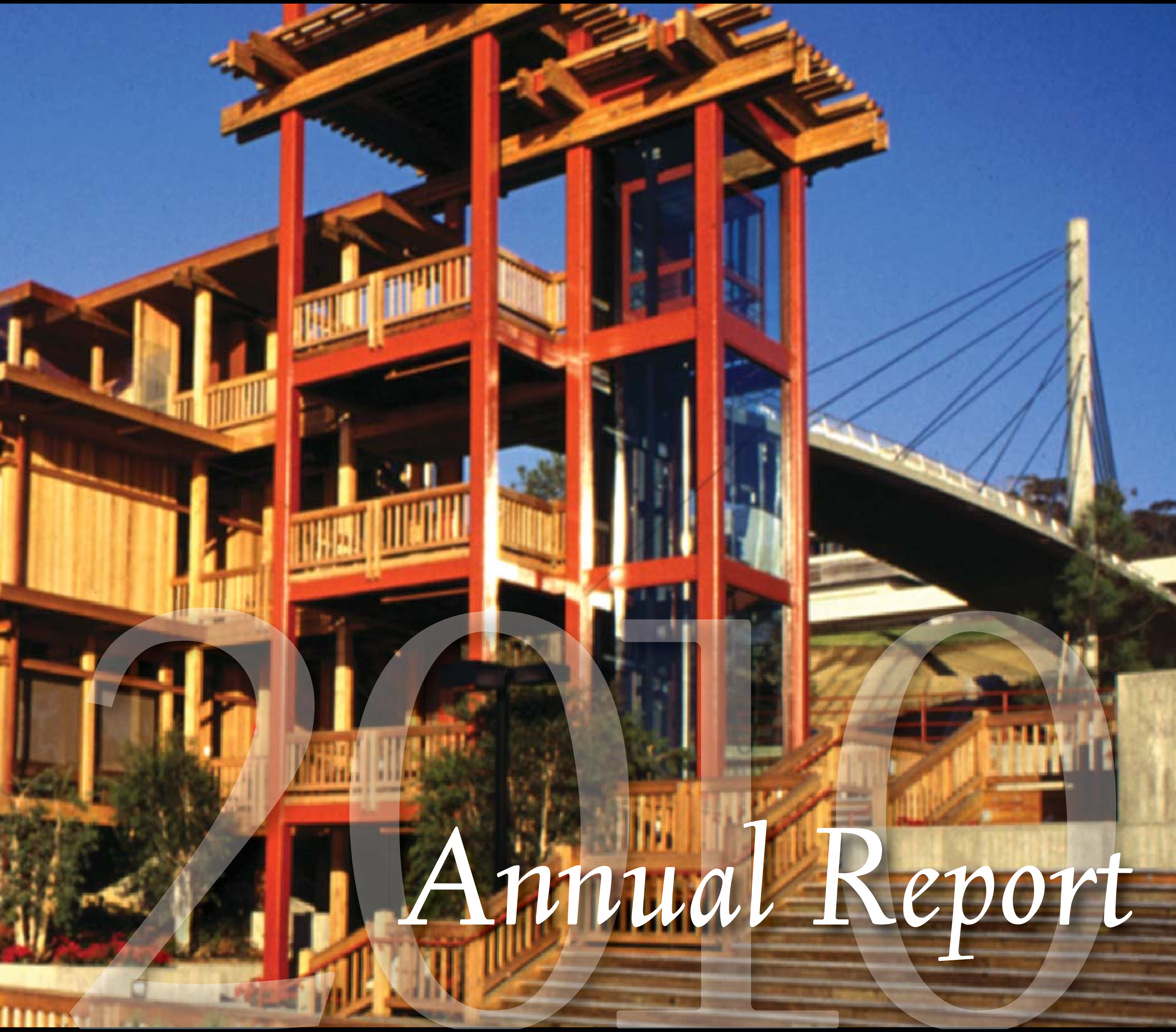
50 Anniversary

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



2010 Annual Report

SCRIPPS INSTITUTION OF OCEANOGRAPHY, UNIVERSITY OF CALIFORNIA, SAN DIEGO

IGPP Annual Report

This is the fifth Annual Report of the Cecil and Ida Green Institute of Geophysics and Planetary Physics. We wish to provide an intelligible summary of our research during the past academic year for colleagues, prospective graduate students, and anyone who has an interest in the Earth sciences, particularly geophysics.

The year 2010 marks the fiftieth Anniversary of the founding of our branch of IGPP. We are celebrating 50 years of exceptional achievement in geophysics and oceanography.

The very first Director of IGPP, Walter Munk, is still going strong. This year he won the Crafoord Prize of the Royal Swedish Academy of Sciences, for "his pioneering and fundamental contributions to our understanding of ocean circulation, tides and waves, and their role in the Earth's dynamics."

Our most senior member was not the only award winner this year: Helen Fricker, one of our most junior faculty was awarded the 2010 Martha T. Muse Prize for Science and Policy in Antarctica, for her research on subglacial lakes, dynamic hydrological systems under the Antarctic ice. You can read about her latest findings in this year's Report.

I hope you find the Report gives you a taste of this and the other exciting research currently being pursued at IGPP in its fiftieth year.

Robert L. Parker
Professor of Geophysics, Emeritus

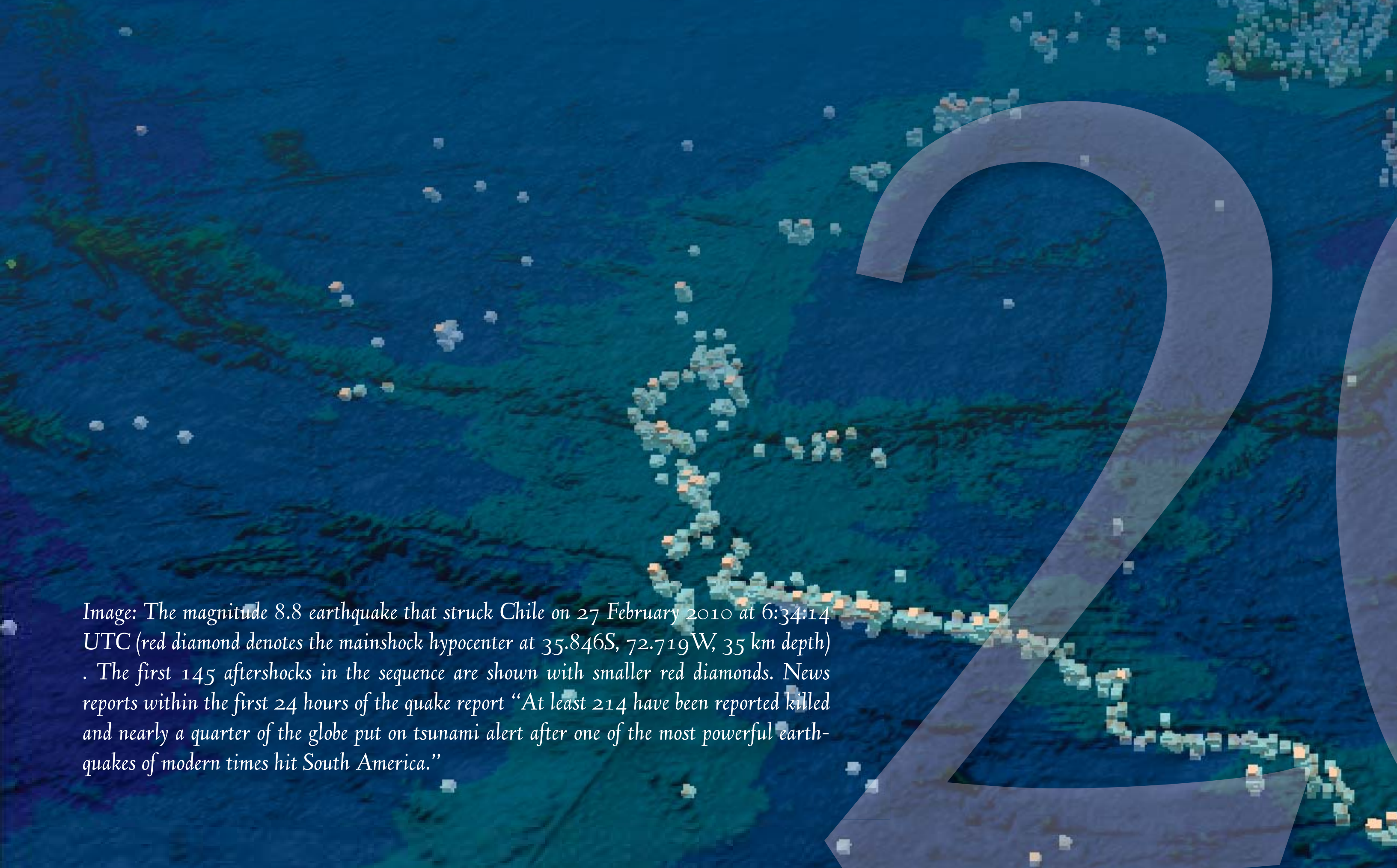


Image: The magnitude 8.8 earthquake that struck Chile on 27 February 2010 at 6:34:14 UTC (red diamond denotes the mainshock hypocenter at 35.846S, 72.719W, 35 km depth) . The first 145 aftershocks in the sequence are shown with smaller red diamonds. News reports within the first 24 hours of the quake report "At least 214 have been reported killed and nearly a quarter of the globe put on tsunami alert after one of the most powerful earthquakes of modern times hit South America."

acoustic thermometry, Dzieciuch, Worcester

acoustics, Blackman, Dzieciuch, Hedlin

Antarctic ice sheets, Fricker

complexity, Werner

crustal deformation, Agnew, Bock, Fialko, Sandwell

crustal seismology, Fialko, Kilb, Shearer, Vernon

cyberinfrastraucture, Bock, Constable, C., Orcutt, Staudigel

Earth's deep interior, Constable, S., Masters

earthquake mechanisms, de Groot-Hedlin, Fialko, Kilb, Minster, Shearer, Vernon

electrical properties, Constable, S.

electromagnetic induction, Constable, C., Constable S., Parker

fluid mechanics, Ireley

geodesy, Agnew, Bock, Fialko

geodynamics, Laske, Sandwell, Stegman

geodynamos, Ireley

geomagnetism, Ierley, Constable, C., Parker

geophysical instrumentation, Agnew, Bock, Berger, Constable, S., Davis, Vernon, Zumberge

global seismology, Davis, Laske, Masters, Shearer

gps, Agnew, Bock, Fialko, Minster

information technology, Bock, Orcutt, Vernon

infrasound, de Groot-Hedlin, Hedlin

inverse theory, Key, Parker

landscape systems, Werner

marine electromagnetic induction, Constable, S., Key

marine geology, Blackman, Harding, Laske, Staudigel

marine seismology, Harding, Laske, Orcutt

mid-ocean ridges, Constable, S., Blackman, Harding

normal modes, Davis, Masters, Laske

numerical methods, Constable, S., Dzieciuch, de Groot-Hedlin, Parker

observational networks, Bock, Davis, Orcutt, Vernon

ocean acoustics, de Groot-Hedlin, Dzieciuch, Munk, Worcester

oceanography, Munk, Worcester

ocean bathymetry, Sandwell

paleomagnetism, Constable, C.

planetary physics, Stegman

radar techniques, Fialko, Fricker, Minster,Sandwell

reflection seismology, Harding

satellite laser altimetry, Fricker

seamounts, Staudigel

seismic anisotropy, Blackman

seismic hazards, Bock, Kent

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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Frank K. Wyatt
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Research Interests: Crustal deformation measurement and interpretation, Earth tides, Southern California earthquakes.

Crustal Deformation (Strainmeters)

We continue to operate longbase laser strainmeters, six supported by the Plate Boundary Observatory, and four others: an activity led by Wyatt and supported by staff members Don Elliott and Billy Hatfield.

Our most interesting results for the last year came from the El-Mayor/Cucupah (EMC) earthquake (magnitude 7.2), in the southern part of the Salton Trough on April 4, 2010 (day 94). The size of this event – the sixth largest earthquake in the last 100 years on the transform part of the Pacific/North-America plate boundary – and its proximity to three sets of strainmeters has provided the best records so far of immediate postseismic deformation.

Figure 1 shows the time series around the time of the event from the seven laser strainmeters installed around the Salton Trough: three at PFO, and two each at SCS and DHL. All strainmeters recorded through the mainshock, but the records do not give a coseismic offset because the strains from the largest seismic waves are large enough that the laser beam is no longer pointed accurately at the far end; when this happens the interference pattern disappears and strain is not measured. We do not have a reliable measure of strain for about 5 to 10 minutes; in the plots we have set removed any across this gap. We do have reliable estimates of coseismic offsets from the EW longbase tiltmeter at PFO, and from the more distant strainmeters in Los Angeles and Cholame.

After this interruption the strainmeters give a continuous record of even small deformations. The plot shows data lowpassed (filter corner at 100 s) to remove the seismic coda. These records show immediate, relatively smooth, strain changes at rates much higher than are observed at any other time. The data shown, and recorded later, suggest a more complex picture than simple afterslip on the fault that caused the EMC earthquake. Afterslip on the part of the fault that had the most coseismic slip (as determined by Prof. Yuri Fialko from InSAR and GPS data) would given the very small ratio of EW to NS strains observed at SCS. If that were the only process at work, we would expect all the other strainmeter records to look like scaled versions of the NS time series; that other records do not look like this implies that other sources of strain were triggered by the mainshock.

Looking at the DHL data, we see a much larger and faster response on the NS, even though the model predicts similar responses for the SCS and DHL NS strains. The ratio of EW to NS response is also larger than predicted by the model. And, we observe several small steps in the DHL data that are not seen elsewhere. Our tentative explanation is that the DHL strainmeters are detecting, not just strains from the EMC earthquake, but also strains from aseismic slip induced on the San Andreas fault, which is only 1.5 km away at the closest. We have observed similar slip events on the DHL strainmeters, without accompanying seismic events, in 1997, 1999, 2003, 2006, and 2008; the last was the largest episode of aseismic strain so far observed, and was also recorded on creepmeters operated across the San Andreas fault by Prof. Roger Bilham. The idea that the post-EMC signals at DHL are caused by near-surface slip on the San Andreas fault is also supported by results from Prof. Bilham's creepmeter array; the instrument at Salt Creek, 9 km NW of DHL, showed a few mm of creep coincident with the EMC earthquake. Triggered surface creep has been observed before on the San Andreas and other faults of the Salton Trough.

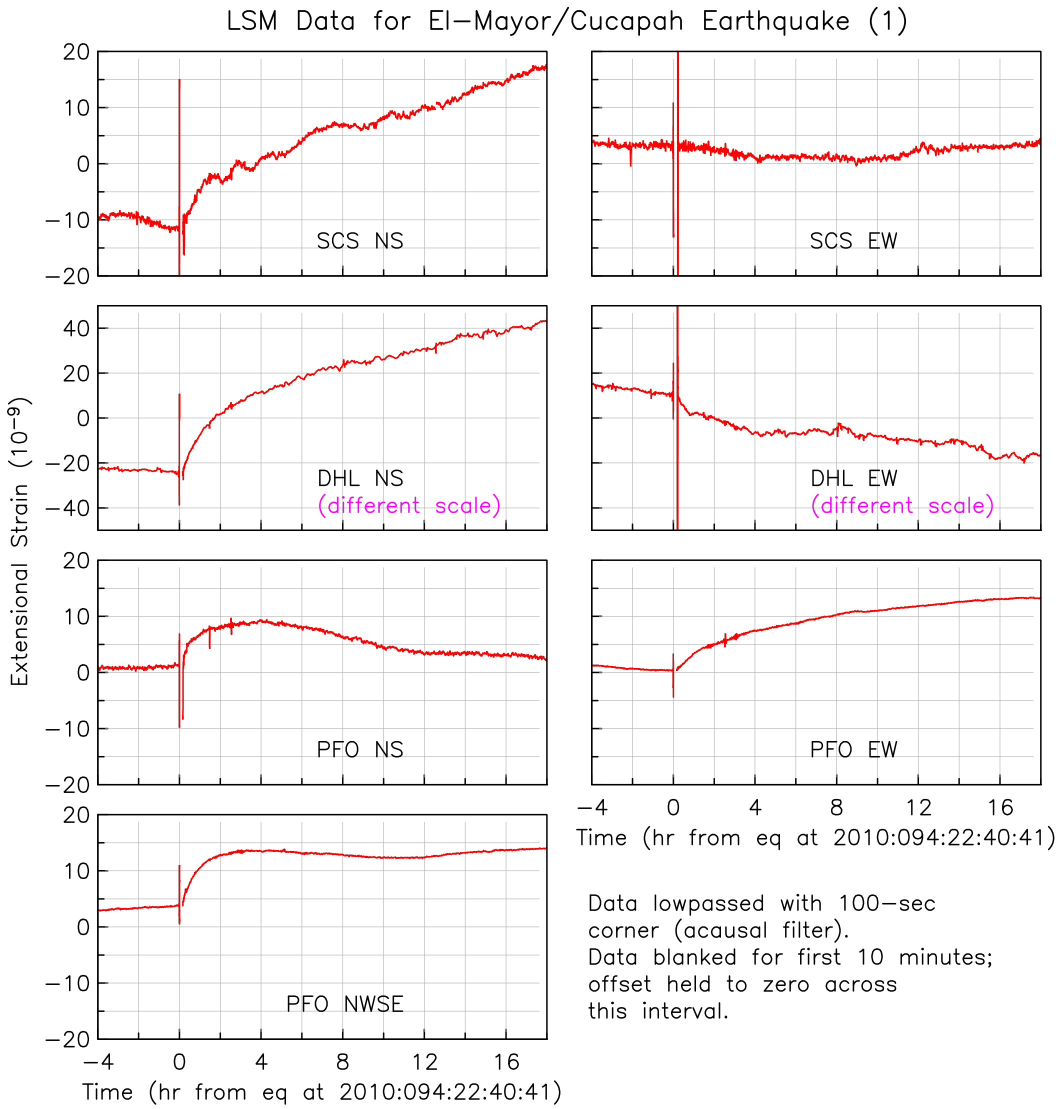

Figure 1

Even more interesting are the signals from PFO, which is closest to the San Jacinto fault. All three strainmeters there start by showing postseismic strains that are roughly consistent, in size and shape, with the source being afterslip from the EMC fault: the signals are of the same sign, and larger on the NWSE and the EW than on the NS. However, the strains over the first month after this earthquake do not fit this pattern at all: instead, the NS and EW show trends of about the same size but opposite sign, while the NWSE shows less change; we also observe a significant change in trend on the long fluid tiltmeter. Slip on the San Jacinto fault would produce exactly this pattern: for example, the NWSE, being parallel to this fault, is the least sensitive to slip on it. Although the trends on the PFO instruments seem to be decreasing in rate, they are doing so only with a long time constant; a similar pattern followed the 2005 Anza earthquake. These strains thus may indicate triggered deep slip on the San Jacinto fault.

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

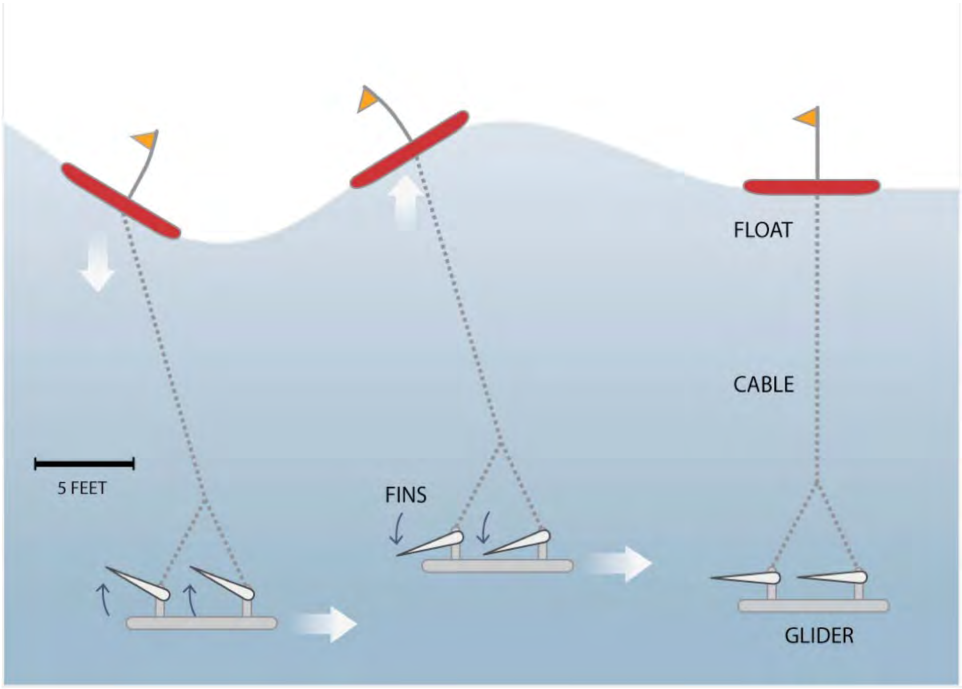
I have been working over the past few years on developing new sensors to replace the obsolete and no longer available STS1 and KS54000 sensors used in the Global Seismographic Network.

