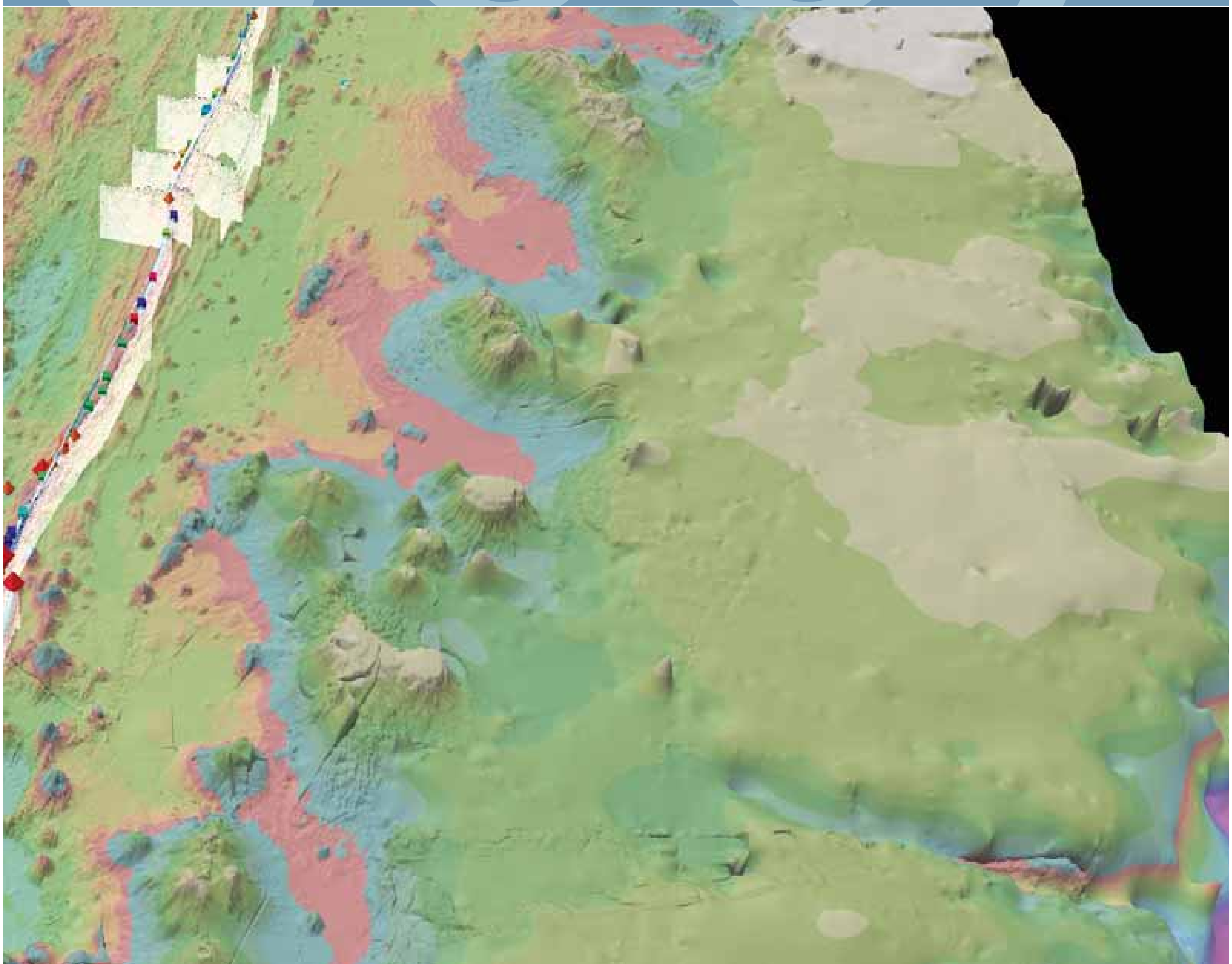
2007 Annual Report

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



SCRIPPS INSTITUTION OF OCEANOGRAPHY, UNIVERSITY OF CALIFORNIA, SAN DIEGO

IGPP Annual Report

The 2007 *Annual Report of the Cecil and Ida Green Institute of Geophysics and Planetary Physics* documents the progress of our investigators over a period of approximately the last academic year. We have tried to summarize the research in a succinct and fairly nontechnical way, so that the scientifically literate, but not necessarily expert, reader will be able to discern the kind of work we do at IGPP, and the contributions to geophysical knowledge that are being made. We hope that prospective students, scanning the Inter net will find this summary useful, as well as friends of IGPP and reviewers.

As you will readily perceive, the work of IGPP covers a broad range. We study marine geophysics and geology; deep and shallow structures in seismology; and the history of the geomagnetic field. We develop new instruments of all kinds: for discovering hydrocarbons by their electrical signature; for monitoring the spatially averaged temperature in the oceans from their acoustic characteristics; and for detecting strain with fiber optical meters. We exploit the latest techniques in satellite radar altimetry to look at the polar icecaps. And there is much more.

In the past year I have retired and become Professor Emeritus, with a part-time appointment as Deputy Director of IGPP. The new Director, Professor Catherine Constable, plans to continue the Report, and I will be responsible for its production. I hope you will find the 2007 Report informative.

Robert L. Parker
Deputy Director, Cecil and Ida Green Institute of Geophysics and Planetary Physics

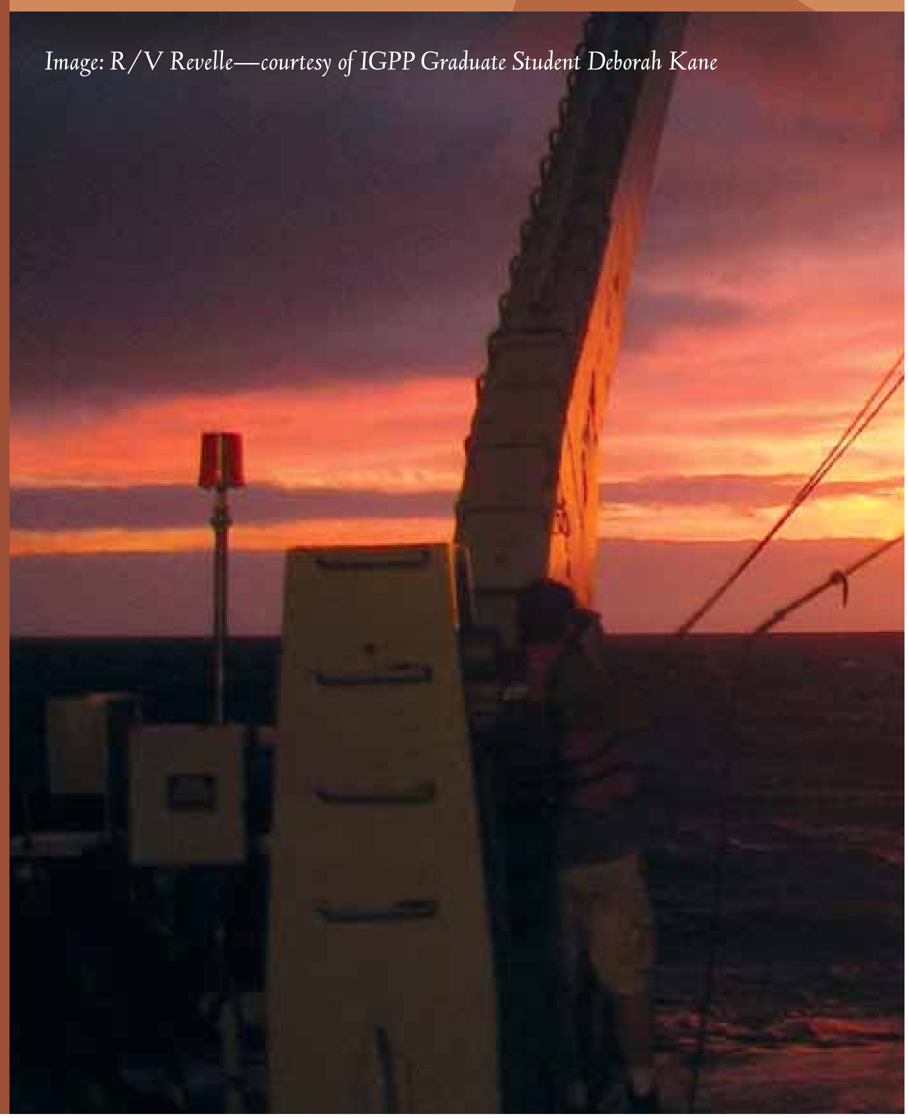


Image: R/V Revelle—courtesy of IGPP Graduate Student Deborah Kane acoustic thermometry, Dzieciuch, Worcester

acoustics, Blackman, Dzieciuch, Hedlin

Antarctic ice sheets, Fricker

complexity, Werner

crustal deformation, Agnew, Fialko, Sandwell

crustal seismology, Kilb, Shearer, Vernon

cyberinfrastraucture, Constable, C., Orcutt, Staudigel

Earth's deep interior, Akber, Constable, S., Parker

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

electrical properties, Constable, S.

