are visible in the record. The NS LSM has a nonlinear response to the larger surface waves, caused by the behavior of the tiltmeter system used to anchor (approximately) the N-end monument. However, neither this nor the other two LSM's show any sign of the offsets found in the BSM records; for the best of the LSM records (the NWSE) the upper limit on a possible step is $10^{-10}$ strain.

Since the BSM at PFO is embedded in the rock bounded by the LSM's, we can be fairly confident that if the latter instruments show no offsets, the BSM offsets are spurious – which naturally suggests that the offsets seen on these instruments elsewhere are also spurious. The cause is unclear, but a plausible source would be hydrological changes, which are known to be triggered by large dynamic strains.

Graduate student Andrew Barbour is also studying the PBO borehole strainmeter data in order to establish the noise levels and usefulness of these instruments in the seismic band. Some of his results are: (1) the 1-Hz data appears to be significantly noisier than the 20-Hz data from which it is supposedly derived; (2) most of the Anza BSM's show noise peaks with periods from 10-20 s, varying with power-supply parameters; (3) while almost all the instruments detect the microseism noise peak, for all of them the noise level at frequencies above 2-3 Hz is set by least-count noise rather than ground noise, except at a few sites with noise spikes caused by local pumping.




## Publications

Agnew, D. C. (2009). Upside-Down Quakes: Displaying 3D seismicity with Google Earth, *Seismol. Res. Lett.*, **80**, 499-505, doi:10.1785/gssrl.80.3.499

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

For the past several years, I have been working with Mark Zumberge and Jose Otero on the development of a optical seismometer. This new seismometer is significantly different from previous instruments: it uses no electronics in the sensor package, only optics. (Zumberge *et al.,* 2009.) It consists of a mass suspended by a leaf-spring and uses optical interferometry to sense the displacement of the mass. Force feedback is not needed because of the combined high resolution and wide dynamic range of the optical displacement transducer. We have demonstrated that this interferometer is capable of resolving ambient ground noise from periods of several hundred seconds to greater than 10 Hz. In particular, it can resolve seismometer mass displacement with a root-mean-square noise per octave band that varies from about $2 \times 10^{-12}$ m at 0.001 Hz to $3 \times 10^{-13}$ m at 1 Hz. The maximum displacement is limited by mechanical issues to a few mm at present, providing a dynamic range of at least $10^9$ equivalent to 30 bits. One sensor can therefore provide the requisite performance from hundreds of seconds to hundreds of Hz.

The use of interferometry rather than traditional electronic displacement transducers provides the following features:

- The optical sensor is a linear, high-resolution digital displacement detector, providing about a 30-bit resolution digital output;
- It measures absolute displacement referenced to the wavelength of the laser light;
- The bandwidth and resolution is sufficient to resolve the GSN low noise model from DC to > 15 Hz;
- The dynamic range is sufficient to record the largest teleseisms and most regional and local earthquakes;
- There is a minimal electronics package — after initial leveling, only an optical fiber connection to the seismometer is required, eliminating heat from electronics in the sensor package and noise pickup from connecting electrical cables.

We have shown that our optical technique is very effective in an observatory model that we have built and tested (Zumberge *et al*, 2009). Except for periods longer than about 500 to 1000 seconds, it appears that we have matched the combined performance of the STS-1 and STS-2 seismometers in the vertical axis.

Our seismometer differs from the normal mainly in that we have replaced an electronic displacement sensor with an optical one, and we have eliminated feedback. A leaf-spring suspension system supports a mass free to oscillate in the vertical direction, and an interferometer measures the displacement between the mass and the frame. An interferometer in which displacement is monitored just by counting whole fringes resolves only $3 \times 10^{-7}$ m (assuming a 633 nm HeNe laser is used as the source). For use in seismomtery however, much finer resolution is required together with large dynamic range. We require resolution in displacement of about $10^{-12}$ m $Hz^{-1/2}$ along with the ability to follow displacements that may span several mm if we want to construct a broadband seismometer. To achieve this, we have developed and tested a digital-signal-processor (DSP) based fringe resolver with a demonstrated resolution of $3 \times 10^{-13}$ m $Hz^{-1/2}$ at 1 Hz (Zumberge *et al*., 2004).

Briefly, laser light is transmitted to the seismometer by an optical fiber, and interference fringes formed by the interferometer inside the seismometer are carried back to the recording system by other optical fibers. A digital signal processor (DSP) analyzes the return optical signals, converting them to displacements with extremely high sensitivity. The DSP is connected via USB to a small computer, which provides a user interface, packages the data into self-contained packets, and communicates with the Internet via a standard Ethernet connection. A single DSP and coupled computer can serve up to four seismometer components. Because only optical fibers are connected to the instrument, the sensor can be located quite far from the data system (hundreds of meters).

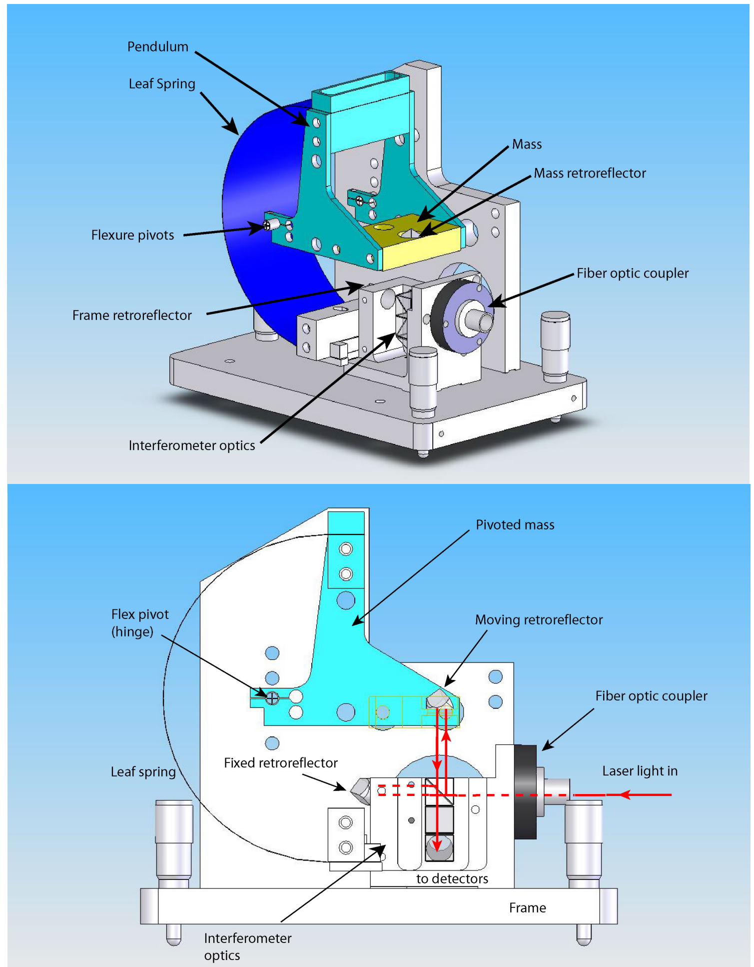


**Figure 1.** An isometric (top) and a side (bottom) view of the prototype seismometer we have assembled. An optical fiber brings laser light to the interferometer optics, and two other optical fibers carry the interference fringes away to detectors. The interferometer senses vertical motion of a retroreflector mounted to the pivoted mass.

The data presented in Zumberge *et al.*, 2009 are very good indications that the performance of the optical seismometer is a candidate for observatory use. First, seismic records of earthquake body and surface waves appear to be as good as or better than those from other sensors. Second, we already observe normal modes with high fidelity to periods as long as 500 seconds, and we have only recently begun to focus on improvements in the long period performance. Third, the bandwidth is broader than those of the existing GSN sensors. Finally, our optical seismometers observe gravity tides with a signal-to-noise ratio of around 100. This is important in that it provides a useful calibration signal. Because of the simplicity of the optical seismometer, its response at tidal frequencies is the same as its response at normal mode frequencies, providing a continuous calibration source without the need to model an electronic feedback transfer function.

### Relevant Publications

Mark Zumberge, Jonathan Berger, Jose Otero, and Erhard Wielandt., A Non-fedback Optical Seismometer. *Bull.Seis.Soc.Am, 2009 submitted.*

Zumberge, M. A., J. Berger, M. A. Dzieciuch, and R. L. Parker (2004). Resolving quadrature fringes in real time. *Applied Optics*, **43,** 771-775.

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*Research Interests:* tectonic and magmatic processes that occur along plate boundaries with emphasis on oceanic spreading centers; deformation of minerals and the development of seismic anisotropy during mantle flow; calibration testing for hydroacoustic monitoring of nuclear tests.

Geophysical investigations of oceanic spreading center processes continue to be the main focus of my research. The approaches I use vary both by design and in response to opportunities for seagoing experiments. In 2008/2009 my analyses incorporated data/results from deep sea drilling, shipboard mapping, and seismic refraction modeling. Non-standard analysis of prior geophysical data from an oceanic core complex on the Mid-Atlantic Ridge provided the basis for tomographic modeling of the upper ~km of the domal core, which has been exposed by a detachment fault. In collaboration with Graham Kent and Alistair Harding, a downward continuation method is being applied by graduate student Ashlee Henig to multi-channel seismic data. She has determined that a tectonic block previously hypothesized to be highly serpentinized throughout has an eastern 'shoulder' that has velocity too high to be explained by this model. Either mafic rock occurs there or the degree of serpentinization is lower. Ashlee's ongoing work will quantify the scales of lateral and vertical heterogeneity throughout the upper km of the core complex. Meanwhile, I have begun analyzing larger-offset refraction data, in collaboration with John Collins at WHOI, in hopes of elucidating structure to few-km depths.

Having wrapped up my duties as Ridge 2000 chair late 2008, I've returned to working on the development of mineral alignment during mantle flow, which results in seismic anisotropy observed by instruments at the Earths surface. My main effort this past year have been to further the collaboration that Green Scholar Olivier Castelnau and I began during his 2006 visit. We have begun incorporating the rheologic anisotropy that is predicted for polycrystalline mineral aggregates into the flow model. The anisotropy of the aggregate's viscosity can affect the predicted flow pattern. At this stage we are assessing the scale of this effect. Based on the rheological anisotropy computed for mineral orientation distributions computed for an isotropic-viscosity flow field, we expect that complex regions of the flow will have non-negligible changes in flow when the anisotropic viscosity is accounted for. However, until the full simulation is run we do not know what feedbacks there may be so that is the focus of our current series of numerical experiments.

The 'strongly-coupled' approach to simulating linked texture-flow calculations described above requires that we compute the texture at a given location within the flow field in a way that produces a description of the full viscosity tensor. While a number of other, less computationally intensive methods to estimate texturing have been published (see Figure), most do not result in a rheologic characterization of the textured mineral aggregate. Apart from this aspect, our work earlier in the year highlighted the ways that the Second-Order ViscoPlastic Self-Consistent method differs in the strength/pattern of alignment (lattice preferred orientation) that develops along a given flowline within a model of mantle flow beneath an oceanic spreading center.

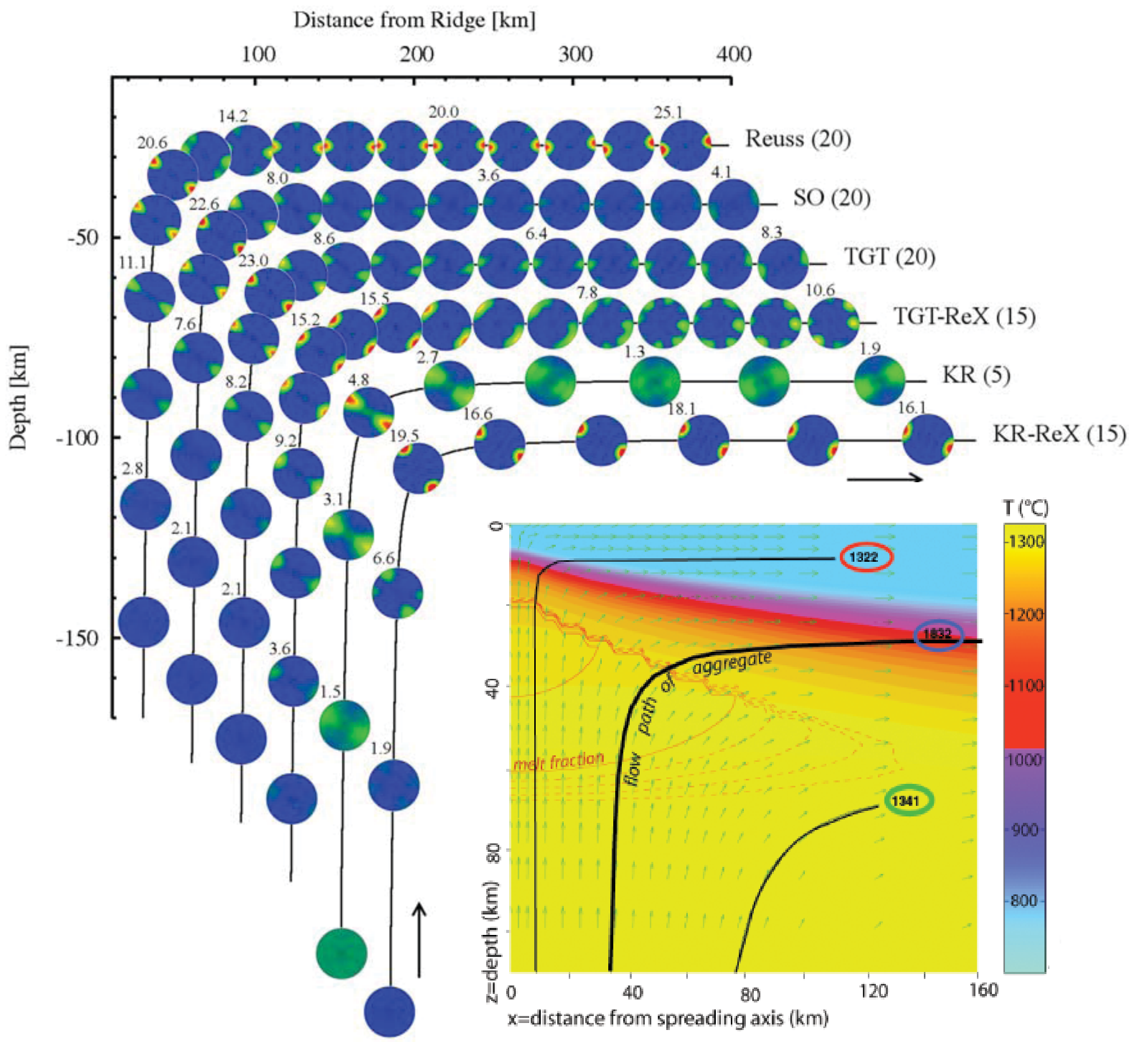


Figure. Texture (lattice preferred orientation, LPO) predictions at positions along streamline for different micromechanical models, as labeled. Both SO (Second Order) and TGT (Tangent) are VPSC methods. KR indicates the kinematic approach of Kaminsky & Ribe 2004. Simulations including recrystallization effects are indicated with "ReX". Pole figures show olivine a-axis orientation distributions, red indicating maximum concentration of axes. Numbers above the pole figures indicate maximum intensity. Inset: The temperature and flow field for the spreading center model is shown by color and vectors, respectively. The flowline used for these texture calculations (#1832) is labeled.

Donna K. Blackman, J. Pablo Canales and Alistair Harding, Geophysical signatures of oceanic core complexes, REVIEW ARTICLE Geophys. J. Int. 178, 593–613, doi: 10.1111/j.1365-246X.2009.04184.x, 2009.

Castelnau, O., D. K. Blackman, T.W. Becker, Numerical simulations of texture development and associated rheological anisotropy in regions of complex mantle flow, Geophys. Res. Letter, 36, L12304, doi: 10.1029/2009GL038027, 2009.

Collins, J.A., D.K. Blackman, A. Harris, R.L. Carlson, Seismic and drilling constraints on velocity structure and reflectivity near IODP Hole U1309D on the central dome of Atlantis Massif, Mid-Atlantic Ridge 30°N, $G^3$ 10, doi:10.1029/2008GC002121, 2009.

de Groot-Hedlin, C., D.K. Blackman, C.S. Jenkins, Effects of variability associated with the Antarctic Circumpolar Current on sound propagation in the ocean, Geophys. J. Intl., 176,478-490, doi: 10.1111/j.1365-246X.2008.04007.x. 2009.

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

Yehuda Bock's research in 2009 was focused on early warning systems for natural hazards and expansion of real-time GPS monitoring in southern California [*Crowell et al*., 2009], continued studies of crustal deformation in Sumatra [*Konca et al., 2008*; *Prawirodirdjo et al*., 2009], and ongoing IT development to provide tools [*Noll et al*., 2009] to explore and model long-term surface deformation observations for understanding earthquakes [*Barbot et al*., 2009] and the processes that drive tectonic motion. He continues to expand the California Real Time Network (http://sopac.ucsd.edu/projects/realtime/) for GPS seismology, GPS meteorology, and precise real-time positioning. In *Crowell et al.* [2009], the early warning system that Yehuda developed with graduate student Brendan Crowell and Mindy Squibb is described. Total (dynamic + static) displacement waveforms are computed once per second for all available network stations using instantaneous GPS positioning. Anomalous strain detection is accomplished by first creating a Delaunay triangulation grid over all stations, and computing the two principle components of strain rate in each triangle. Once strain reaches a pre-specified threshold, an alert is disseminated to key personnel. With the simulated Mw 7.8 2008 Southern California ShakeOut event and 2003 Mw 8.3 Tokachi-Oki earthquake, detection is in the first few seconds, and 20 seconds after the initiation of the earthquake, respectively. The next step is to determine the earthquake hypocenter, which is performed when displacements of four or more stations exceed preset criteria of total displacement, followed by estimate earthquake magnitude. We are investigating rapid estimation of earthquake magnitude through empirical scaling relationships derived from a comparison of coseismic and total displacements, each decaying as a different function of epicentral distance (Figure 1). We have also been experimenting with rapid determination of earthquake source models. For the Tokachi-Oki earthquake, we have reduced the time to generate a full model inversion to about 15 minutes (Figure 2). Although the calculation needs to

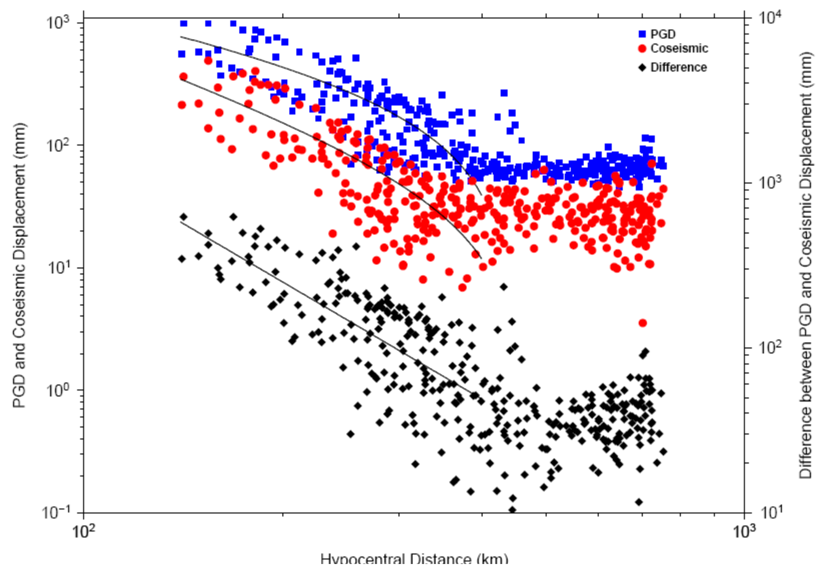


**Figure 1.** Peak ground displacement and coseismic displacement as a function of hypocentral distance for the 2003 Mw 8.3 Tokachi-Oki earthquake. The dashed lines are the best fit of $r^{-1}$ and $r^{-2}$ curves for PGD and coseismic displacement, respectively up to 400 km away from the hypocenter.

be sped up in order to be part of a viable earthquake early warning system, even in its current form, having a source model estimate is extremely useful for decision makers and earthquake researchers, and may be useful for tsunami warning.

Yehuda also directs the Scripps Orbit and Permanent Array Center (http://sopac.ucsd.edu) and the California Spatial Reference Center (http://csrc.ucsd.edu). With funding from NASA, Yehuda, Paul Jamason, Mindy Squibb and Peng Fang are collaborating with investigators at JPL to develop an on-the-fly data analysis and modeling portal for the Earth Sciences, called GPS Explorer (Figure 3). Community resources include access to extensive data and data product archive holdings at SOPAC, a mapping interface, an Oracle database management system, GeodeticML (XML) schema for GPS products, and Geophysical Resource Web Services [*Noll et al*., 2009] .

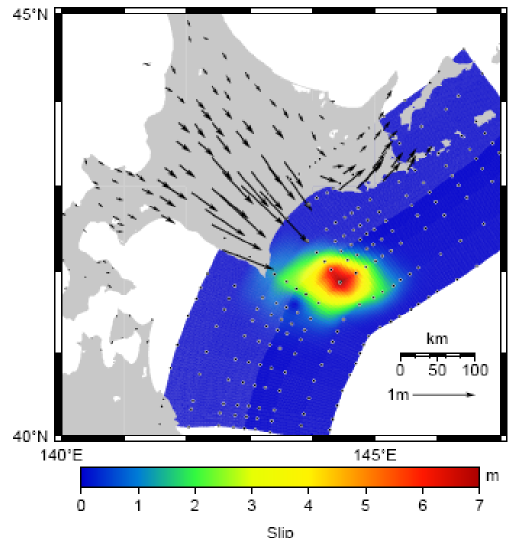


**Figure 2.** Coseismic inversion of the first 10 minutes of 1 Hz GPS data from the 2003 Tokachi-Oki earthquake. The GPS vectors are the coseismic displacements observed from the first 10 minutes of data and used in the inversion.

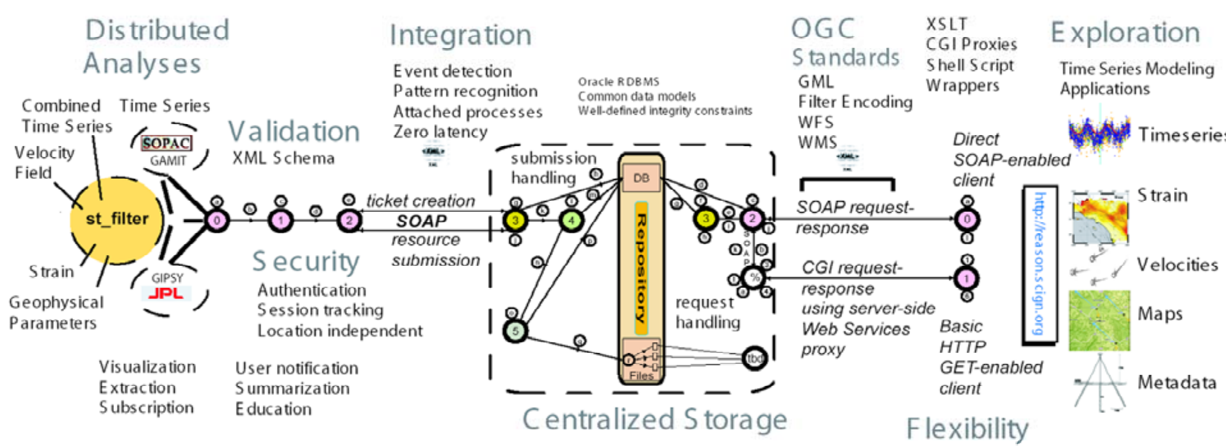


**Figure 3.** GPS Explorer cyberinfrastructure components (http://geoapp03.ucsd.edu/gridsphere/gridsphere).

## Recent Publications

Barbot, S., Y. Fialko, and Y. Bock (2009), Postseismic deformation due to the Mw 6.0 2004 Parkfield earthquake: Stress-driven creep on a fault with spatially variable rate-and-state friction parameters, *J. Geophys. Res*., *114*, B07405, doi:10.1029/2008JB005748.