Progress on the interferometric seismometer developed by my colleague Mark Zumberge has reached a point where we are now funded by the US Geological Survey to deploy a 3-component borehole model at the Albuquerque Seismological Lab next year. We have worked for a couple of years on a vertical-component sensor, which now has nearly the required performance. But that model is not very suitable for borehole deployment. At the very least it would need to be scaled down in size and equipped with a leveling mechanism. So in collaboration with Erhard Wielandt we are experimenting with a new suspension with will not require leveling.

We have also developed a horizontal component seismometer that consists of a simple pendulum suspended by a monolithic, electrical discharge machined flexure. Three units have been built and tested with one now opening in a shallow borehole at PFO. The performance of this unit meets the GSN requirements.

I have also been working with John Orcutt and the OBSIP group at IGPP in developing a system that will allow us to deploy Seismological observatories in the deep ocean. Several years ago we proposed a large moored, floating platform to provide power and communications for a borehole seismometer (and many other instruments) on the ocean floor and in the water column. This was not funded, primarily due to its perceived cost. Still pursuing the goal of ocean floor seismic stations, we have recently teamed up with a small company, Liquid Robotics (http://www.liquidr.com/), which has developed a new device that may provide a breakthrough in deep ocean observations and telemetry.

The Wave Glider is a two-body sea-surface and underwater vehicle comprised of a submerged "glider" attached via a tether to a surface float. The system is propelled by the conversion of ocean wave energy into forward thrust, independent of wave direction. The wave energy propulsion mechanism is purely mechanical; no electrical power is generated. Just as an airplane's forward motion through the air allows its wings to create an upward lifting force, the submerged glider's vertical motion through the calm waters at the glider's depth allows its wings to convert a portion of the upward motion into a forward force. As waves pass on the surface, the submerged glider acts a tug pulling the surface float along a desired course, controlled by a rudder on the glider. Separation of the glider from the float is a crucial aspect of the vehicle design. Figure 1 illustrates the principles of Wave Glider propulsion.



The basic idea is to use the Liquid Robotics technology to provide a surface platform to relay data acquired acoustically from an ocean bottom seismometer to the shore via satellite telemetry. The surface float is equipped with solar panels, an Iridium satellite telemetry modem/GPS and a small processor to provide commands to steer the system via a rudder on the glider. This control system can be used to steer the pair along a course, or to hold station in a very small watch circle. With support of the Green Foundation, we have conducted tests off the island of Hawaii in order to determine the power consumption of the bottom package when telemetering the required data flow from the seafloor to the Wave Glider. These test show that the average power to accomplish this is about the same as the power required by the SIO OBS package.

Our next step is to seek support to build a suitable OBS that would operate form 2+ years and conduct a realistic test in the deep ocean.

Relevant Publications

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

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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.

Geophysical investigations of oceanic spreading center processes remain a main focus of my research. In 2009/2010 I continued with investigation of Atlantis Massif, an ocean core complex just west of the Mid-Atlantic Ridge axis, where detachment faulting has unroofed intrusive crustal rocks and at least lenses of mantle peridotite. New results this year were obtained through analysis of refraction data recorded by seafloor seismometers, in collaboration with John Collins at WHOI. The anomalous character of the massif's central dome crust is clear compared to the neighboring rift valley and similar-age crust on the opposite ridge flank. The domal core has velocities >7.0 km/s at depths below ~2.5 km sub-seafloor, increasing to 7.5-7.8 km/s over the depth range 4.8-6.8 km. Within the core complex, the crust/mantle transition does not appear to be sharp as no PmP arrivals are observed. Within the axial valley, velocities do not reach mantle-transition zone values in the uppermost 6 km. We infer that crust is of normal thickness within the rift valley but that a somewhat thinner than average mafic section is present in the the central portion of Atlantis Massif. In the vicinity of Integrated Ocean Drilling Program (IODP) Hole U1309D, there is a constant velocity interval at 1-3 km depth with velocities of 6.6-6.8 km/s. The recovery of a dominantly gabbroic section from that 1.4 km deep hole and the extents of the relatively high and near-constant velocity region in our tomographic model suggest that this body of mafic intrusives extends a few km both laterally and vertically.

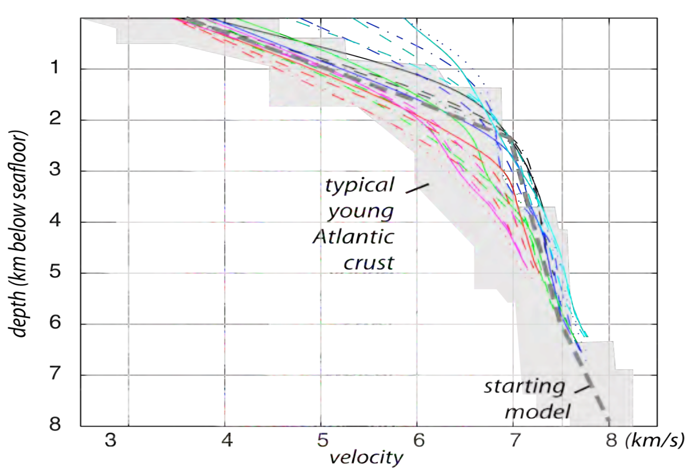
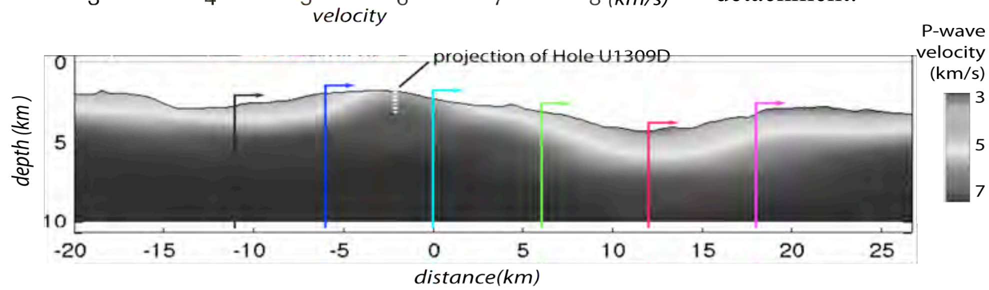


Figure. Velocity-depth profiles along refraction line across Atlantis Massif, spaced 1.5 km in portion of model where coverage is good. Intervals of 6-km length are color coded & line type varies west-east: solid, dash, dot-dash, & dotted. Preferred velocity model is shown below with velocity-depth profile intervals (color) marked at each western edge. Spreading axis is at x=12 km. Hole U1309D is near top of domal core, which is capped by detachment.



I've also made some progress this year in modeling the development of mineral alignment during mantle flow, and associated seismic anisotropy. Working with Olivier Castelnau at University Paris, an 'intermediate coupling' case was completed. This incorporates rheologic anisotropy that is predicted for polycrystalline mineral aggregates that deform during viscous mantle flow beneath oceanic spreading centers. Our intermediate result indicates that proceeding with the 'full coupling' case is warranted– the change in flow velocities exceeds 20% of the plate spreading rate (a relevant metric) in some portions of the field when first-past anisotropic rheology is included in the stiffness matrix for the flow solution. This is not negligible. However, potential feedbacks need to be assessed. In the coming year, we will develop an iterative procedure that can provide the fully-coupled solution.

Planning for potential future projects where ocean drilling is a major component took a significant portion of my broader efforts. The current IODP will finish in 2013 but recent deep drilling and borehole technology appears poised to open some new opportunities for studying the structure and processes that characterize the 'basement' portions of oceanic lithosphere. In particular, there is significant momentum toward pursuing full penetration of a complete crustal section and recovery from well into the uppermost mantle (several hundred meters), as part of a new, post-2013 program. If this project goes forward as envisioned, there would be a number of valuable geophysical studies that could be conducted for the first time, with sensors deep within the ocean crust and upper mantle. So, for this reason, I have participated in several workshops where scientists/engineers have advanced the general plan and begun to lay groundwork for specific milestones along what would be a long-term effort.

Finally, a brief look at spreading center structure approaching the Chile Triple Junction, where the rift is subducting beneath the South American continent, was obtained during a brief research cruise. Graduate student Ashlee Henig (whose main research topic is seismic tomography at Atlantis Massif) and I joined a dominantly biological investigation of deep-sea vent ecosystems. Our contribution was to provide seafloor mapping expertise so that video and dredge targets could be identified. The ship left Chile just a couple days before the magnitude 8.8 Maule earthquake occurred, so we had first-hand views of some of the damage in Santiago when we came into port ~3 weeks later.

Blackman, D.K., and J.A. Collins, Lower crustal variability and crust/mantle transition at the Atlantis massif oceanic core complex, accepted w/minor revision in September, Geophys. Res. Lett. 2010.

Harmon, N. and D.K. Blackman, Effects of plate boundary geometry and kinematics on mantle melting beneath the back-arc spreading centers along the Lau Basin, Earth Planet. Sci. Lett. (2010, in press), doi:10.1016/j.epsl.2010.08.004.

N. W. Hayman, W. Bach, D. Blackman, G. L. Christeson, K. Edwards, R. Haymon, B. Ildefonse, M. Schulte, D. Teagle, andS. White , Future Scientific Drilling of Oceanic Crust , Eos Trans. AGU 91, #15, 2010. p133-134.

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

Highlights of Yehuda Bock's research in 2010 with graduate students Brendan Crowell and Diego Melgar, SOPAC staff, and collaborators at IGPP and Caltech, include studies of transient deformation in the Salton trough, and real-time observation and modeling of the Mw 7.2 April 4, 2010 El Mayor-Cucapah earthquake. We continued to expand the California Real Time Network (CRTN - http://sopac.ucsd.edu/projects/realtime/), now numbering more than 160 continuous GPS stations. The El Mayor-Cucapah earthquake demonstrated convincingly the power of dense near-source, high-rate, real-time GPS networks for earthquake early warning [*Crowell et al.*, 2009] and rapid earthquake response. A robust set of 1 Hz data was collected from over 100 CRTN stations in with a latency of about 0.4 seconds, and inverted to provide on-the-fly total displacement waveforms, which captured the propagation of the S-wave through the southern California crust at stations up to 450 km from the epicenter (Figure 1). By "total displacement" we mean direct measurement of both static and dynamic displacements, previously relegated separately to geodesy and seismology, respectively. While most broadband seismic stations clipped for this earthquake (although accelerometers at the same sites did not), the real-time GPS stations did not saturate and continued to provide on-scale data. We applied a multi-rate Kalman filter to optimally combine data collected by 100 Hz strong motion instruments at local seismic stations and 1 Hz GPS data from CRTN to obtain 100 Hz total displacement waveforms at co-located stations as far as 300 km from the earthquake's epicenter (Figure 2). Displacement waveforms in seismology are traditionally obtained by integration, polynomial fitting and filtering of strong motion records. The displacements so obtained are band-limited since the low frequency components (including the static deformation) are not accurately determined. Our Kalman filter approach does not have these limitations, and is well suited for large dense GPS/seismic networks and real-time processing [*Bock et al.*, 2010].

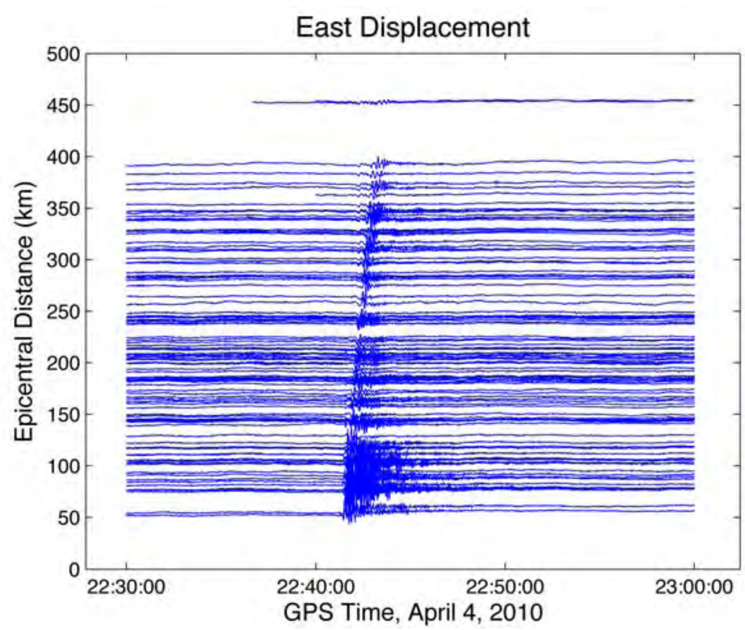

Figure 1. Displacement vs. epicentral distance for the 2010 El Mayor-Cucapah earthquake showing S-wave propagation across the California Real Time Network (CRTN) stations in southern California. The displacement waveforms are available in SAC format from SCEDC (http://www.data.scec.org/research/MayorCucapah20100404/).

We have also been investigating a strain transient centered on the Obsidian Buttes fault just south of the Salton Sea detected from analysis of a long-history of survey-mode GPS measurements taken over the last 25+ years. Using interpolated site velocities over a 0.01 degree grid for field survey data collected before and after 2001 followed by 2-D strain analysis, suggests accelerated slip on the Obsidian Buttes fault between 2001 and 2009, equivalent to a magnitude 5.3 earthquake. The associated strain transient has caused an accelerated fault parallel slip rate deficit of 5-7 mm/yr along the southern San Andreas fault near Bombay Beach, corresponding to a Coulomb stress increase since 2001 of ~0.5 MPa centered along the 2009 Bombay Beach seismic swarm (Figure 3). The ongoing strain transient is loading up the transtensional faults in the Salton Sea and the southern San Andreas fault, presumably reducing the time to its expected rupture [*Crowell et al*., 2010].

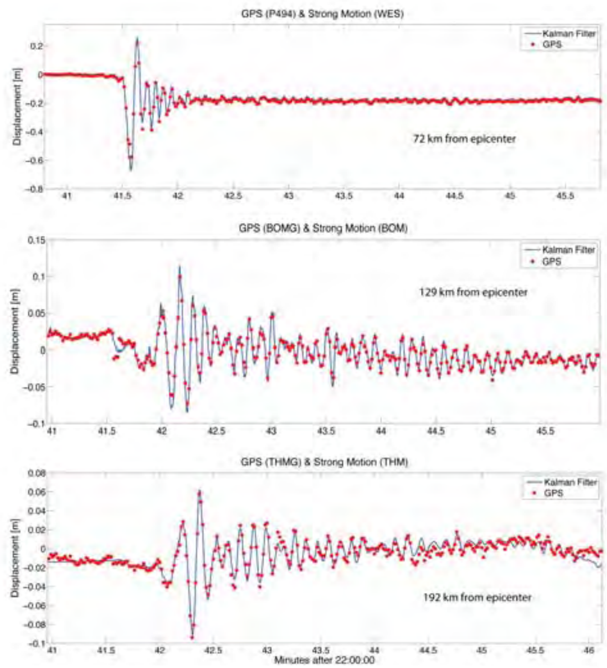

Figure 2. Displacement waveforms for the 2010 El Mayor-Cucapah earthquake obtained by applying a multi-rate Kalman filter to co-located 100 Hz strong motion and 1 Hz GPS stations.

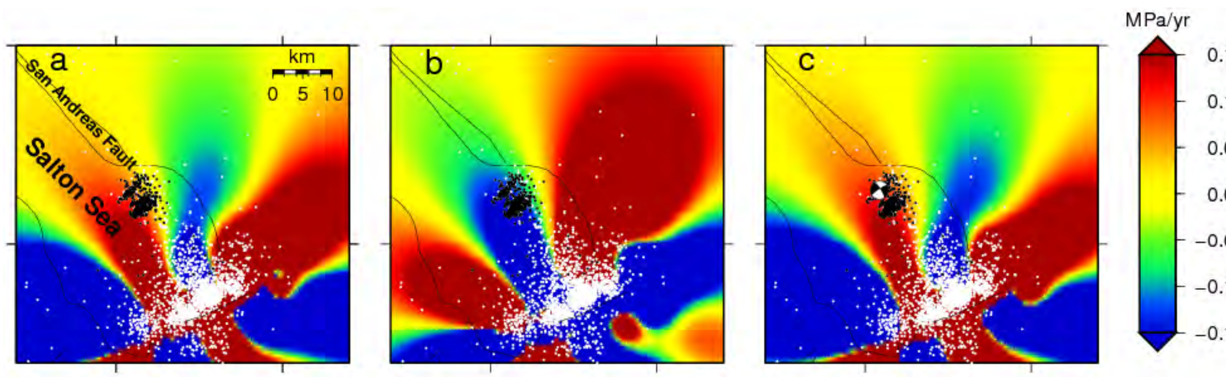

Figure 3. Coulomb stress change associated with slip on the Obsidian Buttes fault for **(a)** vertically oriented right-lateral faults at N45ºW; **(b)** N15ºE; and **(c)** vertically oriented left-lateral faults at N56ºE strike angles, using an effective friction coefficient $\mu' = 0.4$. The focal mechanism of the largest event, Mw 4.8 on March 24, 2009, during the 2009 Bombay Beach seismic swarm is shown in **(c)** and the location of the Bombay Beach Seismic Swarm are the black dots. The white dots are recent seismicity since the 2005 Obsidian Buttes seismic swarm from the SCEC data archive except the Bombay Beach seismic swarm.

Recent Publications and Presentations

Bock, Y., R. Clayton, B. Crowell, S. Kedar, D. Melgar, M. Squibb, F. Webb, E. Yu, Earthquake Early Warning in Southern California Using Real Time GPS and Accelerometer Data: Lessons from the Mw 7.2 2010 El Mayor-Cucapah Earthquake (2010), Poster at SCEC Annual Meeting, Palm Springs, September 12-15, 2010.

Crowell, B., Y. Bock, and M. Squibb (2009), Demonstration of earthquake early warning using total displacement waveforms from real time GPS networks, *Seismo. Res. Lett*., *80*(5), 772-782, doi: 10.1785/gssrl.80.5.772.

Crowell, B. W., Y. Bock, D. Sandwell, and Y. Fialko (2010), Accelerated loading of the San Andreas fault by transient deformation in the Salton Trough, *Nature Geoscience,* resubmitted after review.

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

Four existing projects and one new one have received attention over the past year: (i) geomagnetic field behavior on millennial timescales during the Holocene time period (collaborators former post doc, Fabio Donadini, now at ETH Zurich, and Monika Korte of GeoForschungs Zentrum, Helmholtz Center, 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 global 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. (v) New work has been initiated on a project with postdoctoral researcher Christopher Davies and research associate David Gubbins with the goal of tuning numerical geodynamo simulations to provide a realistic reflection of paleomagnetic observations, and a better understanding of core dynamics.

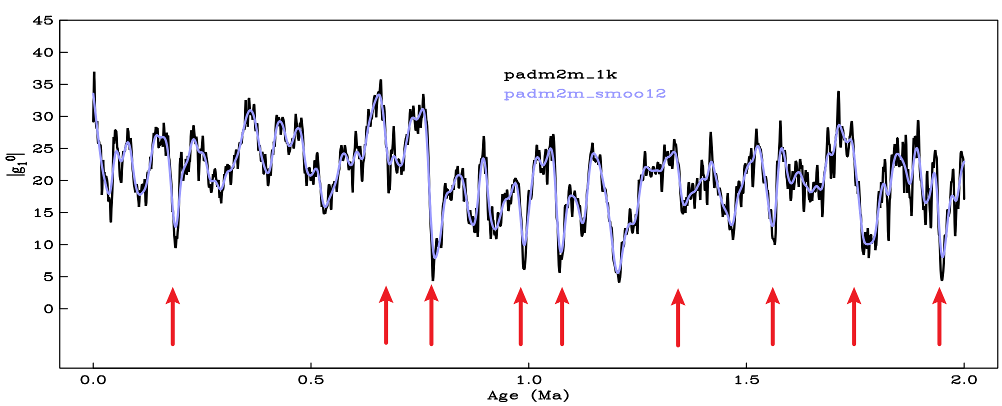

Figure 1 Variations in strength of the geomagnetic axial dipole for the time interval 0-2 Ma given by PADM2M in black, and PADM2M.2-40ky filtered version preserving variations at >40kyr periods in light blue. Red arrows highlight times where there is the tendency for faster growth than decay as the curve moves towards the present day (0.0 Ma age is the present.)

(i) Holocene Geomagnetic Field Behavior: In 2009 we published a new suite of time-varying geomagnetic models for the 0-3 ka time interval based on a global compilation of sediment and archeomagnetic records. Current work is extending these to span the past 10 kyr and conducting syntheses of the global secular variation to determine what statistical properties should be reproducible by numerical dynamo simulations.

(ii) Magnetic Field Variations on Million Year Time Scales: Leah Ziegler recently developed and applied a maximum likelihood method that uses a combination of absolute geomagnetic paleoin-

tensity data from igneous rocks and archeomagnetic artefacts to simultaneously calibrate individual time series of relative paleointensity variations derived from marine sediments and recover a continuous representation of paleomagnetic axial dipole moment (PADM) variations for the 0–2 Ma time interval with about 10 kyr resolution. The result is shown in the estimated variations in the axial dipole for PADM2M in Figure 1. It is noteworthy that the variations exhibit a form of temporal asymmetry, with rapid growth often followed by slower decay. This is suggestive of distinctive physical processes that we hope to be able to understand in our collaborations with Davies and Gubbins using numerical dynamo simulations.