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

fiberoptics, Zumberge

fluid mechanics, Ireley

geodesy, Agnew, Fang, Fialko, Sasagawa

geodynamics, Laske, Sandwell

geomagnetism, Ierley, Constable, C.

geophysical instrumentation, Agnew, Constable, S., Davis, Sasagawa, Vernon, Zumberge

global seismology, Davis, Laske, Shearer

GPS, Agnew, Fang, Fialko

high-pressure petrology, Akber

observational networks, Davis, Orcutt, Vernon

ocean acoustics, de Groot-Hedlin, Dzieciuch, Worcester

ocean bathymetry, Parker, Sandwell

infrasound, de Groot-Hedlin, Hedlin

inverse theory, Parker

landscape systems, Werner

lidar, Kent

lunar magnetism and seismology, Johnson

marine electromagnetic induction, Constable, S.

marine geology, Babcock, Blackman, Harding, Laske, Staudigel

marine gravity, Sasagawa, Zumberge

marine seismology, Babcock, Harding, Laske, Orcutt

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

mineral physics, Akber

normal modes, Davis, Laske

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

paleomagnetism, Constable, C.

paleoseismology, Babcock, Kent

petrology, Akber

radar techniques, Fialko, Fricker, Sandwell

reflection seismology, Babcock, Harding, Kent

satellite laser altimetry, Fricker

seafloor gravity, Sasagawa

seamounts, Staudigel

seismic anisotropy, Blackman

seismic hazards, Kent

seismic networks, Davis, Vernon

seismometers, Zumberge

spectral analysis, Dzieciuch, Parker, Shearer, Vernon

strainmeters, Agnew, Zumberge

tides, Davis, Agnew, Wyatt

turbulence, Ierley

volcanos, Hedlin, Staudigel

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Phone: x42411

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

Crustal Deformation (Strainmeters)

As was true last year, a major activity this year has been constructing and operating long-base laser strainmeters as part of the Plate Boundary Observatory, an activity led by Wyatt, supported by staff members Don Elliott and Stephen Dockter. Figure 1 shows these new instruments, along with those operated with other funding.

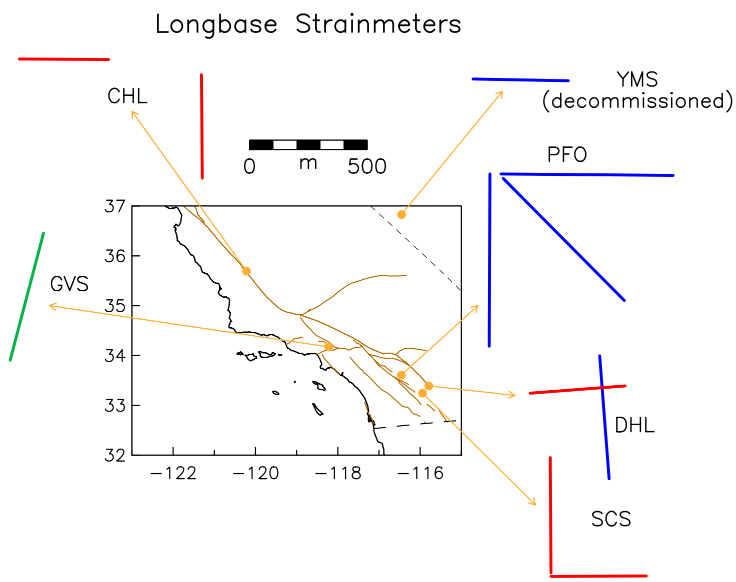

Figure 1. Longbase strainmeters built and under construction in California. Red are PBO instruments, blue are the non-PBO installations, and green non-PBO instruments with operation supported as part of PBO.

The first PBO instrument was a second system at DHL, on the east side of the Salton Sea (Durmid Hill) at 90° to an existing sensor, which began operation in June 2005. The next two were on the other side of the Sea, at SCS (Salton City), and began operation on 1 October 2006, on time and on budget—though meeting this deadline demanded considerable effort. By early 2007 Wyatt and Agnew had located a site for for the next installation, in the Cholame region of California (CHL), and construction on this is proceeding normally; we expect this instrument to be complete by the spring of 2008. The requirements of PBO also extend to prompt handling of data, which has been facilitated both by software development by Agnew, and by the hiring of a dedicated data analyst (Andy Barbour, now becoming a Geophysics graduate student).

The other laser strainmeters at Piñon Flat Observatory (PFO), Durmid Hill (DHL), Glendale (GVS), and Yucca Mountain (YMS) have all continued to operate satisfactorily, capturing the secular (and other) deformations in Southern California. A funding crisis within the Department of Energy caused the closure of the tunnel (for several years at least) in which the YMS laser strainmeter is housed. We were able, despite the short notice, to recover much of our equipment before the tunnel was rendered inaccessible; we plan to try to remove the remainder (mostly vacuum piping) in the fall of 2007.

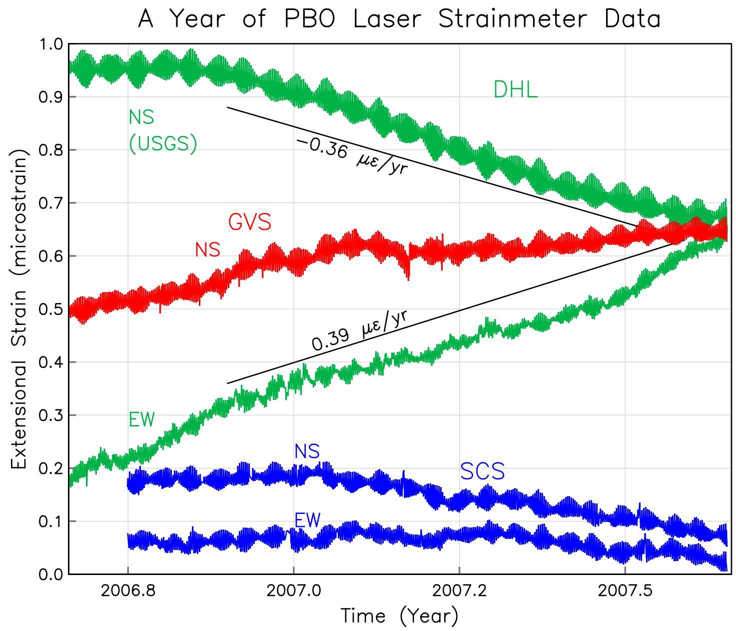

Figure 2. Long-term strains from the current PBO longbase strainmeters, and the NS strainmeter at DHL.

Crustal Deformation (GPS)

Agnew has continued to work with Dr. Z.-K. Shen (UCLA) and Dr. R. W. King (MIT) on on the SCEC Crustal Motion Map; a paper describing the new version of this is expected to be submitted this fall, together with the release of the new version.

Agnew has analyzed data from 1998 through 2006 from the network set up to measure motion in the San Diego area. The baselines for the individual monument clusters show measurement error of 0.3 mm and random walk of about 0.3 mm over a year, levels that verify the design principles of both the network and the precise-centering mount developed for this project. An analysis of time series of data from new continuous stations in the area shows higher strain rates (north-south contraction) close to the Rose Canyon fault and smaller rates inland.

Relevant Publications

Agnew, D. C., and K. M. Hodgkinson (2007). Designing compact causal digital filters for low-frequency strainmeter data, *Bull. Seismol. Soc. Amer.*, **97**, 91-99.

King, N. E., D. Argus, J. Langbein, D. C. Agnew, G. Bawden, R. S. Dollar, Z. Liu, D. Galloway, E. Reichard, A. Yong, F. H. Webb, Y. Bock, K. Stark, and D. Barseghian (2007). Space geodetic observation of expansion of the San Gabriel Valley, California, aquifer system, during heavy rainfall in winter 2004-2005, *J. Geophys. Res.*, **112**, B03409, doi:10.1029/2006JB004448

Agnew, D. C. (2007). Before PBO: an overview of continuous strain and tilt measurements in the United States, *J. Geodetic Soc. Japan*, **53**, 157-182.

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Research interests: mineral physics, petrology, Earth's deep interior

Earth materials both influence and record geological processes, and therefore serve as an account of the history of our planet. With few direct samples of the Earth's deep interior, our knowledge of the Earth's composition and mineralogy relies on comparisons of geological data (constraints provided by seismologists, geodynamicists, and geochemists) with properties of candidate Earth-forming materials under the conditions of the Earth's interior. Most of these properties, chemical and physical, are in principle measurable. However, the Earth imposes stringent requirements even on rapidly advancing experimental efforts: pressures up to 360 GPa, and temperatures approaching a substantial fraction of 10,000 K. State-of-the-art theoretical models complement experiments by extending the pressure-temperature range of material studies; additionally, theoretical frameworks help measurements inform our understanding beyond the particular, and necessarily limited, experimental context.

Aluminum in the lower mantle

Mantle composition is dominated by divalent (Mg,Ca,Fe^{2+}) and tetravalent (Si) cations. While less abundant, the major trivalent atom Al introduces complex chemistry and thereby plays an important role in mantle mineralogy and structure. In the lower mantle, several methods of Al incorporation into $MgSiO_3$ and $CaSiO_3$ perovskite are possible, the two leading ones being charge coupled substitution (Mg^{2+} + Si^{4+} = $2Al^{3+}$) and oxygen vacancy forming substitution ($2Si^{4+}$ + O^{2-} = $2Al^{3+}$ + V_O^0) (Figure 1). Using first-principles density functional theory, as well as atomistic models, we investigate the energetics of aluminum substitutions into perovskite in order to determine Al solubility into and partitioning among lower mantle minerals. From this we evaluate the effects of aluminum on the elasticity of these minerals. Additionally we can create a phase diagram for the $MgSiO_3$-Al_2O_3 join as a function of pressure, including akimotoite as the low pressure $MgSiO_3$ end-member.