Crowell, B., Y. Bock, and M. Squibb (2009), Demonstration of earthquake early warning using total displacement waveforms from real time GPS networks, *Seismo. Res. Lett*., *80*(5), 768-778.

Konca, A. O., J.-P. Avouac, A. Sladen, A. J. Meltzner, K. Sieh, P. Fang, Z. Li, J. Galetzka, J. Genrich, M. Chlieh, D. H. Natawidjaja, Y. Bock, E. J. Fielding, C. Ji & D. V. Helmberger, (2008), Partial rupture of a locked patch of the Sumatra megathrust during the 2007 earthquake sequence, *Nature 456*, 631-635 (4 December 2008), doi:10.1038/nature07572.

Noll, C., Y. Bock, H. Habrich, and A. Moore (2009), Development of data infrastructure to support scientific analysis for the International GNSS Service, *J. Geod*., *83*, 309–325, doi:10.1007/s00190-008-0245-6.

Prawirodirdjo, L., R. McCaffrey, C. D. Chadwell, Y. Bock, and C. Subarya (2009), Geodetic observations of an earthquake cycle at the Sumatra subduction zone: The role of interseismic strain segmentation, *J. Geophys. Res*., in press.

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

Work over the past year has continued on four projects: (i) geomagnetic field behavior during the Holocene time period (with post doc, Fabio Donadini, now at ETH Zurich, and collaborator Monika Korte of GeoForschungs Zentrum, Potsdam); (ii) the magnetic field on million year time scales (PhD student Leah Ziegler, and Adjunct Professor Catherine Johnson); (iii) development of modeling and data processing tools for electromagnetic induction studies using magnetic field observations from low-Earth-orbiting satellites (PhD students, Joseph Ribaudo and Lindsay Smith); (iv) the development with Anthony Koppers and Lisa Tauxe of flexible digital data archives for magnetic observations of various kinds under the MagIC (Magnetics Information Consortium) database project.

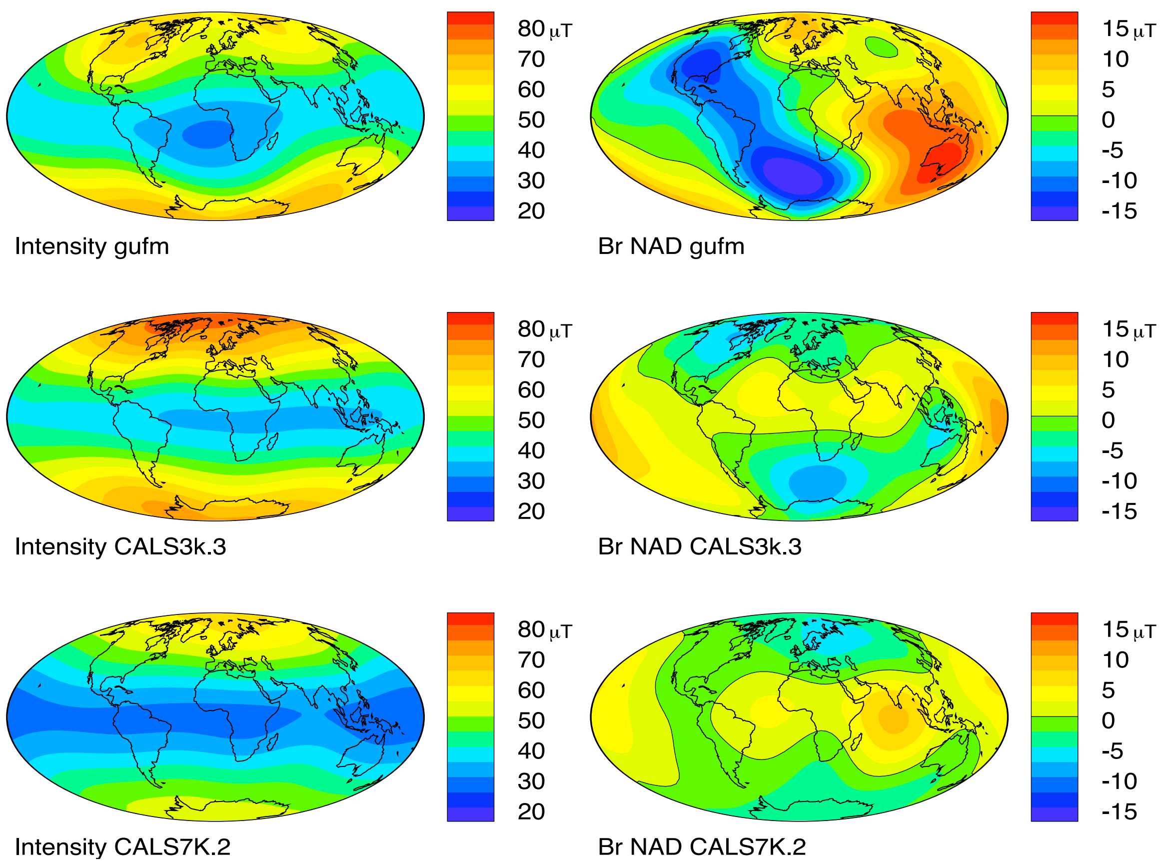


**Figure 1** Intensity and non-axial-dipole radial field contribution (Br NAD) of averaged spherical harmonic field models gufm (1590-1990 A.D.), CALS3k.3 (1000 BC - 1990 A.D.), CALS7K.2 (5000 BC - 1950 A.D.) at the Earth's surface.

*The Holocene Geomagnetic Field:* The geomagnetic field has been measured at a variety of locations since the development of the first compasses, and direct observations on Earth's surface and (more recently) from low-earth orbiting satellites have led to excellent time-varying descriptions of the field for the past 400 years. Longer term variations are not so well documented, but major effort has recently been invested in compiling and evaluating comprehensive paleomagnetic data sets; new models for 0-10 ka also incorporate constraints from the 1590-1990 AD era of direct observations. We have published a suite of improved millennial scale time varying geomagnetic field models for the past 3 kyr and are now extending these back to 10ka. These models are being used to study the evolution of the South Atlantic Anomaly (SAA), currently manifest as a low intensity feature in that general region, and linked to a decrease of geomagnetic dipole strength over the past two centuries. Figure 1 illustrates how the SAA appears to change when viewed on 400, 3000, and 7000 year time intervals, and has evolved in its current form since about 1800 AD. Similar anomalies have appeared at least twice during the past millennium (during the 13th and 16th centuries), but not in quite the same location. In earlier millennia the anomalies become harder to track definitively because of limited data coverage, but they appear in the Australian/Indian ocean region and even in the Pacific. The peak of any given anomaly appears to coincide temporally with local minima in the dipole moment and occurs in the southern hemisphere, raising the possibility that hemispheric asymmetry in the dipole decay may be a recurrent feature of the field. The models also show that the current drop in field strength is consistent with the idea that SAA-like features are a recurrent episodic phenomenon. The dipole moment is currently at, or close to, its lowest value for the past 3 kyr, but the fact that it has been systematically lower in preceding millennia (as in the CALS7k.2 model average) suggests that there is no immediate concern that the field is about to reverse.

*The Magnetic Field on Million year Time Scales:* Graduate student Leah Ziegler has been investigating the extension of time-varying field models to much longer (million year) time scales by combining directional and relative paleointensity data from marine sediments, with directions and absolute paleointensity data recovered from lava flows. Following a study of the robustness and limitations of the 0-1 Ma absolute paleointensity data current work is focussed on the development and application of a maximum likelihood method that uses these data to calibrate individual time series of relative paleointensity variations derived from marine sediments and use the calibrated data to recover a continuous representation of paleomagnetic axial dipole moment variations for the 0–2 Ma time interval with about 10 kyr resolution. A parallel effort to compile lava flow data and assess their temporal and geographic coverage will allow the development of a low resolution global spherical harmonic model like those illustrated in Figure 1 but for the 0-2 Ma time interval.

**Relevant Publications**


Lawrence, K. L., L. Tauxe, H. Staudigel, C. G. Constable, A. Koppers, W. McIntosh, and C. L. Johnson, Paleomagnetic field properties at high southern latitude, *Geochem., Geophys., Geosyst.*, 10, Q01005, doi:10.1029/2008GC002072, 2009.

Donadini, F., M. Korte, & C.G. Constable, The geomagnetic field for 0–3 ka, Part I: New data sets for global modeling, *Geochem. Geophys. Geosyst.*, 10, Q06007, doi:10.1029/2008GC002295, 2009.

Korte, M., F. Donadini, & C.G. Constable, The geomagnetic field for 0–3 ka, Part II: A new series of time-varying global models, *Geochem. Geophys. Geosyst.*, 10, Q06008, doi:10.1029/2008GC002297, 2009.

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*Research interests*:

Marine EM methods, conductivity of rocks, satellite induction studies

Steven Constable is the lead PI for the SIO Marine EM Laboratory, which currently consists of project scientist Yuguo Li, postdoctoral scholar Karen Weitemeyer, and PhD students David Myer, Brent Wheelock, and Samer Naif. Kerry Key, Assistant Research Geophysicist, is also affiliated with the Lab and is involved in much of the research and student advising. Arnold Orange, Research Associate, spends about a week a month working with us at IGPP and comes along on most of our cruises. As the name suggests, much of the Lab's work is involved in developing and using marine EM methods, 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 and the induced electric fields.

This has been a very big year for us in terms of data collection, with projects to map gas hydrate in the Gulf of Mexico, to study the continental margin off California, and a survey of a gas field on the Northwest Shelf of Australia.

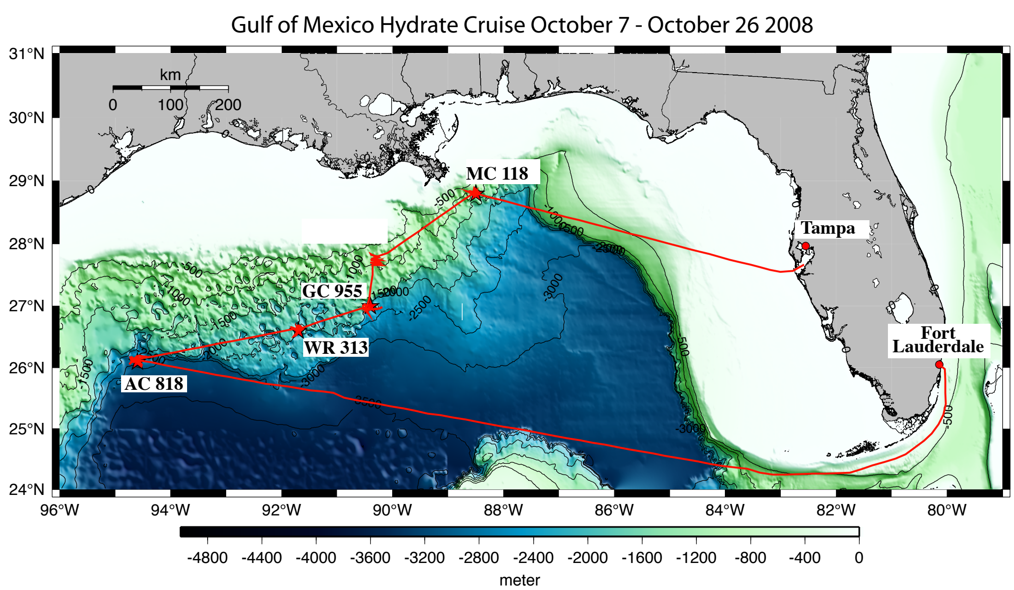


*Figure 1.* The four sites in the Gulf of Mexico over which we collected marine CSEM data to map sub-seafloor gas hydrate.

Marine gas hydrates may variously be viewed as a hydrocarbon resource, a source of greenhouse gases, as a natural hazard, or as a cap-rock for $CO_2$ sequestered in marine sediments. However, very little is known about the total amount of hydrate stored in marine sediments, and EM methods may be the only way of quantifying this (hydrate is more resistive than the host sediments). Because hydrate is widespread and forms in many different geological environments, our project in the Gulf of Mexico in October 2008 targeted four different prospects (Figure 1), one which had been previously drilled by Chevron (AC 818), two of which were later drilled by DoE (WR 313 and GC 955), and one which is a MMS hydrate observatory (MC 118). All four surveys were successful with 94 total deployments and 103 hours of transmitter tow, and Karen is working on these data for her postdoctoral studies.

The second cruise was to augment a land MT survey carried out by German colleagues to study the San Andreas fault zone near Parkfield. During November–January we extended the land arrays with a 200 km long offshore profile of marine MT stations. The objective is to study the interaction of the stalled slab and underplated crust with the plate boundary fault zone. One hypothesis is that fluids migrating into the base of the fault are responsible for non-volcanic tremor observed near Parkfield. We deployed 36 instruments in November 2009, and towed our EM transmitter along the entire length of the array to collect CSEM data. We then left the instruments down until January 2009 to collect MT data. Unfortunately, a newly made circuit board installed to extend the battery life of the instruments failed on some, but there are still plenty of data left for Brent to use in his Ph.D. studies.

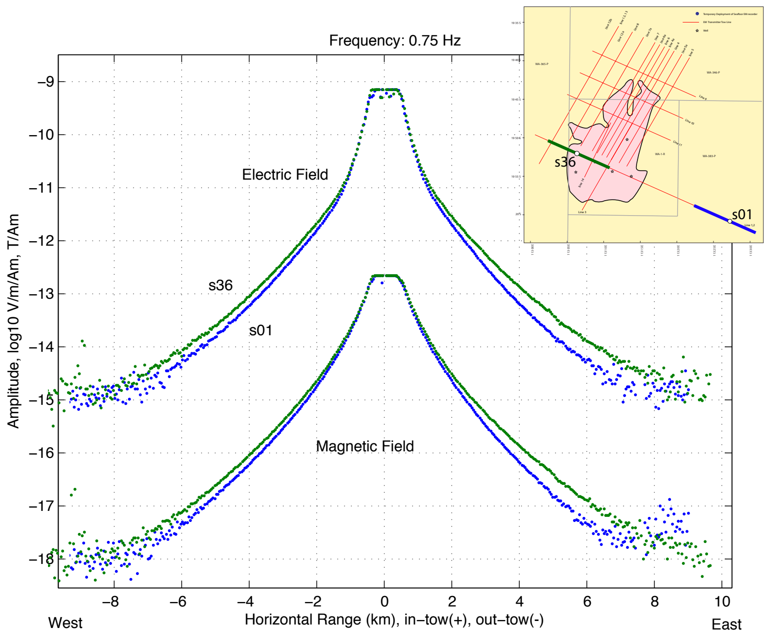


*Figure 2.* A sample of marine CSEM data collected over the Scarborough gas reservoir (shown as the pink outline in the inset) off the Northwest Shelf of Australia. The green site is over the western edge of the reservoir, while the blue site is far off target to the east. The effect of the resistive reservoir is to increase the electric and magnetic fields, which is clearly visible in the data at source-receiver ranges of 1–6 km. The red lines in the inset show the total coverage of our data set.

Marine CSEM has been used for the past 8 years to explore for offshore oil and gas, but almost all the data being collected are proprietary. This year we were funded by BHP Billiton to carry out a fully academic survey of one of their gas fields in order to facilitate the development of the technology and interpretation tools. The survey was large even by industry standards, with 114 deployments and nearly 12 days of CSEM transmitter tow. Figure 2 shows data from just two sites, clearly showing how the gas reservoir is visible in the size of the electric and magnetic fields. This project has produced material for years of work, but most immediately David Myer will be using some of them to finish off his Ph.D. thesis. Ultimately, we may want to use CSEM methods to monitor fields such as this during production, and Arnold has been carrying out model studies to best understand how this might be done (Orange *et al.*, 2009).

Part of the funding for the group comes from a consortium of 36 oil companies (the Scripps Seafloor Electromagnetic Methods Consortium) which are interested in developing marine EM methods for offshore exploration. We host a 2-day workshop for these sponsors every year in March, and this year we were joined by visitors from Japan (Tada-nori Goto), the UK (Martin Sinha), and Germany (Katrin Schwalenberg). Michael Becken, also from Germany, visited earlier in the year to work with Brent on the San Andreas project. Further information can be found at the lab's website, *http://marineemlab.ucsd.edu/*

**Relevant Publications**

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**J. Peter Davis**

**Specialist**

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

Peter Davis's research responsibilities at IGPP center upon monitoring 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's core philosophy, that data integrity may best be maintained by keeping network managers in close contact with research scientists who routinely use the data, has proven well-justified over the 30+ years of IDA's existence.

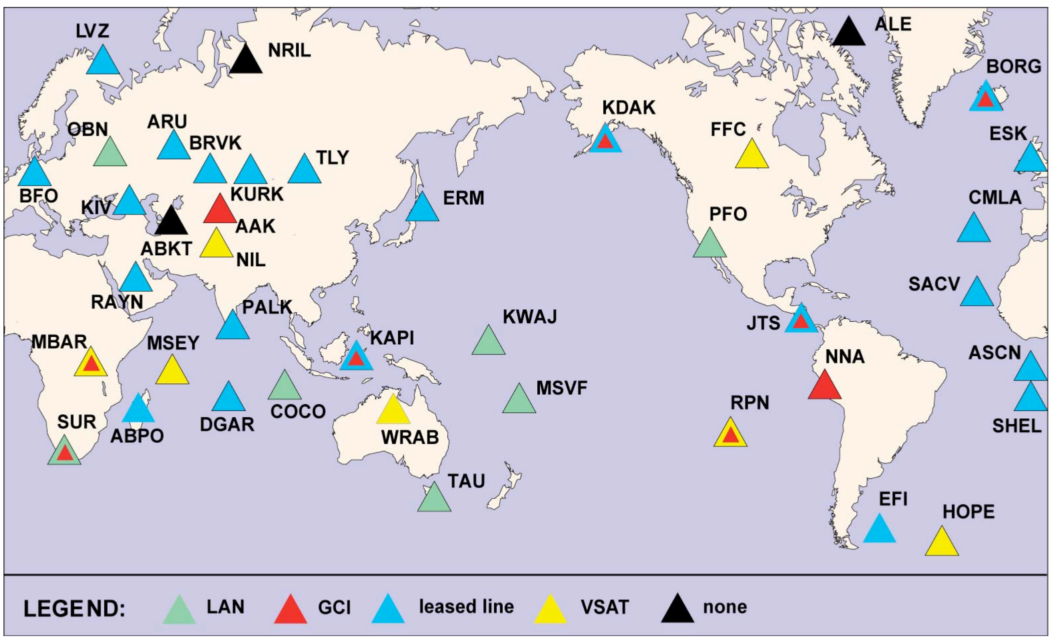


*Figure 1*. Current telemetry topology of the IRIS/IDA network.

Some of Peter Davis's recent work utilized tidal signals to evaluate the accuracy of instrument response information published by the GSN. 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. All GSN network operators including IDA supply this response information along with the seismological time series. Because tides are a continuous background signal observable at nearly all GSN stations not at high latitudes, they are ideal for checking the validity of instrument response over the lifetime of the network. Using information collected by satellites about tidal flow of water in the ocean basins, scientists can now model the effect of tides very accurately at any point on the Earth's surface. With programs provided by Duncan Agnew of IGPP, Pete computed the tidal signal at all GSN stations to the accuracy required for validating their reported instrument response.

This technique was useful both for checking instrument responses and for examining long term changes in the behavior of the network's sensors. Figure 2 shows results for one GSN station. Data segments varying from 60-180 days were used to compare the recorded tidal signal from the stations main seismometer with what was predicted from the ocean models. If the computations agreed, all points should have unity relative amplitude in this plot. It was also possible to compare the principal sensor with a second seismometer deployed at the station. Both sensors behave similarly over the past decade, so their stability is very good.

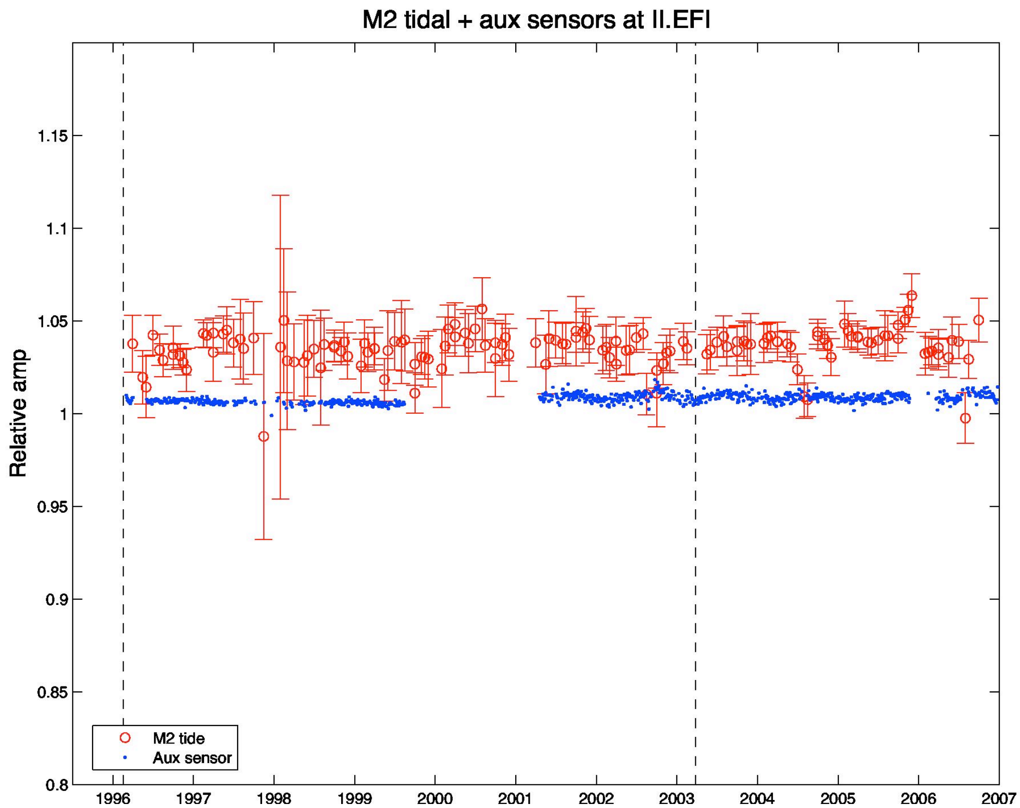


*Figure 2*. Sensor sensitivity tests of the principal and auxiliary sensors at EFI (East Falkland Island). Red symbols denote results from the KS-54000 vertical sensor as measured by tides. The blue symbols represent the ratio of the principal and auxiliary vertical sensor output near the microseismic peak, 0.15 Hz.