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

Joseph Ribaudo has been using scripted finite element tools within the commercial software FlexPDE for flexible 3-dimensional forward modeling to accommodate arbitrary spatial and temporal variations in external source fields and 3D conductivity variations inside the earth. The method has now been validated using several analytical models, ranging from 1-dimensional conductivity shells within the Earth to eccentrically nested spheres. Forward modeling can be conducted in either the time or frequency domain: the former is particularly useful for satellite observations where motion of the satellite through a time-varying field can produce spatio-temporal aliasing, and the method can also accommodate the effects of Earth rotation. Current work is focussed on including near surface heterogeneity via a novel application of the magnetic field boundary condition at Earth's surface.

Lindsay Smith is exploring the use of multi-taper spectral estimation explicitly designed to recover frequency-domain response function estimates from data series with inconvenient gaps. Such gaps which occur as data dropouts in both observatory and satellite data can be especially limiting at long periods with conventional methods for response estimation. A strategy has been developed for evaluating the performance of the tapers designed for incomplete sampling, allowing the user to determine the frequency resolution attainable in the power spectral estimate for any given distribution of missing observations. Bootstrap methods provide confidence limits on the spectrum and Monte Carlo simulation is used to assess the reliability of their coverage. The method has been tested in computing power spectra for several kinds of data, including variations in length of day, relative geomagnetic paleointensity variations, and a series of external magnetic field time variations derived from recent satellite missions. Next steps will involve the extension to cross-spectral techniques for response function estimates.

Relevant Publications

Hulot, G., C.C. Finlay, C.G. Constable, N.Olsen, & M. Mandea, The magnetic field of planet Earth, *Space Science Reviews*, 152, 159-222, doi: 10.1007/s11214-010-9644-0 , 2010.

Donadini, F., M.Korte, & C.G. Constable, Millennial variations of the geomagnetic field: from data recovery to field reconstruction, *Space Science Reviews*, , doi:10.1007/s11214-010-9662-y, 2010.

Ziegler, L., C.G. Constable, C.L. Johnson & L. Tauxe, PADM2M: A penalized maximum likelihood model of the 0-2 Ma paleomagnetic axial dipole moment, *Geophys. J. Int.*, , in review, 2010.

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Research interests: Marine EM methods, conductivity of rocks, satellite induction studies

Steven Constable runs the SIO Marine EM Laboratory along with assistant researcher Kerry Key. As the name suggests, much of the Lab's work is involved in developing and using marine EM methods. The two main techniques are controlled-source EM (CSEM), in which a deep-towed EM transmitter broadcasts energy to seafloor EM recorders, and magnetotelluric (MT) sounding, in which these same receivers record natural variations in Earth's magnetic field. We currently have 4 PhD students, two postdocs, and a research associate (Arnold Orange) working in the group.

The big data collection expedition for this year was Project SERPENT, 56 MT and CSEM deployments over the subduction zone offshore Nicaragua. This 28-day NSF-funded cruise aboard the R.V. Melville was designed to study mantle anisotropy and fluids in the subduction system. See Kerry's entry in the annual report for a more complete description of the data collection.

David Myer continued to work on the CSEM and MT data from the Scarborough gas field, and has re-discovered a zone of extremely high conductivity about 10 km deep in the crust beneath the Exmouth Plateau, a feature first observed using long-period MT equipment by Graham Heinson of Adelaide University. This region is thought to be a shear zone associated with extension of the continental shelf, and we hope that our higher resolution images of part of this structure will help shed light on the origin of this feature. Brent Wheelock's work with data collected last year offshore California uncovered some limitations of our existing instrument calibrations, and so he has spent some time making huge improvements to our calibration data base (which will benefit most of the projects we are currently working on).

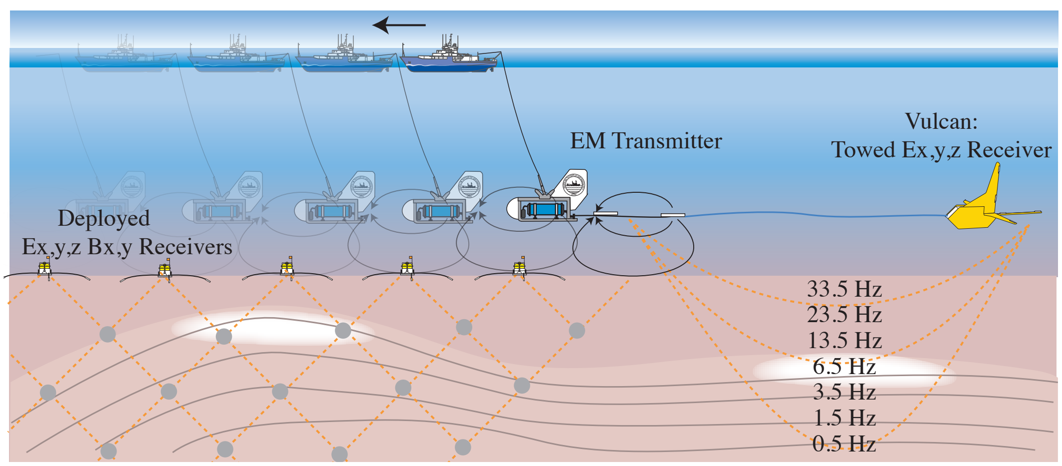

Figure 1. Two approaches to mapping electrical conductivity in the shallow seafloor. The classical CSEM method (left) uses instruments deployed on the seabed and a transmitter towed 50–100 m above the bottom. Our new scheme uses a 3-component electric field receiver (the "Vulcan", right) towed at a constant offset behind the transmitter. For the deployed receivers, source–receiver geometry provides depth sensitivity. For the Vulcan, the frequency content of the transmitted signal performs this function, with low frequencies penetrating deeper into the seafloor.

One area of research, with postdoc Karen Weitemeyer, is the development of marine CSEM methods for mapping gas hydrate in the seafloor section. Gas hydrate, a frozen mixture of water and gas (mostly methane), is extremely important for a variety of reasons. It may be an economically viable source of natural gas, it is a hazard for deepwater drilling, and may be involved in slope failure and rapid climate change, yet we know little about its distribution in seafloor sediments. Figure 1 shows the approach we are taking to look for electrically resistive hydrate in shallow (upper 500 m) sediments. One new innovation employs a 3-component receiver towed behind the EM transmitter.

Last year's annual report described a hydrate data collection cruise to the Gulf of Mexico, and we are beginning to get results from this. One of the four areas we studied during the October 2008 cruise was Mississippi Canyon block 118 (MC118), which is in 800–900 m water south-east of New Orleans and has been designated a hydrate observatory by the Minerals Management Services (now Offshore Energy and Minerals Management). Hydrate occurs as deposits on the seafloor near a carbonate/hydrate crater complex in the south-east quadrant of the block, but there has been no previous evidence of hydrate at depth. Geologically, MC118 is simpler than the other areas we surveyed, and so is a good place to develop our data processing methods. There is a pipeline and a considerable amount of existing scientific equipment in the observatory, so being able to tow our transmitter–receiver system 60 m above the seabed gave us a big advantage over the bottom-dragged resistivity systems other researchers are developing.

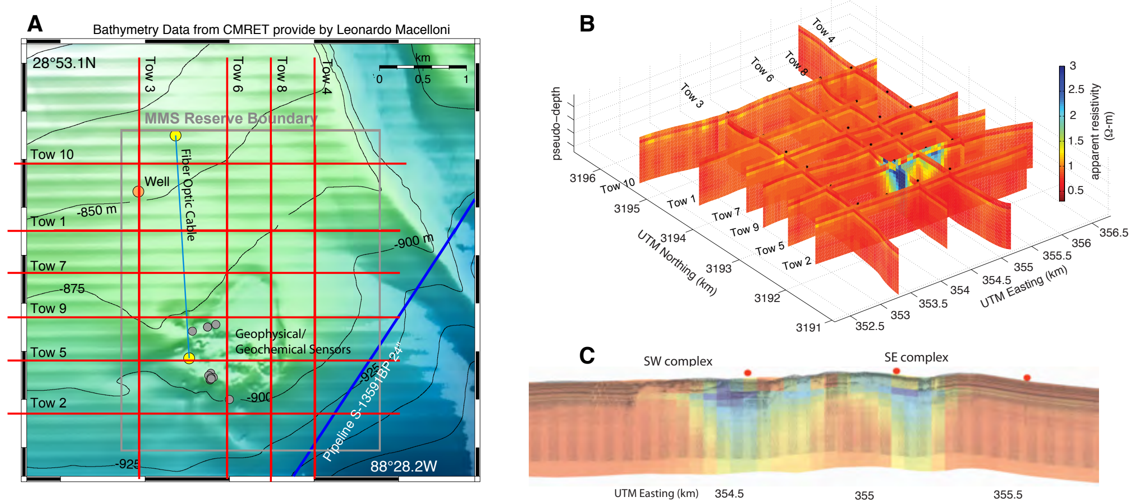

Figure 2. A: MC118 bathymetry and survey geometry showing tow lines. B: Vulcan data transformed into apparent resistivities and projected into depth based on the skin depth of the various frequencies we transmitted. The linear resistivity scale goes from 0.3 to 3 Ωm, with red conductive and blue resistive. A region of high resistivity is seen in the south-east quadrant on Tow 5. C: Tow 5 resistivities overlain on chirp acoustic data from Ken Sleeper, http://www.olemiss.edu/depts/mmri/programs/gulf_res.html

Figure 2 shows apparent resistivity results from the Vulcan data. The sediment resistivity is remarkably uniform at about 1 Ωm except for a region of high resistivity (blue) near the crater complex. Acoustic chirp data collected by others shows high reflectivity in areas of authigenic carbonate and free gas/hydrate. Our high resistivities correlate with areas thought to be associated with hydrate and gas, but not areas of carbonate. This is an important observation – we originally thought that authigenic carbonate would be resistive and act as a confounding signal when using EM to image hydrate. Unlike massive carbonates, which tend to be resistive, it appears that in this case the porosity is high enough to prevent a contrast in resistivity.

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

Relevant Publications

Myer, D., S. Constable, and K. Key, A marine EM survey of the Scarborough gas field, Northwest Shelf of Australia, *First Break*, 28, 77–82, 2010.

Weitemeyer, K., and S. Constable, Mapping shallow geology and gas hydrate with marine CSEM surveys, *First Break*, 28, 97–102, 2010.

J. Peter Davis

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

Peter Davis's research responsibilities at IGPP center upon managing the scientific performance of Project IDA's portion of the Global Seismographic Network (GSN), a collection of 42 seismographic and geophysical data collection stations distributed among 26 countries worldwide. IDA is in the process of upgrading at all stations the core data acquisition and power system equipment using stimulus funding provided by NSF through the IRIS Consortium. A map of the network showing upgraded systems denoted by orange triangles is shown in Figure 1.

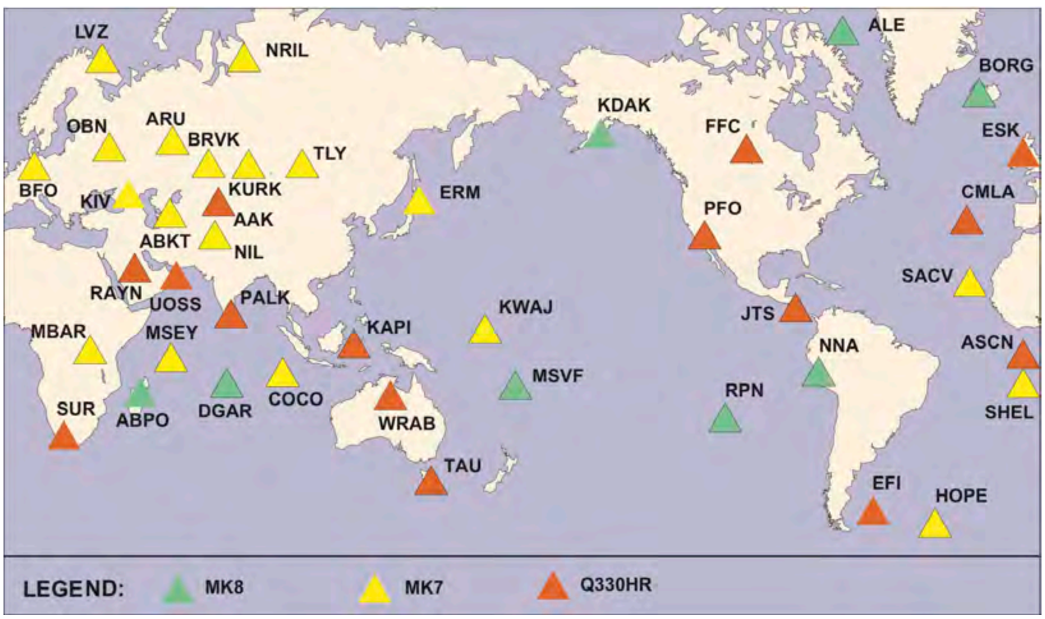

Figure 1. Current data acquisition topology of the IRIS/IDA network.

The GSN has been fully deployed for less than five years, and effort is now being expended to fine tune its performance. Some of Peter Davis's recent work utilized recording from very large earthquakes as well as the Earth's tides 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. 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.

Although they happen infrequently, very large earthquakes like the Maule, Chile event that occurred in February afford excellent opportunities to verify the accuracy of instrument responses. Figure 2 shows a spectrum of this earthquake at one GSN station in Germany. By measuring the amplitudes of the very gravest modes excited by this quake and comparing the results across all stations of the network, it is possible to identify malfunctioning sensors as well as infer properties of the Earth's large-scale fine structure.

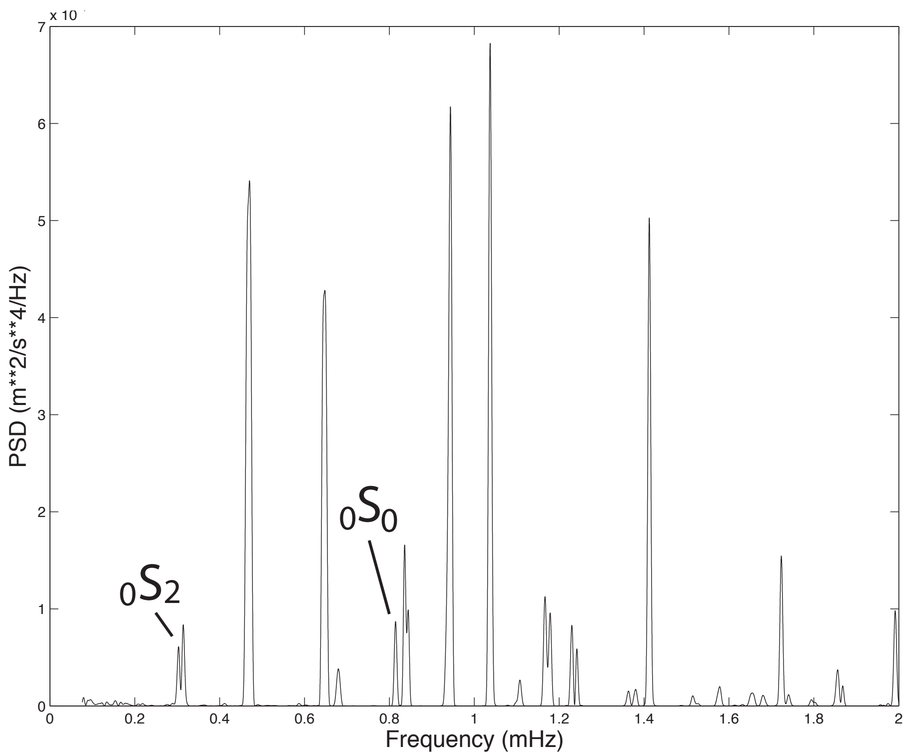

Figure 2. Spectrum of the 2010 Mw=8.8 Maule, Chile earthquake observed at IRIS/IDA station BFO. The GSN produced spectacular data for this large event, including clear evidence of splitting of ${}_0S_2$ at single stations such as in this case. Mode ${}_0S_0$ can be used to assess the quality of the network's published instrument responses.

Relevant Publications

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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 and hazard monitoring; use of dense seismic networks to analyze infrasound signals.

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

Shockwaves: de Groot-Hedlin is sole-PI on a project to develop numerical methods to compute the propagation of nonlinear acoustic waves through the atmosphere – this nonlinearity arises when the pressure perturbation associated with acoustic waves is a significant fraction of the ambient atmospheric pressure; such situations can arise from meteoroid explosions in the upper atmosphere or man-made explosions.

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

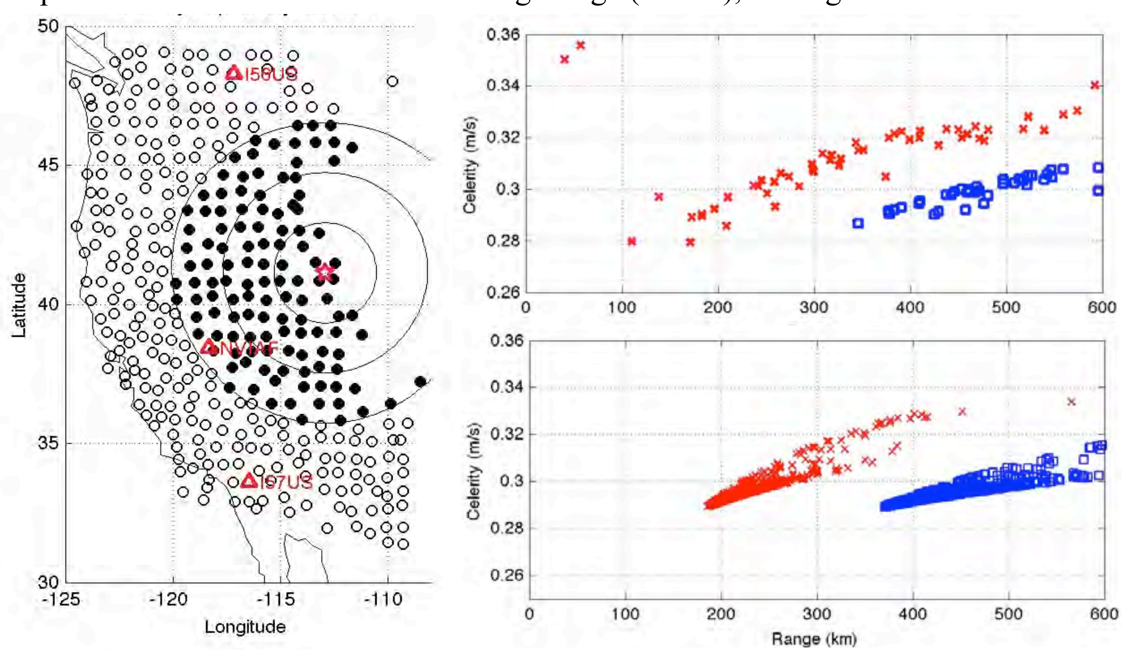

Figure 1. (left) A map of the configuration of the USarray seismic network in June 2007 (circles), also showing the source location (diamond) and sites of infrasound arrays (triangles). Signals at sites within 600 km of the source (dark circles) were analyzed. (right top) Observed celerities (=horizontal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

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

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

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de Groot-Hedlin, C.D., and J.A. Orcutt, 1999, Synthesis of earthquake-generated T-waves, *Geop. Res. Lett.,* 26, 1227-1230.

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Matoza, R.S., M.A. Garces, B.A. Chouet, L., D’Auria, M.A.H. Hedlin, C. de Groot-Hedlin, and G.P. Waite, 2009, “The source of infrasound associated with long-period events at Mount St. Helens”, accepted by *Journal of Geophysical Research (Solid Earth)*, 114, B04305, doi:10.1029/2008JB006128.

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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.

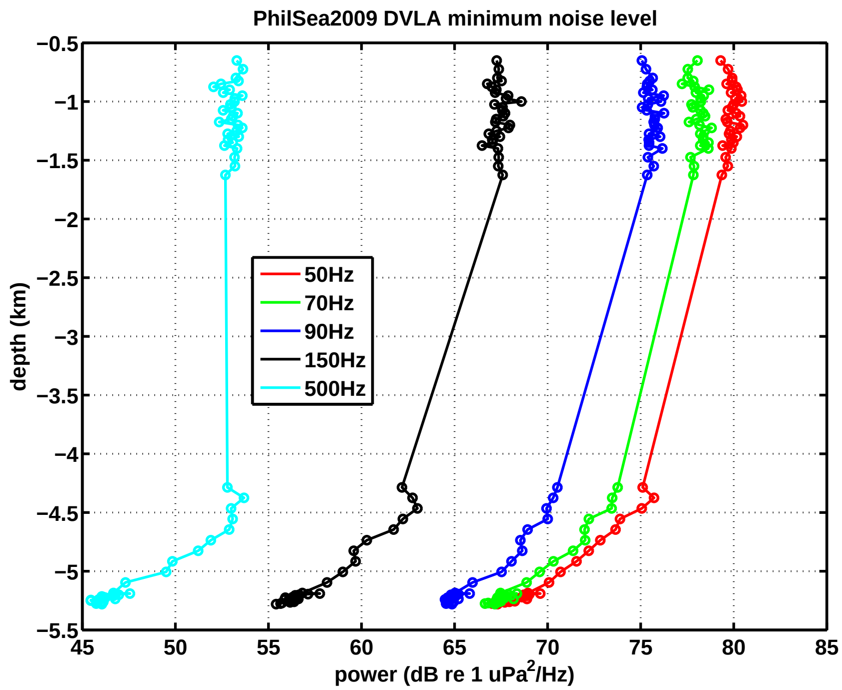

Figure 1: Minimum acoustic noise power at various frequencies as a function of depth.