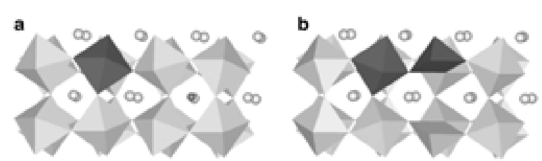

Figure 1: a: Charge coupled substitution of Al into MgSiO3 perovskite. b: Oxygen vacancy forming substitution. The light gray spheres represent Mg atoms, the light gray octahedra contain Si atoms at their centers and O atoms at their vertices. The dark gray sphere represents an Al atom, and the dark gray octahedron contains an Al atom at its center.

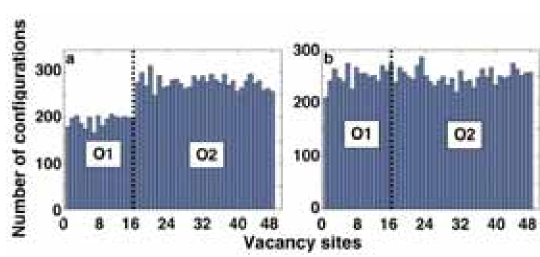

Figure 2: Oxygen vacancy distributions for the lower energy subsets of configurations of (a) $Mg_{16}Al_{16}O_{40}$ and (b) $Ca_{16}Al_{16}O_{40}$ perovskites (6 vacancies in 48 oxygen sites). Vacancies prefer to occupy the O2 sites in case a, and indicate no preference in case b.

We continue towards understanding the configurational entropy of aluminum mixing in $MgSiO_3$ and $CaSiO_3$ perovskites to improve our model of Al partitioning in the CaO-MgO-Al_2O_3-SiO_2 lower mantle assemblage. We find the mixing energetics to be fundamentally different for $MgSiO_3$ and $CaSiO_3$ perovskites, both in the preferred type of substitution mechanism as well as distribution of preferred oxygen vacancy sites in the case of vacancy forming substitution. We conclude that configurational entropy strongly depends on Al concentration in the case of $CaSiO_3$ perovskite, which prefers oxygen vacancy forming substitution; this may have especially important effects on the rheology of the upper part of the Earth's lower mantle.

Partitioning of elements between $MgSiO_3$ perovskite and post-perovskite

We estimate the partitioning of aluminum between $MgSiO_3$ perovskite and the recently discovered post-perovskite phase, at the base of the Earth's lower mantle, and examine the effects of aluminum on the depth and sharpness (and hence seismic visibility) of the phase boundary (Figure 3). Additionally, we investigate the effects of Fe^{3+} and Al^{3+} on the partitioning of a radioactive heat source, radiogenic potassium, via the substitution $2Mg^{2+} = Al/Fe^{3+} + K^{+}$. We find that potassium preferentially partitions into the perovskite phase, and therefore do not expect to find a K-rich layer at the base of the lower mantle.

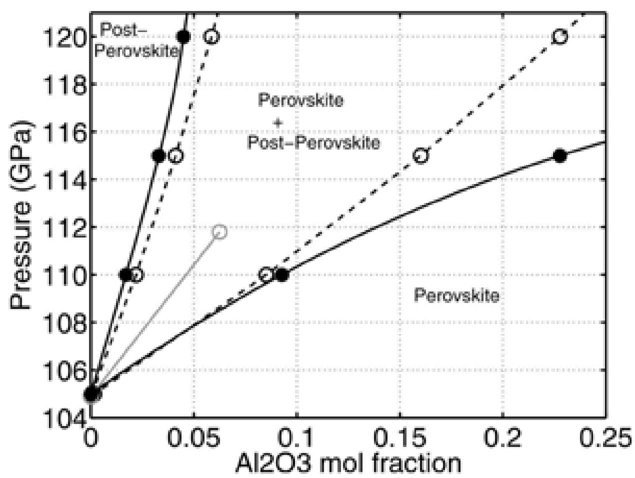

Figure 3: Phase diagram of $MgSiO_3$, for MgSi $\rightarrow$ AlAl substitution. The dashed curves are derived from Henry's Law, whereas the solid black curves are from regular solution theory. The gray curve corresponds to the pseudo-univariant phase transition. A temperature of 2500 K was assumed.

High pressure petrology

To extend the capabilities of computational mineral physics into the realm of petrology, it is necessary to compute free energies of minerals at high temperatures. For solids exhibiting quasi-harmonic behavior, this is possible from lattice dynamics. For solids approaching melting or changes to their structure, and for liquids, other techniques involving molecular dynamics simulations are necessary. While it is not straightforward to compute free energies and entropies from molecular dynamics, several promising techniques are being investigated.

Relevant publications

Akber-Knutson, S., M. S. T. Bukowiski, and P. D. Asimow, The partitioning of Al in a CaO-MgO-Al_2O_3-SiO_2 lower mantle assemblage, (in preparation).

Lee, K. K. M., G. Steinle-Neumann, and S. Akber-Knutson, Ab-initio predictions of potassium partitioning between Fe and Al-bearing $MgSiO_3$ perovskite and post-perovskite, (in review).

Panero, W. R., S. Akber-Knutson, and L. Stixrude, Al_2O_3 incorporation in $MgSiO_3$ perovskite and ilmenite. *Earth Planet. Science Lett.*, 252:152-161, 2006.

Akber-Knutson, S., G. Steinle-Neumann, and P. D. Asimow, Effect of Al on the sharpness of the MgSiO 3 perovskite to post-perovskite phase transition, *Geophys. Res. Lett.* 32, L14303, doi:10.1029/2005GL023192, 2005.

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Research interests: reflection seismology, mid-ocean ridge dynamics, rifted margins, fault hazards, paleoseismology, Southern California tectonics, geophysical instrumentation

During the last year Jeff Babcock led a collaborative investigation between the Unified Port of San Diego and researchers at Scripps to collect sub-bottom seismic-reflection and multibeam bathymetry data in San Diego Bay. The overarching goal was to utilize SIO's state-of-the-art shallow-water technology to study the fundamental processes shaping San Diego Bay (e.g., how sediments move throughout the bay and how fault structure dictates accommodation space and sediment traps). Fieldwork was completed during two separate campaigns aboard the 27' R/V Saikhon, with the area surrounding the Coronado Bay Bridge as the primary site of interest (Figure 1). Over 40 line-km (~25 miles) of seismic reflection data and 3 km^2 (~740 acres) of multibeam bathymetry data were collected and processed for interpretation. These complimentary data sets provide a very high-resolution baseline analysis for water depth, bay floor morphology and shallow sub-bottom fault/stratigraphic structure. Furthermore, previously collected multichannel reflection data (Kennedy and Clarke, 1999) was reprocessed using the latest software for comparison with the shallow chirp profiles, and combining the two data sets constrains the deformation history for the southernmost Rose Canyon fault system over multiple timescales.

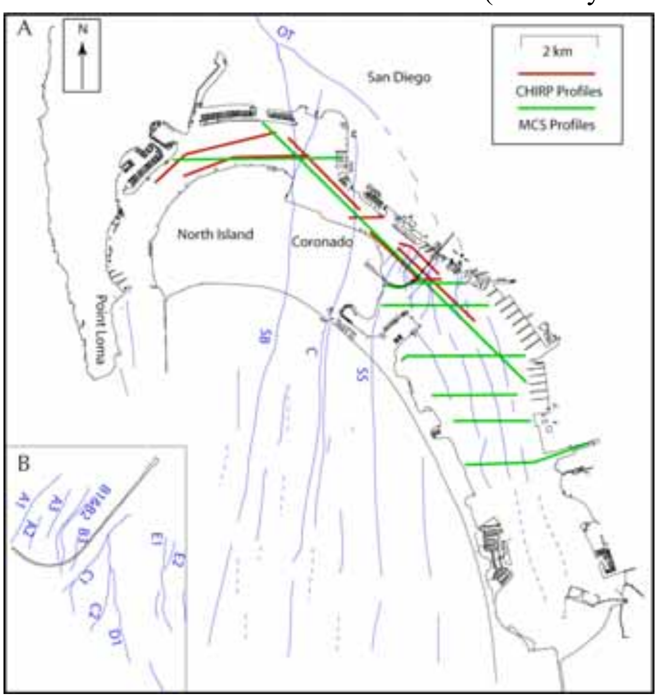

Figure 1: Location of faults and seismic profiles in San Diego Bay. San Diego Bay is an extensional depression formed by a right-step in the Rose Canyon Fault to the offshore Descanso Fault. Major faults in the basin are the Spanish Bight (SB), Coronado (C), Silver Strand (SS), South Coronado Bridge faults and the Old Town (OT). Secondary faults identified by Kennedy and Clarke (1999) are enlarged in figure 1B. Recent studies of the Rose Canyon fault zone suggests significant Holocene (last 10,000 years) displacement and slip rate of ~1.5 mm/yr (Lindvall and Rockwell, 1995).