**Relevant Publications**


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

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

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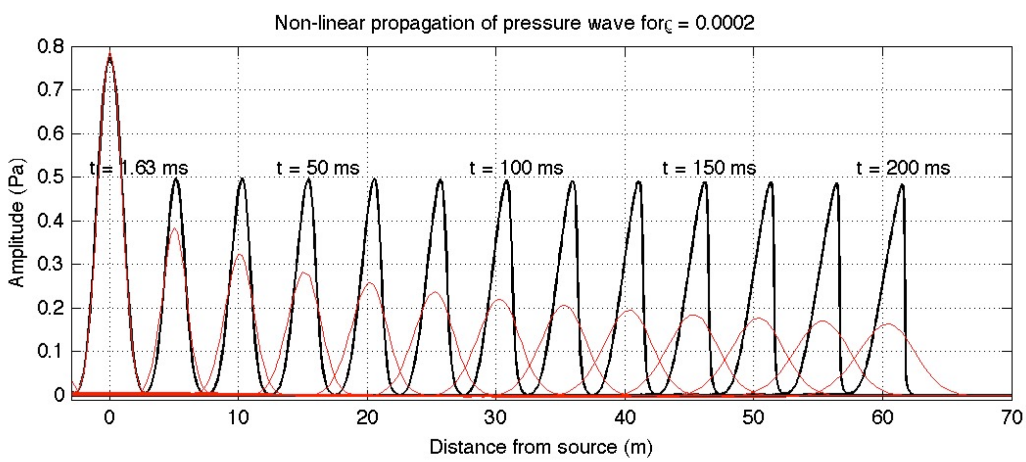
*Research Interests:* Acoustic propagation modeling with application to infrasound and hydroacoustics; application of hydroacoustics and infrasound to nuclear test-ban verification; use of dense seismic networks to analyze infrasound signals; application of infrasonic signals to hazard monitoring.

***Infrasound:*** A primary goal in infrasound research is to understand the transmission of infrasound - sound at frequencies lower than human hearing - to distances of several hundreds to thousands of kilometers. deGroot-Hedlin is co-PI on projects to investigate infrasound propagation from various sources, including natural hazards. de Groot-Hedlin is also the sole-PI on a project to develop numerical methods to compute acoustic shock waves propagation from explosive charges.

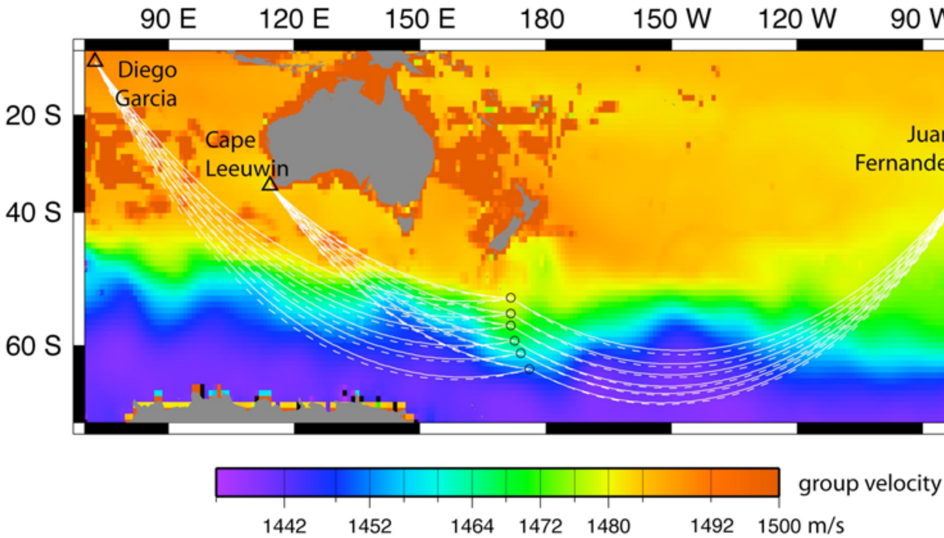
*Shock Waves in the Atmosphere:* deGroot-Hedlin has developed a radial basis function code to compute acoustic shock waves from explosive charges. The code solves for velocities and pressures using the non-linear Navier-Stokes equation, for a uniform sound speed and density. The pressure results are shown below for several time steps, for an initial pressure of 1 Pa, and a density of 0.0002, well up in the mesosphere. A ‘spike’ – represented by an exponential waveform of width 1 m is used as a starting point in pressure at time t=0 s, and the field is propagated to a time of 0.2 s.




Pressure solutions are shown at select times above, both for realistic atmospheric attenuations (black), and atmospheric values of 100 times the true atmospheric viscosity (red) for comparison. At low atmospheric attenuation (and low density), the results show that the wavefront becomes steeper with increasing range from the source. There is greater dispersion with increased dispersion, and the wave front remains smooth since the atmosphere preferentially attenuates high frequencies.

***Hydroacoustics:*** de Groot-Hedlin was co-PI with Donna Blackman on an investigation of the propagation of hydroacoustic energy through the Antarctic Convergence Zone (ACZ), the site of a sharp discontinuity in acoustic velocity. The particular challenges of propagation in this region are that the lateral sound speed gradients at the ACZ boundary causes deflection of hydroacoustic energy, and that propagation of hydroacoustic energy to the south of the ACZ is more dispersive than propagation at equatorial and mid-latitudes. Both effects can cause errors in source locations estimates.

A research cruise was conducted in December 2006, along a transit from Christchurch, New Zealand to McMurdo station in the Antarctic. Small explosive charges were fired at depths from 300m to 600m. The shots were recorded at several hydroacoustic stations that form a part of the International Monitoring System (IMS) at distances of 5000 to 9000km from the source. Our results show that changes in the signal duration and average sound velocity from shots in the ACZ varies with latitude.




Geodesic paths (dotted white lines) and laterally deflected sound paths (solid white lines) for minimum travel time paths from each shot (circles) to each IMS hydrophone station (triangles). The paths are superimposed on a map of group velocities derived using average fall sound speed profiles for mode 1 at a frequency of 50 Hz.

## Relevant Publications


de Groot-Hedlin, C.D., M.A.H. Hedlin, K.T. Walker, D. D. Drob, and M.A. Zumberge, Evaluation of infrasound signals from the shuttle Atlantis using a large seismic network, *J. Acoust. Soc. Am.*, **124**, 1442-1451, (2008a)

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*Research interests*: acoustical oceanography, ocean acoustic tomography, signal processing

**Philippine Sea Experiment**

Over the past year I have been partipating in an ocean acoustic tomography experiment. The experiment has been funded by the Office of Naval Research and is taking place in the Philippine Sea starting in 2009 and ending in 2011. This location is in a challenging and dynamic part of the ocean, which is located near, but not in the origin of a major western boundary current, the Kuroshio. The program has two main goals, one is oceanographic in nature, and the second explores acoustic issues.

It has been speculated from recent modeling work (see the third paper referenced below) that ocean basin western boundary currents radiate barotropic waves that carry a large amount of energy with them. These are difficult to detect with standard oceanographic instrumentation but should be possible to detect with a tomographic array like the one that we have designed. A secondary purpose is to find the limits of ocean model predictability given the strong constraints of the tomography data and thus improve model performance. This questions will be explored with data to be taken during the upcoming year-long deployment of a tomographic array.

The second goal is to continue to explore the limits of ocean acoustic systems whose time and space coherence scales are limited by the ocean's dynamics. Since this experimental location is in a much more energetic location than previous ones in the North Pacific, it will be interesting to see how stable the acoustic paths are in this area. Differences in stratification, and increased mesoscale energy, are expected to strongly influence the results.

Some preliminary results are already available from a month-long engineering deployment of a vertical line array of receivers this past April. This array featured 60 internally-recording autonomous hydrophones that are capable of recording 16 Gbytes of acoustic data. The first-time deployment of this array was configured with 30 hydrophones spaced 25m apart near the sound-channel axis at 1000m, and 30 more hydrophone spanning the surface conjugate depth at about 4600m.

The figure below shows the minimum noise power recorded on the vertical line array as a function of depth. The scientific interest here is to explain the reduction of power with depth and frequency. The minimum noise level is thought to be a combination of distant shipping traffic and wind-driven ocean turbulence near the surface. The figure confirms results that others have qualitatively described, but the data are meant to give a very good quantitative measurement of the effect. The challenge will be to develop a model that has actual predictive power based on wind-speed and shipping traffic density.

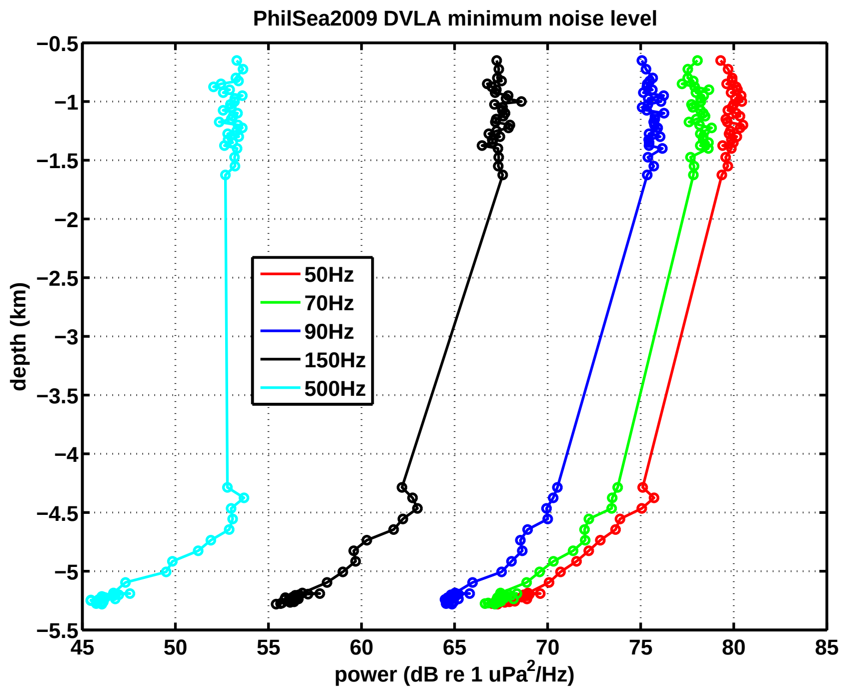


Figure 1: Minimum acoustic noise power at various frequencies as a function of depth.

**Recent publications:**


Dushaw, B. D., Worcester, P. F., Munk, W. H., Spindel, R. C., Mercer, J. A., Howe, B. M., Metzger, K., Jr., Birdsall, T. G., Andrew, R. K., Dzieciuch, M. A., Cornuelle, B. D., and Menemenlis, D., A decade of acoustic thermometry in the North Pacific Ocean, *J. Geophys. Res.*, **114**, C07021, (2009).

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Miller, A.J., Neilsen, D.J., Luther, D.S., Hendershott, M.C., Cornuelle, B.D., Worcester, P.F., Dzieciuch, M.A., Dushaw, B.D., Howe, B.M., Levin, J.C., Arango, H.G., and Haidvogel, D.B., Barotropic Rossby wave radiation from a model Gulf Stream, *Geophysical Research Letters*, **34** (23), [DOI 10.1029/2007GL031937], (2007).

Dzieciuch, M., W. Munk, and D. Rudnick, Propagation of sound through a spicy ocean, the SOFAR overture, *J. Acoust. Soc. Am.*, **116**, 1447-1462, (2004).

Dzieciuch, M., P. Worcester, and W. Munk, Turning point filters: Analysis of sound propagation on a gyre-scale, *J. Acoust. Soc. Am.*, **110**, 135-149, (2001).

**Yuri Fialko**
**Professor**
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Phone: 2-5028

*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. One of the recent discoveries are massive damage zones around several faults in the Eastern California Shear Zone. Such zones were initially identified from subtle (centimeter-scale) surface displacements in response to coseismic stress changes from two large nearby earthquakes: the 1992 M7.3 Landers and the 1999 M7.1 Hector Mine earthquakes. This discovery inspired a large seismic experiment on the Calico fault (one of the faults with inferred large damage zones). Several research groups from UCSD, UCLA and USC participated in a field deployment of an array consisting of 100 seismometers to probe the 3-D velocity structure of the inferred compliant fault zone. Figure 1 shows the tomographic model of the Calico fault obtained from analysis of active and passive seismic sounding (left panel) and interpretation of InSAR results using a compliant model zone model consistent with seismic data (right panel). The inferred dramatic variations in damage density and effective elastic moduli have important implications for our understanding of the earthquake rupture dynamics, long-term evolution and effective strength of major crustal faults, and mechanics of faulting.

To enable modeling of geometrically and mechanically complex structures such as fault damage zones, Prof. Fialko's group has been developing a new method for evaluating deformation in elastic media with arbitrary variations in elastic properties. In particular, graduate student Sylvain Barbot derived and implemented an efficient algorithm based on use of ficticious body forces that mimic the effect of material heterogeneities. The method relies on the use of elasic Green's functions in the Fourier domain (taking advantage of the correspondence theorem). Currently the work is focused on extending this approach to include inelastic and time-dependent deformation. This approach has proved sucessful in simulations of fault creep driven by sudden stress changes - for example, from a nearby earthquake. The new model was applied to study the coseismic and postseismic deformation due to the $M_w$6.0 2004 Parkfield, California, earthquake (joint work with Dr. Yehuda Bock, IGPP). Kinematic inversions of postseismic GPS data over a time period of 3 years show that afterslip occurred in areas of low seismicity and low coseismic slip, predominantly at a depth of $\sim$5 km. Inversions suggest that coseismic stress increases were relaxed by predominantly aseismic afterslip on a fault plane. The kinetics of afterslip was found to be consistent with a velocity-strengthening friction generalized to include the case of infinitesimal velocities. The San Andreas fault around Parkfield is deduced to have large along-strike variations in rate-and-state frictional properties. Velocity strengthening areas may be responsible for the separation of the coseismic slip in two distinct asperities and for the ongoing aseismic creep occurring between the velocity-weakening patches after the 2004 rupture.

**Recent publications:**

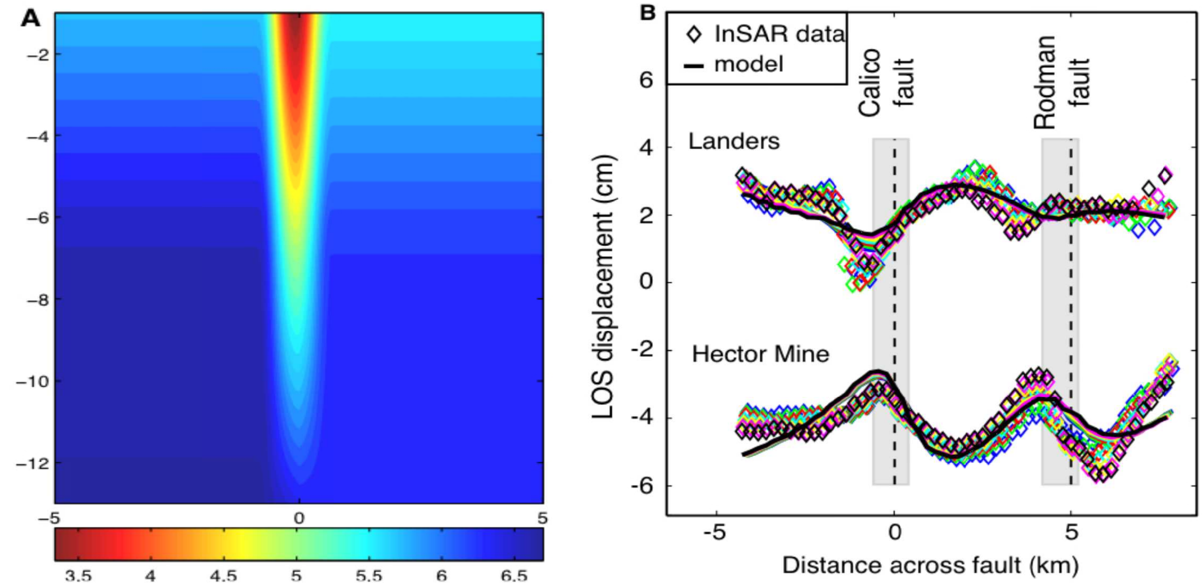


Figure 1: (A) Seismic tomography model of the low velocity zone associated with the Calico fault. (B) InSAR observations (color symbols) and predicted changes in the radar range (solid lines) for deformation across the Calico and Rodman fault zones caused by the 1992 Landers and 1999 Hector Mine earthquakes.

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LaBonte A. L., K. M. Brown, Y. Fialko (2009), Hydrologic detection and finite element modeling of a slow slip event in the Costa Rica prism toe, *J.Geophys.Res.*, 114, B00A02, doi:10.1029/2008JB005806.

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**Helen Amanda Fricker**

**Associate Professor**

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*Research Interests:* cryosphere, Antarctic ice sheet, subglacial lakes, ice shelves, satellite laser altimetry

Helen Amanda Fricker's main research focuses on the Earth's **cryosphere**, in particular the **Antarctic ice sheet**. One of the primary questions in Antarctica is whether its mass is changing due to climate change. Due to the vast size of the ice sheet, and the long time periods over which it can change, satellite data are crucial for routine monitoring, in particular data from radar and laser altimetry, and also imagery. Since the launch of NASA's Ice, Cloud and land Elevation Satellite (ICESat) in January 2003 Helen has used data from the Geoscience Laser Altimeter System (GLAS) on ICESat, which provides accurate elevation data for ice sheet change detection. She has been affiliated with the ICESat Science Team since 1999 and has been a Team Member since April 2006. She is also a member of the ICESat-II Science Definition Team (since December 2008).

***Antarctic subglacial water:*** In 2006 Helen and her colleagues discovered active subglacial water systems under the fast-flowing ice streams of Antarctica using ICESat data. They found large elevation change signals in repeat-track ICESat data (up to 10m in some places) corresponding to draining and filling of subglacial lakes beneath 1-2 km of ice. Changing the basal conditions of an ice sheet, particularly beneath fast flowing ice streams and outlet glaciers, is one possible mechanism to increase its contribution to sea level rise, through increased ice flow rates in the ice streams. With the current interest in Antarctic ice sheet mass balance and its potential impact on sea-level rise, it is important to understand the subglacial water process so that it can become incorporated into models; IGPP postdoc Sasha Carter works works with Helen on this aspect of the problem. Her team continues to monitor active lakes, and have found 124 in total throughout Antarctica (e.g. Figure 1 for MacAyeal Ice Stream (MacIS) example).

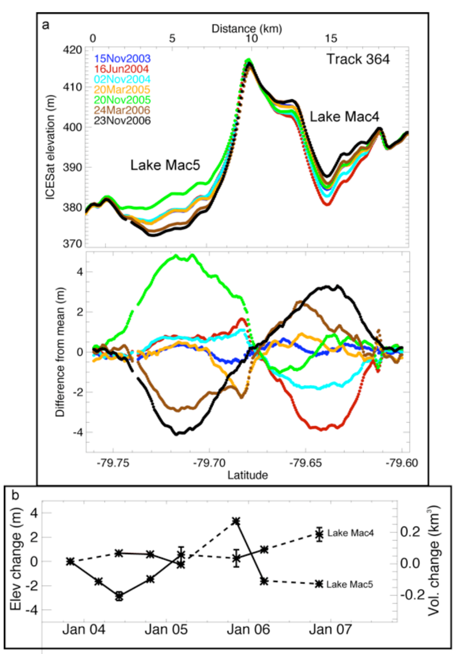


**Figure 1.** a) ICESat elevation profiles and elevation anomalies for Track 364 across two lakes on MacIS (Mac4 and Mac5); b) Averaged time series for Lake Mac4 and Mac5 derived from ICESat tracks 325 and 364.

***Ice shelf grounding zones:*** Helen also uses ICESat data to map the grounding zones (GZs) of the ice shelves - the dynamically-active transition zones between grounded and floating ice. GZs are important because they are the gateway through which ice flows off the grounded ice sheet into the ice shelves and ultimately to the ocean; monitoring them is an important part of ice sheet change detection. Her analysis of data from repeated tracks, sampled at different phases of the ocean tide, has shown that ICESat can detect the tide-forced flexure zone in the GZ, providing accurate GZ location and width information for each track. Helen and postdoctoral researcher Kelly Brunt are using this new technique to map the GZ for large parts of the ice sheet (including Ross Ice Shelf, Amery Ice Shelf and Filchner-Ronne Ice Shelf); see Fricker and others 2009. This combined with surface elevation at the grounding lines will contribute to improved calculations of the ice sheet's mass balance.

***Glacio-seismology:*** In 2008 Helen started a new NSF project with Jeremy Bassis and Shad O'Neel (both ex-IGPP postdocs) investigating the source processes for seismic signals recorded in three different glaciological environments: the Amery Ice Shelf; the Ross Ice Shelf; and Columbia Glacier, Alaska. IGPP postdoc Fabian Walter works on this project.

**Publications 2008-09**

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BORSA, A. A. **H. A. FRICKER**, B. G. BILLS, J.-B. MINSTER, C. C. CARABAJAL, K. J. QUINN (2008) Topography of the salar de Uyuni, Bolivia from kinematic GPS, *Geophysical Journal International*, 172(1), 31-40.

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

We, Dr. Alistair Harding & Dr. Graham Kent, are at present collaborating with Prof. Satish Singh and graduate student Adrien Arnulf from IPGP, Paris on the refraction analysis of the SisMoMar 3-D reflection dataset from the Lucky Strike segment of the Mid-Atlantic Ridge (MAR). SisMoMar was the first experiment to conclusively document the presence of a steady state magma chamber beneath the elevated central volcano of a MAR spreading segment. A central goal of our collaboration is to produce a detailed 3-D velocity model of the upper oceanic crust that can be used to investigate processes associated with crustal creation, faulting and hydrothermal circulation at the MAR. This model will also form the basis for improved 3-D reflection image of the crust using pre-stack migration methods. More conventional focusing analysis techniques used for iteratively improving the velocity model and imaging in sedimentary environments cannot be used in the igneous oceanic basement due to the paucity of primary reflections.

With current equipment, marine multichannel seismic (MCS) data contain a wealth of refraction information in addition to the reflections that are their primary focus. A modern MCS streamer can often have a maximum source-receiver offset of 4.5–6 km, which for typical mid-ocean ridge structures and depths, corresponds to continuous refraction coverage of the upper ~1 km of the oceanic crust. A single 20 km MCS line can easily yield over 50,000 travel times & ray paths. This coverage of the upper crust is much better, denser and more uniform, than can be obtained by conventional refraction experiments which rely on ocean bottom seismographs.

One significant disadvantage of the MCS data, as recorded, is that only a relatively small part of the refraction returns, those turning a hundreds of meters or more into basement are first arrivals, and typically it is only first arrival refraction times that can be picked accurately and (semi-)automatically for use in tomographic inversions. These characteristics are a practical necessity with such a large volume of data. We have sought to overcome the limitations of the surface recorded data by exploiting the spatial density of the MCS to downward continue the source and receivers to a level just above the seafloor. A true ocean bottom experiment would record the refractions as first arrivals and the aim of the downward continuation is to create a Simulated Ocean Bottom Experiment, a SOBE dataset.