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).

Van Uffelen, L. J., Worcester, P. F., Dzieciuch, M. A., and Rudnick, D. L., The vertical structure of shadow-zone arrivals at long range in the ocean, *J. Acoust. Soc. Am.*, **125**, 35693588. (2009).

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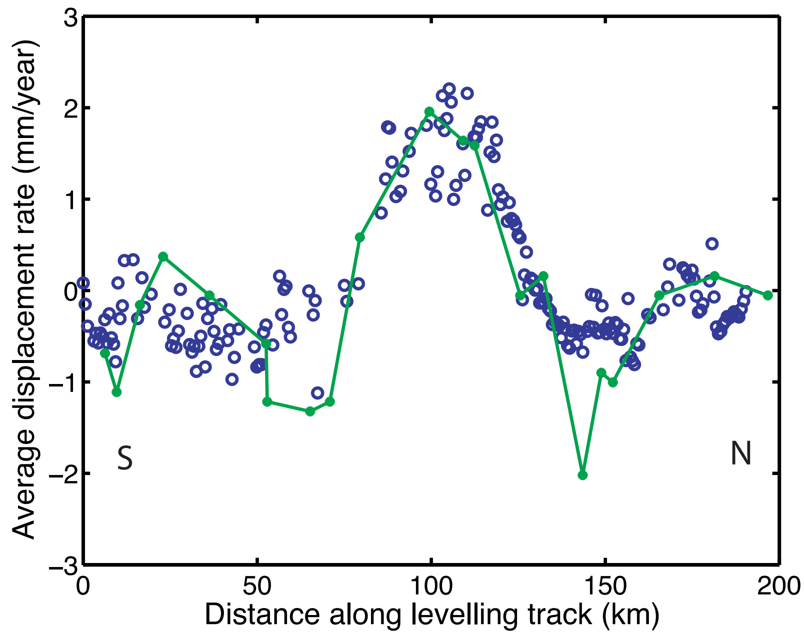
Research interests: earthquake physics, crustal deformation, space geodesy, volcanology

Yuri Fialko's research is focused on understanding the mechanics of seismogenic faults and magma migration in the Earth's crust, through application of principles of continuum and fracture mechanics to earthquakes and volcanic phenomena. Prof. Fialko is using observations from space-borne radar satellites, including the ERS and ENVISAT satellites of the European Space Agency, and the ALOS satellite of the Japanese Space Agency, as well as the Global Positioning System, to investigate the response of the Earth's crust to seismic and magmatic loading.

An ongoing transition of space geodesy from a data-poor to a data-rich discipline warrants increasingly sophisticated models of deformation of the Earth that take into account material heterogeneities (generally, in three dimensions), and time-dependent behavior such as fault creep, viscoelastic relaxation, and poroelastic effects. A former graduate student Sylvain Barbot (now a postdoctoral fellow at Caltech) has been developing a framework for a generalized viscoelastoplastic rheology whereby some inelastic strain relaxes a physical quantity in the material. The relaxed quantity is the deviatoric stress in case of viscoelastic relaxation, the shear stress in case of creep on a fault plane and the trace of the stress tensor in case of poroelastic rebound. In this framework, the instantaneous velocity field satisfies the linear inhomogeneous Navier's equation with sources parameterized as equivalent body forces and surface tractions. The surface velocity field is evaluated using the Fourier-domain Green's function for an elastic half-space with surface buoyancy boundary condition. The proposed method allows one to model post-seismic transients that involve multiple mechanisms (afterslip, poroelastic rebound, ductile flow) with an account for the effects of gravity, non-linear rheologies and arbitrary spatial variations in inelastic properties of rocks (e.g. the effective viscosity, rate-and-state frictional parameters and poroelastic properties).

In collaboration with a former postdoc Jill Pearse (now a research scientist at the NASA's Jet Propulsion Laboratory), Prof. Fialko investigated long-term deformation due to the Socorro Magma Body (SMB) in central New Mexico. The SMB is one of the largest active intrusions in the Earth's continental crust. This project involved elaborate measurements using Interferometric Synthetic Aperture Radar (InSAR) observations and equally elaborate finite element simulations. InSAR data spanning 15 years (1992-2007) indicate that the magma body is associated with a steady crustal uplift at a rate of about 2 mm/yr. Figure 1 shows a remarkable agreement of old leveling data with new InSAR measurements, suggesting that the uplift persisted at a constant rate over the last century. Our previous work (e.g., Fialko et al., 2001) showed that while the pattern of surface uplift is consistent with an elastic inflation of a large sill-like magma body, the SMB could not have formed via steady elastic inflation because the latter would be outpaced by magma solidification. We resolve this problem using coupled thermovisco-elastic models, and place constraints on the intrusion history as well as the rheology of the ambient crustal rocks. We demonstrate that observations rule out the linear Maxwell response of the ductile crust, but are consistent with laboratory-derived power law rheologies. Our preferred model suggests that the age of the SMB is of the order of 10^3 years, and that the apparent constancy of the present-day uplift may be due to slow heat transfer and ductile deformation in a metamorphic aureole of a giant sill-like magma intrusion, rather than due to a steady increase in the magma over-

Figure 1: A comparison of uplift rate inferred from leveling data spanning a time period from 1912 to 1951 (solid green line) and satellite lin-of-sight velocity inferred from InSAR data spanning a time period from 2000 to 2006 (blue circles).



pressure. The SMB is a contemporaneous example of "magmatic intraplating," a process by which large volumes of mafic melt stall and spread at midcrustal depths due to density or rheology contrasts.

Another area of Prof. Fialko's research interests involves modeling of deformation due to large crustal earthquakes. The object of a most recent study was the M_w 7.9 Wenchuan (China) earthquake of 2008. Available interferometric synthetic aperture radar (InSAR) data provided a nearly complete coverage of the surface deformation along both ascending (fine beam mode) and descending orbits (ScanSAR to ScanSAR mode). The best fit model has fault planes that rotate from shallow dip in the south (35 degrees) to nearly vertical dip toward the north (70 degrees). The inferred rupture model is complex with variations in both depth and rake along two major fault strands. Our model suggests that most of the moment release was limited to the shallow part of the crust (depth less than 10 km). Interestingly, aftershocks were primarily distributed below the section of the fault that ruptured coseismically.

Recent publications:

Barbot, S. and Y. Fialko (2010), A unified continuum representation of postseismic relaxation mechanisms: Semi-analytic models of afterslip, poroelastic rebound and viscoelastic flow, *Geophys.J.Int.*, 182, 1124-1140.

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Barbot, S. and Y. Fialko (2010), Fourier-domain Green function for an elastic semi-infinite solid under gravity, with applications to earthquake and volcano deformation, *Geophys.J.Int.*, 182, 568-582.

Tong, X., D. Sandwell, and Y. Fialko (2010), Coseismic slip model of the 2008 Wenchuan earthquake derived from joint inversion of interferometric synthetic aperture radar, GPS, and field data, *J.Geophys.Res.*, 115, B04314.

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.** She leads the Scripps Glaciology Group which currently has two postdocs (Sasha Carter and Fabian Walter) and three graduate students (Linghan Li, Fernando Paolo and Matthew Siegfried). One of the primary questions in Antarctica is whether its mass is changing due to climate change. Due to its vast size, and the long time periods over which it can change, satellite data are crucial for routine monitoring of Antarctica, in particular data from radar and laser altimetry, and also imagery. Since the launch of NASA's Ice, Cloud & land Elevation Satellite (ICESat) in January 2003 Helen has used ICESat laser altimetry, 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). In 2010 Helen was awarded the Martha T. Muse prize for her contribution to Antarctic research.

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 with Helen on this aspect of the problem. Her team continues to monitor active lakes, and have found 124 in total throughout Antarctica. Helen is now a PI on a large, interdisciplinary project (Whillans Ice Stream Subglacial Access Research Drilling; WISSARD) to drill into one of the subglacial lakes that she discovered – Subglacial Lake Whillans (SLW) on Whillans Ice Stream (WIS; Figure 1) – and the region of the grounding line across which the subglacial water flows.

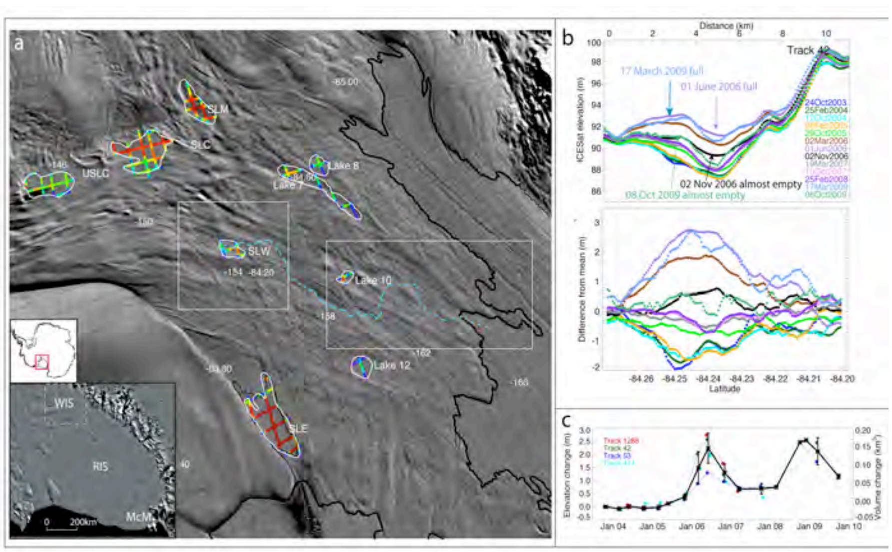

Figure 1. a) Map of WIS lake system with annotation of the estimated flowpath from SLW to the grounding line. Inset maps show the location of WIS in Antarctica (McM is McMurdo Station); b) averaged time series of estimated surface elevation and volume changes since Oct 2003 for SLW.

Ice shelf grounding zones: Helen and her group also use 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. In 2009-2010 Helen and IGPP postdoctoral researcher Kelly Brunt (now at GSFC) used this technique to map the GZ for all of Antarctica, see Brunt and others (2010). This combined with surface elevation at the grounding lines will contribute to improved calculations of the ice sheet's mass balance.

Glacio-seismology: In 2009-2010 Helen also worked on an 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, and published a paper on the changing calving style of the Columbia Glacier before and after its terminus became floating, assessed through changes in seismic signals.

Publications June 2009-Sept 2010

FRICKER, H.A., R. POWELL, J. PRISCU, S. TULACZYK, S. ANANDAKRISHNAN, B. CHRISTNER, D. HOLLAND, H. HORGAN, R. JACOBEL, J. MIKUCKI, A. MITCHELL, R. SCHERER, J. SEVERINGHAUS (2010). Siple Coast Subglacial Aquatic Environments: The Whillans Ice Stream Subglacial Access Research Drilling (WISSARD) project. In *Subglacial Antarctic Aquatic Environments* (M. Siegert, C. Kennicutt, B. Bindschadler, eds.). AGU Monograph. Washington DC.

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W. ABDALATI, H. J. ZWALLY, R. BINDSCHADLER, B. CSATHO, S. L. FARRELL, **H. A. FRICKER**, D. HARDING, R. KWOK, M. LEFSKY, T. MARKUS, A. MARSHAK, T. NEUMANN, S. PALM, B. SCHUTZ, B. SMITH, J. SPINHIRNE, C. WEBB (2010), The ICESat-2 Laser Altimetry Mission, *Proceedings of the IEEE*, 98(5), 735-751.

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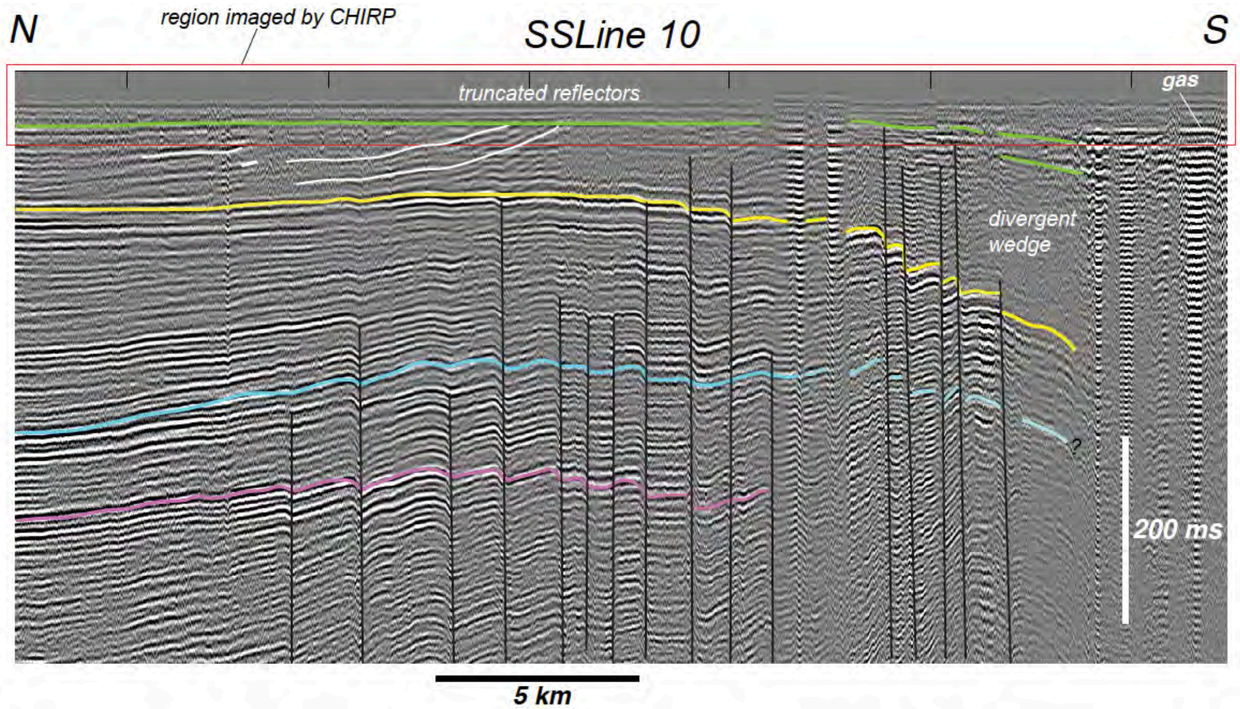
The southern terminus of the modern San Andreas fault lies along the eastern shore of the Salton Sea in the Imperial Valley east of San Diego. Just to the north the San Andreas undergoing transpression within the Durmid Hills but to the south the nature of the deformation is poorly understood. The Brawley seismic zone outlines a band of deformation passing beneath the southern Salton Sea that connects San Andreas to the Mesquite basin at the northern end of the Imperial fault. The right-lateral jog between the Imperial and San Andreas faults should produce transtension within the step over region but in the absence of active seismic imaging models of deformation have had to rely primarily on the historic seismicity patterns.

In April and May 2010, we conducted a pilot MCS survey of the Salton Sea collecting approximately 460 km of data in a 13 day survey. The investigators included Dr. Alistair Harding & Prof. Neal Driscoll from Scripps, Prof. Graham Kent from University of Nevada, Reno, Rob Baskin from the USGS, and Mike Barth from Subsea Systems who provided the equipment. We used a three-tipped sparker system as a source and a digital 24 channel streamer with 3.125 m group spacing with a maximum offset of 84 m as a receiver. In general data quality was excellent in areas without near-surface gas accumulations with detailed stratigraphy recorded down to ~500-800 m. This survey was a follow up to our earlier high-resolution Chirp survey of the sea (*Brothers et al,* 2009; doi:10.1038/NGEO590).

Preliminary processing of the MCS lines reveals a divergent wedge of sedimentary material in the upper part of the section that systemically thickens towards the southern shore of the Salton Sea, Figure 1. The divergence records the onset of the rapid subsidence in the southern part of the Sea, south of the San Andreas. If modern sedimentation rates of 1-2 cm/yr are representative of earlier rates then rapid subsidence, >5 mm/yr, has been ongoing for the last 10-20 kyr. This result is consistent with the earlier Chirp survey results which revealed subsidence > 6mm/yr for the last few thousand years. It is possible that the onset of subsidence was triggered by the northern propagation of the Imperial fault, creating the active step over with the San Andreas



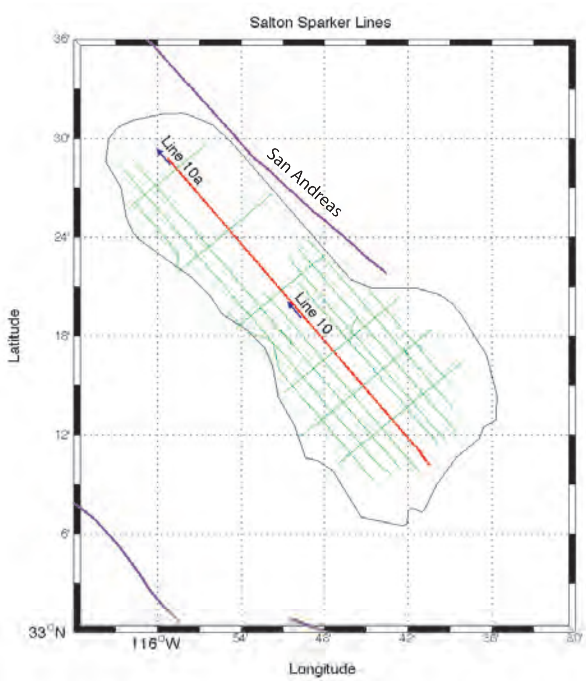


Figure 1: Preliminary processing of line 10 (red line on map left) taken from the 400+ km of lines collected during the survey (greens lines on map). There is pronounced divergence above the yellow horizon as well as a marked change in the acoustic character. Beneath the yellow horizon the layering is predominantly parallel and mostly concordant. The hinge for the divergent wedge is roughly perpendicular to the southern end of the San Andreas.

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

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

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

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

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

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

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

Relevant Publications

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This year saw a continuation of collaboration with my former postdoc Phil Livermore (now in a permanent post at Leeds) and Andy Jackson (ETH) as we used the analytic tools developed over the past several years (the latest of which are noted in the publications listed below) to devise a suitable time-stepping scheme for a model of the Earth's magnetic field.

The preeminent problem in nearly all numerical simulations of geophysical processes is our inability to resolve all the dynamically significant space and time scales of motion that the governing parameters warrant. This is especially acute for the geodynamo, where the dimensionless measure of viscosity of the liquid iron core is of order 10^{-15}. Large simulations that consume many hours on the world's fastest supercomputers (e.g. Japan's Earth Simulator) may get us down to 10^{-6} or so but, for want of a rigorous theory, it is not possible to say whether computations in that range are substantially similar to the results that would obtain at the smaller value.

Owing to the extreme delicacy of one particular balance, the so-called "Taylor constraint" that is expected to be operative in the geodynamo, one can reasonably doubt that 10^{-6} is yet sufficiently small, although those calculations do broadly suggest the increasing relevance of the constraint. So it is of considerable interest to find alternate, and more important, independent means to characterize how the dynamical balance might operate in the limit that the viscosity tends to zero in order to have an end point of comparison.

The magnetic and velocity fields in the Earth's core obey the "pre-Maxwell" and Navier Stokes equations respectively. On the assumption that the field must at every instant satisfy the "Taylor constraint", we find using the tools noted above that the evolution must follow a specially restricted version of these equations. It is our capacity to describe that restriction explicitly (as a sequence of dozens to hundreds of nonlinear constraints) as well as having a particularly efficient numerical representation of the fields that leads naturally to a time-stepping scheme. In conceptual terms, one can imagine that the evolution of the geodynamo absent any constraints corresponds to the motion of a point in three dimensions, whose instantaneous time rate of change depends on position in that space. The addition of the constraint can be thought of as a requirement that the squares of the three coordinates sum to unity, that is, $x^2 + y^2 + z^2 = 1$. So the solution we seek is one that lies of the surface of a sphere, rather than a trajectory visiting arbitrary points in the space. At a given point on the sphere, representing an initial condition of the system, the instantaneous rate of change obtained from the unconstrained equations is a vector that, in general, will point partly away from the sphere and partly parallel to it (parallel meaning lying in the "tangent plane"). For the constraint to continue to hold, we must keep only the parallel component, and then the point representing the state of the system will continue to trace a pattern confined to the surface of the sphere.

As Taylor noted, in principle this process of discarding the perpendicular component is automatically achieved if we simply compute a particular portion of the velocity field, the geostrophic flow. Taylor's work dates to the early 60s and what was inviting about it was that one did not need to *have* any characterization of the machinery for parallel and perpendicular components, which was in any case not available. But, while formally true, numerically Taylor's prescription alone leads inevitably to disaster owing to exponential growth of error.