Each of the fault strands identified by Kennedy and Clarke were identified in the uppermost 15 m of sediments. One significant observation is that fault offset extends much nearer to the bay floor than previously thought. Multiple profiles show faults extending to within ~2 m of the bay floor (Figure 2), thus providing evidence that fault activity is recent.

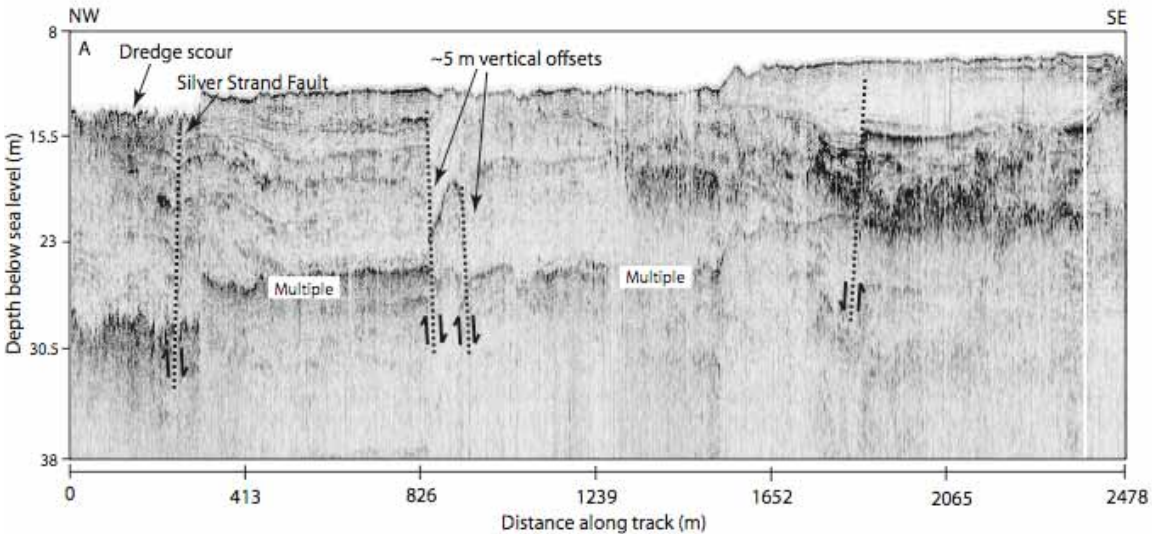

Figure 2: NW-SE trending chirp profile showing significant fault related deformation. Chirp profiles help locate potential sites for sediment cores.

However, due to extensive dredge and fill activity during the last century, it is unlikely any morphological features on the bay floor associated with faulting can be identified (Figure 3). Radiocarbon Age constraints for sedimentary horizons are provided by Kennedy and Clarke's analysis of cores collected beneath the Coronado Bridge. This data set offers a baseline analysis for bay floor morphology and acoustic properties of the upper ~30 m of sediments and has already proven to be extremely useful for understanding several processes affecting the bay.

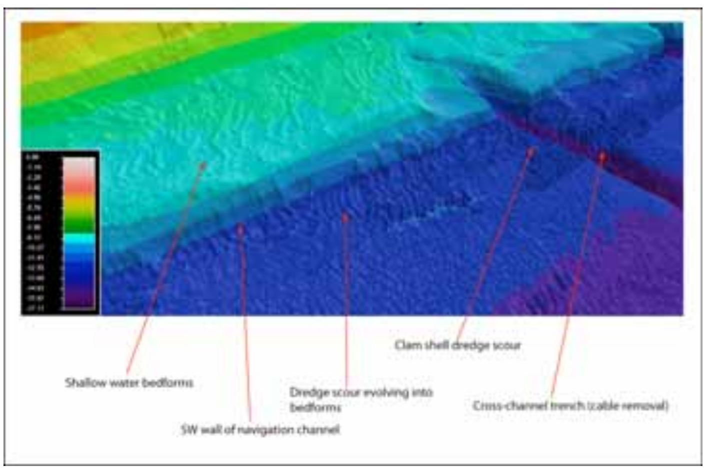

Figure 3: Shallow water bedforms near the Coronado side of the channel (looking east).

References:

Babcock, J., G. Kent, N. Driscoll, D. Brothers, High-Resolution Sub-bottom and Bathymetric Surveys in San Diego Bay, Report for the Unified Port of San Diego, (45 pages), Dec., 2005.

Kennedy, M.P. and S.H. Clarke, 1999, Analysis of late Quaternary faulting in San Diego Bay and Hazard to the Coronado Bridge, *California Division of Mines and Geology Open-File Report 97-10A,* 25 p, 3 plates.

Lindvall, S. and Rockwell, T.K., 1995, Holocene activity of the Rose Canyon fault, San Diego, California: *Journal of Geophysical Research*, 100, B12, 24121-24132.

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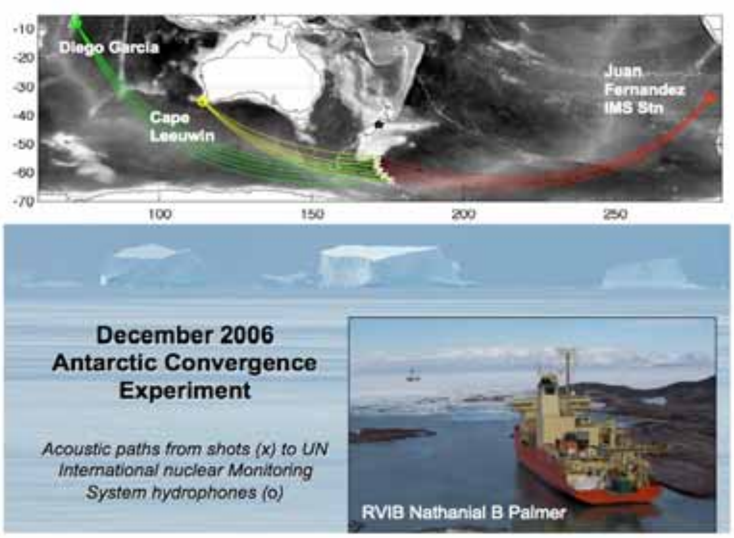
Research Interests: tectonic and magmatic processes in the vicinity of ridge-transform plate boundaries, deformation of minerals and the development of seismic anisotropy during mantle flow, hydroacoustic calibration experiments for nuclear test monitoring

Geophysical investigations of oceanic spreading center processes are the central theme of my research. The approaches I use vary both by design and in response to opportunities for seagoing experiments. In 2006/2007 my analyses incorporated data/results from deep sea drilling, shipboard mapping, gravity modeling, and seismic refraction/reflection. My colleagues on a prior IODP project and I developed a revised model of how oceanic core complexes form. In contrast to previous models, we hypothesize that episodes of greater than normal magmatic intrusion beneath a spreading segment that normally has modest melt supply are the key to formation of the shallow, domal cores that are unroofed via detachment faulting. This model requires additional testing and this is the focus of seismic and drilling proposals that I am working with others to design.

Recent computer simulations during work with Jolante Van Wijk provide insights into en-echelon volcanic centers in oblique spreading centers and the importance of axial zone weakness in allowing them to orient perpendicular to the direction of plate motion. Collaboration with Green Scholar Olivier Castelnau focused on the rheologic effects of texturing that develops during mantle flow beneath a spreading center.

In my second year as chair of the NSF Ridge 2000 program (http://www.ridge2000.org), I worked with colleagues and members of the R2K Office at SIO to facilitate interdisciplinary research on oceanic spreading centers. This research involves biologists, chemists, geophysicists, geologists, and oceanographers, all working to understand the interplay between processes that control rifting and hydrothermal venting along spreading centers.



Hydroacoustic work this year involved a cruise in the Southern Ocean. Small calibration shots were recorded at hydrophone stations that are part of the UN nuclear monitoring system. These data are being analyzed in the lab and Catherine de Groot-Hedlin is modeling propagation along the source-receiver paths. At sea, there were many spectacular scenes of Antarctic sea ice and even some penguins.

Publications in the past year

Ildefonse, B., D.K. Blackman, B.E. John, Y. Ohara, D.J. Miller, C.J. MacLeod, IODP Expeditions 304/305 Science Party, Oceanic core complexes and crustal accretion at slow-spreading ridges, Geology 35, 623-626, 2007.

Van Wijk, J.W. and D.K. Blackman, Development of en echelon magmatic segments along oblique spreading ridges, Geology 35, 599-602, 2007.

Blackman, D.K., Use of mineral physics, with geodynamic modeling and seismology, to investigate flow in the Earth's mantle, Reports on Progress in Physics 70, 659-689, 2007.