The results of this process is illustrated in Figure 1, which is a source gather from the SisMoMar data for a source over the axis of the MAR. In this rough environment, the surface data, Fig. 1a, is dominated by scattering from the seafloor, and although the refraction arrival is visible behind the seafloor reflection it is first arrival and thus easily pickable, for only ~0.5 km. After downward continuation of the sources & receivers to a depth 1.37 km, ~0.4 km above the seafloor, Fig 1b, much of the seafloor scattering has either collapsed or moved out of the aperture of the gather. More importantly, the refraction arrival is now a first arrival for ~2 km and includes, near the intersection with the seafloor reflection, a segment with significantly lower apparent velocities; these are arrivals that sampled the crust just below the seafloor. Even where the refraction is not a first arrival it is now the dominant signal in the data and could be used for as the base for efficient waveform inversion of the data.

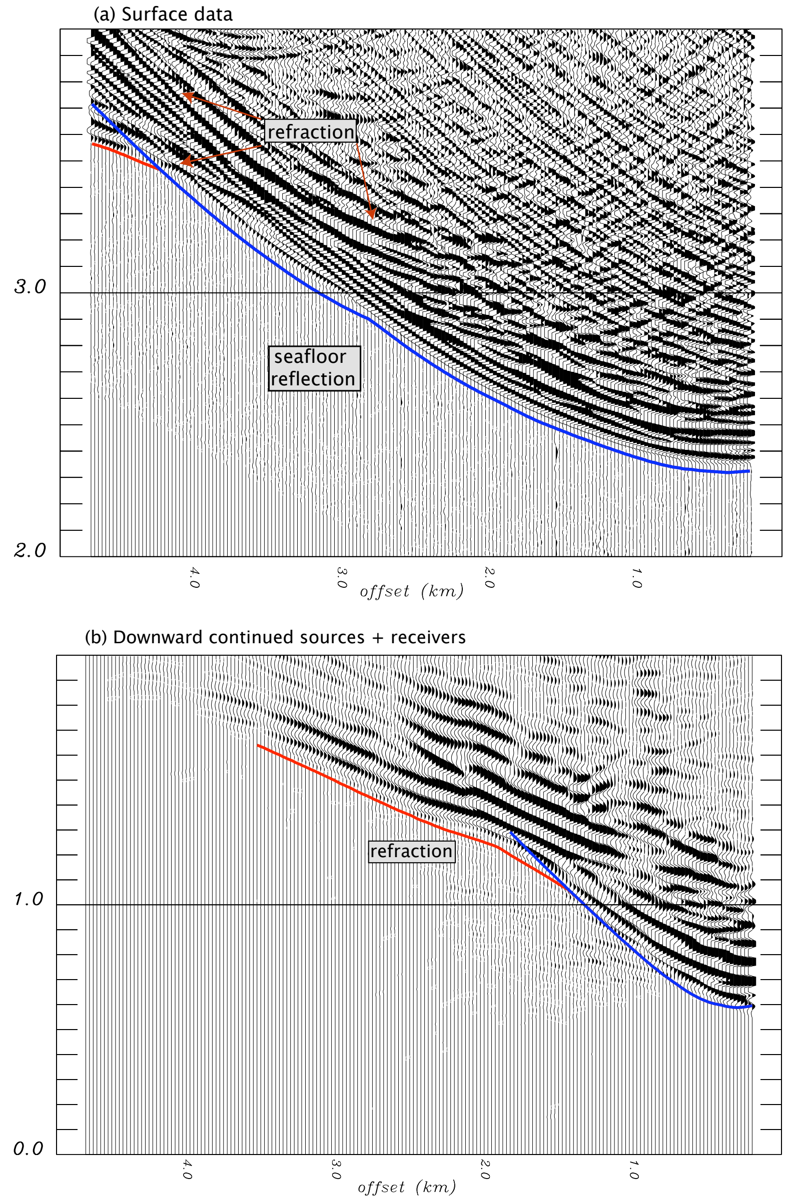


*Figure 1: A source gather from the axis of the MAR. The predicated times of the seafloor reflection, blue line, and first arrival refractions, red line, are from the 2-D tomographic model of this line. For the surface data, upper panel, the refraction arrival is visible beneath the seafloor diffractions but is a pickable first arrival for only ~0.5 km. After downward continuation, the refraction that are first arrivals include energy that has turned just below the seafloor*

Much of the development of the downward continuation process has focussed on improving its numerical behavior as less noise and better data quality allows greater automation of the travel time picking. The current implementation is based upon a Kirchhoff integral representation that allows us to more easily control truncation artifacts and spatial aliasing, as well as more accurately account for the true acquisition geometry, including streamer feathering. Figure 2 shows the same gather after processing with a frequency-wavenumber, *f-k*, implementation of downward continuation that used a less accurate representation of the acquisition geometry. In addition to the prominent numerical artifacts before the main arrivals, the seafloor reflections and diffraction have not been collapsed as fully and the refraction event shows poorer continuity.

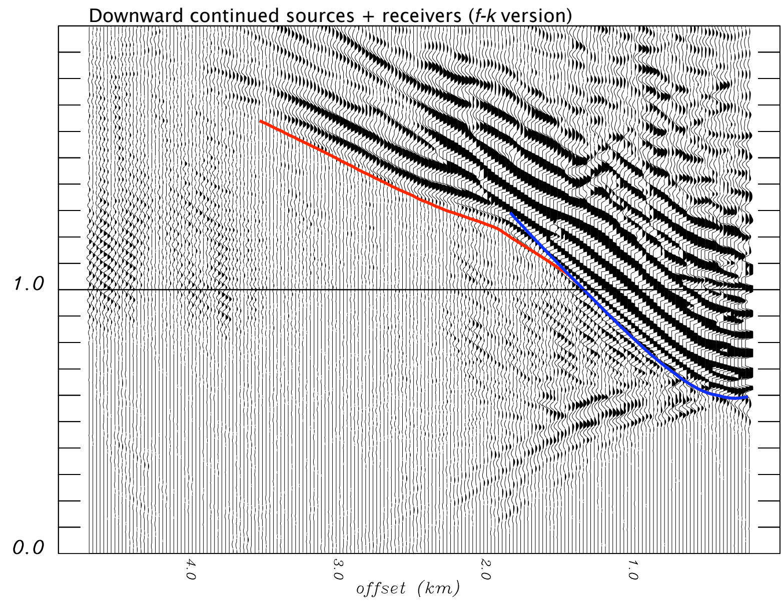


*Figure 2 Same source gather as Figure 1 after using an f-k implementation of downward continuation. The gather contains both high frequency noise, due to spatial aliasing, and a prominent negatively dipping event at small offsets before the seafloor reflection due to truncation. Although the f-k implementation can be modified to mitigate these artifacts, it cannot handle an irregular acquisition geometry and thus event continuity is not as good as for the Kirchhoff implementation.*

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*Research Interests:* Analysis of acoustic signals from large-scale atmospheric phenomena; use of seismic and acoustic energy for nuclear test-ban verification.

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

*Research at L2A:* The new Laboratory for Atmospheric Acoustics (L2A) is the home of research in this field at IGPP. Several faculty, post-docs and PhD students work full or part time in L2A, supported by engineers and technicians in the lab and the field. Presently we study a broad suite of problems related to both natural and man-made sources.

**Volcano acoustics**: We believe that to properly characterize activity within volcanoes it is necessary to study the entire wavefield – that is downgoing seismic and upgoing acoustic energy. We anticipate that infrasound will also emerge in the next few years as an important tool for closely monitoring volcanoes for ash releases that might threaten aircraft and might not be detected on other monitoring systems, such as seismic networks and satellites. Following the recent eruptive activity at Mount Saint Helens (MSH), our group joined forces with the Geological Survey of Canada to deploy two infrasound arrays near this volcano. One was located on the northern flank of MSH. The other was positioned ~ 240 km to the east to detect stratospherically ducted infrasound waves. We study faint recurring long-period infrasound signals (Figure 1) that sometimes occur before large eruptions. We believe these signals will shed light on the internal workings of this volcano. We are also studying large eruptions, including one event in which ash was released to above 30,000 feet. This event was aseismic but was very prominent acoustically.

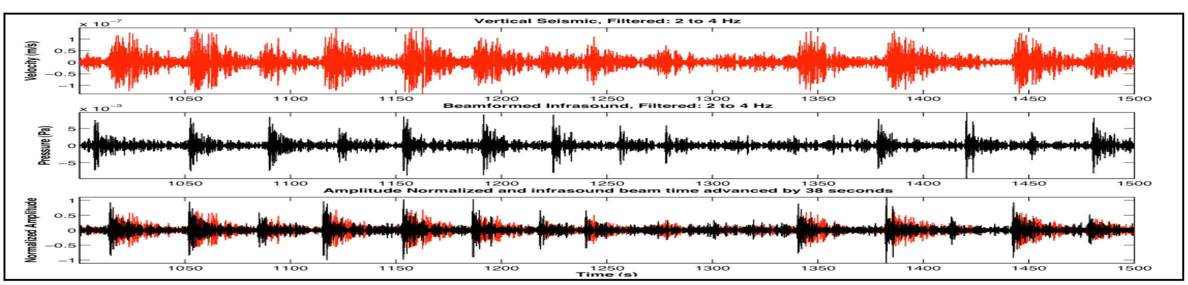


*Figure 1:* Seismic and infrasound signals from Mt St Helens are shown in the upper two traces. The two records are plotted together (bottom) after advancing the infrasound record 38 seconds to account for the propagation delay. The infrasound and seismic signals clearly have a common source within the volcano

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

**Miscellaneous studies: 1) Rocket experiments**: Controlled sources (i.e. well known in terms of yield, 3-D location and time) can be used to study the propagation of infrasound through our turbulent atmosphere. Over the past few years we have collaborated with a number of other institutions across the United States to detonate 50-pound charges of high explosives at altitudes ranging up to 50 km. Such small charges detonated at high altitudes disturb a large volume of air, due to low confining pressure, and generate infrasound waves. We are presently modeling recordings of these explosions to improve our ability to locate infrasonic sources, and to study atmospheric structure **2) Ocean noise**: Using data from our permanent array in the Anza-Borrego desert and two more arrays near San Diego we detect surf noise from along the coast of California. Infrasonic waves from the crashing surf propagate through the stratosphere to our stations up to 200 km away. We see further avenues for research in this area in that lower frequency signals, known as microbaroms, are known to propagate 1000's of km and can be used to probe atmospheric structure**. 3) Natural hazards**: Our group is using infrasound energy to detect and monitor emerging hazards (such as volcanic eruptions, major storms at sea, tornadoes).

*Field operations:* Our group has built two permanent infrasound arrays in the US and one in Africa. In recent years we have deployed infrasound arrays across the southwestern US to record signals from high-altitude explosions and natural phenomena. We currently operate research arrays located near San Diego with another planned for northern California. A typical temporary array comprises 4 to 8 aneroid microbarometers 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.

## Relevant Publications


Arrowsmith, S.J., Drob, D.P., Hedlin, M.A.H. and Edwards, W., 2006, A joint seismic and acoustic study of the Washington State bolide: Observations and modeling, in review with Journal of Geophysical Research. v**112**, D09304, doi:10.1029/ 2006JD008001.

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Hedlin, M.A.H. and Alcoverro, B., 2005, The use of impedance matching capillaries for reducing resonance in rosette spatial filters, J. Acoust. Soc. Am, **117**, 1880-1888.

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Matoza, R.S., Hedlin, M.A.H., Garces, M.A., 2006, An infrasound array study of Mount St Helens, *Journal of Volcanology and Geothermal Research*. **v160**, issues 3-4, p249-262.

Walker, K., Zumberge, M., Hedlin, M.A.H., and Shearer, P., .., 2007, Methodologies for determining infrasound phase velocity direction with an array of directional acoustic sensors, *J. Acoust. Soc. Am. **124**, 2090-2099.*

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*Research interests*: turbulence, applied mathematics

This past year has seen a continuation of work begun with Dr. Phil Livermore in mid-2007. The first phase of that project, to understand the nature of a particular constraint on the magnetic field in the conducting core of the Earth, is complete with three manuscripts now in the review phase and one in press. (Two additional manuscripts currently under review address a primarily mathematical offshoot of that inquiry, in which we discovered a generalized family of "orthogonal polynomials", characterized - in contrast with the classical results - by specified boundary conditions.)

This constraint, due to J. B. Taylor in 1963 states that, in the absence of viscosity, the net zonal Lorentz force on each "geostrophic contour" must vanish. A "geostrophic contour" is defined as as a constant density surface at a given distance from the axis of rotation. For this purpose the Earth's core is sufficiently uniform in density that such surfaces are cylindrical shells concentric with the rotation axis, complicated topologically by the presence of the solid inner core.

We have subsequently learned of an important codicil to Taylor's prescription in the form of an additional set of quadratic constraints required for dynamical consistency in the case of a solid inner core. These are derived in a paper by Rainer Hollerbach from 1994. The same approach to these as we took for the Taylor constraint should yield a similar algebraic prescription for the exact enforcement for a given set of basis functions. The characterization of these may elucidate the origin of a seeming adventitious degeneracy we discovered in the enumeration of the (inner core) algebraic equations for Taylor's constraint itself.

At issue now is how one best employs these constraints; in application to the "forward problem" or the "inverse problem". Each has its merits in exposing aspect of the dynamo process, the first primarily on dynamics in the temporal domain and the second the parametric origin of gross energetic balances. In addition, it is fairly clear how to proceed in the case of the inverse problem and we have already had some initial results in that direction. It is less evident how best to bring these constraints to bear on the forward problem and that has hence been a focus of our work in the early spring. We have now in hand a feasible time-stepping algorithm for which a working draft is in progress. With this method it should be possible to evolve a model dynamo problem in which the so-called Ekman number ($10^{-15}$ in the case of the Earth, the nondimensional value of viscosity which makes invocation of Taylor's constraint appropriate) is identically zero to begin to understand the dynamics of that regime and test the degree to which ambitious direct numerical simulations at currently feasible values of $10^{-7}$ begin to approach the proper scaling of the fields.

Dr. Livermore will carry forward much of this work as he departs SIO this summer, headed first for a three month visit to ETH in Zürich, and then taking up a permanent post in the Department of Earth Sciences at the University Leeds, with award of a five year NERC fellowship as well. At that point I will return to work on "upper bound" theory, continuing ualong the lines noted in the 2007 version of this report.

**Relevant Publications**

Livermore, P., Ierley, G. R., and Jackson, A., The structure of Taylor's constraint in three dimensions, *Proc. Roy. Soc. A*, v 464, 3149-74, 2008

Livermore, P, A Compendium of Galerkin Orthogonal Polynomials, Scripps Institution of Oceanography Technical Report. http://repositories.cdlib.org/sio/techreport/98, April 2009.

Livermore, P., and Ierley, G. R., A new identity linking coefficients of a certain class of homogeneous polynomials and Gauss hypergeometric functions, *Discrete Mathematics*, accepted, June 2009

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*Research Interests:* Marine electromagnetic exploration of subduction zones, mid-ocean ridges and the continental shelves, hydrocarbon exploration, numerical methods for electromagnetic modeling, marine geophysical instrumentation.

My research focuses on the remote detection and quantification of geologic fluids contained beneath the seafloor using electromagnetic (EM) geophysical methods. Geologic fluids tend to be either more resistive (e.g., oil and gas) or more conductive (e.g., magma) than their host rocks, making them good targets for imaging with EM methods. I am co-PI of the SIO Marine EM Laboratory, consisting of lead PI Steven Constable and a team of two engineers, three technicians, one postdoc, one project scientist, four students and our visiting research associate Arnold Orange.

This spring we were funded by BHP-Billiton to collect a marine EM data set over the Scarborough gas field on the northwest shelf of Australia (Figure 1). Our successful 32 day cruise this past May resulted in 144 receiver deployments and 12 days of controlled-source EM transmissions—a record amount of data for our group. This gigantic data set is being used to advance our understanding of marine EM methods for imaging gas reservoirs and to test several new instrumentation developments. David Myer, a Ph.D. student that I co-supervise along with Constable, is analyzing this reservoir imaging data for his Ph.D. thesis. We knew ahead of time that accurate positioning of our deep-towed EM transmitter is required for optimal resolution of the Scarborough gas field, and therefore we designed and implemented a special inverted long-baseline acoustic navigation system for this project. Using two surface-towed acoustic transponders and an acoustic ranging system mounted on our transmitter, we were able to determine in real-time the transmitter's horizontal position to within about 5 m accuracy, despite the 900 m towing depth (Figure 1).

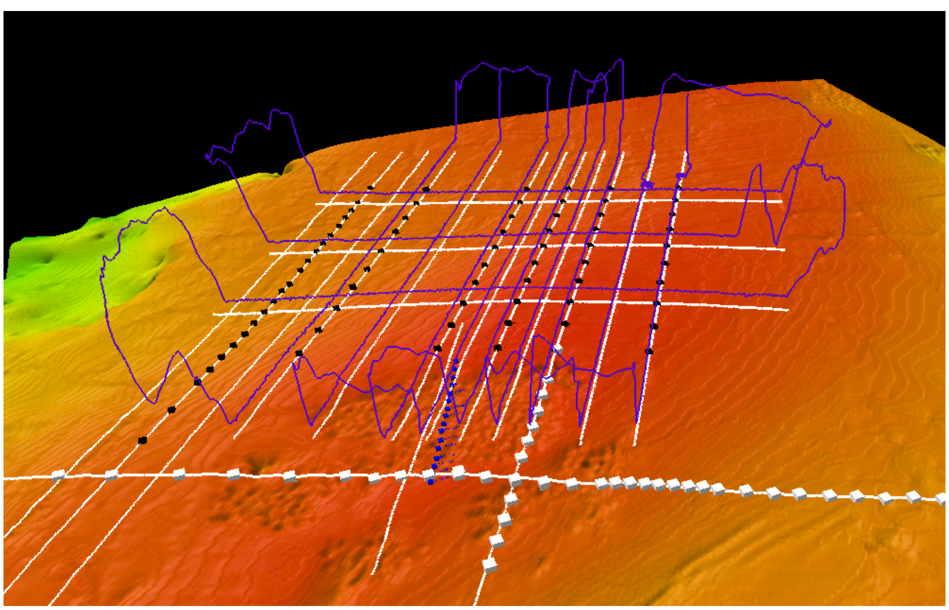

Figure 1. Marine EM survey of Scarborough gas field, offshore Western Australia. White, black and blue cubes show the locations of seafloor electromagnetic field recorders deployed over the gas field. Purple lines show the position of the Scripps Undersea EM Source Instrument (SUESI) as it was towed in a grid pattern around the EM recorders. http://marineemlab.ucsd.edu/Projects/Scarborough.

In Key (2009) I developed a new generalized 1D CSEM modeling algorithm that allows for arbitrarily located and oriented EM transmitters and receivers, providing a significant improvement over the limitations of our previous codes. Using this new capability, I showed that the ocean's conductivity-depth profile needs to be included in numerical models in order to obtain optimal resolution of seafloor hydrocarbon reservoirs—an unexpected result that arises from the interaction of EM energy diffusing both through the seabed and along the air-sea interface. By systematically studying the three fundamental transmitter orientations and all corresponding electric and magnetic field components, I was able to show that the inline transmitter and receiver geometry offers the best resolution of buried resistive hydrocarbon layers, and that the inclusion of additional data such as broadside transmitters or vertical electric field measurements offers no resolution improvement—much to the contrary of what a few industrial contractors have been claiming.

In Orange et al. (2009), we show theoretically how marine CSEM data could provide useful geometrical information for monitoring where hydrocarbons are being draw down during the decade or more production time of a typical offshore reservoir, and thus could be highly useful to reservoir engineers applying enhanced oil recovery techniques.

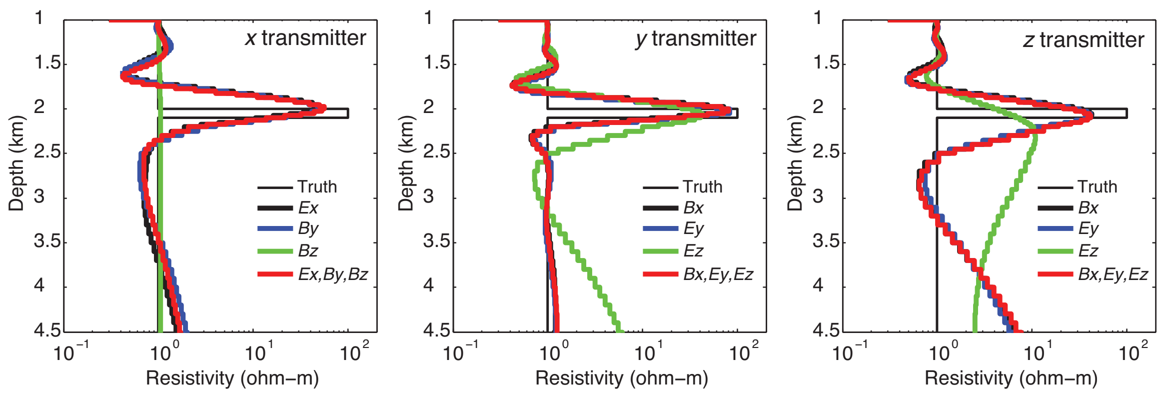


Figure 2. The resolution of the electric (E) and magnetic (B) field components for the three fundamental transmitter orientations (broadside x, inline y, and vertical z). Synthetic inversion models are shown for inversion of each component separately and all three together, as indicated in the legends. The transmission frequencies were 0.1 and 1.0 Hz and all models fit the data to RMS 1.0.

## Relevant Publications


Key, K. (2009), 1D inversion of multicomponent, multifrequency marine CSEM data: Methodology and synthetic studies for resolving thin resistive layers: *Geophysics*, **74**, F9–F20.

Orange, A., K. Key, and S. Constable (2009), The feasibility of reservoir monitoring using time-lapse marine CSEM, *Geophysics*, **74**, F21–F29.

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

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

***A Case Study of Two Magnitude ~5 Mainshocks In Anza, California: Is The Footprint of an Aftershock Sequence Larger than We Think?*** It has been traditionally held that aftershocks occur within one to two fault lengths of the causative mainshock. Kilb's work with Karen Felzer (USGS) demonstrates that this perception has been shaped by the sensitivity of seismic networks. The 2001 and 2005 magnitude ~5.0 earthquakes near Anza in southern California occurred in the middle of the densely instrumented ANZA seismic network and were unusually well recorded. Examining these data Kilb and Felzer find that, for both sequences, the decay of aftershock density with distance is similar to those observed elsewhere in California. This indicates there is no need for any additional triggering mechanisms and suggests that given widespread dense instrumentation, aftershock sequences would routinely have footprints much larger than currently expected (Figure 1; Felzer & Kilb, 2009).