We have shown that turning instead to our geometric approach to maintain the evolution on the equivalent of that elementary example of the sphere is stable.[1] This is key. It means that we can meaningfully address the question of how magnetic and velocity fields would evolve in the absence of any viscosity at all. It may seem curious that this should be feasible when the largest supercomputers in the world can barely hit 10^{-6}. The reason for that is that we propose to solve the problem not for 10^{-15} but for zero identically and this lets us simplify the fluid mechanics in a significant way with major implications for numerics. Again for want of rigorous theory, one cannot be certain that the result at zero must be generally similar to that at 10^{-15}. But that is our conjecture, along with the belief that Taylor's constraint must hold.

While these ideas are at one level easy enough to describe, understandably there is much work required for their practical implementation as efficient verified code. But that is not all. Beyond the Taylor constraint, one further one is known, identified by Rainer Hollerbach and Michael Proctor. It too must go into this mix. But Phil Livermore has recently identified several more and we are still grappling with this enriched spectrum of constraints since they raise certain technical issues that are quite subtle.

It may emerge that results at zero do not differ significantly from those at 10^{-6} for a range of particular geodynamo models. If so, that is good news for the most ambitious models and lessens the pressure to focus exclusively on progressive decrease in the (dimensionless) viscosity and allows one instead to explore other parts of parameter space, necessary owing to present uncertainties in other aspects of the geodynamo. But it may well happen the results differ qualitatively. Then we face a far more formidable challenge for the future, perhaps foremost the theoretical one of understanding the limiting process that connects one to the other.

Relevant Publications

Livermore, P., Ierley, G. R., and Jackson, A., The construction of exact Taylor states. II: The influence of an inner core, *Phys. Earth Planet. Int.*, v 178, 16-26, 2010

Livermore, P, and Ierley, G. R., Quasi L^p norm orthogonal Galerkin expansions in sums of Jacobi polynomials, *Num. Alg.*, v 54(4), 533-569, 2010. doi:10.1007/s11075-009-9353-5

[1] As described in a recent submission to GJI, with our revised version just returned to the referees.

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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.

SERPENT: Serpentinite, Extension and Regional Porosity Experiment across the Nicaraguan Trench: This NSF funded project uses electromagnetic (EM) exploration techniques to study the fluid content of the subducting oceanic plate offshore Nicaragua and was funded in collaboration with Steven Constable (IGPP/SIO) and Rob Evans and Dan Lizarralde (Woods Hole Oceanographic Institution). The month-long research cruise for this project took place in April-May this year aboard the R/V Melville and was my first big cruise as Chief Scientist. We collected 54 stations of marine magnetotelluric (MT) data and deep-towed nearly 800 km of controlled-source electromagnetic (CSEM) data (Figure 1). This is a huge milestone for marine EM as our project's size far exceeds previous MT surveys of subduction zones, and is the first CSEM survey of a subduction zone. We now have a huge volume of marine EM data, from which we will learn a great deal about the nature of cracking, extension, porosity and serpentinization of the oceanic lithosphere as it is subducted beneath the continental margin. This data will provide constraints on the amount of water entering the subduction system and allow us to study its implications for seismicity and the onshore volcanic system.

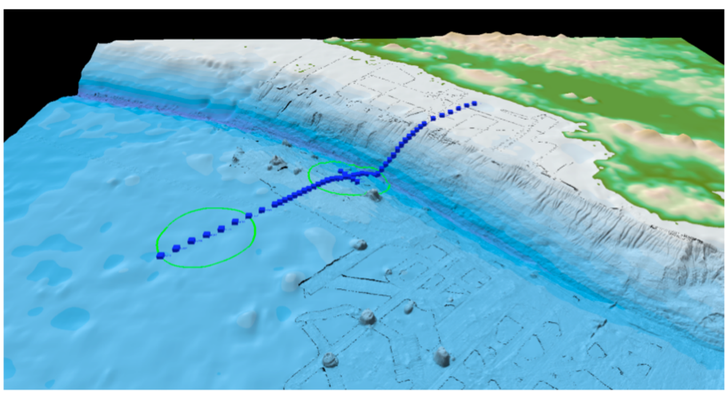

Figure 1. Marine EM survey of the subduction zone offshore the west coast of Nicaragua. Blue dots show the location of 54 marine EM receivers deployed across the deep-ocean, the Middle America Trench and up the continental slope. Green circles show circular CSEM tows used to constrain anisotropic conductivity before (left) and after (right) reactivation of normal faults associated with the bending of the oceanic plate.

Interpretting vector marine CSEM data with an unknown orientation: Marine CSEM data is now routinely collected on the continental shelves for offshore oil and gas exploration. In some cases, the seafloor electric and magnetic field recordings have unknown orientations due to the absence of magnetic compass and tilt data. Key and Lockwood (2010) considers the practical case of how to best interpret this data, showing that the orthogonal Procrustes rotation method that is commonly applied for image analysis can also be used to solve for the sensor orientations. This is accomplished by coupling the Procrustes method into a non-linear inversion method that iteratively solves for the unknown sensor orientations and the seafloor conductivity (Figure 2).

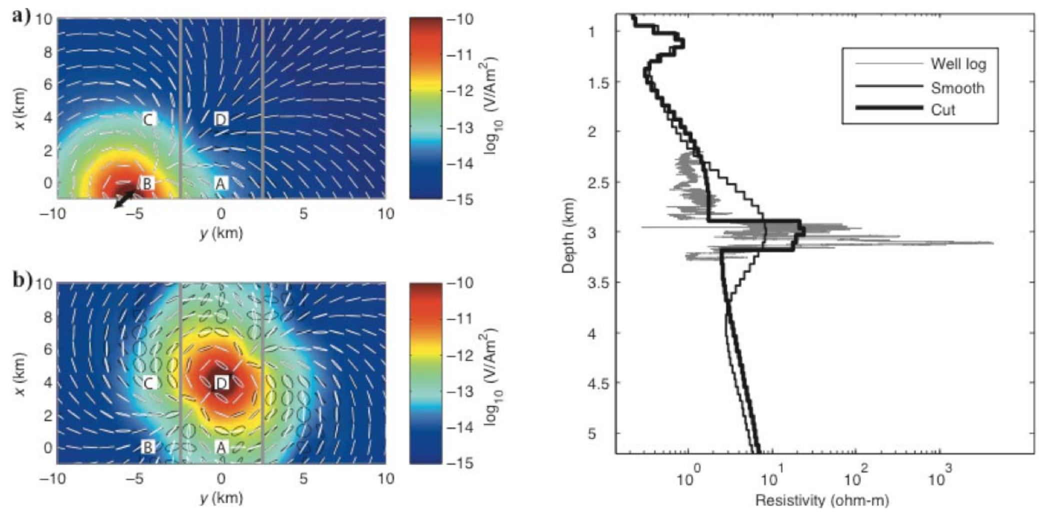

Figure 2. Left: Map view of the electric field strength (colors) and polarization ellipses for a transmitter located off (a) and over (b) a resistive 2D hydrocarbon reservoir. Right: resistivity-depth profile obtained from non-linear inversion (smooth and cut) of CSEM data collected over the Pluto gas field offshore Australia, obtained while jointly applying the Procrustes method to estimate the unknown sensor orientations. The gray line shows resistivity measured in an exploration well located 40 km away.

Review of Marine EM: In September 2010 I presented an invited review paper on "Marine electromagnetic studies of seafloor resources and tectonics" at the 20th International Workshop on Electromagnetic Induction in the Earth, held in Giza, Egypt. My charge was to cover interesting developments in marine EM since previous reviews were given in 2004. As shown in Figure 3, the dramatic increase in the publication rate after 2004, associated with the rapid industrial uptake of marine EM methods, gave me no shortage of material to cover.

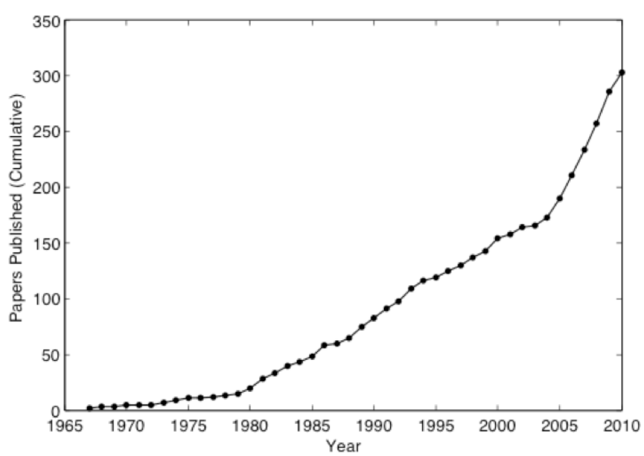

Figure 3. Cumulative number of peer-reviewed papers published on marine electromagnetic methods since early work in the 1960's. The increase in the publication rate in 2004 onward is associated with the industrial adoption of marine EM methods for offshore hydrocarbon exploration.

Recent Publications

Myer D., S. Constable, and K. Key (2010), A marine EM survey of the Scarborough gas field, Northwest Shelf of Australia, *First Break*, **28**, 77–82.

Key K. and A. Lockwood (2010), Determining the orientation of marine CSEM receivers using orthogonal Procrustes rotation analysis, *Geophysics*, **75**, F63–F70.

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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.

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

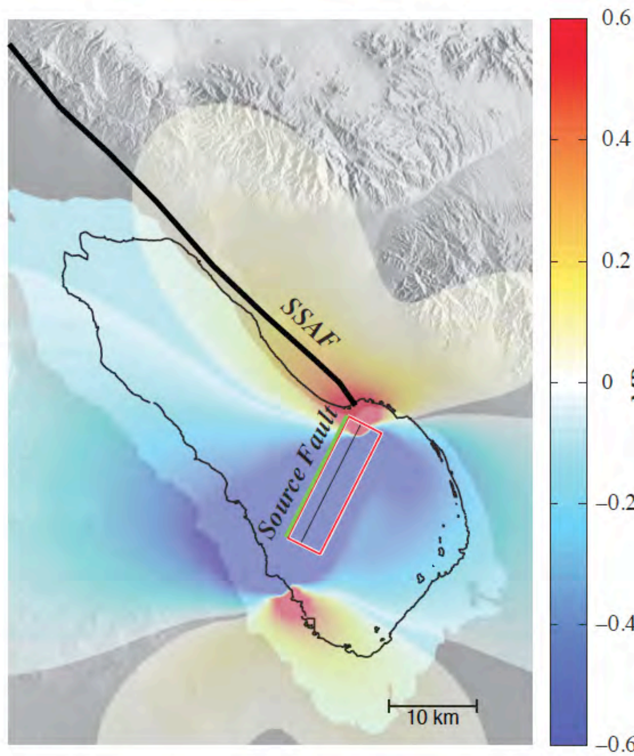

Figure 1. *Map of Coulomb static stress change. Static Coulomb stresses at a depth of 4 km generated by rupture of an extensional fault (green line shows surface trace; red rectangle shows the extrapolated fault plane; black line shows the calculation depth) embedded in an elastic half-space, using a friction coefficient of 0.6. The simulation applies 1.0 m of normal displacement to a 65°SE dipping plane that is 15 km long and 8 km deep. Resulting stresses are derived on fault planes oriented similar to the SSAF (strike=325°; dip=90°; rake=180°). Warm colors indicate areas where failure is promoted and cool colors where failure is inhibited. Stress lobes are saturated at ±0.6 MPa.*

from lake level changes. In general, these results highlight the importance of including lake loading and secondary fault ruptures in seismic hazard assessments, as both have the potential to modulate earthquake cycles on major plate boundary faults such as the SSAF (Brothers *et al.,* In Review).

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 (Felzer & Kilb, 2009).

Cyberinfrastructure Enabled Science Learning: This year, Kilb was the seismology domain expert for two different projects related to improving science learning. Collaborations with a Chicago based group created the "RoomQuake" project, in which the student's classroom becomes an active seismic field (Moher *et al.,* 2010). This project includes simulated seismographs depicting continuous strip-chart seismic recordings, which are located in three different locations of the classroom. Most of the time, the seismograms reflect a low level of background vibration. At (apparently) unpredictable times, a crescendoing rumble emanating from a subwoofer signals the occurrence of an earthquake. Upon hearing this signal students move to the seismic stations to assess the data, identify P- and S-wave arrival times, and in turn determine the earthquake epicenter and magnitude. The teacher hangs a sized and color-coded (representing magnitude) Styrofoam ball from the ceiling at the epicenter location. Over the course of about two-dozen earthquakes spread over six weeks, a classroom "fault line" emerges. In a different study collaborating with a CSSM group, Kilb assisted in the creation of a web-based interactive earthquake location tool. This Flash-based Earthquake Location Tool (FELT) allows its user to perform computations and interact with Google Maps API as it loads data, images and audios asynchronously, and redraws sections of the screen, all independent of the server with which it is connected. FELT retrieves seismic data for select recent earthquakes from the IRIS databank and displays seismograms that students can interact with to determine an earthquake's epicenter (Ouyang *et al.,* 2009; to access to the tool and other resources see http://www.csusm.edu/cyberteam/resources/TechQ1Modified.html#tq1).

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

Recent Publications

Brothers, D., D. Kilb, K. Luttrell, N. Driscoll and G. Kent, Potential triggers for large ruptures along the southern San Andreas Fault, in Review, 2010.

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Ouyang, Y., Lehmann, M., Hayden, K., and Kilb, D., Opportunities Presented when Developing Learning Resources for Middle Schoolers, *The Journal of Computing Sciences in Colleges,* 24:04, p 144 – 150, 2009.

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Research interests: regional and global surface wave seismology; seismology 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 also collaborates with Masters and current graduate student Zhitu Ma to study the cooling signal of the Pacific plate and to compile a refined global crustal and lithosphere model. Laske has also 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 important aspect of this research is to find the cause for the uplift of the Arabian Plateau east of the Dead Sea Transform Fault.

The PLUME project: Laske is the lead-PI of the Hawaiian PLUME project (Plume–Lithosphere–Undersea–Mantle Experiment) to study the plumbing system of the Hawaiian hotspot. The project aims to resolve the fundamental question whether a plume or other mechanisms feed Hawaii's extensive volcanism. PLUME researchers conduct comprehensive seismic tomographic studies using the unique broadband ocean bottom data collected for PLUME. Before PLUME, observations from stations on the Hawaiian island chain provided incomplete models 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. With two 1-year deployments in 2005 through 2007, PLUME has been one of the first large, long-duration deployments of broadband OSBs.

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 trace the supply route of Hawaii's magma (Figures 1 and 2). This low-velocity body is associated with a marked temperature anomaly of roughly 250°C and very likely contains melt pockets on the order of 2%. The PLUME crustal receiver function study (Leahy et al., 2010) shows extensive crustal underplating beneath the Hawaiian Swell, thereby supporting the anomalies imaged by the surface waves. SWELL, a pilot study leading into the PLUME project, showed conclusively that the Hawaiian lithosphere has undergone a thermal rejuvenation process with no extensive mechanical erosion and the results from the PLUME project confirm this. A pronounced low-velocity feature in the PLUME surface wave model is imaged in the asthenosphere to the west of Hawaii, documenting that the magma supply cannot come from a straight conduit located southeast of Hawaii as conventional models suggested. The PLUME body wave tomography (Wolfe et al., 2009) reveals that the low velocity body penetrates into the lower mantle thereby lending strong support that Hawaii's volcanism is fed by a deep-rooted mantle plume rather than from passive magmatism that

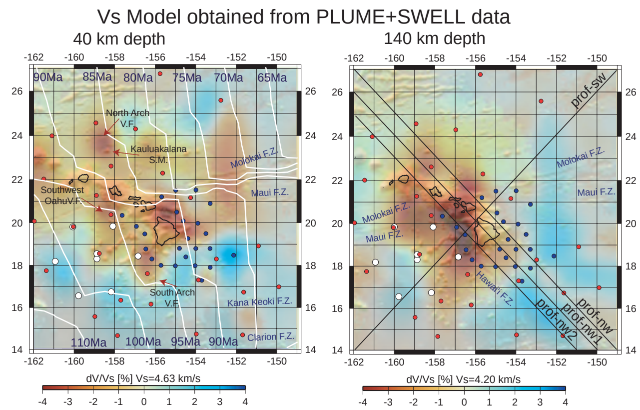

Figure 1: Two depth maps of the 17-layer shear-velocity model obtained from inverting two-station Rayleigh wave phase velocity curves collected from the SWELL and PLUME deployments. Also shown are crustal ages (white lines), the grey-shaded bathymetric relief and the location of the cross sections of Figure 2.

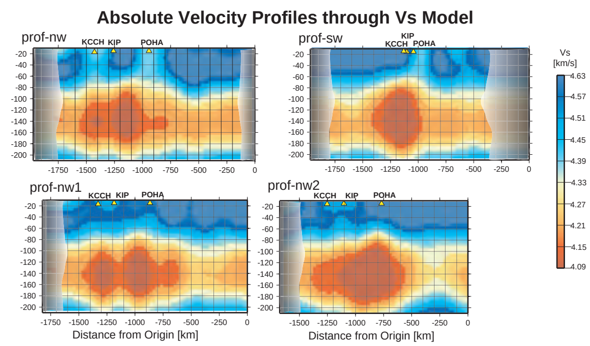

Figure 2: Cross sections through the Vs model, now displayed as absolute velocities. The locations of the sections are marked in Figure 1. Structure near the ends of the profiles is poorly resolved and therefore has been shaded over. The projections of stations POHA, KIP, and KCCH on the islands of Hawaii, Oahu, and Kauai onto the sections are also marked.

results from a cracking plate. Tomography also shows that the plume undergoes marked undulations in the mantle wind that is generated by global convection. Graduate student Paula Chojnacki currently conducts a detailed study of surface wave azimuthal anisotropy to constrain patterns of mantle flow and fabric.

Recent publications:

Leahy, G.M., Collins, J.A., Wolfe, C.J., Laske, G, Solomon, S.C. Underplating of the Hawaiian Swell: evidence from teleseismic receiver functions, *Geophys. J. Int.*, 183, 313–329, DOI: 10.1111/j.1365-246X.2010.04720.x, 2010.

Laske, G., Collins, J.A., Wolfe, C.J., Solomon, S.C., Detrick, R.S., Orcutt, J.A., Bercovici, D. and Hauri, E.H., Probing the Hawaiian hot spot with new broadband ocean bottom instruments, *EOS Trans. AGU*, 90, 362-363, 2009.

Wolfe, C.J., Solomon, S.C., Laske, G., Collins, J.A., Detrick, R.S., Orcutt, J.A., Bercovici, D., Hauri, E.H., Mantle shear-wave velocity structure beneath the Hawaiian hotspot, *Science*, 326, 1388–1390, doi: 10.1126/science.1180165, 2009.

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.

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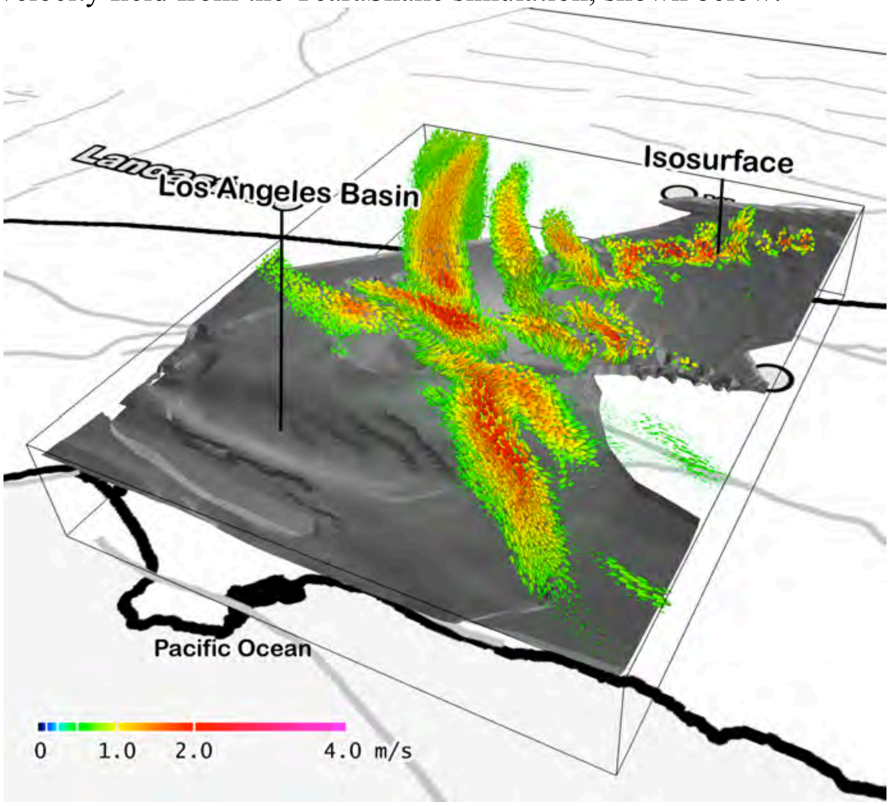
Research Interests: Plate tectonics and plate deformation; Application of space-geodetic techniques to study crustal dynamics; Satellite laser altimetry and Satellite Synthetic Aperture Radar applications to Earth studies; Earthquake source physics and large-scale supercomputer earthquake simulations; 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 super-computers 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.