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Research interests: Paleomagnetism and geomagnetism; inverse problems; statistical techniques; electrical conductivity of the mantle; paleo and rock magnetic databases

Cathy Constable's research during 2007 has continued along familiar themes in geomagnetic and paleomagnetic data analysis, with particular emphasis on the recent and long term secular variations of the geomagnetic field. This research also includes recent efforts by PhD student Leah Ziegler and recently arrived postgraduate researcher Fabio Donadini and continues long standing collaborations with **Catherine Johnson**, Monika Korte (GeoForschungsZentrum, Potsdam), and Andy Jackson (ETH, Zurich). Other work includes exploring new methodology for using satellite magnetic field data to study mantle conductivity (PhD students Joseph Ribaudo and Lindsay Smith), and the development with **Anthony Koppers** and Lisa Tauxe of flexible digital data archives for magnetic observations of various kinds under the MagIC (Magnetics Information Consortium) database project.

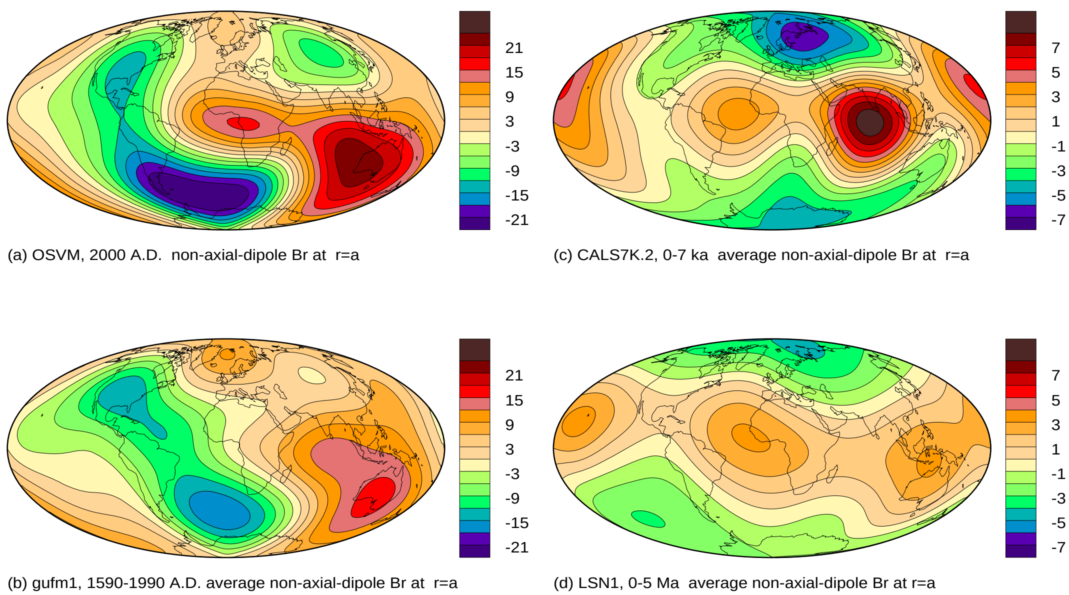

Figure 1: (a) Vertical component of the non-axial-dipole field in μT evaluated at Earth's surface using the geomagnetic field models *OSVM* for 2000A.D., (b) *GUFM1* averaged over 400 years, (c) *CALS7K.2* averaged over 7 kyr and (d) *LSN1* averaged over 5 Myr. Note scales for (c) and (d) differ by factor of 3 from (a) and (b).

The geomagnetic field has been measured at a variety of locations ever since the development of the first compasses, and direct observations on Earth's surface and (more recently) from low-earth orbiting satellites have led to excellent time-varying descriptions of the field for the past 400 years. The fact that the field varies over a broad range of time scales and has frequently reversed in the past is also well-documented, with much of our understanding about these changes coming from paleomagnetic data of various kinds. These provide the means to study the longer term changes on thousands to millions of years. Descriptions of long term magnetic field variations are often restricted to changes in the axial dipole which are intrinsically interesting for a variety of reasons. A predominantly dipolar field structure has been sustained by dynamo action for several billion years of Earth's history despite numerous geomagnetic reversals, and ongoing geomagnetic secular variation with accompanying dissipation of energy. At SIO in addition to studying temporal variation in the dipole moment for the past few millennia, we have gradually been developing a global view of the non-axial-dipole parts of the field using sparsely distributed paleomagnetic directional data that are of rather low accuracy compared with direct observations. Figure 1 shows an emerging view of the non-axial-dipole parts of the field averaged over four different time scales. Roughly speaking the scales are annual, centennial, millennial, and millions of years, and this figure clearly shows similarities in spatial structure, but differences in amplitude for the paired models on the left at historical time scales and for the millennial and million year models on the right part of the figure. The structure seen in the longer term models is believed to reflect the influence of spatial variations in thermal structure of the mantle near the core-mantle boundary. Improving the resolution of these structures and understanding their origin better are ongoing research topics.

Over the past year Lisa Tauxe, **Hubert Staudigel**, **Catherine Johnson** and Cathy Constable have continued work on the Time-Averaged Field Investiagtions (TAFI) project, with compilations and analyses of paleomagnetic samples from lava flows in the age range 0-5 Ma from globally distributed locations. Graduate student Leah Ziegler is investigating the feasibility of extending time-varying field models to much longer (million year) time scales using directional and relative paleointensity data from marine sediments. Fabio Donadini and Monika Korte are collaborating on the production of a new millennial scale time-varying field at higher resolution for the past 3kyr. The new models will be used by post doc Philip Livermore working with **Glen Ierley** and Andy Jackson to place bounds on Ohmic dissipation in Earth's core. Other work with Andy Jackson (ETH, Zurich) on algorithm development has produced new strategies based on maximum entropy regularization for inverting modern observations for magnetic field models. The resulting geomagnetic models are sharper than those produced by more conventional quadratic regularization schemes, and the modeling strategy may also be useful for paleofield data.

Relevant Publications

Constable, C.G., 2007. Archeomagnetic and paleomagnetic studies of centennial to millennial-scale geomagnetic field variations . **In** "*Treatise on Geophysics, Geomagnetism Volume*", ed. M.Kono, Ed in Chief: G. Schubert, Elsevier, pp. 1.

Constable, S.C. & C.G. Constable, Observing geomagnetic induction in magnetic satellite measurements and associated implications for mantle conductivity, *Geochem. Geophys. Geosyst.*, 5(1), Q01006 doi: 10.1029/2003GC000634, 2004.

Jackson, A., C.G. Constable, M.R. Walker, & R.L. Parker, Models of Earth's main magnetic field incorporating flux and radial vorticity constraints, *Geophys. J. Int.*, , doi: 10.1111/j.1365-246X.2007.03526.x, 2007.

Jackson, A., C. G. Constable & N. Gillet, Maximum entropy regularization of the geomagnetic inverse problem, *Geophys. J. Int.*, , doi: 10.1111/j.1365-246X.2007.03530.x, 2007.

Johnson, C.L., C.G. Constable, L. Tauxe, R. Barendregt, L.L. Brown, R. Coe, P. Layer, V. Mejia, N.D. Opdyke, B. Singer, H. Staudigel, & D. Stone, 2007. Recent Investigations of the 0-5 Ma Geomagnetic Field recorded by Lava Flows. *Geochem. Geophys. Geosyst.*, in press.

Korte, M., and C.G. Constable, Centennial to millennial geomagnetic secular variation, *Geophys. J. Int.*, 167, 43–52, doi: 10.1111/j.1365-246X.2006.03088.x, 2006.

Korte, M., and C.G. Constable, Spatial and temporal resolution of millennial scale geomagnetic field models, *Advances in Space Research*, , doi:10.1016/j.asr.2007.03.094, 2007.

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

Steven Constable is the lead PI for the SIO Marine EM Laboratory, which currently consists of postdoctoral scholars Kerry Key and Yuguo Li, and PhD students Karen Weitemeyer, David Myer, and Brent Wheelock. As the name suggests, much of the lab's work is involved in developing and using marine EM methods, with financial support from the oil industry and (very) occasionally the NSF. Although Constable occasionally works on other subjects such as mantle conductivity, this year has been mostly dedicated to marine EM.

Work has been ongoing this year to interpret and publish magnetotelluric (MT) and marine controlled source EM (CSEM) results from the spreading ridge at the East Pacific Rise (Figure 1). Magnetotelluric data collected across the East Pacific Rise at 9°30'N reveals high mantle conductivity at 60–200 km depth. This implies that hydrogen (water) enhanced partial melting starts deeper than expected and reaches a maximum of 1-5% at 80 km. The mantle is devoid of melt above 30 km, and to the west of the ridge is unmolten to 60 km depth. A highly conductive region 30 km east of the axis and 40 km deep suggests melt ponding beneath a freezing horizon and episodic migration to the crust, supporting earlier evidence of off-axis melt supply and eruptions.