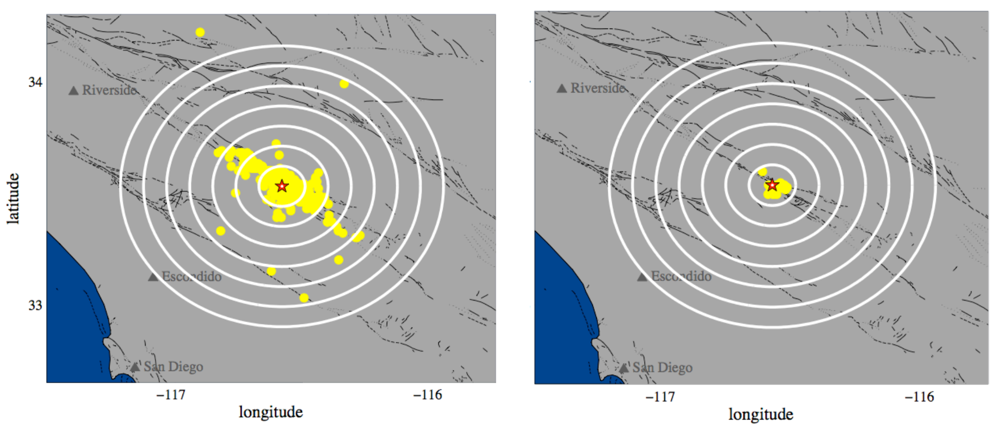


*Figure 1: Maps of aftershocks (yellow circles) in the first 48 hours of the Anza 2005 aftershock sequence. Aftershocks extend out to distances of ~40 km (left panel; 1615 aftershocks) from the mainshock (red star); but if the network could only detect aftershocks over magnitude 2 (right panel; 25 aftershocks), the extent of the aftershocks is drastically reduced to <10 km. For reference we include concentric circles about the mainshock that extend out to a 80 km radius (160 km diameter) in increments of 10 km. Known fault traces (black lines) and select town locations (labeled triangular markers) are also included.*

***Ability for Large Earthquakes to Trigger Mud Volcano Eruptions:*** In collaboration with Dr. Mellors (SDSU) and his coworkers, Kilb investigates the ability for large earthquakes to trigger mud volcano eruptions. They find the temporal correlation between earthquakes and eruptions is most pronounced for nearby earthquakes (within ~100 km) that produce seismic intensities of Mercalli 6 or greater at the location of the mud volcano (Mellors *et al.,* 2007; Kilb 2008).

***3-D Interdisciplinary Visualization: Tools for Scientific Analysis and Communication:*** Kilb, in collaboration with Graham Kent and graduate student Allison Jacobs, used four case studies to demonstrate how 3-D visualizations can be used in scientific research. These examples highlight how scientists can merge presentation-ready (*e.g.,* already processed) 2- and 3-D datasets into single visualizations and then use these for interdisciplinary analyses and/or communicating the results to those unfamiliar with the data and research (Jacobs *et al.,* 2008).

***Quantifying the Remote Triggering Capabilities of Large Teleseismic Earthquakes:*** Kilb and graduate student Deborah Kane are establishing new techniques to quantify the remote triggering capabilities of large teleseismic earthquakes. They search the ANZA catalog for evidence of remote triggering, using three statistical tests to determine the significance of quantity and timing of earthquakes in southern California. They find minimal differences between the spectral amplitudes and maximum ground velocities of the local triggering and non-triggering earthquakes. Similar analysis of remote earthquakes shows that the related ground motion regularly exceeds that of local earthquakes, both at low frequencies and in maximum velocity. This evidence weakly suggests that triggering requires larger amplitudes at high frequencies and that a maximum ground velocity alone is not the primary factor in remote triggering (Kane *et al.,* 2007).

***The Temporal Lag Between a Mainshock and the First Aftershocks:*** Aftershocks can be obscured by the large decaying amplitude of the mainshock's seismic waves (coda), making it difficult to identify early aftershocks. Working with Drs. Vernon and Martynov, Kilb examined the temporal lag between the mainshock and the first aftershocks in the M5 Anza 2001, southern California, sequence. Results show the size of the magnitude differential between a mainshock and its largest aftershock is likely dictated by a combination of factors including the complexity of the fault system and propensity for relatively large earthquakes to occur in the region (Kilb *et al.,* 2007).

***Seismogenic, Electrically Conductive, and Fluid Zones at Plate Boundaries:*** Working with Dr. George Jiracek (SDSU) and his-coworkers, Kilb examines the seismogenic, electrically conductive, and fluid zones at plate boundaries in New Zealand, Himalaya, and California. The results indicate that there is increasing evidence that processes removed from the actual seismogenic zone, such as the occurrence of trapped fluidized zones in the ductile crust, may be very important in the earthquake nucleation process (Jiracek *et al.,* 2007).

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

**Recent Publications**

Felzer, K. & D. Kilb, A Case Study of Two M~5 Mainshocks In Anza, California: Is The Footprint Of An Aftershock Sequence Larger Than We Think?, *Bull. Seism. Soc. Am.,* doi: 10.1785/0120080268, in press 2009.

Jacobs, A. M., D. Kilb and G. Kent, 3-D Interdisciplinary Visualization: Tools for Scientific Analysis and Communication, *Seis. Res. Lett.,* doi: 10.1785/gssrl.79.6.867, 2008.

Kane, D.L., D. Kilb, A. S. Berg & V. G. Martynov, Quantifying the Remote Triggering Capabilities of Large Earthquakes Using Data From The ANZA Seismic Network Catalog (Southern California), *J. Geophys. Res.*, 112, B11302, doi:10.1029/2006JB004714, 2007.

Kilb, D. Throwing Mud, *Nature Geoscience,* doi:10.1038/ngeo299, 2008.

Kilb, D., V. G. Martynov, & F. L. Vernon, Aftershock Detection Thresholds as a Function of Time: Results from the ANZA Seismic Network following the 31 October 2001 *M*L 5.1 Anza, California, Earthquake, *Bull. Seism. Soc. Am.*, doi: 10.1785/0120060116, 2007.

Mellors, R., D. Kilb, A. Aliyev, A. Gasanov, & G. Yetirmishli, Correlations Between Earthquakes and Large Mud Volcano Eruptions, *J. Geophys. Res.*, 112, B04304, doi:10.1029/2006JB004489, 2007.

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*Research interests*: regional and global surface wave seismology; seismic recordings on the ocean floor; observation and causes of ocean noise; natural disasters and global change

Gabi Laske's main research area is the analysis of seismic surface waves and free oscillations, and the assembly of global and regional 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 student Christine Houser used her data to compile an improved model of mantle shear and compressional velocity and bulk sound speed. Laske has been involved in the DESERT project (Dead Sea Rift Transect) to image crustal and mantle structure beneath the Araba Valley south of the Dead Sea. An intriguing aspect of this research is to find the cause for the uplift of the Arabian Plateau east of the Dead Sea Transform Fault. Thermo-mechanical modeling suggests that a plume responsible for the Red Sea rifting could have eroded the Arabian lithosphere though Laske's surface wave study does not appear to support this idea. All other seismic component of this project were either equivocal or inadequate to address this issue.

*The PLUME project:* Laske is the lead-PI of the Hawaiian **PLUME** project (Plume–Lithosphere–Undersea–Melt Experiment) to study the plumbing system of the Hawaiian hotspot (Figure 1). The project aims to resolve the fundamental question whether a plume or other mechanisms feed Hawaiian volcanism. PLUME researchers aim to obtain comprehensive seismic tomographic images with a properly designed network of broadband stations that reaches deep into the lower mantle. Before PLUME, observations from stations on the Hawaiian island chain provided incomplete tomographic images of only the upper mantle as well as spotty receiver function estimates . The PLUME project includes co-PIs from SIO (Laske, Orcutt), WHOI (Collins, Detrick), U. Hawaii (Wolfe), DTM (Solomon, Hauri) and Yale Univ. (Bercovici). The centerpiece of the project is a large broadband OBS network which is augmented by 10 temporary land stations. Occupying a total of over 80 sites and having an aperture of over 1000km, this experiment is one of the largest in the world. It is one of the first large, long-duration deployments of broadband OSBs. A 35–station, small–aperture array deployed in 2005 focussed on the island of Hawaii, where a plume is proposed to be located. The later 38–station, large-aperture array deployed in 2006 reached into the lower mantle and gathered off-swell reference data for the undisturbed Pacific mantle.

Both deployments collected nearly 200 earthquakes each, providing excellent azimuthal coverage. Surface wave dispersion analyses reveal a roughly 30km thick low-velocity anomaly in the lower lithosphere beneath the islands of Hawaii and Maui that may be manifest of plume material stagnating and ponding beneath the lithosphere, and reheating it (Figure 2). This low-velocity body likely contains a high degree of melt and may supply magma for the Hawaiian volcanoes through conduits too narrow to be images by surface waves. Features imaged at greater depths suggest that the proposed plume is not located to the southeast of Hawaii as a conventional plume model would suggest. Rahter, we image a strong anomaly to the west of Hawaii. A plume at this location was proposed to ascend through the transition zone in an earlier but incomplete receiver function study. These results are consistent with Laske's earlier findings from the 97/98 SWELL pilot experiment that covered an area in the southwestern corner of PLUME. SWELL showed conclusively that the Hawaiian lithosphere has undergone a thermal rejuvenation process with no exten-

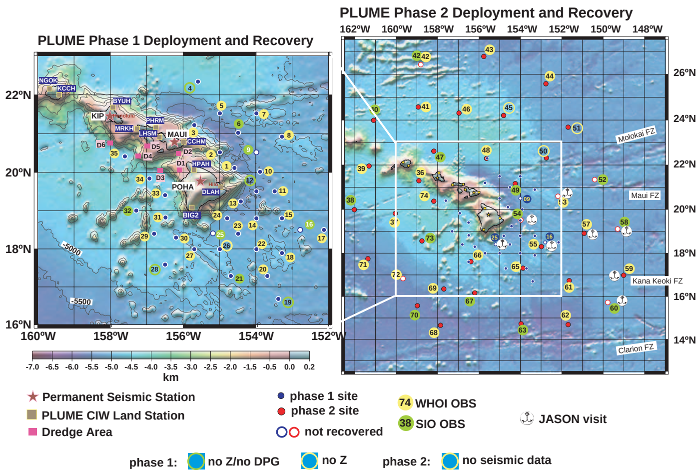


Figure 1: Deployment plan and instrument return for the two-stage PLUME experiment. Phase 1 operated Jan 2005 to Jan 2006, phase 2 from Apr 2006 to May 2007. A rescue visit of lost instruments with submersible JASON followed in Nov 2007.

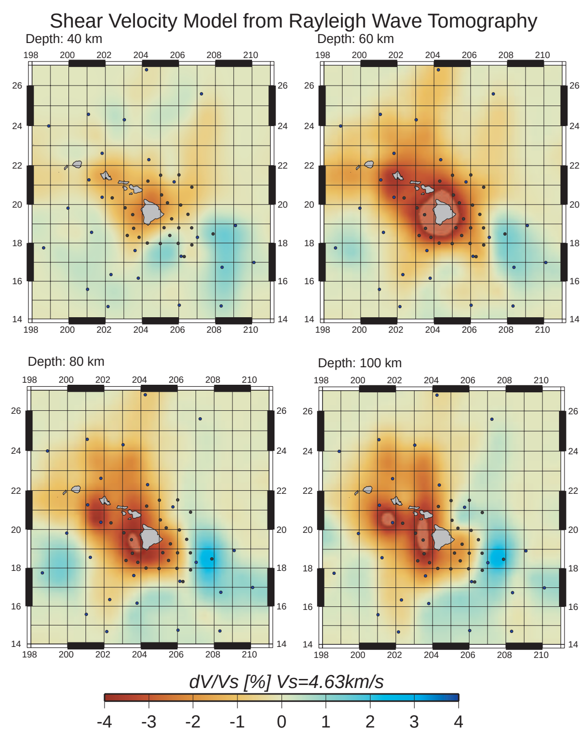


Figure 2: Four depth slices through the shear-velocity model obtained from inverting two-station Rayleigh wave phase velocity curves.

sive mechanical erosion.

## Recent publications:

Laske, G., Collins, J.A., Wolfe, C.J., Solomon, S.C., Detrick, R.S., Orcutt, J.A., Bercovici, D. and Hauri, E.H., The Hawaiian PLUME Project – Probing a Hotspot with State-of-the-Art Ocean Bottom Seismometers, *EOS Trans. AGU*, in press, 2009.

Houser, C., Masters, G., Shearer, P. and Laske, G., Shear and compressional velocity models of the mantle from cluster analysis of long-period waveforms, *Geophys. J. Int.*, 174, 195-212, 2008.

Laske, G., Weber, M. and the DESERT Working Group. Lithosphere Structure Across the Dead Sea Transform as Constrained by Rayleigh Waves Observed During the DESERT Experiment, *Geophys. J. Int.*, 173, 593-610, 2008.

**Guy Masters**
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*Research interests*: Global seismic tomography using free oscillations, surface waves and body waves; interfacing seismology and mineral physics.

In 2008, Guy Masters has continued to focus on improving global 3D models of the Earth using seismic tomography. We have paid particular emphasis to developing fast interactive techniques for measuring arrival times of long-period body waves using a cross-correlation/cluster analysis technique. The technique is described in Houser et al (2008a) along with new 3D whole-mantle models of P and S velocity built from our greatly enhanced data sets. Graduate student Urska Manners has adapted the technique to measure large data sets of travel times of core-diffracted waves to elucidate the nature and structure of the D" (core-mantle boundary) region. The addition of diffracted phases greatly improves sampling, particularly in the southern hemisphere and has allowed us to better define the "superplume" structures in the deep mantle. These new data sets have been jointly inverted with existing data sets to give improved models of deep mantle structure using both ray theory and finite frequency kernels (Manners and Masters, 2008a, Manners et al, 2008).

One of the more intriguing aspects of these models is the anticorrelation of bulk sound speed anomalies to shear velocity anomalies seen in the superplume structures beneath Africa and the central Pacific. Almost all models show this feature in the D" region but there is little agreement on how high above the CMB (core-mantle boundary) it extends. It is important to nail this down since, if the anticorrelation is confined to the lowermost mantle, it could be related to the recently discovered post-perovskite phase transformation. However, if it extends signfiicantly above the CMB, we must invoke compositional variations to explain the signal. We have found that the variability among current bulk-sound speed models is largely explained by differences in how various researchers handle the signal from earthquake mislocation. This aspect is studied in Manners and Masters (2008c) where we determine which methods can give unbiased answers. Our best models now have the anticorrelation extending several hundred kilometers and the CMB, suggesting this must be a chemical effect rather than a result of the phase transformation. Finally, we note that Manners and Masters (2008b) introduce a novel technique to construct bulk-sound speed travel time residuals directly from S and P travel time residuals for the same source-receiver pairs. These bulk sound speed residuals also imply that the anticorrelation of bulk sound speed and shear velocity extends well above the CMB.

During the last year, Masters has extended the cross-correlation/cluster analysis technique to work with surface wave envelope functions – essentially measuring relative group arrival times. The technique has allowed us to measure 300,000 relative arrival times for Rayleigh waves for each of several frequencies spanning 7.5mHz to 35mHz. The data can be very accurately represented by a group velocity map for each frequency which can reproduce the group arrival times very accurately. Fig 1. shows group velocity maps for a variety of frequencies. At the highest frequencies (top of Figure 1), the signal is primarily due to variations in crustal thickness and such maps can be used to improve our global crust and lithosphere models. A preliminary inversion reveals that our current global crustal model (CRUST 2.0) has many deficiencies and we can anticipate much better models in the near future.

## Recent Publications

Houser, C., G. Masters, P.Shearer, and G.Laske., Shear and compressional models of the mantle from cluster analysis of long-period waveforms , *Geophys. J. Int.*, 174, doi: 10.1111/j.1365-246X.2008.03763.x, 2008a.

Houser, C., G. Masters, M. Flanagan, and P.Shearer, Determination and analysis of long-wavelength transition zone structure using SS precursors, *Geophys. J. Int.*, 174, doi: 10.1111/j.1365-246X.2008.03879.x, 2008b.

Gubbins, D., G. Masters and F. Nimmo, A thermochemical boundary layer at the base of Earth's outer core

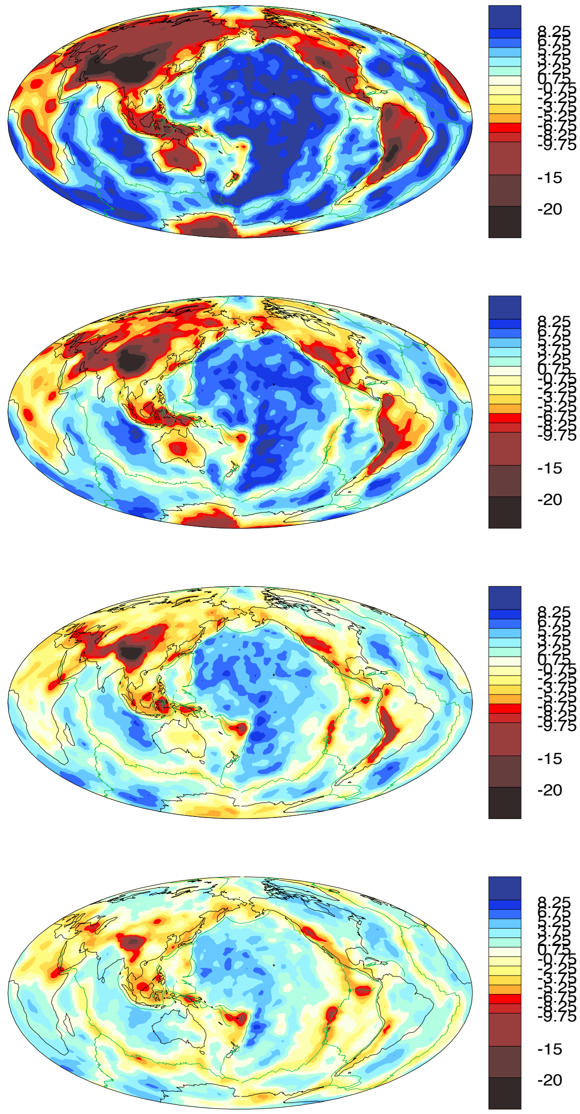


**Figure 1**: Group velocity maps for Rayleigh waves (perturbations in percent) at four different frequencies: from bottom to top, 15mHz, 20mHz, 25mHz, and 30mHz. At the lowest frequencies, slow anomalies can be identified in oceanic regions which disappear at higher frequencies but the most obvious features are associated with thick continental crust (Himalayas and Andes) and get extremely large in amplitude at short periods.

and independent estimate of core heat flux, *Geophys. J. Int.*, 174, doi: 10.1111/j.1365-246X.2008.03719.x, 2008.

Manners, U., and G. Masters, Analysis of core-mantle boundary structure using S and P diffracted waves, *Geophys. J. Int.*, , submitted, 2008a.

Manners, U., Q. Liu, G, Masters, and J. Tromp, Modeling the lowermost mantle using diffracted phases and finite frequency kernels, *Geophys. J. Int.*, , submitted, 2008.

Manners, U., and G. Masters, Relations between shear velocity and bulk sound speed in the lower mantle, *Geophys. J. Int.*, , submitted, 2008b.

Manners, U., and G. Masters, A comparison of methods for global teleseismic earthquake relocation, *Bull.Seism. Soc. Am.*, , submitted, 2008c.

**Jean-Bernard Minster**
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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 IT technologies—in particular 4D visualizations—to earthquake modeling; Verification of nuclear Test Ban Treaties by geophysical means (seismic, imaging, ionosphere). Application of hyperspectral imaging to paleoseismology. Member of the ICESat science team since 1989.

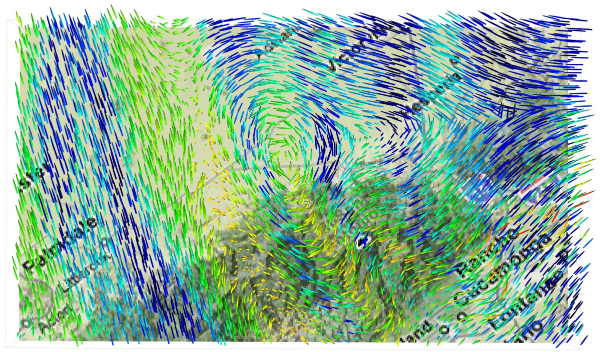
*Recent research:*
Large-scale simulations of seismic events and seismic wave propagation on supercomputers typically generate an enormous volume of output, often in the range of tens of Terabytes. Except to answer very limited, narrow questions where the answer can be expressed in terms of a few numbers, it is impractical to study such output by means other than visualization. This has been used very successfully at the Southern California Earthquake Center to highlight the results of the *TeraShake, PetaShake, and CyberShake* series of simulations. However, the movies generated have typically been restricted to surface fields. Visualizing the interior of the Earth during a dynamic phenomenon has proved a very difficult task. Research over the past year has focused on visualizing seismic wave fields in the interior of the crust. This was done with Computer Science Graduate Student Emmett McQuinn, in collaboration with San Diego SuperComputer Center researcher Amit Chourasia, and Calit2 researcher Jürgen Schulze.

The approach we adopted was to represent field values (scalar, vector or tensor) at the nodes of a mesh covering the visualization volume, using "glyphs" of various sorts. Glyphs offer a reasonably flexible way to display the fields as a function of time. For instance in the case of vector displacement, velocity or acceleration fields, the glyphs may be oriented to indicate the vector direction, and size and color may be used to represent the vector magnitude. With complex time-dependent volumetric fields, it is very helpful to minimize the need for elaborate thought processes involved in interpreting the images, so a major part of our effort was aimed at creating as intuitive a display as possible. We have experimented with a wide variety of glyphs. Only a few proved to be adequate for our purpose.

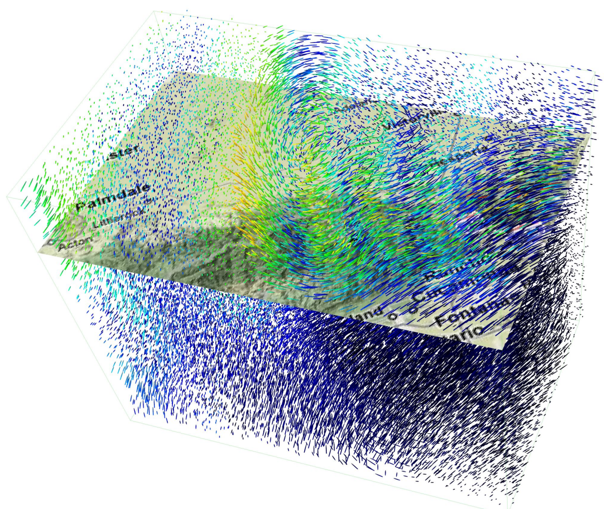
Display capabilities are also a major issue. At the high end we have used various three-dimensional visualization display technologies which have now been available for several years, as well as the total immersion approach made possible through a visualization "cave" at Calit2. At the same time, we intend this same capability to be portable, and thus to require only modest computing power, and a simple screen display, such as that provided by a laptop computer equipped with a graphics processor.

Most seismic simulations use a regular three-dimensional mesh, and this unfortunately generates Moiré patterns that prove extremely distracting, and prevent the spectator from understanding the full field. In order to combat that problem, we have dithered the mesh, imposing slight, random glyph position offsets, and interpolating the field to the new

positions.. We found this to be quite effective, and also to reduce annoying occlusions of remote glyphs by proximal ones.  To further reduce occlusions, we take advantage of the fact that relatively large portions of the volume often contain uninteresting features (e.g. trivial values or quasi-static fields). These portions of the volume can be rendered almost transparent, thereby making more distant features of interest readily visible.
Finally, we have found that it is essential to make the displays interactive. Typical spectators adjust camera positions and view angles almost constantly in order to gain a better feeling for the three-dimensional structure of the objects being viewed.