Seismic simulations allow us to study earthquakes in a manner not feasible with the real world. Simulations of earthquakes produce time-dependent vector fields that contain interesting geophysics. Prior visualization strategies focused on slices and volumetric rendering of scalar fields which reduces the observable phenomena. This thesis studies visualization techniques implemented in an interactive glyph visualization application called "GlyphSea" that allows scientists to explore seismic velocity fields. This work draws from a large body of work in glyph rendering and focuses on time-dependent seismic vector fields and is the result of collaboration between domain experts in visualization and seismology. Through the study of vector visualization, several novel techniques were formed. A novel procedural dipole and cross mark texturing enhancement encodes unambiguous xii vector orientation on any geometry with volume. A novel lattice method was created to show neighborhood which also enables glyph distinction. Visualization is further enhanced by using screen space ambient occlusion, jitter, halos, and displacement.

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. One of these is the "comet glyph" rendering of the volumetric velocity field from the TearaShake simulation, shown below.



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

McQuinn, Emmett, Visualization of Time-Dependent Seismic Vector Fields With Glyphs, MS. Thesis UCSD, 2010

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Research Interests: Physical Oceanography, Ocean Acoustics and Climate.

The year 2010 was dominated by the award of the Crafoord Prize by the Swedish Academy of Sciences for "Lifetime Achievement." Instead of pontificating about past work, I gave the Award Lecture on some highly risky future plans for research on the global rise in sea level (SLR). Present predictions have 100% uncertainty limits and are almost useless. Arctic and Antarctic glaciers slide down the mountain sides into the sea until they comes off the bottom at the grounding line (GL). The floating ice sheet may extend toward the ice front (IF) for more than 100 km. Lying between the floating ice sheet and sea floor is an ocean cavern, the only piece of ocean never visited by men. Some very recent work suggests that much of the sea level rise is associated with the melting at the bottom of the ice near the GL where it is in contact with relatively warm ocean water. We are proposing monitoring the temperature in the ocean cavern using acoustic methods (references 1 and 2).

By accident the Crafoord Prize award coincided with the publication of my career (3).

I have continued the work on waves in the 1 mm to 1 m scales, straddling the transition from gravity to surface tension (4, 5). 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 at 5 km depth and measurements of ocean surface slopes from satellites at 500 km elevation.

Relevant Publications

1. Munk, W. (2010) The Sound of Climate Change: Crafoord Prize Scientific Lecture, *Tellus*, submitted.
2. Dushaw, B.D., P.F. Worcester, W.H. Munk, R.C. Spindel, J.A. Mercer, B.M. Howe, K. Metzger Jr., T.G. Birdsall, R.K. Andrew, M.A. Dzieciuch, B.D. Cornuelle, and D. Menemenlis (2009). A decade of acoustic thermometry in the North Pacific Ocean. *Journal of Geophysical Research,* **114**, C07021, doi: 10.1029/2008JC005124.
3. von Storch, H. and K. Hasselman (2010) Seventy Years of Exploration in Oceanography: A Prolonged Weekend Discussion. Heidelberg, Germany: Springer, 137 pp.
4. 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.
5. Farrell W.E. and Walter Munk (2010). Booms and Busts in the Deep. *J. Phys. Oceanography,* in press.
6. Munk, W. and C. Pendarvis (2010) Where the Swell Begins. *Groundswell Publication Annual Publication*, **5**, 242-255, in press.

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

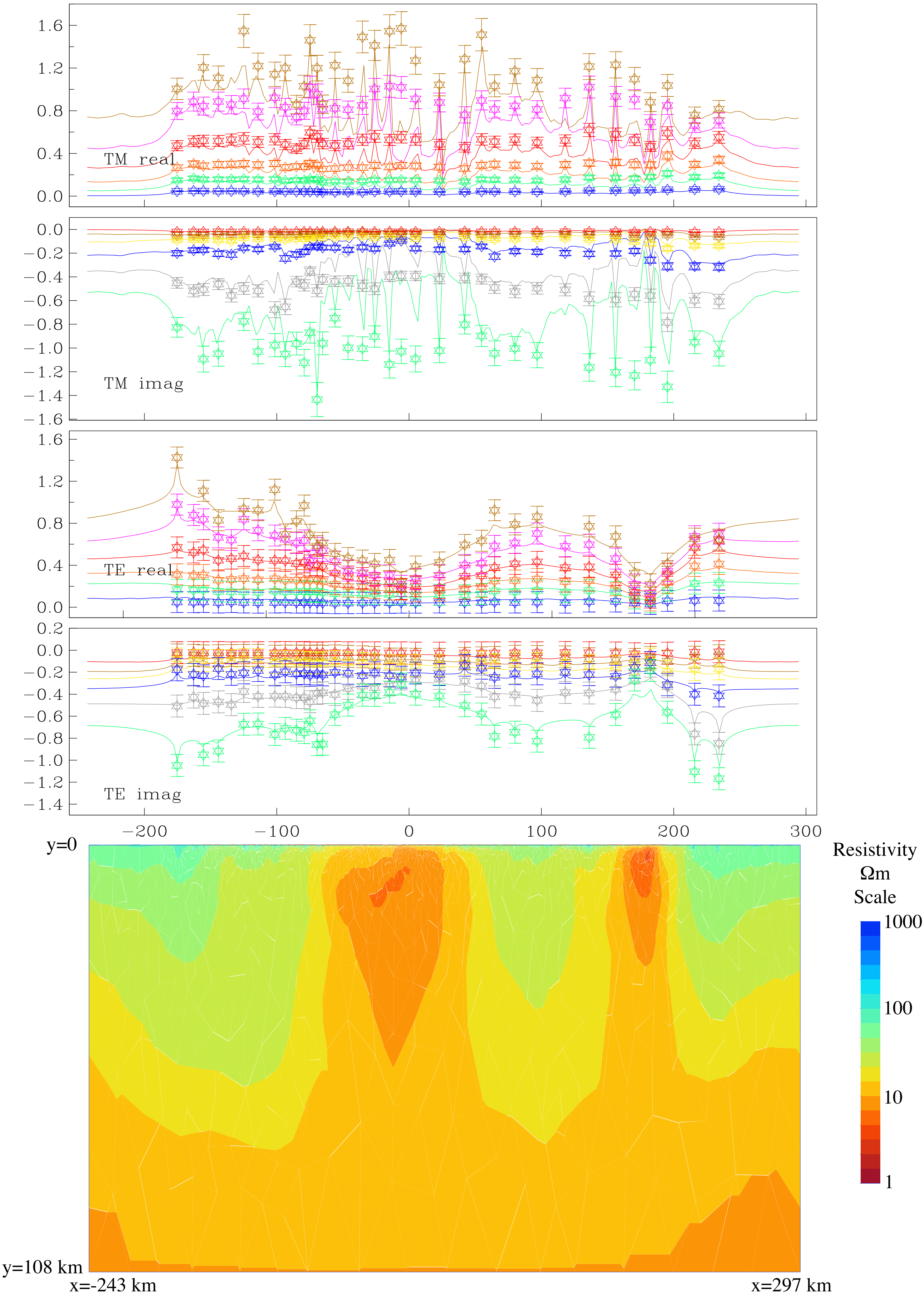
The past year has been occupied with bringing to publication work that was the subject of Ashley Medin's PhD project. In collaboration with Prof Steve Constable in IGPP, and two colleagues in the UCSD Mathematics Department, Profs Randy Bank, and Philip Gill, Bob Parker and Dr Medin (now Ashley Van Beusekom) have been pursing a radical approach to the numerical solution of large-scale inverse problems, applying the ideas to the 2-dimensional magnetotelluric (MT) inverse problem. MT sounding consists in the simultaneous measurement of electric and magnetic fields on an array of instruments at the Earth's surface, relying on naturally generated time-varying fields from the ionosphere and magnetosphere to provide a driver for electromagnetic induction. As readers of the Annual Report will be aware, electrical methods have risen to prominence as powerful tools for exploring the Earth, particularly beneath the seafloor. The observational techniques have made enormous strides in the last decade, with IGPP leading the way. New theoretical methods are needed to deal with the volume of data and the demands for higher resolution.

As a first step in this direction we have adopted a strategy for the solution of the 2-dimensional MT problem embedded within a numerical optimization program. In the conventional approach to nonlinear inverse problems like this one, we begin with a model structure and compute its response and thus predict the observations that would be obtained; this is the solution of the forward problem. Naturally, at first these predictions fail to match the actual values, and so the discrepancies are used as a basis for a calculation seeking perturbations to the model that will bring predictions and observation into better accord—the inverse problem. The response of the modified model is computed and the process repeated. In this traditional scheme optimization plays an important part in the second phase to minimize undesirable features of the new solution (like excessive short-wavelength undulations).

The new technique places the whole process under the control of an optimization algorithm, by including the solution of the forward problem as well as the matching of the observations and the stabilization issues into a single objective function, symbolically:

$$P = w_1 \cdot [\text{PDE violation}] + w_2 \cdot [\text{data misfit}] + w_3 \cdot [\text{model roughness}]$$

The solution the forward problem entails the numerical solution differential equations derived from Maxwell's equations, and that process is framed as minimizing an error function; this avoids solving the forward problem to needless accuracy and high resolution in the early stages. To realize these ideas we adopted a general-purpose, multigrid optimizer, PLTMG, created by Prof Bank.



TM real
TM imag
TE real
TE imag
−200
−100
0
100
200
300
y=0
y=108 km
x=-243 km
x=297 km
Resistivity
Ωm
Scale
1000
100
10
1

The plot illustrates the solution based a standard 2-dimensional MT data set employing both transverse and transverse magnetic responses. Among the advantages of the optimization method developed here is the ability to include inequality constraints on the model, in addition to, or instead of common regularization penalties. Inequalities in inverse problems have been one of Bob Parker's obsessions: they provide a means for extract reliable information from an inverse problem, something lamentably absent in most cases. A paper covering the work described here is under review with Geophysical Journal International.

Recent Publications

Parker, R. L., Can a 2-D MT frequency response always be interpreted as a 1-D response?, *Geophys. J. Internat.,*doi: 10.1111 /j.1365-246X.2010.04512.x 181, pp 269-74, 2010.

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Research Interests: Geodynamics, global bathymetry, crustal motion modeling

During the 2010 academic year, Dave Sandwell's research was focused on solid Earth Geophysics with an emphasis on understanding the dynamics of the crust and lithosphere. Our group comprises three graduate students Karen Luttrell, Meng Wei, and Xiaopeng Tong. Our research is mostly supported by three grants; two are from the National Science Foundation with titles Observations and Modeling of Shallow Fault Creep Along the San Andreas Fault Zone and High-Resolution Gravity, Topography, and Seafloor Roughness while the third is from NASA to perform Geodetic Imaging and Modeling of the San Andreas Fault System.

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

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

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

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

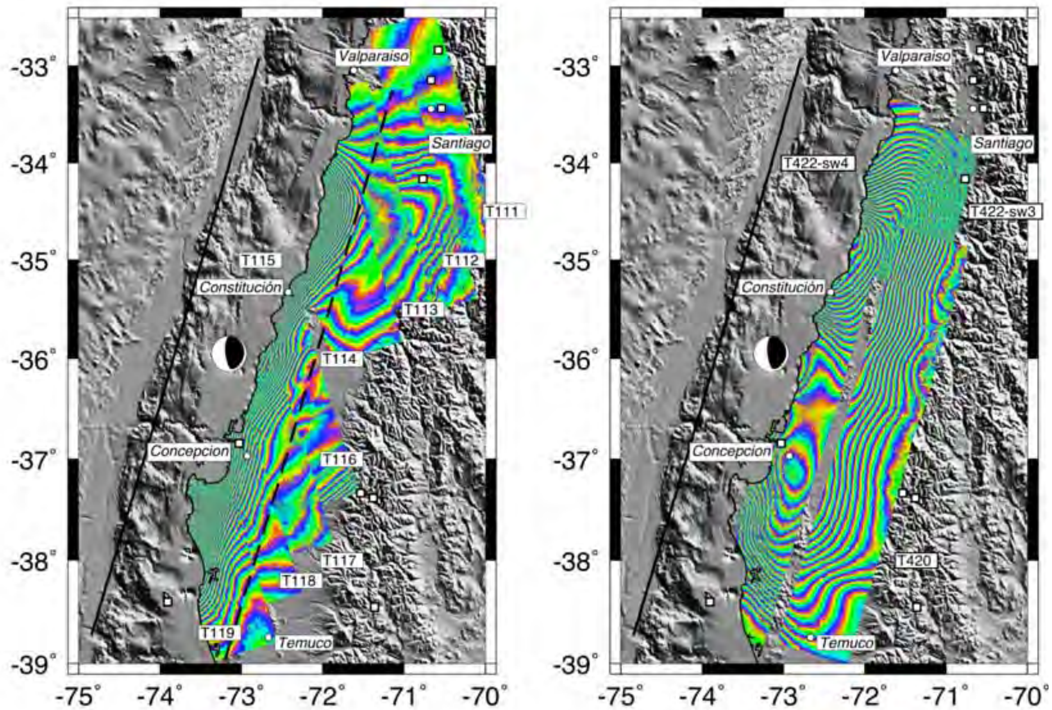

Figure 1. Radar interferometry of the 2010 M8.8 Maule, Chile Earthquake. Nine tracks of ALOS ascending interferograms and two tracks of ALOS descending interferograms cover a wide area from the coastline of central Chile to the foothills of the southern Andes.

Relevant Publications

Becker, J. J., D. T. Sandwell, (2008) Global estimates of seafloor slope from single-beam ship soundings, *J. Geophys. Res., 113,* C05028, doi:10.1029/2006JC003878.

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

Luttrell, K., and D. Sandwell (2010), Ocean loading effects on stress at near shore plate boundary fault systems, *J. Geophys. Res., 115,* B08411, doi:10.1029/2009JB006541.

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

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

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

Sandwell, D. T., and P. Wessel, (2010) Seamount discovery tool aids navigation to uncharted seafloor features, *Oceanography, 23:1* , p. 24-26.

Tong, X., D. T. Sandwell, and Y. Fialko, (2009) Coseismic Slip Model of the 2008 Wenchuan Earthquake Derived From Joint Inversion of InSAR, GPS and Field Data, *J. Geophys. Res., 115,* B04314, doi:10.1029/2009JB006625.

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: seismology, Earth structure, earthquake physics

Peter Shearer's research uses seismology to learn about Earth structure and earthquakes, both globally and in California, and has involved the development of new analysis approaches to handle efficiently the large digital data sets that are now emerging from the global and regional seismic networks. Recent work with former postdoc Catherine Rychert (now at the University of Bristol, U.K.) applies seismic receiver function analysis in a comprehensive study of the lithosphere-asthenosphere boundary (LAB), showing that it is a globally pervasive feature that varies in depth depending upon the tectonic environment (*Rychert et al.,* 2010). Receiver functions provide information only near seismic stations, limiting studies to continents and excluding most of the oceanic crust and lithosphere. *SS* precursor studies provide more complete global coverage, but traditionally have been used only to image interfaces deeper than the LAB, such as the 410 and 660-km discontinuities, which appear as distinct *SS* precursor phases. *Rychert and Shearer* (2010) show that subtle differences in *SS* waveform stacks can be used to resolve crustal structure, in particular to measure crustal thickness, even in the absence of a separate Moho-reflected phase. They are currently using this approach to map LAB depth and other properties beneath the Pacific and compare their results to those predicted by plate cooling models.

Shearer's southern California work has focused on improving earthquake locations using robust methods, waveform cross-correlation, and the development of new crustal tomography models to account for 3D velocity variations. Work with former student Guoqing Lin (now at the University of Miami) presents a new unified statewide seismic velocity model for California *(Lin et al.*, 2010), which should help to improve earthquake locations, especially for events situated between the northern and southern California networks. *Lin and Shearer* (2010) apply a new method to estimate seismic Vp/Vs ratios within 142 similar event clusters across southern California. They obtain a median in situ Vp/Vs ratio of 1.67, which is too low to explain with likely rock types. Instead it suggests the presence of water-filled cracks with several percent porosity in earthquake source regions, which likely has a profound effect on faulting and earthquake activity. In another earthquake location project, visiting scientist Raúl Castro applied the COMPLOC location algorithm of *Lin and Shearer* (2005) to relocate long-lived aftershocks of the 1887 M 7.5 Sonora, Mexico, earthquake (*Castro et al.*, 2010).

Shearer and Bürgmann (2010) present a review of lessons learned from the 2004 Sumatra-Andaman earthquake, which has been extensively studied because of its great size and devastating consequences. Large amounts of high-quality seismic, geodetic, and geologic data have led to a number of proposed models for its length, duration, fault geometry, rupture velocity, and slip history. The latest of these models vary in their details but now largely agree in their large-scale features, which include significant coseismic slip along the entire 1300- to 1500-km rupture, the bulk of which occurred fast enough to radiate seismic waves (see Fig. 1). The earthquake's enormous size has challenged conventional processing approaches and stimulated the development of new analysis and inversion methods, including multiple-source inversions, high-frequency body-wave imaging, and satellite observations of tsunami heights and gravity changes. The Sumatra megathrust earthquake was the largest in 40 years and is by far the best documented, but it does not seem fundamentally different in its properties from other large subduction-zone earthquakes. In particular, early reports of anomalously slow slip along its northern segment have not survived more detailed analysis.

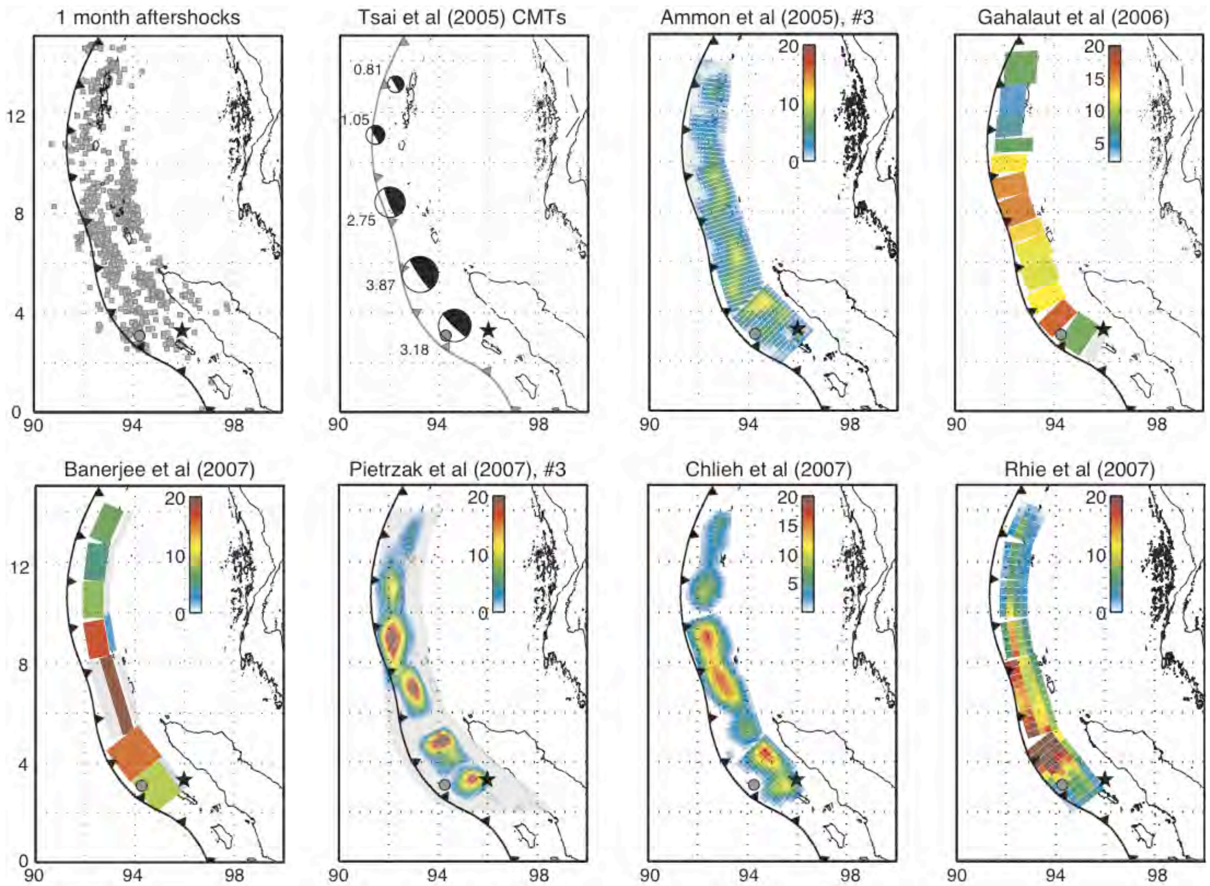

Figure 1. Published finite-slip models of the 2004 Sumatra-Andaman earthquake compared with the distribution of the first month of aftershocks and the multiple–centroid moment tensor (CMT) solution of Tsai et al. (2005). The black star shows the location of the earthquake hypocenter, and the gray circle shows the original single CMT location. These plots and the compilation of slip models are courtesy of Martin Mai (http://www.seismo.ethz.ch/srcmod/). From *Shearer and Bürgmann* (2010).

Recent Publications

Castro, R., P. M. Shearer, L. Astiz, M. Suter, C. Jacques-Ayala and F. Vernon, The long-lasting aftershock series of the 3 May 1887 M_W 7.5 Sonora earthquake in the Mexican Basin and Range Province, *Bull. Seismol. Soc. Am*., **100**, 1153–1164, doi: 10.1785/0120090180, 2010.