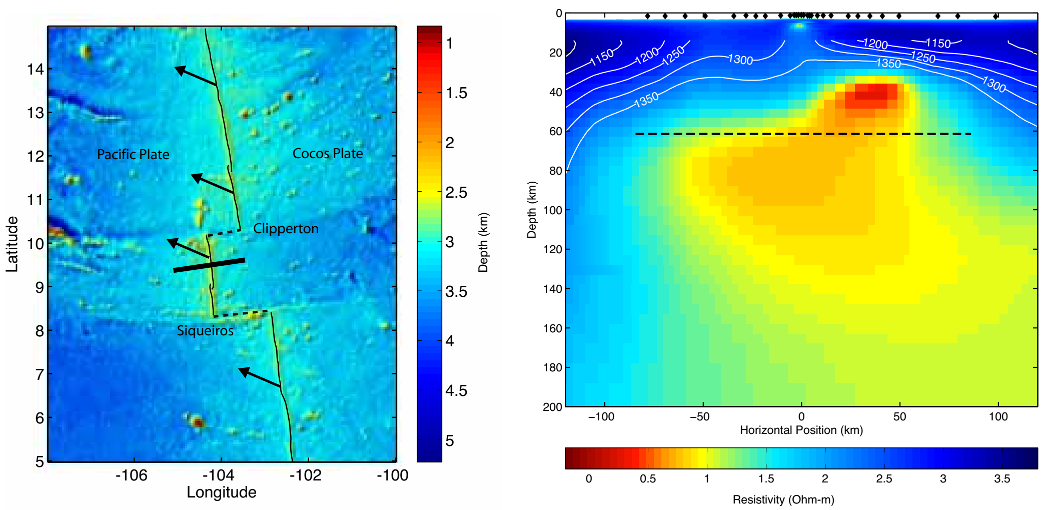

Figure 1. (left) Magnetotelluric survey location at 9°30'N on the East Pacific Rise (thick black line), where 39 MT receivers were deployed along a 200 km long transect. The spreading ridge axis (thin black line) is migrating to the northwest with respect to a fixed hotspot reference frame, shown as black arrows. (right) Inversion model from magnetotelluric data showing electrical resistivity (shaded colors) beneath the spreading ridge. Seafloor MT site locations are shown as black diamonds. Isotherms (white lines) were computed using SEO3, and new model of the thermal dependence of resistivity for subsolidus olivine. The dashed black line shows the dry peridotite solidus depth, which coincides with the bottom of the zone where water solubility is much greater in orthopyroxene than olivine.

As part of this work we needed to relate mantle conductivities to temperature. Several schemes based on empirically derived relationships to do this exist, but we derived a more versatile and reliable relationship, called SEO3, based on mathematical models of the mineral physics behind conduction.

We continue to carry out instrument tests in the San Diego Trough, this year in support of a planned experiment in the Gulf of Mexico to study gas hydrate. We tested a two-axis deployable transmitter and a 3-axis towed receiver system. The Gulf experiment was supposed to happen in July 2007, but has been postponed pending MMS permits. The instrumentation, however, is well tested and ready to go.

Figure 2. Instrument tests offshore San Diego.

The group was recognized by the Society of Exploration Geophysicists in a number of ways. Karen Weitemeyer and David Myer were both awarded SEG scholarships. Scripps was awarded the SEG's Distinguished Achievement Award for its role in commercializing marine CSEM, and an article which appeared in *The Leading Edge* last year attracted a honorable mention for best paper.

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

Relevant Publications

Constable, S., SEO3: A new model of olivine electrical conductivity, *Geophys. J. Int.*, 166, 435–437, 2006.

Constable, S., US Patent no. 7,116,108, *Method and system for seafloor geological survey using vertical electric field measurement*, 2006.

Constable, S., US Patent no. 7,109,717, *System and method for hydrocarbon reservoir monitoring using controlled-source electromagnetic fields*, 2006.

Constable, S., Conductivity, ocean floor measurements, in *Encyclopedia of Geomagnetism and Paleomagnetism*, edited by D. Gubbins and E. Herrero-Bervera, Springer, 71–73, 2007.

Constable, S., Induction from satellite data, in *Encyclopedia of Geomagnetism and Paleomagnetism*, edited by D. Gubbins and E. Herrero-Bervera, Springer, 413–416, 2007.

Medin, A.E., R.L. Parker, and S. Constable, Making sound inferences from geomagnetic sounding, *Phys. Earth Planet. Int.*, 160, 51–59, 2007.

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Li, Y., and K. Key, 2D marine controlled-source electromagnetic modeling: Part 1 – An adaptive finite-element algorithm, *Geophysics*, 72, WA51–WA62, 2007.

Li, Y., and S. Constable, 2D marine controlled-source electromagnetic modeling: Part 2 – The effect of bathymetry, *Geophysics*, 72, WA63–WA71, 2007.

J. Peter Davis

Specialist

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Research Interests: time series analysis, geophysical data acquisition

Among Peter Davis's responsibilities at IGPP is monitoring the scientific performance of Project IDA's portion of the Global Seismographic Network (GSN), a collection of 41 seismographic and geophysical data collection stations distributed among 25 countries worldwide. IDA's philosophy that data integrity may best be maintained by keeping network managers in close contact with data consumers has proven well-justified over the 30 years the project has existed. IGPP is the perfect venue for IDA personnel to interact directly with many scientists who use GSN data on a daily basis.

Peter Davis's recent work utilized tidal signals to evaluate the accuracy of instrument response information published by the GSN. Investigators use this information to remove from recorded data 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.

Key to this proposition is the ability to predict accurately the amplitude and phase of a tide at any point on the earth. Most of a tide's signal results from the direct gravitational pull of the moon or sun (well known from astronomy) and the elastic response of the earth to those forces (also well known from seismology and geodesy). Until recently, the third major contributing factor to tidal signals, the shift in mass of the oceans in response to the gravitational pull of the moon and sun, was poorly quantifiable. Using information collected by satellites, scientists can now model the tidal flow of water in the ocean basins. With programs provided by Duncan Agnew of IGPP, Peter 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 response and for examining behavior of the sensors over the period studied. Figure 1 shows results for station PFO, the GSN station locally operated by IGPP. As the IDA flagship station, this site serves as a testbed for all new generations of devices to be deployed throughout the network, so equipment turnover is particularly high here. Data segments varying from 60-180 days were used to compare the recorded tidal signal with what was expected from the modeling process. If the computations agreed, all points should have unity relative amplitude in this plot. For PFO, this ideal was approached from mid-2002 onward. In the first half of the decade, the results were close but slightly higher, then lower than what is desirable. Late in 2001, the published response information was highly inaccurate and will have to be corrected.

This same analysis was repeated for all GSN stations with some surprising results. One station's response was very stable over the entire decade but inaccurate by 40%. Another station's response changed suddenly even when no equipment change was noted in the station's history.

Each of these analyses can be used to track down instrumentation changes that apparently affected the recording system's sensitivity. As these key changes are uncovered, more accurate information for that time period can then be published.

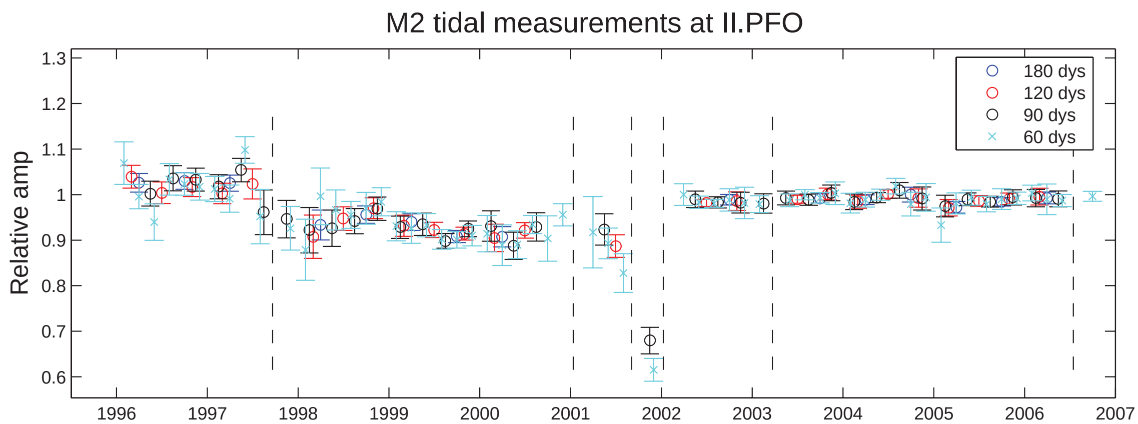

Figure 1: Measurements of the relative amplitude (ratio of observed to predicted amplitude) of the principal lunar tide M2 at GSN station PFO (Pinyon Flat, CA). Vertical dashed lines represent times when equipment was changed and a re-calibration procedure, performed.

Relevant Publications

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

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

Park, J., R. Butler, K. Anderson, J. Berger, H. Benz, P. Davis, C.R. Hutt, C.S. McCreery, T. Ahern, G. Ekström, and R. Aster, Performance review of the Global Seismographic Network for the Sumatra-Andaman megathrust earthquake, *Seis. Res. Lett.,* **76**, 331-343, 2005.

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

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

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Research Interests: Acoustic propagation modeling with application to infrasound and hydroacoustics; application of hydroacoustics and infrasound to nuclear test-ban verification; application of hydroacoustic signals to estimating rupture properties of sub-oceanic earthquakes.