*Surface displacement  field near the tip of a propagating rupture on the San Andreas fault. Note the interesting vorticity pattern which could not be easily detected without such visualization.*




*Same as above, with perspective view into the volume.  The map is depicted at interactively-controlled position in the vertical direction. Note the pattern of surface waves emanating from the rupture.*

**Relevant Publications**


Ely, Geoffrey P. Steve M. Day and Jean-Bernard Minster, A support-operator method for viscoelastic wave modeling in 3-D heterogeneous media, *Geophys. J. Int.*, doi:10.111/j.1365- 246X.2007.03633.x, 2007

Olsen, K. B., S. M. Day, J. B. Minster, Y. Cui, A. Chourasia, D. Okaya, P. Maechling, and T. Jordan, TeraShake2: Simulation of Mw7.7 earthquakes on the southern San Andreas fault with spontaneous rupture description, *Bull. Seism. Soc. Am.*, **98**, doi:10.1785/0120070148, pp. 1162 -1185, 2008

Cui, Y., Moore, R., Olsen, K., Chourasia, A., Maechling, P., Minster, B., Day S., Hu, Y., Zhu J., Majumdar, A. and Jordan, T., 'Enabling Very-Large Scale Earthquake Simulations on Parallel Machines ', Advancing Science and Society through Computation:Lecture Notes in Computer Science series, Springer, (2007): pp. 46-53. 2008

Cui Yifeng, Reagan Moore, Kim Olsen, Amit Chourasia, Philip Maechling, Bernard Minster, Steven Day, Yuanfang Hu, Jing Zhu and Thomas Jordan,  Toward Petascale Earthquake Simulations, Acta Geotechnica, doi: 10.1007/s11440-008-0055-2, 2008

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*Research Interests:* Ocean Acoustics and Physical Oceanography.

AN INCONVENIENT SEA-TRUTH: Spread, Steepness and Skewness of Surface Slopes. In press in Volume 1, No 1 of Annual Reviews on Marine Science.

I have worked on waves in the 1 mm to 1 m scales, straddling the transition from gravity to surface tension. These scales have received very little attention as compared to the longer surface waves, yet these are the scales at which momentum is transferred from atmosphere to ocean (wind stress). The incentive for this study came from a recent French compilation of 8 million satellite images of sun glitter. The compilation raises more questions than it answers, hence the title. Significant information concerning the short waves comes (surprisingly) from measurements of pressure on the deep-sea bottom (the microseism problem) reported separately in a short paper with William Farrell, a former IGPP student.

**Relevant Publications**

1. Farrell W. E., W. Munk (2008) What do deep sea pressure fluctuations tell about short surface waves?. *Geophys. Res. Lett.*, **35**, L19605, doi:10.1029/2008GL035008.

2. Munk, W. and D. Day (2008) Glimpses of Oceanography in the Postwar Period. *Oceanography,* **21(3)**: 16-23.

3. Munk. W. (2009) An Inconvenient Sea-Truth: Spread, Steepness and Skewness of Surface Slopes. Annual Review of Marine Science, 1: 377–415, 10.1146/annurev.marine.010908.163940.

4. Munk, W. (2008) The William Leighton Jordon, Esq. Award, submitted.

5. Munk, W., H. von Storch, and K. Hasselman (2008) Munk Interview, in progress.

6. Worcester, P.F. and W.H. Munk, (2009) Sound Transmission Through a Fluctuating Ocean (1979) and Ocean Acoustic Tomography (1995): An intertwined history. *J. Acoustical Soc. Am.*, submitted.

**John A. Orcutt**

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**NSF Ocean Observatories Initiative –** Ocean science has long been the franchise of individuals or small groups of scientists working to solve problems within a single science domain (e.g. chemical oceanography) at a time. However, the broad scientific and civil demands for multidisciplinary and interdisciplinary research coupled with exponential growth in information technology are irrevocably changing oceanography.

The US National Science Foundation has initiated a transformation of ocean science with the Ocean Observatories Initiative (OOI), which began on 1 September 2009. The costs of construction over a five year period is $400M and $32M, not including 30% contingency, will be available for designing, constructing and testing the required information technology or cyberinfrastructure. Including construction costs, contingency and operations and maintenance expenditures, the total cost over the coming five years will be approximately $50M. Construction of the OOI CI began on 12 October 2009.

The OOI is designed to provide new, persistent, interactive capabilities for ocean science, and has a global physical observatory footprint. Two implementing organizations (IOs) have been constituted to construct the Regional Scale Nodes (RSN – University of Washington) and Coastal/Global Scale Nodes (CGSN – Woods Hole, Oregon State University and Scripps/UCSD) comprising cabled and multiple buoyed observatories, respectively.

The OOI CyberInfrastructure (CI) comprises the integrating element that links and binds the physical infrastructure into a coherent system-of-systems, and is being constructed at UCSD, Calit2 and Scripps. The core capabilities and the principal objectives of the OOI are collecting real-time data, analyzing data and modeling the ocean on multiple scales and enabling adaptive experimentation within the ocean. A traditional data-centric CI, in which a central data management system ingests data and serves them to users on a query basis, is not sufficient to accomplish the range of tasks ocean scientists will engage in when the OOI is implemented. Instead, a highly distributed set of capabilities are required that facilitate:

- *End-to end data preservation and access,*
- *End-to-end, human-to-machine control of how data are collected and analyzed,*
- *Direct, closed loop interaction of models with the data acquisition process,*
- *Virtual collaborations created on demand to drive data-model coupling and share ocean observatoriy resources (e.g. instruments, networks, computing, storage and*

*workflows),*

- *Near-real-time, open access to data with latencies as small as seconds,*
- *End-to-end preservation of the ocean observatory process and its outcomes, and*
- *Automation of the planning and prosecution of observational programs.*

In addition to these features, the CI must provide the background messaging, governance and service frameworks that facilitate interaction in a shared environment, similar to the role of the operating system on a computer; in particular the cyberinfrastrucutre facilitates the compilation of diverse instruments, sensors, and autonomous vehicles into observatories.


Figure 1: The OOI is unusual in that the information technology component extends well beyond the collection of data and subsequent storage for file access. This figure does include these functions (e.g. data collection) in green and storage of the data as a component of knowledge. However, the data will be immediately analyzed or modeled (orange) and the results will be fed to a component, which will exploit the knowledge gained from the analysis to modify the observational network itself (blue). For example, gliders associated with the fixed network can be redirected to locations where new data can be collected to reduce the estimated errors in the models. Ultimately, the goal is to remove humans from this loop in order to reduce errors and the costs of operations and maintenance.

The CI integration strategy is based on two core principles: messaging and service-orientation. A high-performance message exchange provides a communication conduit with dynamic routing and interception capabilities for all interacting elements of the system-of-systems. The message interface is isolated from any implementation technologies, and provides scalability, reliability and fault-tolerance. Service-orientation is the key to managing and maintaining applications in a heterogeneous distributed system. All functional capabilities and resources represent themselves as services to the observatory network, with precisely defined service access protocols based on message exchange. Services are also defined independently of implementation technologies. Assembling and integrating proven technologies and tools provide the functional capabilities of the CI. While the network will be coupled through the Internet, the usual IP Layer 3 including FTP and SSH will not be used – this functionality is provided by the message passing service.

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

This year Bob Parker has continued looking into problems associated with electromagnetic induction. A seemingly simple technical question has required some surprisingly heavy machinery to solve. In calculating the electromagnetic fields due to a controlled source in a realistic model it is useful to find the response from a layered medium, which provides a starting point for more detailed, finite-element calculations; in particular, the singular behavior near the transmitter is dealt with much more naturally. The standard solution of the 1-dimensional system demands the numerical evaluation of the Hankel transform:

$$P(r) = \int_0^\infty Q(\lambda)\, J_0(r\lambda)\, \lambda\, d\lambda$$

where $Q(\lambda)$ is a complex function computed from the solution of an ordinary differential equation. While $Q$ is very smooth, values of $r$ encountered in practice generate very oscillatory integrands; see Fig 1. Traditional numerical quadrature techniques become impractical when good accuracy is needed for hundreds thousands of such integrals.

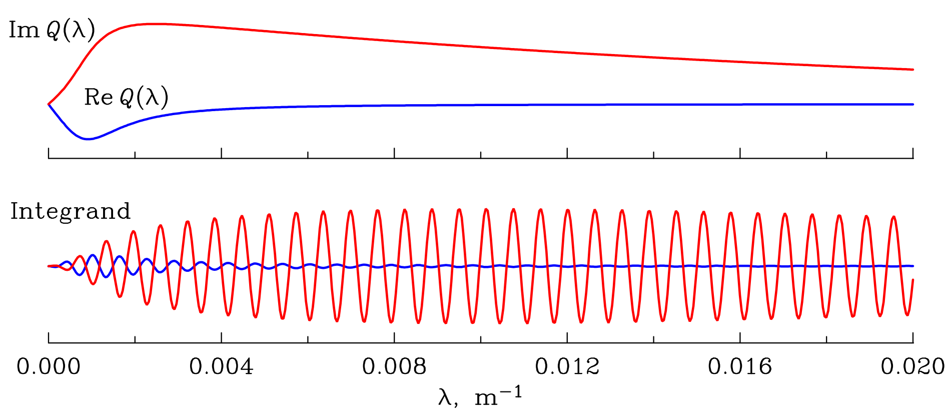
The solution to this problem has been to approximate $Q$ with an expansion in a set of functions whose transforms can be evaluated exactly:

$$Q(\lambda) = \sum_{n=1}^{N} \beta_n g_n(\lambda)$$

$$P(r) = \sum_{n=1}^{N} \beta_n \hat{g}_n(r), \quad \text{where} \quad \hat{g}_n(r) = \int_0^\infty g_n(\lambda)\, J_0(r\lambda)\, \lambda\, d\lambda\,.$$

Even this approach has its limitations, since a very high degree of approximation is required when $r$ becomes large, and 200 terms may be needed in the

**Figure 1:** Typical kernel function $Q(\lambda)$ and integrand of the transform when $r = 10$ km.



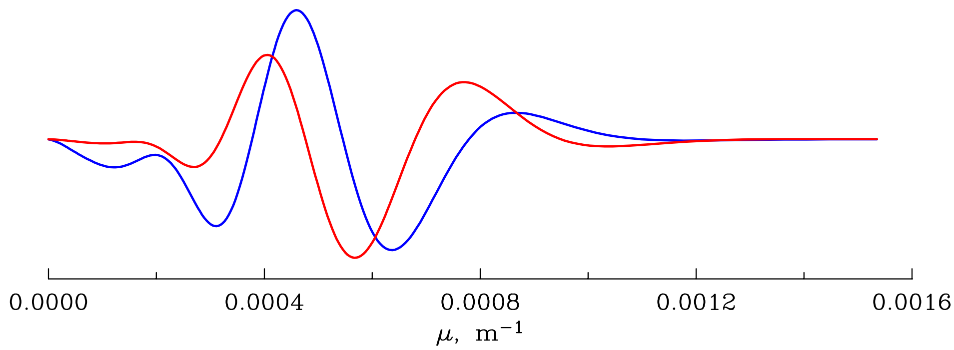



**Figure 2:** Integrand of transform on the imaginary axis.

expansion with functions that have elementary transforms. My resolution is to exploit the fact that $Q(\lambda)\exp(h\lambda)$ is an analytic function, regular at infinity, so that one can employ an orthogonal polynomial expansion of this function in the variable $\eta = \lambda/(\lambda + \lambda_0)$; this expansion requires far fewer terms (typically 30) to achieve a comparable precision.

These basis functions however must now be integrated numerically. To do this effectively the transform can be regarded as a contour integral, and the path of integration rotated onto the positive imaginary axis as there are no singularities of the approximate integrand in the first quadrant. Now the integral to be evaluated are in the form

$$P(r) = \int_0^\infty F(\mu)\, K_0(r\mu)\, \mu\, d\mu$$

where the Bessel function $K_0(r\mu)$ decays exponentially instead of oscillating like $J_0(r\lambda)$. The new integrand is quite benign, as can be seen above.

The papers below reflect work in other areas of interest. The one concerning reduction of bias in multitaper estimation was briefly described in the 2007 Annual Report.

## Recent Publications

Jackson, A. Constable, C. G., Walker, M. R., and Parker, R. L., Model of Earth's main magnetic field incorporating flux and raidal vorticity constraints, *Geophys. J. Internat.,* 171, pp 133-44, doi:10.111/j.1365-246. X.2007.03526.x, 2007.

Prieto, G. A., Parker, R. L., Thomson, D. J., Vernon, F. L., and Graham, R., L., Reducing bias in multitaper spectrum estimates, *Geophys. J. Internat.,* 171, 1269-81, doi:10.1111/j.1365-246 X.2007.03592.x, 2007.

**David T. Sandwell**
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*Research Interests:* Geodynamics, global bathymetry, crustal motion modeling

During the 2009 academic year, Dave Sandwell's research was focused on solid Earth Geophysics with an emphasis on understanding the dynamics of the crust and lithosphere. Our group comprises three graduate students Karen Luttrell, Meng Wei, and Xiaopeng Tong. Our research is mostly supported by three grants; two are from the National Science Foundation with titles *Observations and Modeling of Shallow Fault Creep Along the San Andreas Fault Zone* and *High-Resolution Gravity, Topography, and Seafloor Roughness* while the third is from NASA to perform *Geodetic Imaging and Modeling of the San Andreas Fault System*.

*Radar Interferometry* - After three years in orbit, the L-Band synthetic aperture radar (SAR) aboard the Japanese ALOS spacecraft is performing beautifully and is providing global interferometric crustal motion measurements. Dave Sandwell, Xiaopeng Tong, Rob Mellors (SDSU) and Yuri Fialko, are using these data to investigate the coseismic and postseismic deformation associated with the major ($M_w$ 7.9), and highly destructive, earthquake which occurred on May 12, 2008 in the eastern Sichuan province of China. We are developing new methods for mosaicking the numerous interferograms covering the 400 km by 400 km zone of deformation. This involves the development of new ScanSAR interferometry methods and code.

*Global Bathymetry* - David Sandwell and Water Smith (NOAA - Silver Spring Maryland) continued their collaboration on retracking the raw radar altimeter waveforms from ERS-1 and Geosat to further improve the accuracy and resolution of the global marine gravity field (*Sandwell and Smith*, 2009). In addition they continue to advocate a new altimeter mission with a 5-fold improvement in accuracy (*Sandwell et al.*, 2006). J.J. Becker has used ship soundings to estimate the slope of the ocean floor in relation to the critical slope needed to convert tidal energy into internal waves (*Becker and Sandwell*, 2008). This research helps to resolve the issue of, where and how, deep-ocean mixing occurs. The global bathymetry grid is used in Google Earth (Figure 1.)

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

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

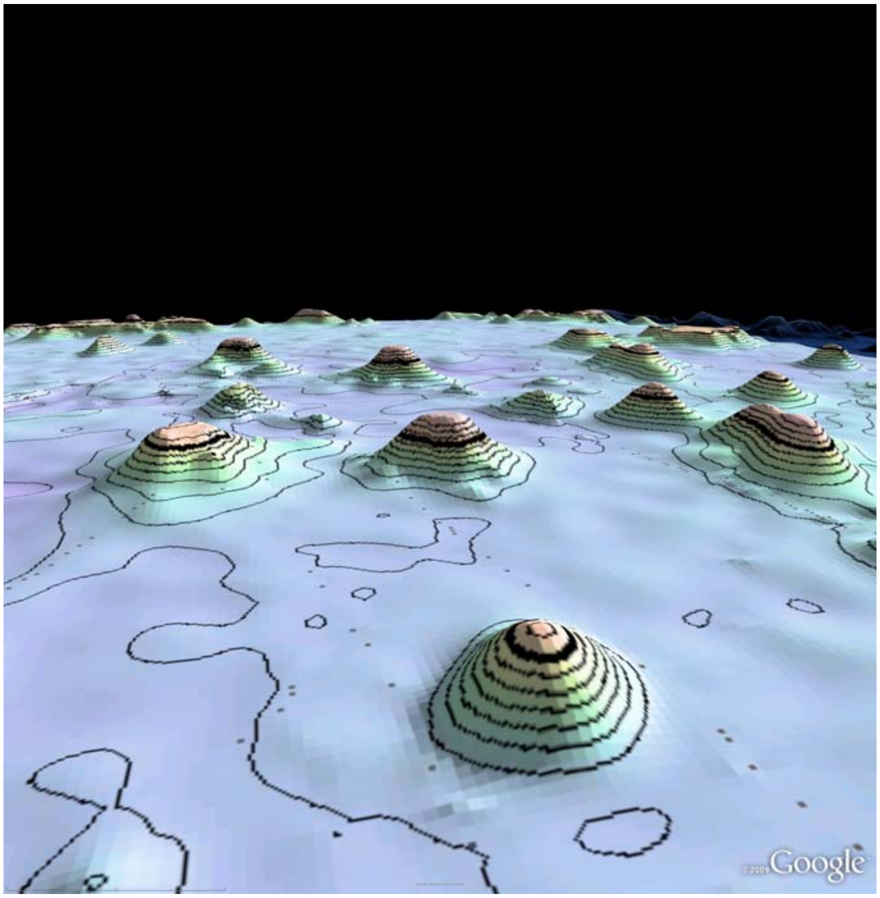


Figure 1. Bathymetry of large seamounts in the western Pacific based on a new global bathymetry grid (SRTM30_PLUS). This grid provides the ocean base later for Google Earth. Contour interval is 500 m.

**Relevant Publications**


Becker, J. J., D. T. Sandwell, Global estimates of seafloor slope from single-beam ship soundings, *J. Geophys. Res., 113,* C05028, doi:10.1029/2006JC003879 30 May 2008.

Luttrell, K., D. Sandwell, B. Smith-Konter, B. Bills, and Y. Bock, Modulation of the earthquake cycle at the southern San Andreas fault by lake loading, *J. Geophys. Res., 112*, B08411, doi:10.1029/2006JB004752, 2007.

Sandwell, D. T., D. Myer, R. Mellors, M. Shimada, B. Brooks, and J. Foster, Accuracy and resolution of ALOS interferometry: Vector deformation maps of the Father's Day Intrusion at Kilauea, *IEEE Trans. Geosciences and Remote Sensing, 46, no. 11*, p. 3524-3534, 2008.

Sandwell, DT; Smith, WHF; Gille, S; Kappel, E; Jayne, S; Soofi, K; Coakley, B; Geli, L., Bathymetry from space: Rationale and requirements for a new, high-resolution altimetric mission. *Comptes Rendus Geoscience. 338* (14-15) : 1049-1062, 2006.

Sandwell, D. T., and W. H. F. Smith, Global marine gravity from retracked Geosat and ERS-1 altimetry: Ridge segmentation versus spreading rate, *J. Geophys. Res., 114, B01411,* doi:10.1029/2008JB006008, 2009.

Smith, B., and D. T. Sandwell, Stress evolution of the San Andreas fault system: Recurrence interval versus locking depth, *Geophys. Res. Lett., 36*, L13304, doi:10.1029/2009GL037235, 2009

Wei, M., D. Sandwell, and Y. Fialko (2009), A silent Mw 4.7 slip event of October 2006 on the Superstition Hills fault, southern California, *J. Geophys. Res., 114,* B07402, doi:10.1029/2008JB006135.

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*Research Interests:* Seafloor geodetic measurements.

Glenn Sasagawa's research focuses on the design, development, and deployment of scientific instrumentation to investigate geodetic questions in the marine environment. In the 2008-2009 academic year, we continued to test a prototype seafloor pressure reference. A prototype gravimeter for deployment on an Autonomous Underwater Vehicle (AUV) tested at sea on its second test cruise. The geodetic research is a group effort that includes Mark Zumberge.

**Seafloor Pressure Standard**

Continuously recording seafloor pressure gauges have been used to monitor episodic vertical deformation on the seafloor. However, the instrument readings slowly drift in time, masking any slow signals due to seafloor deformation. We have built a laboratory prototype that can provide a stable pressure reference signal for geodetic applications. A fixed mass resting on a precisely machined hydraulic cylinder provides a known and stable pressure signal; standard pressure calibration systems use this technique. A seafloor pressure gauge would periodically measure, in situ, the reference pressure signal. In turn the pressure gauge drift would be determined and the uncontaminated slow deformation signals would be extracted. Tests with the prototype show a repeatability 0.736 mbar (5.3 ppm), corresponding to seawater changes of 0.7 cm.

We have been designing a follow-on system for autonomous deployment on the seafloor. The demonstration target site is Axial Volcano on the Juan de Fuca ridge, which is an active area of seafloor volcanic deformation associated with eruptive cycles.

**AUV Gravimetry**

Marine gravity measurements are almost always collected with gyroscopically stabilized instruments about surface ships. Surface measurements are, however, limited by physical laws to resolving seafloor features with dimensions greater than the water depth of the water. Surface measurements must also filter out the acceleration noise of the surface vessel motions.

An autonomous underwater vehicle (AUV) is essentially a robotic submarine. An AUV can carry a gravimeter much closer to the features of interest. The underwater flight of an AUV is also much smoother than that of a surface vessel. On the other hand, an AUV presents challenges in terms of relatively limited endurance, payload capacity, and navigational uncertainties. With proper design, all of these problems can be overcome.

We constructed and deployed a prototype gravimeter on board the SIO Bluefin AUV in June 2008. Initial results were encouraging, although a noise source attributed to the vehicle propulsion system was uncovered. A quieter propulsion system was tested in August of 2009; the analysis is on-going.

**Seafloor Gravimetry**

For the past 12 years, our group has been working with StatoilHydro on using seafloor gravity measurements as a means of monitoring natural gas reservoirs and a carbon sequestration site. During May-July of 2009, our group deployed the ROVDOG (Remotely Operated Vehicle Deployable Deep Ocean Gravimeter) at several Norwegian natural gas fields, as well as the Sleipner carbon sequestration site. We have also continued to test and improve the precision of the instrumentation. This work also included contributions from Scott Nooner (SIO Ph.D. 2005) at the Lamont Doherty Earth Observatory.


Figure 1. ROVDOG deployment in the North Sea. The instruments are visible in the front of the ROV. The Troll A gas platform is visible in the background. Note the exceptionally calm weather even for July in the North Sea.

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

Peter Shearer's research uses seismology to learn about Earth structure and earthquakes, both globally and in California, and has involved the development of new analysis approaches to handle efficiently the large digital data sets that are now emerging from the global and regional seismic networks. Recent work with postdoc Catherine Rychert applied seismic receiver function analysis in a global study of the lithosphere-asthenosphere boundary, showing that it is a globally pervasive feature that varies in depth depending upon the tectonic environment (*Rychert and Shearer,* 2009). Student Bettina Allmann used a spectral stacking method to investigate global variations in stress drop among ~2000 $M > 5.5$ earthquakes and found that intraplate earthquakes have higher average stress drops than interplate earthquakes (*Allmann and Shearer*, 2009). Working with former student Paul Earle, Shearer developed stacking methods that work with high-frequency data and a Monte Carlo implementation of radiative transfer theory for modeling whole-Earth scattering (*Shearer and Earle*, 2008).