Lin, G., and P. M. Shearer, Evidence for water-filled cracks in earthquake source regions, *Geophys. Res. Lett*., **36**, L17315, doi:10.1029/2009GL039098, 2009.

Lin, G., C. H. Thurber, H. Zhang, E. Hauksson, P. M. Shearer, F. Waldhauser, T. M. Brocher and J. Hardebeck, A California statewide three-dimensional seismic velocity model from both absolute and differential times, *Bull. Seismol. Soc. Am*., **100**, 225-240, doi: 10.1785/0120090028, 2010.

Rychert, C. A. and P. M. Shearer, Resolving crustal thickness using SS waveform stacks, *Geophys. J. Int*., **180**, 1128–1137, doi:10.1111/j.1365-246X.2009.04497.x, 2010.

Rychert, C. A., P. M. Shearer and K. M. Fischer, Scattered wave imaging of the lithosphere-asthenosphere boundary, *Lithos*, doi: 1016/j.lithos.2009.12.006, 2010.

Shearer, P. and R. Bürgmann, Lessons learned from the 2004 Sumatra-Andaman megathrust rupture, *Annu. Rev. Earth Planet. Sci*., **38**, 103–131, doi: 10.1146/annurev-earth-040809-152537, 2010.

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

Hubert Staudigel's research and teaching focuses on seamounts and volcanoes including their petrology, igneous and low temperature geochemistry, hydrothermal processes, microbiology, their magnetic properties, density distribution (gravity) and seismic structure and activity. Recent work includes the geological history and structure of seamounts (Staudigel and Clague, 2010), their role in subduction systems (Staudigel et al., 2010) and deep sea metal deposits (Hein et al., 2010), microbial consortia in their hydrothermal systems (Sudek et al., 2009) and the discovery that fungi in these systems, demonstrating that seafloor alteration is much more similar to soil formation than previously thought (Connell et al., 2009). Staudigel also led the organization of the Seamount Biogeoscience Network (SBN) and the publication of "Mountains in the Sea", a special volume of Oceanography on seamounts (Staudigel et al., 2010).

Hubert Staudigels' involvement in volcanology includes interests in submarine volcanism, dike intrusion and collapse and he also teaches a class in volcanology on the Big Island of Hawaii (http://earthref.org/ERESE/courses/HVFT/2010/index.html). Recent volcanological studies include the paleomagnetic research in Antarctica (Lawrence et al., 2009) and on Jan Mayen, exploring the 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 Sudek (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; Bailey et al., 2009), how they colonize rock surfaces and the mechanisms by which microbes may dissolve in particular volcanic glass (Templeton et al, 2010). In a continued collaboration with colleagues at the University of Bergen, (Norway), he contrasted processes of abiotic and biotic tunneling into rock, further exploring how the geological record can be used to study microbial life in volcanoes as far back as 3.5 Ba (McLoughlin et al., 2010). Staudigel continues his ongoing work of microbe-rock interaction in Anarctic extreme environments (http://earthref.org/ERESE/projects/GOLF439/index.html).

Hubert Staudigel and co- principal investigator Cheryl Peach (Stephen Birch Aquarium) collaborate in an NSF-funded GK-12 program, the "Scripps Classroom Connection", supporting nine Scripps graduate students (per year), in a project that runs until 2014 (http://earthref.org/SCC/). These fellowships offer one year of full-time support to any qualified Scripps PhD student to spend one third of their time in K-12 education while pursuing their thesis work in the remaining time. This project is now in its second year and it involves a close collaboration with nine teachers of the San Diego Unified School District. Fellowships include participation in a four-week summer institute learning about pedagogy and communication, and then they work with their partner teacher for the rest of the year planning and enacting lesson plans in any earth science discipline.

Recent Publications

Bailey B, A. Templeton, H. Staudigel, B. M. Tebo, (2009) Potential utilization of substrate components during basaltic glass colonization by Pseudomonas and Shewanella isolates, Geomicrobiology Journal, Volume 26, 648-656.

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Staudigel, H., A.A.P. Koppers, J.W. Lavelle, T.J. Pitcher and T.M. Shank (eds. 2010). Mountains in the Sea. Oceanography 23(1): 16-227

Staudigel, H., A.A.P. Koppers, T.A. Plank, and B.B. Hanan, 2010, 176-181.Seamounts in the Subduction Factory Oceanography 23-1, 176-181

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McLoughlin, N., H. Staudigel, H. Furnes. B. Eickmann and M. Ivarsson (2010) Mechanisms of microtunneling in rock substrates: distinguishing endolithic biosignatures from abiotic microtunnels, Geobiology, 8, 245–255 DOI: 10.1111/j.1472-4669.2010.00243.x

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

Dr. Stegman's research involves computer simulation of plate tectonics using numerical models and high performance computing. The period from 2009-2010 was primarily focused on understanding how the motions of tectonic plates are an expression of the driving forces generated by cooling of the Earth.

Recent work has been aimed to further develop a 3-D numerical model of subduction based on a simplified rheology of mature oceanic lithosphere. This approach offers a distinct advantage over traditional mantle convection based studies because the properties of the subducting plate are prescribed *a priori* and can be controlled exactly for the entire duration of the experiment. The subducting plate has uniform properties for the duration of the experiments, allowing direct comparison with laboratory experiments using analog materials. The numerical models successfully reproduce the entire range of behaviors reported by previous laboratory experiments (shown in Figure 1). Each mode of subduction produces distinct slab morphologies in the upper mantle resulting from their associated motions of the plate and plate boundary (Stegman et al., 2010b). Additional work reported the influence of far-field boundary conditions on the system (Stegman et al., 2010a) as well as some 2-D models exploring the interactions with overriding plate (Capitanio et al., 2010).

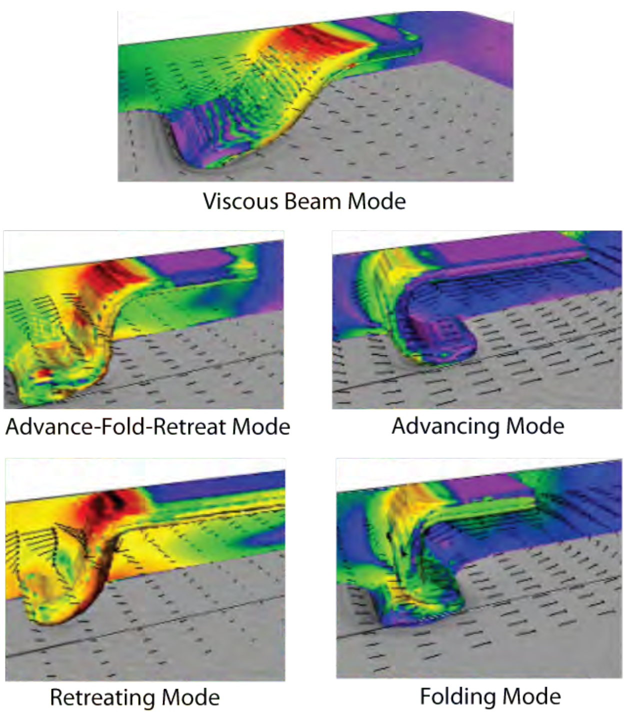

Figure 1: The first suite of numerical models of subduction that exhibit the full range of behavior previously reported by analog laboratory experiments (Stegman et al., 2010b).

After successfully identifying the parameters that produce the most Earth-like behavior, the work continued to explore how the lateral extent of the plate (i.e. width of the subduction zone) influenced the sinking dynamics and associated plate motions. Another suite of models helped develop a fluid dynamic scaling theory that correctly predicts the behavior of the subducted plate, which is essentially based on the same physics as a penny sinking through a jar of honey. The experiments showed that the velocities of both the plates and the plate boundaries depend on the width of subduction zones and the presence of subduction zone edges. The findings were published in *Science* (Schellart et al., 2010). The computer models demonstrate that the subducted portion of a tectonic plate pulls on the portion of the plate that remains on the Earth's surface. This pull results in either the motion of the plate, or the motion of the plate boundary, with the size of the subduction zone determining how much of each. Figure 2 shows a non-linear effect in plate width controls the partitioning for both subducting plates on the Earth as well as the simplified plates in the numerical models. For narrow plates, the subduction is accommodated primarily through slab rollback and trench retreat with very little forward plate motion, but plates with much wider subduction zones subduct almost entirely through plate advance and tend to have more stationary trenches.

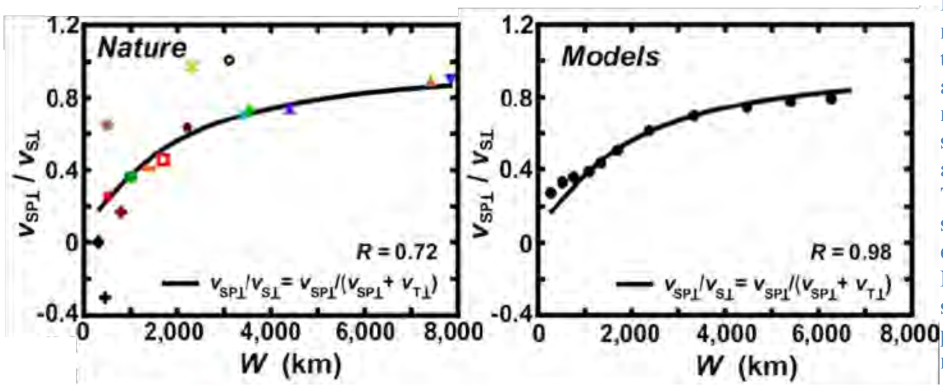

Figure 2: Partitioning of plate motions shown as the fraction of the subduction rate (Vs) that is accommodated by forward plate motion (Vsp) for 16 natural subduction zones on Earth (left) and 11 numerical models (right). The curve uses the fluid dynamic scaling based on the sinking dynamics of an oblate ellipsoid. Narrow plates preferentially subduct through motion of the plate boundary rather than motion of the subducting plate.

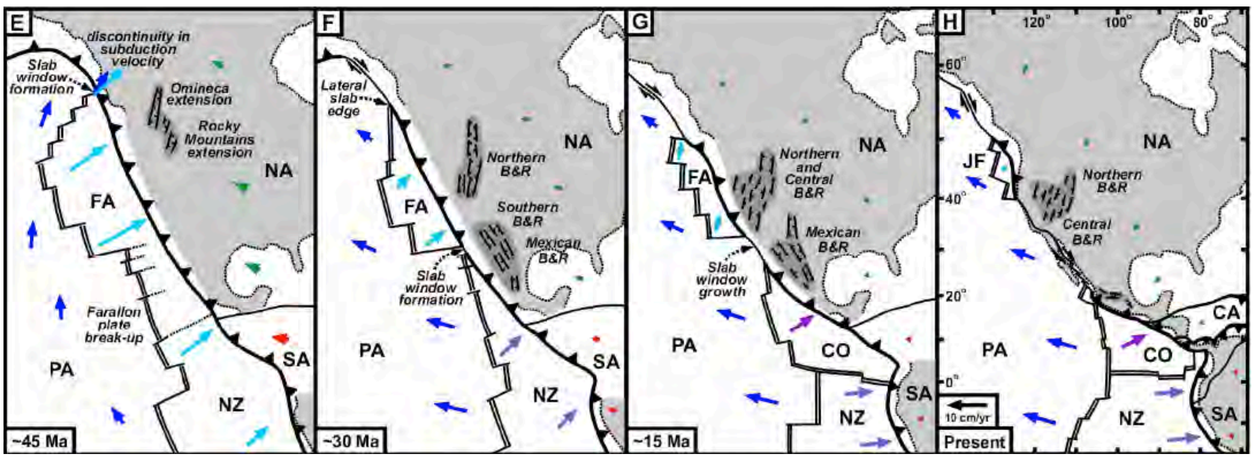

Figure 3: Cenozoic evolution of North America illustrating time-evolution of the Farallon plate from an initial width of nearly 11000 km (E) into two narrow plates (G), and corresponding transition from plate advance (E-F) causing compression in the North American continent to trench retreat (G-H) and extension in the Basin and Range province.

Publications for 2009-2010

Capitanio, F.A., **D. R. Stegman**, L. Moresi and W. Sharples. "Upper plate controls on deep subduction, trench migrations and deformations at convergent margins", *Tectonophysics*, doi:10.1016/j.tecto.2009.08.020, 483, 80-92, 2010.

Farrington, R., **D. R. Stegman**, L. Moresi, M. Sandiford and D.A. May. "Interactions of 3D Mantle Flow and Continental Lithosphere near Passive Margins," *Tectonophysics*, 483, 20-28, 2010.

Stegman, D.R., W.P. Schellart, and J. Freeman. "Competing influences of plate width and far-field boundary conditions on trench migration and morphology of subducted slabs in the upper mantle," *Tectonophysics*, doi:10.1016/j.tecto.2009.08.026, 483, 46-57, 2010a.

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Yanagisawa, T., Y. Yamagishi, Y. Hamamo, and **D. R. Stegman**. "Mechanism for generating stagnant slabs in 3-D spherical mantle convection models at Earth-like conditions", *Physics of the Earth and Planetary Interiors*, 2010 (in press).

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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.

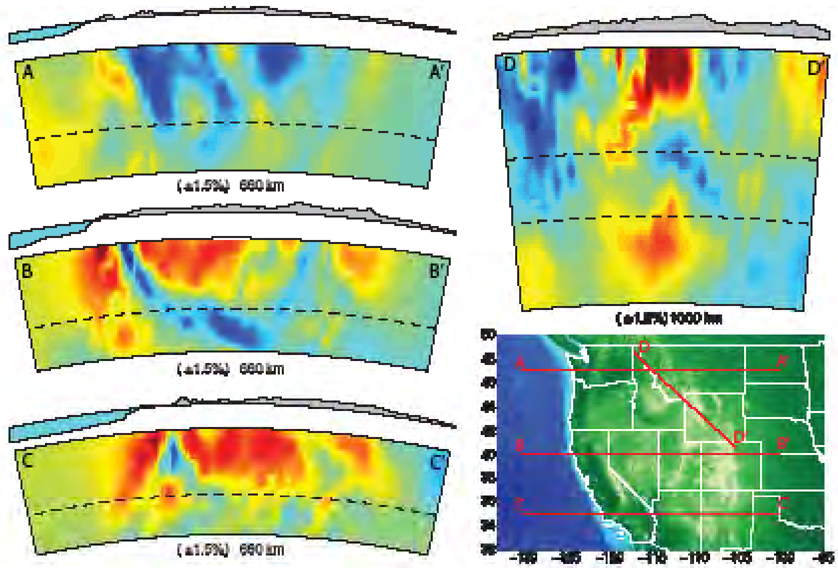
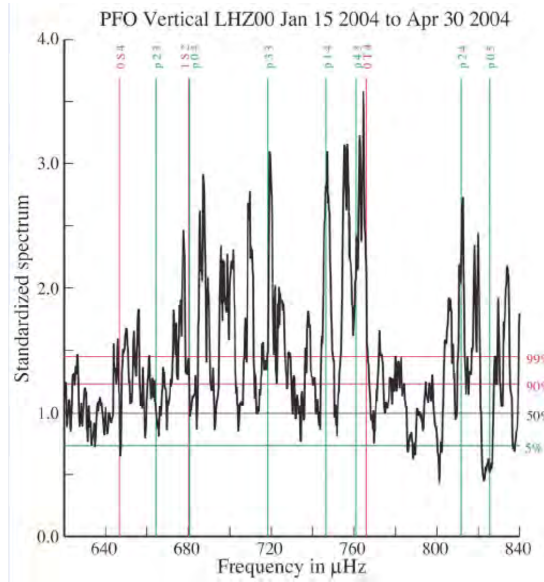


Figure 1. Cross sections through MITP_USA_2008DEC for the same locations as in Figure 7 of Burdick et al. (2008), which displayed model MITP_USA_2007NOV. The three east-west sections reveal additional heterogeneity to the east, while the updated D-D' section shows a greater degree of heterogeneity at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

The next major observing system is the NSF MRE Ocean Observatory Initiative which started 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://ci.oceanobservatories.org/)

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.

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Prieto, G. A., R. L. Parker, D. J. Thomson, F. L. Vernon and R. L. Graham (2007). Reducing the bias of multitaper spectrum estimates. Geophys. J. Int., 171,1269-1281, doi: 10.1111/j.1365-246X.2007.03592.x

Thomson, D. J., L. J. Lanzerotti, F. L. Vernon, III, M. R. Lessard, and L. T. P. Smith (2007). Solar Modal Structure of the Engineering Environment. Proc. IEEE, 95,1085-1132, Doi: 10.1109/JPROC.2007.894712

Burdick, Scott, Li, Chang, Martynov, Vladik, Cox, Trilby, Eakins, Jennifer, Mulder, Taimi, Astiz, Luciana, Vernon, Frank L., Pavlis, Gary L., van der Hilst, Robert D. (2008). Upper Mantle Heterogeneity beneath North America from Travel Time Tomography with Global and USArray Transportable Array Data Seismological Research Letters, 79, 384-392

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: infrasound, seismology, array processing methods

Kris Walker has focused on several atmospheric infrasound projects during 2009-10. Most of these projects have led (or are leading) to scientifically interesting results. The other projects are geared toward building infrastructure that will benefit future research.

Infrasonic Source Imaging with the USArray:
In collaboration with Michael Hedlin, Catherine de Groot-Hedlin, and other researchers at the Naval Research Lab and Commissariat à l'Energie Atomique, Kris compared the performances of the USArray and four globally spaced infrasound arrays to analyze a meteor explosion that occurred in northeast Oregon in 2008 (Walker et al., in press). He used reverse-time migration to back-project USArray vertical broadband recordings of acoustic-to-seismic coupled signals that were observed out to a range of 800 km. The source imaging suggests that these signals are explained by a terminal burst rather than a line source associated with a hypersonic trajectory through the atmosphere. Using the bootstrap method, he determined the 95% confidence region of the source location in 3-D space and time (Fig. 1). The source altitude, video camera constraints, and variance in final source locations provided by different algorithms suggest that the hypersonic trajectory had a minimum speed of 40 km/s. The spatial source location uncertainty was an order of magnitude smaller than that typically provided by globally spaced infrasound arrays, suggesting that despite the complexities associated with station-to-station variations in subsurface geology, it is more useful, for location purposes of energetic events, to analyze seismic recordings from dense seismometer networks than to analyze infrasound recordings from infrasound arrays with an average inter-array spacing of 2300 km.

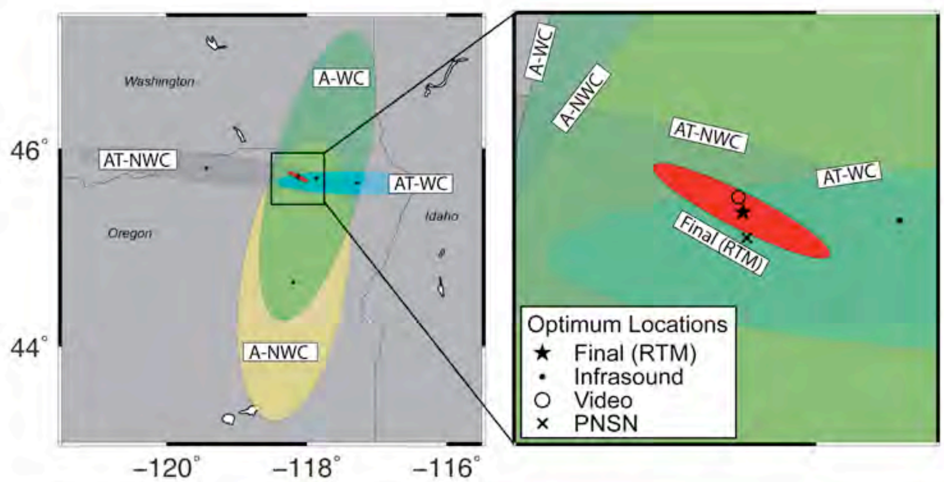

Fig. 1. Comparison of source locations and 95% confidence regions for the bolide burst source location estimated with the USArray seismic network (Final RTM) and infrasound arrays in North America. The infrasound array source locations are derived with different techniques and assumptions depending on if only back azimuths were used (A), if both back azimuths and times were used (AT), and if a wind correction is performed (WC or NWC). PNSN is the Pacific Northwest Seismic Network source location.

Kris is also using reverse-time migration (RTM) with the USArray to systematically locate infrasonic sources with undergraduate Richard Shelby and Michael Hedlin. Hundreds of sources have been detected thus far using this technique in 2008. For example, Fig. 2 is a USArray "infrasonic image" of a Vandenberg Air Force Base rocket launch. This figure shows the analyst's picking tool used to identify events of interest by manually inspecting peaks in an automatically calculated detector function, which is based on the RTM data. There is on average one U.S. event observed per day. More interesting are the propagation and source patterns observed in the data. Kris submitted an NSF proposal to extend this study to span 2004-2009. The development of a catalog of events detected with the USArray has a broader impact in infrasound research because there are generally few publically available ground truth catalogs of infrasonic events, which can be used to test a variety of infrasound propagation hypotheses as well as validate new 4-D velocity models.