Hydroacoustics: Catherine de Groot-Hedlin is co-PI with Donna Blackman on an investigation of how hydroacoustic energy propagates through the Antarctic Convergence Zone (ACZ), the site of a sharp discontinuity in acoustic velocity. Propagation of hydroacoustic energy through this region and to the south of it is of interest for the purpose of developing a worldwide nuclear test-ban monitoring system. The particular challenges of propagation through this region and to the south of it are that: a) the lateral sound speed gradients at the ACZ boundary causes deflection of hydroacoustic energy, causing errors in source locations estimates, and b) that propagation of hydroacoustic energy to the south of this region is surface limited, that is, energy is trapped between the ocean surface and sound speed gradients within the ocean. Surface limited energy can be significantly attenuated through scattering at a rough ocean surface.

A research cruise was conducted in the southeast Pacific Ocean in late December of 2006, In collaboration with Dr. Donna Blackman, where a number of SUS charges with sizes varying from 2 to 12lb were fired at depths from 300m to 600m, along a transit from Christchurch, New Zealand to McMurdo station in the Antarctic. This experiment was conducted in support of nuclear test-ban research, with the purpose of determining whether the lateral sound speed gradients at the ACZ boundary caused significant deflection of the energy. These shots were recorded at several hydroacoustic stations that form a part of the International Monitoring System (IMS) at distances of 5000 to 9000km from the source. Our results place lower limits on the amount of scattering caused by the rough ocean surface and upper limits on the errors in source location estimates in this area.

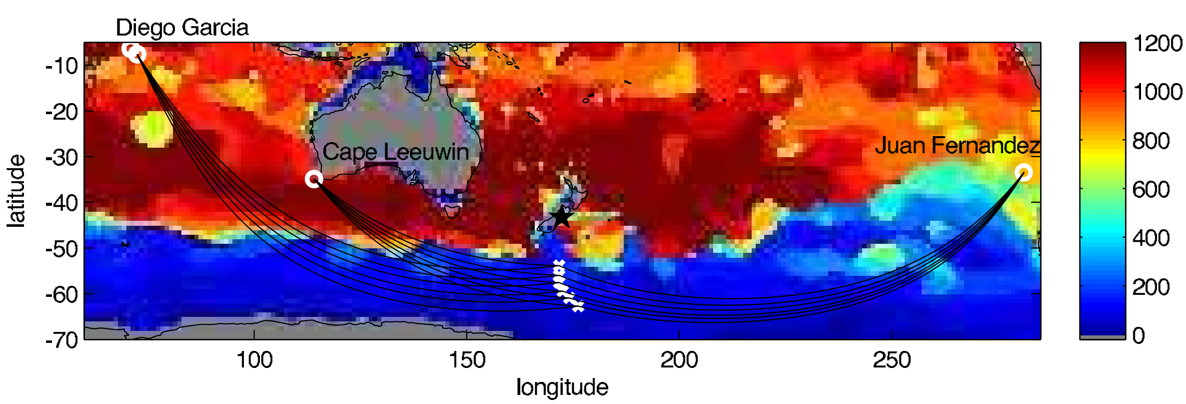

Figure 1: Shot locations (xes), IMS hydrophone station locations (circles), and geodesic paths from source to receiver, superimposed on a map of the depth at which the ocean sound speed is at a minimum. Note the sharp transition at approximately 50^{o}S, indicating the ACZ.

Infrasound: de Groot-Hedlin is the sole-PI on a project to develop numerical methods to compute infrasound propagation through realistic atmospheric conditions, for sources near or below Earth's surface. Coupling of sound at this interface is a complicated problem due to the large contrast in density and acoustic velocity at this boundary. She is also co-PI on another project to investigate infrasound propagation from various sources, with the aim of comparing predictions based on various numerical synthesis techniques to observations.

A primary goal in infrasound research is to accurately model the transmission of low frequency acoustic energy to distances of several hundreds to thousands of kilometers; a task complicated by the fact that propagation of this energy is highly dependent on winds and atmospheric temperatures, properties which vary spatially, as well as seasonally and diurnally. Unlike in seismology, in which the Earth's velocity structure is essentially time invariant and largely derived from travel times of seismic signals, our knowledge of Earth's acoustic properties comes largely from climatology. That is, atmospheric models used for infrasound propagation modeling are not derived from direct recordings of sound waves, so there are no assurances that these models will yield predictions that agree with the observations. There are few opportunities to test our atmospheric models using signals from sources for which we know exactly when and where the source occurred.

The recent re-entry of the space shuttle Atlantis over the heavily instrumented western United States provided an opportunity for such a test. Although the shuttle usually lands at the Kennedy Space Center (KSC) in Florida, severe weather in the vicinity of KSC on June 22, 2007 forced NASA to direct Atlantis (STS-117) to the alternate landing site at Edwards Air Force Base in the Mojave Desert in southern California. On its approach to Edwards, the shuttle passed just west of Baja California and then across San Diego and Los Angeles before passing below the sound barrier just above the Mojave Desert. The double sonic boom was heard by millions of people and, fortunately for this study, was recorded by over one hundred 3-component seismic stations in the USArray, various regional seismic networks and three infrasound stations in southern California and western Nevada. The temporary 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. Observations of infrasound arrivals in the region to the northwest of Los Angeles indicate the presence of a tropospheric duct in that region that traps the sound between the ground and sound speed gradients at an altitude of about 1km. This feature is not observed in atmospheric models, which are based on meteorology and climatology.

Relevant Publications

de Groot-Hedlin, C.D., "Estimation of the rupture length and velocity of the Great Sumatra earthquake of Dec 26, 2004 using hydroacoustic signals ", Geop. Res. Lett., **32**, L11303, doi:10.1029/2005GL022695 (2005).

de Groot-Hedlin, C.D., D.K. Blackman, and C.S. Jenkins, "Hydroacoustic Propagation through the Antarctic Convergence Zone: Study of Errrors in Yield and Location Estimates for Explosive Charges ", 29th Monitoring Research Review, **29**, Denver, Colorado (2007).

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Research interests: ocean acoustic tomography, signal processing

Travel-Time Sensitivity Kernel

Low-frequency sound can be used to monitor ocean temperatures and currents on scales that are important for understanding climate change. Ray theory has long been the model used when trying to reconcile ocean acoustic measurements with environmental parameters. Measured travel time changes are ascribed to sound-speed changes along the unperturbed ray path. Since sound is governed by the wave equation, the travel time can also be affected by environmental changes that are not on the geometric ray path.

An example of this are the non-geometric shadow zone arrivals recently measured in the NPAL 2004 experiment. A simulated example is shown in the top panel of Figure 1. The arrow points to an arrival at a receiver at 3500m depth which is below the turning point depth of the geometric ray arrival. Arrivals below the turning points are thought to be scattered by a combination of internal waves and ocean spiciness. Internal waves are vertical displacements of the oceans isopycnals (constant density surfaces) and spiciness is sound speed variation along those surfaces. The exact contributions of these processes to acoustic scattering has been a mystery.

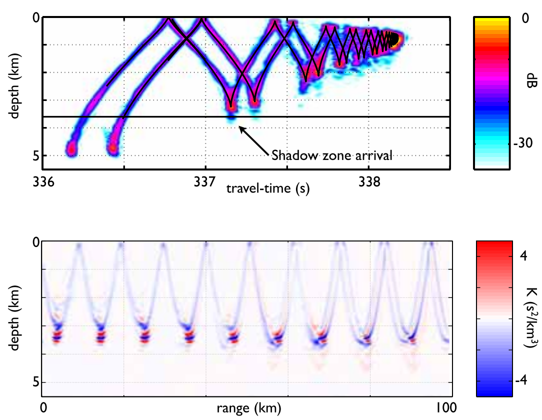

Figure 1: Shadow zone tsk.

In collaboration with Bruce Cornuelle, we have developed the full-wave acoustic sensitivity kernel for ocean sound propagation. The sensitivity kernel is a map in physical space of the change in the acoustic measurement for a given change in environmental parameters (the Frechet derivative). This could be calculated by brute force, but a mathematical formulation of the problem relying on the Born approximations and the principle of reciprocity allows a much simpler (although still challenging) computational problem. We have extended this work to include the effects of range dependence and can now calculate the kernel using the RAM parabolic equation code, in a much more realistic ocean environment.

An example of the result is shown in the bottom panel of Figure 1. It shows the sensitivity of travel-time measurements of a single arrival made by a receiver at 3500m depth and 500km range to a 75 Hz, Q=4, source at 750m depth. The geometrical ray path is also shown as a black line. The alternating blue and red colors show zones of negative and positive sensitivity with negative sensitivity along the ray path as expected. The width of first Fresnel zone is demarcated by first zero crossing from blue to red. There is clearly sensitivity which extends beyond the first Fresnel zone. Also there are a number of higher wavenumber features that have no ray path equivalent.

Horizontal coherence

Another example of the lack of agreement between theory and experiment is shown in Fig. 2. Here the horizontal coherence of a 75Hz acoustic arrival from a source 3500km distant is shown in black. It was measured by a set of 5 moorings transverse to the propagation path. The data is shown with error bars and two different fits are shown as line plots. Also shown in color are expected results from various models. The agreement is not very good and the discrepancy could be used in an inverse for ocean small scale structure, but work to date has shown that the inverses give an unreasonable structure. This calls into question the validity of the scattering models used. An alternate using the TSK described above is now being developed.