Another research topic has involved experimenting with applying backprojection (reverse time migration) to seismic records in order to directly image seismic radiation from earthquake ruptures. This method has some advantages over conventional finite-source modeling—it requires fewer assumptions about the fault geometry, it works with high-frequency data, and its computational efficiency makes it ideal for near-real-time applications. Postdoc Kris Walker used backprojection to show that two recent large strike-slip earthquakes in Tibet and Alaska involved supershear rupture speeds (*Walker and Shearer*, 2009). Although supershear rupture (faster than shear-wave velocity) had previously been suggested by some studies for these events, Walker's results provided more definitive constraints on the rupture speeds and where the supershear rupture initiated.

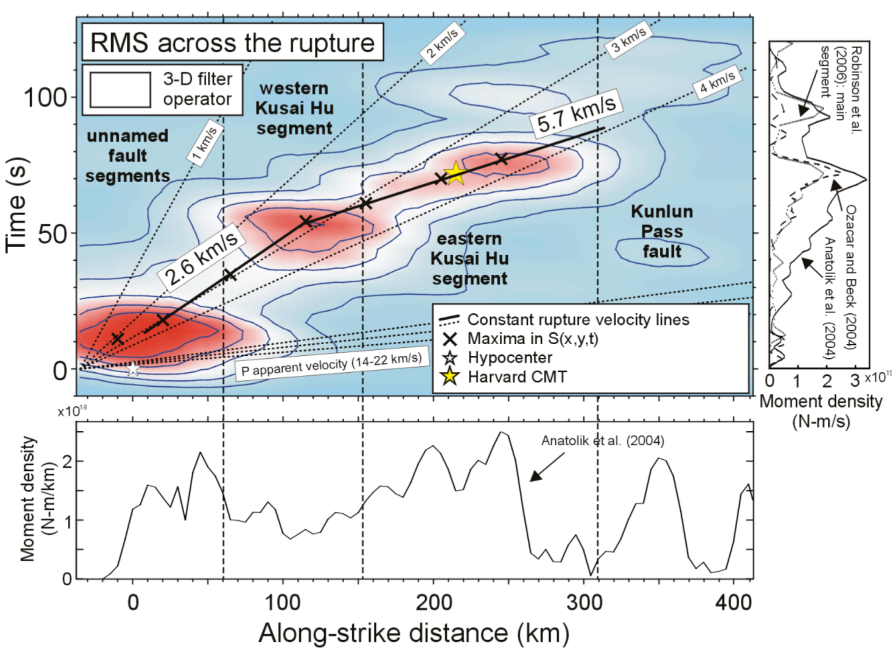


**Figure 1.** Supershear rupture of the 2001 *Mw* 7.8 Kunlun earthquake as imaged using a teleseismic *P*-wave backprojection method. The rupture begins at ~2.6 km/s but accelerates to ~5.7 km/s after about 100 km. From *Walker and Shearer* (2009).

Shearer's southern California work has focused mostly on improving earthquake locations using robust methods and waveform cross-correlation. Working with former student Guoqing Lin, he used these more accurate earthquake locations to study the time/space clustering of precursory seismicity prior to earthquakes of different sizes, and identified regions of enhanced activity in a 1-day period preceding larger earthquakes at distances comparable to their predicted source radii (*Shearer and Lin*, 2009). This result indicates that many standard earthquake triggering models do not account for all of the processes involved in earthquake occurrence. They also used the precise times provided by waveform cross-correlation to search for possible temporal changes in seismic travel times across southern California (*Lin et al*., 2008), and found no evidence for large-scale velocity changes larger than ±0.2%, although there is increased scatter in travel-time residuals immediately following major earthquakes from regions near the mainshock rupture.

In 2006, postdoc Elizabeth Cochran led a UCSD/UCLA/USC seismic experiment on the Calico fault in the eastern California shear zone. Analysis of these data confirm geodetic evidence for a 1.5-km-wide damage zone around the fault with 40–50% seismic velocity reductions (*Cochran et al*., 2009), a result with implications for the amount of energy expended during rupture to drive cracking and yielding of rock and development of fault systems.

Finally, recent collaborations with SIO's Peter Gerstoft on analysis of seismic noise have shown that global *P*, *PP* and *PKP* wave microseisms can be observed from distant storms by using array analysis on southern California seismic stations, and that high-frequency *P*-wave noise at Parkfield and the Mojave desert is highly correlated with off-shore windspeeds (*Gerstoft et al*., 2008; *Zhang et al*., 2009).

**Recent Publications**


Allmann, B.P., P. M. Shearer, and E. Hauksson, Spectral discrimination between quarry blasts and earthquakes in southern California, *Bull. Seismol. Soc. Am.*, **98**, 2073–2079, doi: 10.1785/0120070215, 2008.

Allmann, B. B., and P. M. Shearer, Global variations of stress drop for moderate to large earthquakes, *J. Geophys. Res.*, **114**, doi: 10.1029/2009JB005821, 2009.

Cochran, E. S., Y.-G. Li, P. M. Shearer, S. Barbot, Y. Fialko, and J. E. Vidale, Seismic and geodetic evidence for extensive, long-lived fault damage zones, *Geology*, **37**, 315–318, doi: 10.1130/G25306A.1, 2009.

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Lin, G., P. M. Shearer and E. Hauksson, A search for temporal variations in station terms in southern California from 1984 to 2002, *Bull. Seismol. Soc. Am*., **98**, 2118–2132, doi: 10.1785/0120070243, 2008.

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Peng, Z., K. D. Koper, J. E. Vidale, F. Leyton, and P. Shearer, Inner-core fine-scale structure from scattered waves recorded by LASA, *J. Geophys. Res.*, **113**, doi: 10.1029/2007JB005412, 2008.

Rychert, C. A., and P. M. Shearer, A global view of the lithosphere-asthenosphere boundary, *Science*, **324**, doi: 10.1126/science.1169754, 2009.

Shearer, P. M., and P.S. Earle, Observing and modeling elastic scattering in the deep Earth, in *Advances in Geophysics, Volume 50: Earth Heterogeneity and Scattering Effects on Seismic Waves*, H. Sato and M. C. Fehler (ed.), Elsevier Ltd., Oxford, p. 167-193, 2008.

Shearer, P. M., and G. Lin, Evidence for Mogi doughnut behavior in seismicity preceding small earthquakes in southern California, *J. Geophys. Res.*, **114**, doi: 10.1029/2009JB005982, 2009.

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Zhang, J., P. Gerstoft, and P. M. Shearer, High-frequency P-wave seismic noise driven by ocean winds, *Geophys. Res. Lett*., **36**, doi: 1029/2009GL037761, 2009.

**Hubert Staudigel**

**Research Geologist, Lecturer**

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*Research Interests:* Seamounts, Volcanology, Biogeoscience, Science Cyberinfrastructure and Education

Seamounts and volcanoes have been a central theme in Hubert Staudigel's research since his PhD work on the seamount series of La Palma, Canary Islands (Staudigel and Schmincke, 1984). Since then he has worked on numerous aspects of seamounts and volcanology, from petrology and isotope geochemistry to their alteration, macrobenthic communities and microbiology, their magnetic properties, density distribution (gravity) and seismic structure. Over the last few years most of his seamount research focused on the geochronology, geochemistry and the microbial communities colonizing them, in particular around active hydrothermal vents. Recent papers include: (1) the demonstration of a systematic age progression and the "hot-spot" origin of Savaii (Samoa; Koppers et al., 2008 ), and (3) An isotopic investigation of previously dated seamount samples in the Western Pacific (Konter et al., 2008) showed that three recently active hot spot volcanoes in the Cook-Austral island chain have been consistently producing isotopically extreme magmas suggesting an origin by long-lived hot spots.

Hubert Staudigels' involvement in volcanology includes interests in submarine volcanism and dike intrusions and he also teaches a class in volcanology on the Big Island of Hawaii. Recent volcanological studies include the discovery of potentially the oldest ophiolite on earth in the Isua Supracrustal Belt (Furnes et al., 2007) and volcano-based paleomagnetic research in Antarctica (http://earthref.org/ERESE/projects/GOLF182/index.html) and on Jan Mayen, in collaboration with Lisa Tauxe, Cathy Constable and Geoff Cromwell). The key objective of the paleomagnetics work is to study the fine scale (secular) variation of the magnetic field.

Hubert Staudigel collaborates Brad Tebo, Alexis Templeton, Laurie Connell, Katrina Edwards, Craig Moyer and Dave Emerson and graduate students Brad Bailey and Lisa Sudeck (Haucke) to study the chemical and biological controls of water-rock interaction during seafloor alteration of the oceanic crust. Current work focuses on the characterization and isolation of microbes that facilitate these processes (Sudek et al, 2009 in press; Bailey et al., in press 2009), how they colonize rock surfaces and the mechanisms by which microbes may dissolve in particular volcanic glass. A collaboration with Laurie Connell (UMaine/Orono) resulted in the discovery that single celled fungi are very commonly associated with the deep seafloor wathering of basalt (Connell et al., 2009, in press). These papers will be published in the last issue of Geomicrobiology Journal in 2009. H. Furnes and N. McLoughlin (U. Bergen, Norway) and others joined Hubert Staudigel in the study of characteristic corrosion features reflecting bioalteration of basaltic glass, and they could show that the majority of glass alteration is caused by microbial activity, back through time to almost 3.5 Ba (Staudigel et. al., 2008). Hubert Staudigel recently completed the first of three field seasons studing microbe-rock interaction in the McMurdo extreme environments of Antarctica (http://earthref.org/ERESE/projects/GOLF439/index.html).

Hubert Staudigel is also involved in efforts creating a Cyberinfrastructure for earth science and science education, in collaboration with A. Koppers, J. Helly, C. Manduca and D. Mogk. Key data base components include the reservoir data base for the Geochemical Earth Reference Model (GERM) initiative, the Seamount Catalog for the Seamount Biogeoscience Network (SBN) and the ERESE project (Enduring Resources for Earth Science Education), all accessible at earthref.org. Collaboration with K. Manduca of the Science Education Resource Center (SERC) at Careleton College (http://serc.carleton.edu/sp/erese/activities.html). Hubert Staudigel's website includes a more complete bibliography (http://earthref.org/whoswho/ER/hstaudigel/index.html).

**Recent Publications**


Koppers, AAP, J.A. Russell, M. G. Jackson, J. Konter, H. Staudigel, S. R. Hart, 2008, Samoa reinstated as a primary hotspot trail, Geology, v. 36; no. 6; p. 435–438; doi: 10.1130/G24630A.1; 4 fi gures; Data Repository item 2008102008 .

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Santelli, CM, B. N. Orcutt, Banning, E., Bach, W., Moyer, C.L., Sogin, M.L., Staudigel, H., Edwards, KJ, 2008, Abundance and diversity of microbial life in ocean crust, Nature 453. Doi:10.1038/Nature06899

Staudigel, H., H. Furnes, N. McLoughlin, Neil R. Banerjee, Lauri B. Connell, Alexis Templeton, 2008, 3.5 billion years of glass bioalteration: Volcanic rocks as a basis for microbial life? Earth Science Reviews 89: 156-176.

Konter, J.G., B. B. Hanan, J. Blichert-Toft, A.A.P. Koppers, T. Plank, H. Staudigel, 2008, One hundred million years of mantle geochemical history suggest the retiring of mantle plumes is premature, Earth and Planetary Science Letters 275 285–295

Sims, Kenneth, W.W., Stanley R. Hart, M.K. Reagan, J. Blusztjan, H. Staudigel, R.A. Sohn, G.D. Layne, 2008, 238U-230Th – 226Ra – 210Pb 210Po, 232TH-228Ra and 235U-213Pa constraints on the ages and petrogenesis of Vailulu' and Malumau Lavas, Samoa, Geochem. Geophys. Geosyst. Vol 9 4 doi: 10.1029/2007GC001651.

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Konter, J.G., H. Staudigel, J. Blichert-Toft, B.B. Hanan, M. Polve, G.R. Davis, N. Shimizu, P. Schiffman (2009) Geochemical stages at Jasper Seamount and the origin of intraplate volcanoes., G-cubed 10, doi 10.1029/2008GC002236.

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

In 2008-2009, work was underway in several areas of computational geodynamics including numerical modeling of tectonic plates, the interior of a Saturnian moon, and real-time visualization of large-scale computer simulations.

*Towards robust numerical models of a subducting tectonic plate:*

One important step in achieving more realistic Earth-like behavior of subducting tectonic plates is including the coupling between the colder, more viscous tectonic plate and the surrounding mantle. This type of simulation has been difficult in the past because it incorporates aspects of both solid mechanics and fluid mechanics into a single model. Three different approaches with the same set-up were applied to this problem, each using a different numerical method, but were eventually able to reproduce similar results (Figure 1).

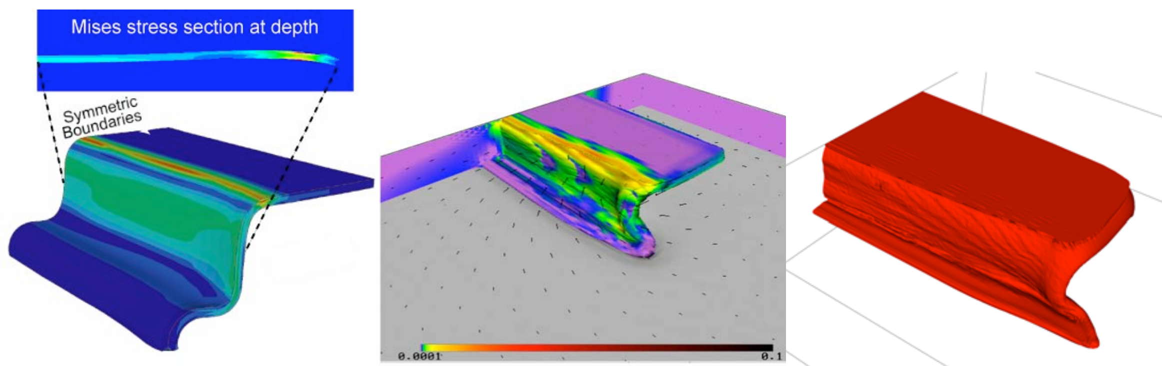



**Figure 1. Characteristic "S-bend" trench curvature of a wide slab (cf Schellart et al., Nature, 2007) reproduced with different hybrid finite element numerical methods coupled with: boundary element (left), Lagrangian integration points (center), and level sets (right).**

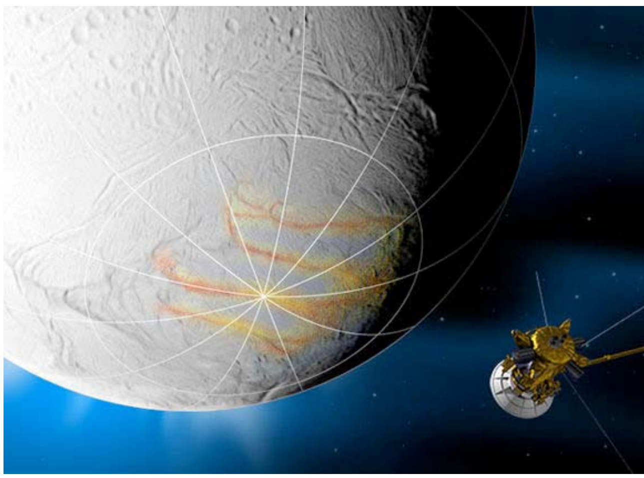
A similar model was used to show that there are links between surface tectonics and subducted slabs, which likely originate from slab behavior in the mantle transition zone. Clark et al. (2008) investigated subduction zone dynamics as they relate to evolution of back-arc basins. These results were able to attribute a range of different observed behaviors to those seen in numerical models and led to proposing a new classification of back-arc basins into three types: pseudo–. quasi–, and hyper–episodic.

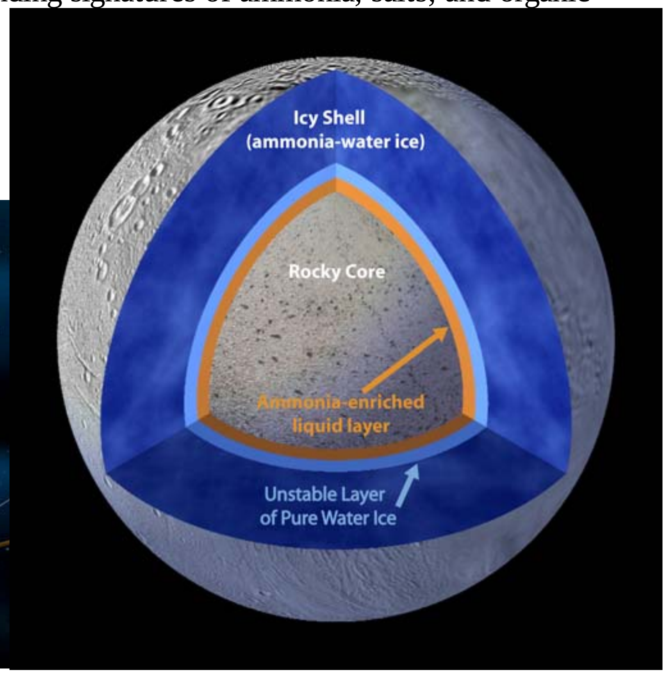
*The role of ammonia in the evolution of Enceladus:*

In 2006, NASA's Cassini spacecraft revealed Enceladus as a dynamic place, recording geological features such as geysers emerging from the 'tiger stripes' which are thought to be cracks caused by tectonic activity on the south pole of the moon's surface (Figure 2, left). Initially, the anomalously high temperatures near the stripes were unexplained, but are now thought to result from tidally induced shear heating along them. In addition, there is evidence suggesting the satellite experienced true polar wander (TPW) and perhaps has a subsurface ocean. Presently, no self-consistent evolution for the origin of all these features exists.

We proposed a new model for Enceladus' interior that describes the differentiation of its icy shell and its subsequent thermochemical evolution. Initially, the frozen shell was entirely composed of a mixture of ammonia and water ice surrounding a rocky core. Over time, as Enceladus interacted with other moons, a small amount of heat was generated above the silicate core which made the ice shell separate into chemically distinct layers. An ammonia-enriched liquid layer formed on top the core while a thin layer of pure water ice formed above that (Figure 2, right). Numerical models then showed that if a layer of pure water ice formed near the core, it would have enough buoyancy to rise upwards. Such a redistribution of mass can drive TPW, which in turn generates large tectonic stresses at the surface. However, the hemispheric-scale diapir of pure water ice rising up is also slightly warmer which causes the differentiation to occur again, this time forming an ammonia-enriched ocean just under the surface. Importantly, this ocean allows tectonic stresses to concentrate asymmetrically in the brittle ice shell directly above, leading to formation of the tiger stripes. The presence of ammonia, which acts as an anti-freeze, then allows the ocean to remain in its liquid state, helped from heat generated in the tiger stripes above. Recent measurements of the composition of the vapor plume have reported finding signatures of ammonia, salts, and organic compounds, all of which suggest that there may indeed be a much larger reservoir of ammonia deep within Enceladus' interior.

**Figure 2. Left: Artist's view of the Cassini spacecraft flying over the "Tiger Stripes" (credit: NASA). Right: Cutaway view of Enceladus' interior subsequent to differentiation of the ammonia-water ice overlying the silicate core. This results in an unstable layer of pure water ice that forms into a hemispherical-scale diapir.**






**Stegman, D.R.,** J. Freeman and D.A. May. "Origin of ice diapirism, true polar wander, subsurface ocean, and tiger stripes of Enceladus driven by compositional convection", *Icarus*, 202, 669-680, doi:10.1016/j.icarus.2009.03.017, 2009.

Gottschaldt, K., U. Walzer, **D.R. Stegman,** J.R. Baumgardner, and H.B. Mulhaus. "V. Mantle Convection – A Case Study," *Advances in Geocomputing* (ed H. Xing), Lecture Notes in Earth Sciences, 119, 139-170, Springer-Verlag Berlin Heidelberg, doi:10.1007/978-3-540-85879-9_5, 2009.

OzBench, M., K. Regenauer-Lieb, **D.R. Stegman,** G. Morra, R. Farrington, A. Hale, D.A. May J. Freeman, L. Bourgouin, H. Muhlhaus, and L. Moresi. "A model comparison study of large-scale mantle-lithosphere dynamics driven by subduction", *Physics of the Earth and Planetary Interiors*, 171, 224-234, doi:10.1016/j.pepi.2008.08.011, 2008.

Clark, S**., D.R. Stegman,** D. Mueller. "Episodicity in back-arc basin formation", *Physics of the Earth and Planetary Interiors*, 171, 265-279, doi:10.1016/j.pepi.2008.04.012, 2008.

Schellart, W.P., **D.R. Stegman,** and J. Freeman. "Global trench migration velocities and slab rollback-induced mantle fluxes: Constraints to find an absolute Earth reference frame based on minimizing viscous dissipation", *Earth Science Reviews*, doi:10.1016/j.earscirev.2008.01.005, 2008.

**Stegman, D.R.,** L. Moresi, R. Turnbull, J. Giordani, P. Sunter, A. Lo and S. Quenette. "gLucifer: Next Generation Visualization Framework for High Performance Computational Geodynamics", *Visual Geosciences,* doi:10.1007/s10069-008-0010-2, 2008.

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*Research Interests:* Real-Time Sensor Networks, Ocean Observing Systems Time Series Analysis, Earthquake Source Physics, Seismic Instrumentation

We operate the USArray Array Network Facility (http://anf.ucsd.edu), which is a key component for the NSF EarthScope MRE. This network currently has 434 seismic stations delivering real-time data to UCSD, which are redistributed to multiple sites. The ANF is responsible for real-time state-of-health monitoring for the network in addition to the real time data processing, archiving, and distribution. Data are acquired over multiple types of communication links including wireless, satellite, and wired networks. The large volumes of broad band waveform data from the transportable array element of

USArray offers a unique opportunity for seismic imaging. Constraining structures on a range of length scales and understanding their physical and chemical causes is a prerequisite for understanding the relationship between near surface and deeper mantle processes. With existing methods, we can produce 3-D models of P wavespeed variations in the mantle beneath North America using travel times from the USArray TA . This is just one example of the many scientific opportunities provided by this unique experiment.