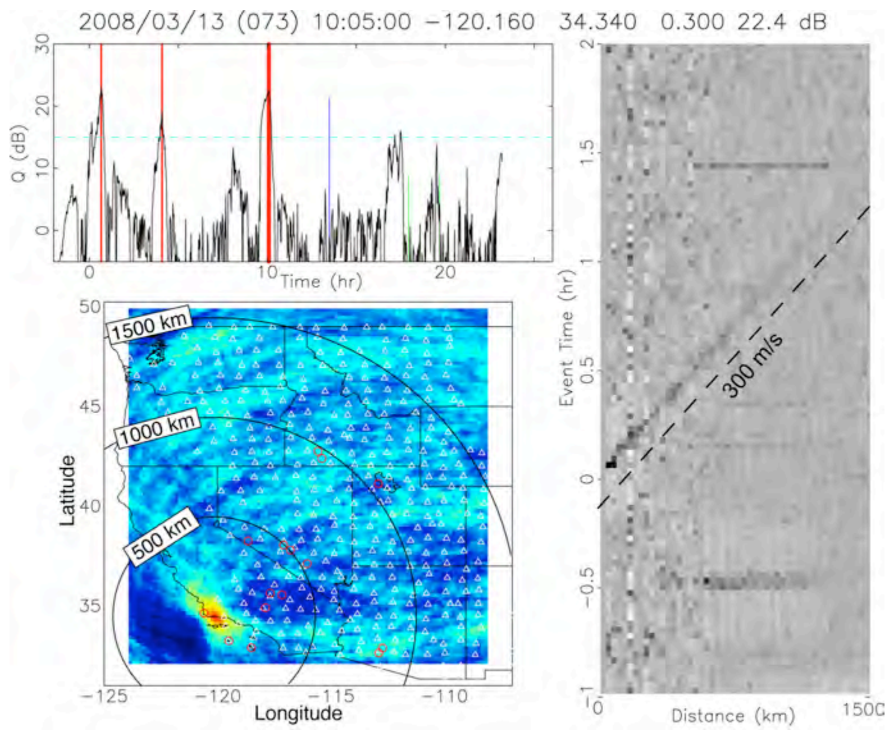

Fig. 2. The Q detector function (upper left) images the source in time; there is a peak at the launch time (thick red line) with a signal-to-noise ratio of 22 dB. Other colored lines indicate known regional and teleseismic earthquake times. The map shows the seismic energy migrated back to the source, where it constructively interferes, imaging the source in space at the source time. The record section to the right shows that the energy associated with the peak moves out at ~300 m/s, indicating that rocket infrasound is observed via acoustic-to-seismic coupling on USArray seismometers (white triangles in map) out to ~1500 km. Horizontally aligned signals are earthquakes.

Optical Fiber Infrasound Sensor (OFIS):

The second project Kris is working on is the development of a ruggedized, DC-powered OFIS for remote, autonomous deployments. The OFIS has proven to be more effective than pipe rosettes in mitigating the negative effects of wind in the measurement of infrasound (Walker and Hedlin, 2010). But until recently, this technology has been "fragile" and not been suitable for remote, autonomous deployments. This new development effort is an SIO collaboration with David Chavez, Michael Davis, Ph.D. graduate student Scott DeWolf, David Howitt, Mike Kirk, undergraduate Richard Shelby, Joel White, Frank Wyatt, and Mark Zumberge. In 2008, the OFIS system was an A/C powered research project with a large footprint comprising swappable rack modules, a bench-top laser, an optical polarization manipulation device, a digital signal processor, and a computer attached to an internet switch. The 2008 system also had an interferometer uptime issue associated with temperature change. Fabricated and tested in September 2010, OFIS v. 2.0 is a DC-powered system comprising miniaturized electronic boards, a lower-noise OEM laser with advanced feedback circuit, a low-power computer and digitizer, and a 900 MHz radio that transfers data to an internet switch. Scott DeWolf and Mark Zumberge addressed the uptime issue by adding Faraday mirrors to the sensing and reference optical paths, which eliminate the cumulative effects of temperature-dependent anisotropy. The new system will be deployed in northern California for one year as part of a NOAA-funded research project to study Pacific microbaroms. The new system is now capable of being deployed around volcanoes or in other remote environments where it is necessary to acquire high-quality, broadband recordings of infrasound in the presence of wind.

El Mayor Mw 7.2 Earthquake:

Kris is also collaborating with Catherine de Groot-Hedlin on a study of the infrasound generated by the Baja California Mw 7.2 earthquake (Walker and de Groot-Hedlin, 2010). Two infrasound arrays in southern California (MRIAR and I57) recorded a long infrasound wavetrain from this earthquake. Array processing of MRIAR data identifies a clear back azimuth rotation with time that spans the entire ~100 km long rupture. Ray tracing using 4-D velocity models suggests that the wavetrains are refracted thermospheric arrivals, which are inherently interesting because their existences are not predicted based on the classic thermospheric attenuation model. The ray tracing also shows that the MRIAR rotation of back azimuth with time is due to the fact that the northern end of the bilateral rupture is much closer to MRIAR than the southern end. Experiments suggest that we can image the rupture with the MRIAR data in a similar manner to earthquake rupture imaging (e.g. Walker and Shearer, 2009). More information is available at http://hpwren.ucsd.edu/news/20100413/.

Southern California Infrasound Network:

Southern California has an impressive seismic network. . Kris is working on the creation of an analogous infrasound array network, which will permit a number of studies in regional sources, propagation, signal processing methods, and wind noise reduction. This collaboration with Mark Zumberge and Michael Hedlin culminated in June 2010 with the deployment of SMIAR, the third southern California infrasound array. More information about SMIAR is available at http://hpwren.ucsd.edu/news/20100701/.

Infrastructure Building for Global and Regional Infrasonic Studies:

Infrasonics can be though of as surface-wave seismology turned upside down. There is a renewed interest in infrasonics because of the recent creation of the IMS global infrasound array network and the advent of 4-D global atmospheric velocity models. There are now many opportunities to make contributions to our understanding of infrasound sources, propagation, sensor development, and inversion methods. To facilitate future infrasonics research, Kris is also creating a database of global infrasound array network data and 4-D atmospheric velocity models with which to model infrasonic propagation. Roughly 60% of the global array data and 80% of the 4-D velocity models from 2004 to present are archived at IGPP. Some of these data are considered restricted, but may be published with permission from federal government entities, which is done routinely. Kris seeks undergraduate or graduate students interested in atmospheric acoustics to begin or assist with new research projects.

References:

Walker, K.T. and Shearer, P.M., 2009, Illuminating the near-sonic rupture velocities of the intracontinental Kokoxili Mw 7.8 and Denali fault Mw 7.9 strike-slip earthquakes with global P wave back projection imaging, *JGR*, v. 114, doi:10.1029/2008JB005738.

Walker, K.T., and Hedlin, M.A.H., 2010, A review of wind noise reduction methodologies, in "Global Continuous Infrasound Monitoring for Atmospheric Studies", eds. A. Le Pichon, E. Blanc, and A. Hauchecorne, Springer Geosciences, p. 141-182.

Walker, K.T. and de Groot-Hedlin, C., 2010, Infrasonic observations of ground shaking along the 2010 Mw 7.2 El Mayor rupture: a new tool for creating ground shaking intensity maps?, SCEC Meeting [abstract].

Walker, K., Hedlin, M., de Groot-Hedlin, C., Vergoz, A., Le Pichon, A., Drob, D., Source location of the 19 February 2008 Oregon bolide using seismic networks and infrasound arrays, *JGR,* [in press].

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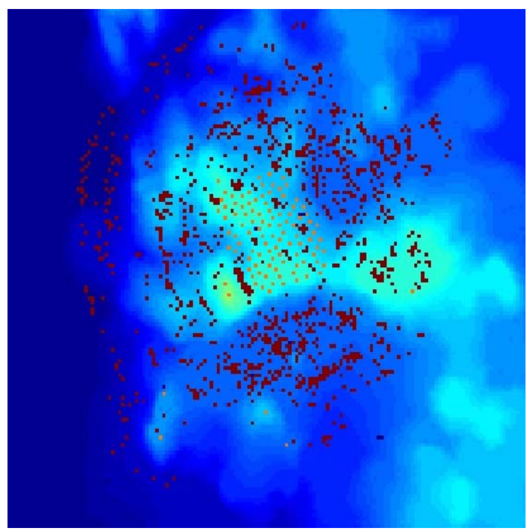
Research interests: complexity, nonlinear dynamics and pattern formation; permafrost terrain; dynamics of human systems and human-landscape interactions; urban landscapes; dynamics of western and indigenous science; resistance movements; and independent media.

Brad Werner and co-workers Marcel Madison, Weini Mehari, Alice Nash, Christina Rios, Chris Shughrue, Gabriel Velin and Ben Volta (Anthropology/IGPP) in the Complex Systems Laboratory and collaborator D. Emily Hicks (Chican@ Studies/SDSU) been working to develop and refine the tools used to investigate complex systems, 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.

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. Weini, Christina, Marcel, Chris and Gabriel have developed 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. The individual modules have been completed and their integration is in progress. 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 Oxpemul and Chichén Itzá, in Yucatan, Mexico, which were thriving Maya cities starting around 700-800, underwent significant changes, and later collapsed. The sites are 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 soil degradation from farming; urban dwelling construction and cooperative agriculture based on lineage and social group formation, immigration and emigration, and cultural evolution (An Agent-Based Model for Self-Organization in Growth of Maya Urban Centers, Journal of Archeological Science, in preparation). The model currently lacks organized political action, external trade and social hierarchy (to be added later) in an attempt to test the extent to which village-type dynamics can reproduce the temporal development and spatial layout of the cities. Nonlinear spatial forecasting and other techniques are being used to compare the model with available data and to compare the layout of different cities.



Modeled location of residences (orange) and agricultural fields (red) on elevation map (dark to light blue) of ancient Maya city of Oxpemul, in southern Campeche, Mexico. The settlement is distributed on the elevated areas at the center of the grid, whereas the fields are located in the more fertile seasonally inundated low-lying areas surrounding the settlement.

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. To clarify the dynamics of borders, Emily and Brad developed a theoretical description of the Mexico-US border as a hierarchical complex system (The Mexico-US Border as a Complex System, Theory, Culture and Society, in preparation). Past descriptions of borders were reinterpreted using complexity. For example, the apparent conflict between Bhabha's view that hybrid border culture is subversive and Kraidy's argument that hybridity follows the contours of existing power relations can be resolved by interpreting Bhabha's argument as applying to a short time scale level of description and Kraidy's to a longer time scale, where the dynamics of co-optation of subversive behaviors has had time to play out. Similarly, criticism of Hardt and Negri's argument that nation-states are becoming increasingly irrelevant and globally acting systems of economic, political and social power are united into a single overarching phenomenon they call Empire - based on the continuing considerable power exerted by nation states, especially the US - can be resolved by recognizing that the dynamics of Empire acts on longer time scales than the dynamics of nation states. In addition, the tools of complexity were employed to analyze a series of problems regarding the border, including the femicides of Cuidad Juarez and the dynamics of the painful experience of an undocumented individual leaving her village, traveling across the border, and becoming established in a community in the US.

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, 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. We are investigating the hypothesis that the emergent capitalist/democracy cultural system is a relatively formless resource exploiting and consuming machine whose direction and focus are principally determined by its interaction with resistance. Chris is developing an agent-based model for the dynamics of the occurrence of oil spills by coupling oil industry exploration, production and technology development, oil spill response and environmental damage, government regulation, media coverage, environmental advocacy groups and public perception.

Response to UCSD's Racism Crisis and Democratizing Dynamics: Following the most recent manifestation of UCSD's racism crisis, the series of racist provocations in February, 2010, members of the CSL supported student-led responses by attending and documenting protests and providing assistance and advice to individual students through the crisis. In March-May, a series of reflective interviews were conducted with participants that are being combined with live footage into a documentary. To foster better relations between UCSD and working class communities, a community service component was added to undergraduate courses, working with organizations or schools in City Heights and Chula Vista, and a new graduate course, Community Based Science, was developed. In contrast to common ways in which universities interact with working class communities of color - mining their most skilled youth as recruits and giving nothing in return or using interactions with communities for marketing purposes - this course is aimed at teaching students to develop genuine, two-way interactions with communities by learning about and participating in the community's struggles, exchanging knowledge and skills, and engaging in projects that are jointly determined and relevant to the community. These efforts are part of a broader project to help make UCSD more welcoming and to support community struggles in the border region, including founding Grassroots Diversity Action Working Group in spring 2007 and remaining an active member through February 2010, and participating in immigrant rights and indigenous struggles using media technology. Members of the CSL 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; meeting with on-the-ground resource managers; developing a park exhibit; and writing popular books on urban complexity and the dynamics of resistance.

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--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.

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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.

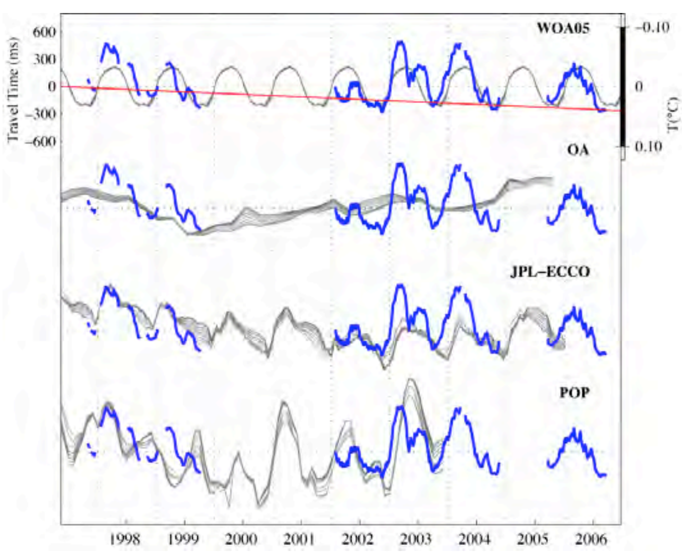

Figure 1. Comparison of measured travel times for transmissions from Kauai to receiver k, approximately 4000 km northwest of Kauai, (blue) with travel times calculated using sound-speed fields derived from WOA05, estimates of upper ocean temperature profiles produced by an objective analysis (OA) procedure 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 increase 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, 2010; *Stephen et al.*, 2010]. The NPAL Group is now conducting acoustic propagation experiments in the much more energetic and variable northern Philippine Sea. A short-term Pilot Study/Engineering Test was conducted in April-May 2009. The one-year-long 2010–2011 NPAL Philippine Sea Experiment, consisting of six acoustic transceivers and a new Distributed Vertical Line Array (DVLA) receiver, was deployed during April 2010. The 2010–2011 experiment combines 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.

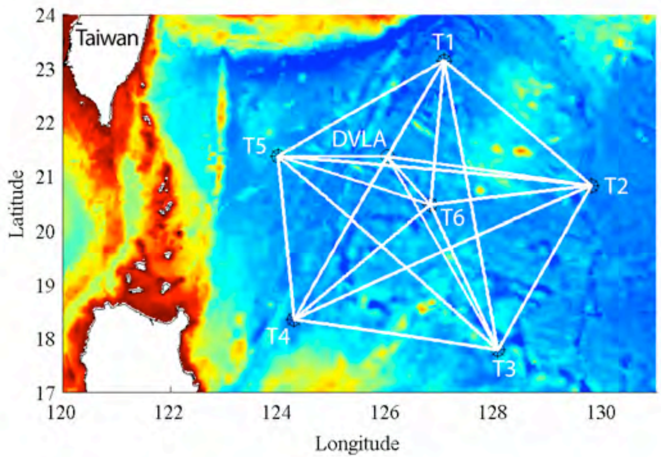

Figure 2. Overall mooring geometry of the 2010–2011 Philippine Sea Experiment, consisting of six 250-Hz acoustic transceivers (T1, T2, … T6) and a new DVLA receiver. The array radius is approximately 330 km.

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

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Van Uffelen, L. J., P. F. Worcester, M. A. Dzieciuch, D. L. Rudnick, and J. A. Colosi, 2010: Effects of upper ocean sound-speed structure on deep acoustic shadow-zone arrivals at 500- and 1000-km range. *Journal of the Acoustical Society of America*, **127,** 2169-2181.

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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

Monitoring the world's largest CO_2 sequestration reservoir with gravity
(In collaboration with Glenn Sasagawa)

A mainstay of our group's research is the measurement of Earth's gravity on the seafloor. Gravity, being sensitive to the density of the underlying rock, changes from place to place depending on the geologic structure nearby. We can use it to help create an image of the layered Earth below the survey area. We have carried out gravity surveys to study the structure of mid-ocean ridges and to help reveal the densities of ore bodies in deep ocean sulfide deposits. Such surveys are known as 3D gravity surveys because we make measurements over a three dimensional region, recording gravity as a function of latitude, longitude, and height.

Figure 1: During the summer of 2009, a seafloor gravity survey was done over the Sleipner CO_2 sequestration reservoir in the North Sea. A 100 m thick layer of sandstone, capped by an impermeable layer of shale, lies a km beneath the seafloor. On a nearby natural gas production platform, CO_2 (which comprises 10% of the extracted gas) is separated from the produced hydrocarbon and re-injected into the sandstone layer, where we hope it will remain for eternity. To confirm this expectation, gravity is monitored as a function of time on the seafloor. Shown in this photo is a Remotely Operated Vehicle (ROV) which sets our gravity meters (seen held in the ROV's manipulator arms) on an array of seafloor benchmarks. These benchmarks are reoccupied by the gravity meters every few years.

Gravity also can change with time at a given location if the density of the underlying rock changes. This makes it useful for monitoring the evolution of an oil or gas reservoir. Normally, as hydrocarbons are extracted from a reservoir beneath the seafloor, water gradually flows in to replace the extracted oil or gas. Because its density is different from that of the fluid it has replaced, gravity changes observed above the reservoir reveal the spatial pattern of water influx. This is important information that is utilized for planning future production. Such gravity surveys are known as 4D surveys because the dimension of time is included.

We are applying this method in reverse in a large scale CO_2 sequestration experiment. A million tons of CO_2 have been injected annually over the past decade into a reservoir beneath the Sleipner platform in the North Sea. Repeated gravity measurements over the reservoir reveal the density of the sequestered CO_2, which replaces water in the pore spaces. Over time, a leak in the reservoir would cause the fit of the gravity measurements to no longer match the model of the known amount of injected CO_2.

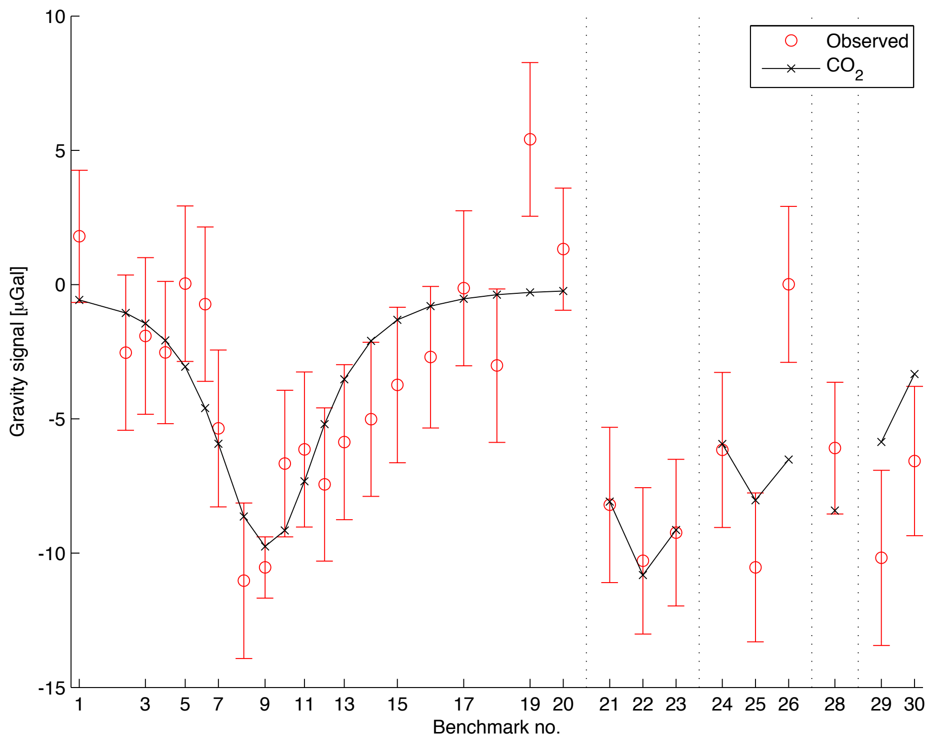

Figure 2. Results showing the difference in gravity observed in 2002 from the values obtained in the 2009 survey of 30 benchmarks spread out over a 10 km region overlying the reservoir (benchmarks 1 through 20 are arranged in a straight line crossing the reservoir). The gravity observations closely match the modeled carbon dioxide signal.

Relevant Publications

Eiken, O., T. Stenvold, M. Zumberge, H. Alnes, and G. Sasagawa (2008). Gravimetric monitoring of gas production from the Troll field, *Geophysics*, **73**, WA149; doi:10.1190/1.2978166.

Image: *Revelle Laboratroy and the Scripps Crossing footbridge.*

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