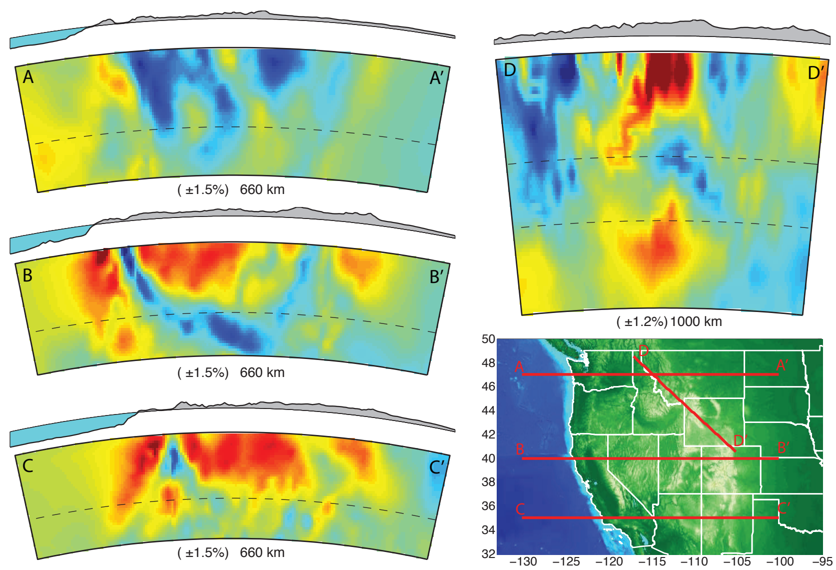
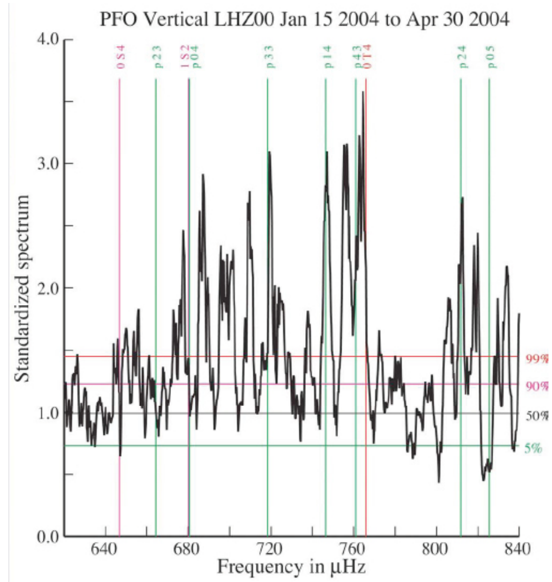



*Figure 1. Cross sections through MITP_USA_2008DEC for the same locations as in Figure 7 of Burdick et al. (2008), which displayed model MITP_USA_2007NOV. The three east-west sections reveal additional heterogeneity to the east, while the updated D-D' section shows a greater degree of heterogeneity at shallow depths.*

The next major observing system is the NSF MRE Ocean Observatory Initiative which starts in September 2009 with the objective of deploying long term observing platforms with sensors that observe the physical, chemical, and biological attributes of the oceans in near real-time. This program is the locus of the next generation oceanographic sensor network innovation (http://www.siovizcenter.ucsd.edu/ooi/index.php)

Another research specialization is in spectral analysis, which has undergone a revolution with the development of sophisticated techniques in which the data are multiplied in turn by a set of tapers that are designed to maximize resolution and minimize bias. In addition to minimizing the bias while maintaining a given resolution, the multi-taper approach allows an estimate of the statistical significance of features in the power spectrum. We are developing a quadratic inverse theory that utilizes not only the spectral estimators, but also the time and frequency derivatives of the spectrum, to generate much higher resolution spectra. We are extending the theory from a univariate to a generalized multivariate theory. While the specific applications researched here are seismic, it is clear that there are other geophysical, scientific, and engineering applications that will benefit from the proposed studies.

Another result based on multitapers is are some unanticipated effects of the normal modes of the sun on engineering and scientific systems. Our results, based on extensive time-series studies of diverse data sources from operational communication and other engineered systems as well as the natural environment, show that much of the phenomena observed in space physics, including geomagnetic and ionospheric phenomena, exhibit a multitude of discrete frequencies over a wide frequency range superimposed on a noise background. We have hypothesized that these discrete frequencies can be explained in terms of the normal modes of the sun (solar theory, confirmed by data from helioseismology instruments that resolve spatial structure on the sun, shows that there are several million solar modes). That is, the normal modes of the sun are a dominant driver of the discrete frequencies that are measured in natural phenomena and also of the “noise” in engineered systems.




*Spectral peaks in seismic data at solar mode frequencies.*

**Relevant Publications**


Prieto, G. A. , D. J. Thomson, F. L. Vernon, P. M. Shearer and R. L. Parker (2006). Confidence intervals of earthquake source parameters, Geophys. J. Int., doi: 10.1111/j.1365-246X.2006.03257.x, Published online. Schulte-Pelkum, V., P. S. Earle, and F. L. Vernon (2004), Strong directivity of ocean-generated seismic noise, Geochem. Geophys. Geosyst., 5, Q03004, doi:10.1029/2003GC000520.

G. A. Prieto, R. L. Parker, F. L. Vernon, P. M. Shearer and D. J. Thomson (2007). Uncertainties in Earthquake Source Spectrum Estimation using Empirical Green Functions. AGU Monograph on Radiated Energy and the Physics of Earthquake Faulting , R. E. Abercrombie, A. McGarr, H. Kanamori, and G. di Toro eds. Doi: 10.1029/170GM08 69-74.

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Scott Burdick, Robert D. van der Hilst, Frank L. Vernon, Vladik Martynov, Trilby Cox, Jennifer Eakins, Taimi Mulder, Luciana Astiz, and Gary L. Pavlis (2009). Model Update December 2008: Upper Mantle Heterogeneity beneath North America from P-wave Travel Time Tomography with Global and USArray Transportable Array Data. Seismological Research Letters 80(4), 638-645

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*Research interests:* complexity, nonlinear dynamics and pattern formation; permafrost terrain; dynamics of human systems and human-landscape interactions; urban landscapes; dynamics of western and indigenous science; resistance movements; and independent media.

Brad Werner and co-workers Marcel Madison, Weini Mehari, Alice Nash, Christina Rios, Nav Sarna, Chris Shughrue, Gabriel Velin and Ben Volta (Anthropology/IGPP) in the Complex Systems Laboratory and collaborators D. Emily Hicks (Chican@ Studies/SDSU) and Dylan McNamara (Physical Oceanography/UNC) have been working to develop and refine the tools used to investigate complex systems - those systems for which simple and complicated descriptions, and often a range of intermediate representations, can be constructed - particularly those tools that are necessary to make useful predictions for the coupled human/Earth surface system. We also aim to democratize knowledge of nonlinear dynamics, so that a broader range of people can participate in analyzing and shaping the future of Earth's surface and the role of humans within its systems.

*Interplay between Resistance, Economic/Political Dynamics, and Landscapes:* Given the considerable influence of humans on landscapes and of natural processes on humans, and widespread resistance to resource extraction and land use policies, coupling between the political and economic dynamics determining land use, landscape processes and resistance will be central to determining the future evolution of Earth's surface. Undergraduates Marcel, Weini, Alice, Christina, Chris and Gabriel are developing an agent-based model for the interaction between forest and grassland ecosystems, economic exploitation of natural resources, and indigenous land use and resistance to exploitation and displacement in Madagascar.

*Dynamics of Urban Landscapes*: Slums are the fastest growing segments of cities, and they are often located in marginal zones most at risk for disasters. The growth of slums and their nonlinear interaction with economic and landscape systems will play a critical role in Earth surface dynamics as human population reaches a projected maximum later this century. The undergraduates are developing a model for the slum Kibera in Nairobi, Kenya, including modules that simulate flooding, disease transmission, housing/development, employment, water, food and fuel use, sanitation and waste, crime, migration to and from slums, government and NGOs, and resistance. Of particular interest is how the nature of coupled slum-landscape dynamics might change as migration and slum populations increase, and regional and global economies become stressed.

Ben is modeling Chichén Itzá, in Yucatan, Mexico, which was a thriving Maya city starting around 700, underwent significant changes, and later collapsed. The site is located in a karstic landscape highly dependent on episodic rains for water supply and agriculture. Ben's agent-based model includes hydrology and water storage and use, vegetation and agriculture, economic production and trade, urban dwellings and infrastructure, and Maya culture, and will be used to probe whether self-organized interactions between cultural, economic, political and environmental factors led to urban pattern shifts and, ultimately, catastrophe, Ben is employing a nonlinear spatial forecasting method to test for the evolution of spatial relationships amongst structures and natural features as the city developed and to test for differences with other Maya cities.

*Border Complexity:* Acting as filtration systems at intermediate time scales to goods and people, nation-state borders interact nonlinearly with distant land use and resource extraction patterns. Emily, Dylan and Brad are developing a theoretical description of the Mexico-US border as a hierarchical complex system and an agent-based model that includes fast-scale models for border crossers and border policing, and legal and illegal goods; intermediate-scale political decisions about the border based on cost-benefit analyses coupled to resource extraction and land use tied to commodities that cross the border; and longer-scale political, economic, cultural and informational systems co-evolving with changing landscapes, ecosystems and resource availability.

*Dynamics of Resource and Earth System Management:* Dynamically, commodification causes a collapse in time scales, by reducing the 'friction' of the interchange of goods and services, which in commons-based cultures allows for emergent levels of description. All associated dynamics are compressed to the faster time scale of commodity exchange. Management restores a set of slower time scales to what otherwise would be a fast, unstable system via a weighted longer-time-scale filtering of shorter term economic activity, principally through cost-benefit analyses. In contrast, in many indigenous cultures, highly frictional exchanges can be described on a range of time scales, and individual and group decisions about resource and Earth system management are constrained by, for example, the presence of the spirits of one's ancestors and relatives in the various elements of Earth systems and ecosystems. Rather than being a separate process, stabilization and management across a number of levels of description are integral parts of the exchange process.

Aspects of this theoretical framework are being investigated in an extension of our New Orleans model (Werner and McNamara, 2007) to include differing political/management strategies, including permit fees based on discounted calculations of future flood damage and adaptive management aimed at maximizing benefits minus costs.

*Boundary between Dynamical and Extra-Dynamical Phenomena:* Free will and spiritual worlds are two categories of extra-dynamical phenomena that potentially can influence human-landscape coupled systems. Subjective worlds of conscious beings are accessible to objective observation and modeling neither in practice nor in principle, If free will and spiritual worlds connect to the dynamical world through the short-time-scale subjective dynamics of individuals only, then western science and these extra-dynamical phenomena can be compatible. Short-time-scale extra-dynamical phenomena can have an influence on longer time scales if their effect is applied near transitions (the existence of which can be modeled dynamically). A potential criticism of this chain of reasoning is that western science applies well to short-time-scale (reductionism) and long-time-scale (universalism) behaviors, but less well to intermediate time scales, where heterogeneity of dynamics and state variables are common, and the ability to conduct repeated, controlled experiments is compromised; therefore, the relative lack of models and measurements at these intermediate scales makes the assumption that extra-dynamical phenomena are unconnected at these scales problematic. Indeed, indigenous science ascribes direct connections to spiritual worlds to intermediate scale landscape phenomena.

*Patterns on Earth's Surface in 200 Years*: Phenomena 200 years into the future can be connected to present-day phenomena only by dynamical behaviors with time scales of centuries. We are modeling three situations at these scales for which we have developed models at faster scales: developed coastlines under rising sea level, nation-state borders with degrading ecosystems, declining resource availability and increasing transportation costs, and slums in megacities under economic/environmental stress. Preliminary results indicate that present-day coherent patterns are expected to fragment, with disintegration of economic and power concentrations and networks, and localization of the presently globalized coupled human-landscape system.

*Democratizing Dynamics:* We are working to broaden access to the tools of complexity by: participating in community workshops and meetings; organizing complexity-related discussion groups; sharing technical and knowledge skills and equipment with community activists; volunteering with GDAWG-SIO to improve the environment at SIO, enhance diversity and connect to communities, meeting with on-the-ground resource managers; developing a park exhibit; and writing popular books on urban complexity and the dynamics of resistance.

--B. T. Werner & D.E. McNamara (2007) Dynamics of coupled human-landscape systems, Geomorphology, 91, 393-407.
--D.E. McNamara & B. T. Werner (2008) Coupled Barrier Island-Resort Model: 1. Emergent instabilities induced by strong human-landscape interactions, JGR-Earth Surface, 113, F01016, doi:10.1029/2007JF000840.
--D.E. McNamara & B. T. Werner (2008) Coupled Barrier Island-Resort Model: 2. Tests and Predictions along Ocean City and Assateague Island National Seashore, Maryland, JGR-Earth Surface, 113, F01017, doi:10.1029/2007JF00084.
--L.J. Plug & B.T. Werner (2007) Modelling of ice-wedge networks, Permafrost & Periglacial Processes, 19, 63-69.

**Peter F. Worcester**
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*Research Interests:* acoustical oceanography, ocean acoustic tomography, underwater acoustics

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

**Acoustic Thermometry**. Over the decade 1996–2006, acoustic sources located off central California (1996–1999) and north of Kauai (1996–1999, 2002–2006) transmitted to receivers distributed throughout the northeast and north central Pacific [*Dushaw et al.*, 2009]. The acoustic travel times are inherently spatially integrating, which suppresses mesoscale variability and provides a precise measure of ray-averaged temperature. Daily-average travel times at four-day intervals provide excellent temporal resolution of the large-scale thermal field. The interannual, seasonal, and shorter period variability is large, with substantial changes sometimes occurring in only a few weeks. Linear trends estimated over the decade are small compared to the interannual variability and inconsistent from path to path, with some acoustic paths warming slightly and others cooling slightly. The measured travel times are compared with travel times derived from four independent estimates of the North Pacific: (i) climatology, as represented by the World Ocean Atlas 2005 (WOA05), (ii) objective analysis of the upper ocean temperature field derived from satellite altimetry and in situ profiles, (iii) an analysis provided by the Estimating the Circulation and Climate of the Ocean project as implemented at the Jet Propulsion Laboratory (JPL-ECCO), and (iv) simulation results from a high-resolution configuration of the Parallel Ocean Program (POP) model. The acoustic data show that WOA05 is a better estimate of the time-mean hydrography than either the JPL-ECCO or the POP estimates, both of which proved incapable of reproducing the observed acoustic arrival patterns. The comparisons of time series provide a stringent test of the large-scale temperature variability in the models. The differences are sometimes substantial, indicating that acoustic thermometry data can provide significant additional constraints for numerical ocean models.

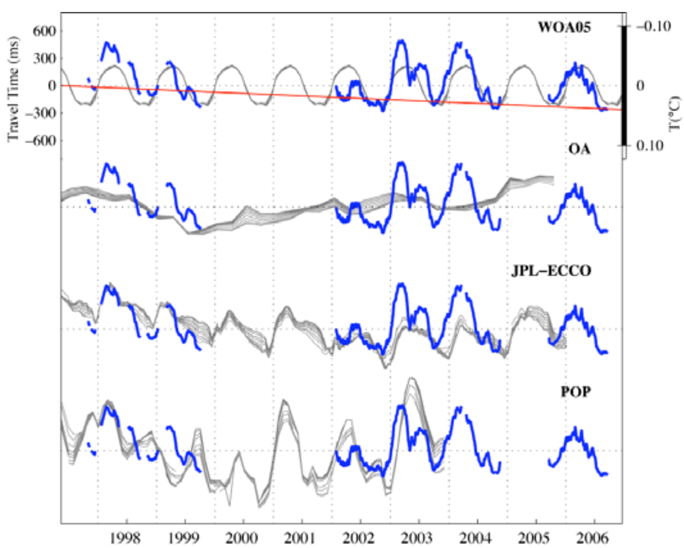


*Figure 1*. Comparison of measured travel times for transmissions from Kauai to receiver k, approximately 4000 km northwest of Kauai, (blue) with travel times calculated using sound-speed fields derived from WOA05, estimates of upper ocean temperature profiles produced by an objective analysis (OA) procedure that combines satellite altimetric height with in situ temperature profiles, the JPL-ECCO solutions, and the POP model (gray). The time means have been removed from all of the time series. For comparison, the trend in travel time corresponding to a 5 m°C/year change in temperature at the sound-channel axis is also shown (red).

**North Pacific Acoustic Laboratory (NPAL)**. Over the last twenty years, long-range, deep-water acoustic experiments have been performed almost entirely in the relatively benign northeast and north central Pacific Ocean [e.g., *Van Uffelen et al*., 2009]. The NPAL Group is now conducting acoustic propagation experiments in the much more variable northern Philippine Sea. A short-term Pilot Study/Engineering Test was conducted in April-May 2009. Preparations are in progress for a one-year experiment in 2010–2011. The 2010–2011 experiment will combine measurements of acoustic propagation and ambient noise with the use of an ocean acoustic tomography array to help characterize this highly dynamic region. The tomographic measurements, when combined with satellite and other in situ measurements and with ocean models, will provide an eddy-resolving, 4-D sound-speed field for use in making acoustic predictions. The receivers include a new Distributed Vertical Line Array (DVLA) receiver that spans the water column.

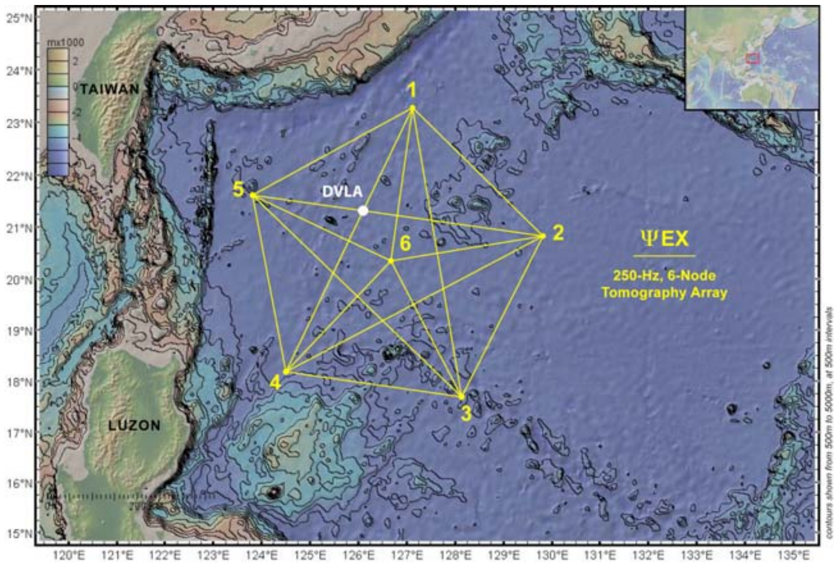


*Figure 2.* Overall mooring geometry of the 2010–2011 Philippine Sea Experiment, consisting of six 250-Hz acoustic transceivers (T1, T2, … T6) and a new DVLA receiver. The array radius is 330 km.

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

**Relevant Publications**

Dushaw, B. D., Worcester, P. F., Munk, W. H., Spindel, R. C., Mercer, J. A., Howe, B. M., Metzger, K., Jr., Birdsall, T. G., Andrew, R. K., Dzieciuch, M. A., Cornuelle, B. D., and Menemenlis, D. (**2009**). A decade of acoustic thermometry in the North Pacific Ocean, *J. Geophys. Res.* **114**, C07021.

Van Uffelen, L. J., Worcester, P. F., Dzieciuch, M. A., and Rudnick, D. L. (**2009**). The vertical structure of shadow-zone arrivals at long range in the ocean, *J. Acoust. Soc. Am.* **125**, 3569–3588.

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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

**Construction of an interferometric tiltmeter and seismometer**

Our group has been investigating a new type of seismic sensor for the past seven years. Using funds primarily from the National Science Foundation, we have replaced the electronics in a traditional seismometer with an optical system. The motivation is to facilitate use of a long-period seismometer in a deep borehole, where noise from anthropogenic sources and natural surface effects are attenuated. We can make use of optical fibers to bring laser light to and from the sensor without the need for electrical cables and downhole circuitry — two problematic features of traditional borehole seismometry.

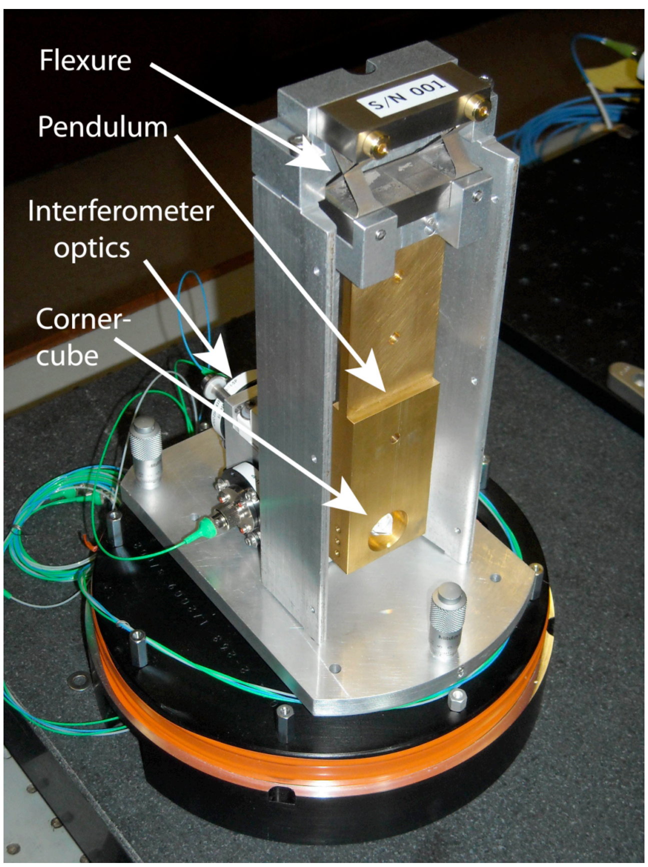


*Figure 1:* The new horizontal seismometer has a mechanical design based on a simple pendulum. It consists of a monolithic flexure suspension and a brass mass holding a corner cube retroreflector. A Michelson interferometer linked to an electro-optical system by optical fibers determines the position of the end of the pendulum. An advanced digital-signal-processor-based data logger converts the optical phase into displacement and transmits the data to an archival computer at IGPP. The interferometer provides an extremely sensitive measurement of the mass's displacement while retaining the high dynamic range and linearity required for detecting both distant tremors as well as local earthquakes.

Working with postdoc Jose Otero and colleague Jon Berger, we have studied the implications of abandoning electronics (including electronic force feedback — long considered a requirement for success in building a seismometer). We have found that the performance of the new seismometer is quite good and approaches that of the best observatory seismometers currently available.

Having successfully completed a vertical component seismometer we have turned our attention recently to a horizontal component. There are two key differences. First, in a vertical seismometer, a mass is suspended from a spring. The thermal characteristics of the spring are one of the most important factors governing the long-period performance of the seismometer. Indeed one of our most important improvements during our research on the vertical component came about simply through better insulation (we expect that, ultimately, operation within a borehole will produce excellent results owing to the temperature stability there). A horizontal seismometer, however, does not require a spring. It is just a simple pendulum. This removes a significant source of noise from the instrument. Secondly, the background seismic noise spectrum is markedly higher for the horizontal components than for the vertical component.

The combined result of these two factors makes the construction of a horizontal seismometer much simpler, in principle. In both types, a relationship exists between the required resolution of the optical displacement transducer and the free period of the mass suspension in order to keep sensor self noise lower than seismic noise. While the necessary free period for a vertical component is three to five seconds, it turns out that we only require a one second free period in the horizontal direction.

We have built a horizontal component sensor and initiated testing at Piñon Flat Observatory. The sensor, depicted in Figure 1, is a relatively short prototype. The pendulum length is only 15 cm and the period is 0.6 s. It is, however, producing promising results in its current location on the seismic pier. A longer pendulum destined for deployment in a borehole is planned to be completed by the end of 2009.

### Relevant Publications


Zumberge, M., Berger, J., Otero, J., and Wielandt, E., A Non-fedback optical seismometer, *Bulletin of the Seismological Society of America*, in press (2009).

Otero, J., Development and characterization of an observatory-class, broadband, non-fedback, leaf-spring interferometric seismometer, PhD thesis, Univ. of Calif., San Diego (2009).

*Image: Midnight-noon deployment crew on the New Horizon offshore Morro Bay. Left to right: Cambria Colt (Marine EM Lab technician), Jake Perez (Marine EM Lab technician, Brent Wheelock (IGPP/Scripps graduate student), Josh (resident technician), Kerry Key (assistant researcher). Photo captured via remote timer by Kerry Key.*

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