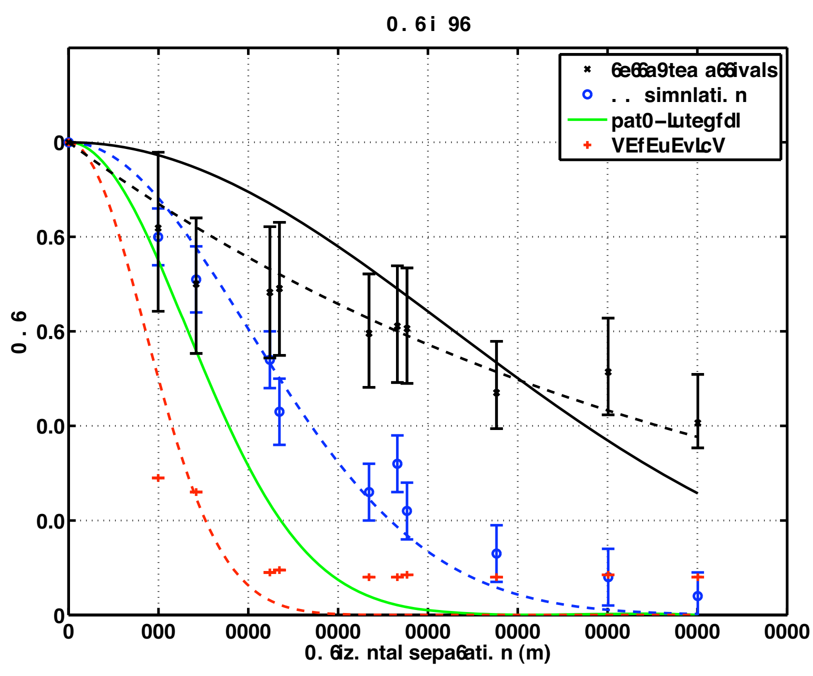

Figure 2: Horizontal coherence.

Recent publications:

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).

Peng Fang

Specialist

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Research Interests: High precision GNSS positioning and its applications to geodynamics and meteorology. Data processing and analysis automation.

Peng Fang is responsible for the operation of high precision GPS data processing and analysis in both regional and global scale in high volume. The results directly contribute to the International GNSS Service (IGS) in terms of precise satellite orbits, the Earth orientation parameters, and the global reference frame in positions and their velocities. Those fundamental geodetic quantities are of great importance to a wide range of scientific researches and practical applications. After more than a decade long valuable IGS service to the GPS community and related fields of sciences, the demand for high quality products is growing rapidly. To meet such a demand, IGS initiated an effort to re-analyze all historical data using the much improved physical models, conventions and processing strategy. In 2006, Peng Fang has been requested by the IGS governing board to take the responsibility for coordinating this effort. Currently the participating institutions include ESA, MIT, NGS, PDR (GFZ/Potsdam & Technical University of Dresden, Germany), and SIO. Along with greatly increased complexity of physical models, in both theoretical and imperial terms, involved in the data reduction, plus the shear volume of the data set, a sophisticated yet efficient data processing/analysis strategy and procedures have to be developed. Peng Fang played a crucial role in the development. His work in this regard also contributed to two related research publications, one deals with analyzing GPS error sources in terms of seasonal signals (Dong, et al., 2002), and one with time-spatial filtering using principal component analysis method (Dong, et al., 2006).

Peng Fang has developed a near realtime GPS precise orbit determination/prediction scheme, known as 'sliding widow' approach, together with a tropospheric delay estimation system for the GPS meteorology application. The former has been used for many meteorological and non-meteorological applications. The latter has been ported to quite few research institutions and government agencies worldwide. The most successful one is at the Earth System Research Laboratory (ESRL)/NOAA. Currently, this system injects the GPS derived moisture field, in a timely manner, to the operational numerical forecasting system in a NOAA facility in Boulder, directly contributing to the weather forecasting in the northern America, with significant positive impact. The related work is documented in the ESRL technical review (2005 GPS-MET Tech Review.) and its website (http://gpsmet.noaa.gov/jsp/index.jsp). Figure 1. shows an example of the 3h forecast of CAPE, 21 April, 2004, with and without GPS contribution.

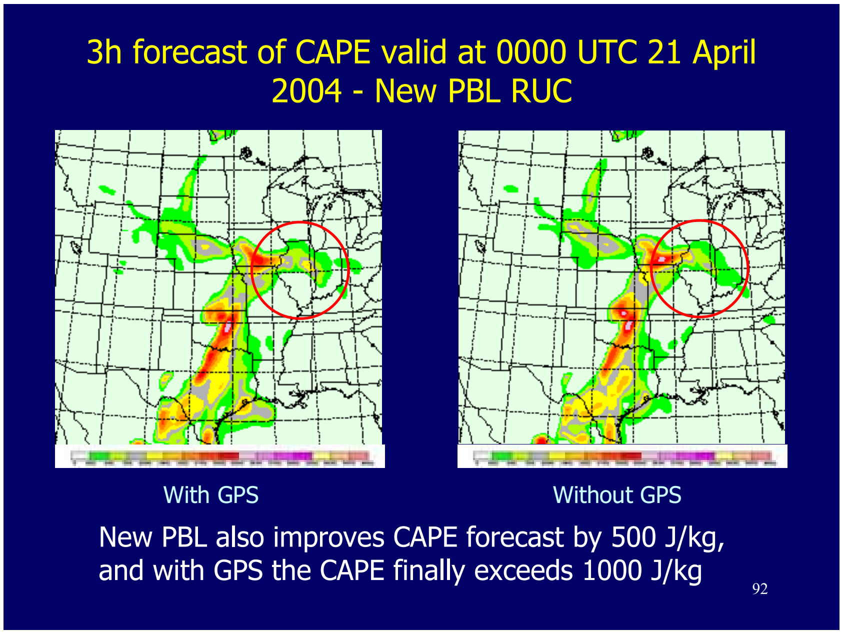

Figure 1. When weather forecasting system uses GPS derived integrated (total atmospheric column) precipitable water vapor distribution, spatial and intensity of moisture field is much better defined. (graphics provided by Tracy Lorraine Smith, ESRL/NOAA).

Due to long and extensive experiences and cross field knowledge in GPS data analysis and its applications, Peng Fang is constantly on requests to provide technical and scientific consultation or to provide GPS or GPS derived solutions directly for both internal and external GPS system users.

Relevant Publications:

Dong D., P. Fang, Y. Bock, M. K. Cheng, and S. Miyazaki, Anatomy of apparent seasonal variations from GPS-derived site position time series, J. Geophys. Res., 107 (B4), doi:10.1029/2001JB000573, 2002.

Dong D., P. Fang, Y. Bock, F. Webb, L. Prawirodirdjo, S. Kedar, P. Jamason, Spatiotemporal filtering using principal component analysis and Karhunen-Loeve expansion approaches for regional GPS network analysis, J. Geophys. Res., 111, B03405, doi:10.1029/2005JB003806, 2006.

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Research interests: earthquake physics, crustal deformation, space geodesy

Yuri Fialko's research involves studies of deformation due to the earthquake cycle, from the large-scale displacements due to major earthquakes, to the identification of mechanisms of postseismic relaxation, to detection and interpretation of subtle deformation in the interseismic period. Recent work includes investigation of damage zones around major crustal faults. Building on a previous discovery of massive compliant fault zones in the Mojave desert (eastern California), Hamiel and Fialko (2007) analyzed Interferometric Synthetic Aperture Radar (InSAR) images of the 1999 Izmit (Turkey) earthquake. The InSAR data reveal small-scale changes in the radar range across the nearby faults of the North Anatolian fault system (in particular, the Mudurnu Valley and Iznik faults). These anomalous range changes were found to be consistent with an elastic response of compliant fault zones to the stress perturbation induced by the Izmit earthquake. The spatial variations and mechanical properties of fault zones around the Mudurnu Valley and Iznik faults were further studied using three-dimensional finite element models. In these models, compliant fault zones having various geometries and elastic properties were introduced in the ambient crust. The best fitting models suggest that the inferred fault zones have a characteristic width of a few kilometers, depth in excess of 10 km, and reductions in the effective shear modulus of about a factor of 3 compared to the surrounding rocks. The characteristic width of the best fitting models is consistent with field observations along the North Anatolian Fault system. These results are also in agreement with InSAR observations of small-scale deformation on faults in the Eastern California Shear Zone in response to the 1992 Landers and 1999 Hector Mine earthquakes (Fialko et al., 2002; Fialko, 2004). The inferred compliant fault zones likely represent intense damage and may be quite commonly associated with large crustal faults.

Another project investigated the effect of a compliant fault zone on the coseismic slip distribution inferred from inversions of geodetic data. Barbot et al. (in press) developed a new theoretical model that allows one to calculate the fault-induced deformation in an elastic medium with arbitrarily varying material properties. The model employs integral transformations to reduce the governing partial differential equations to the integral Fredholm equation of the second kind. Dislocation sources, as well as spatial perturbations in the elastic properties are modeled using equivalent body forces. The solution to the Fredholm equation is obtained in the Fourier domain using a method of successive over-relaxation, and is mapped into the spatial domain using the inverse Fast Fourier Transform. This method has been applied to investigate the effect of a soft damage zone around an earthquake fault on the coseismic10 displacement field, and on the earthquake slip distribution inferred from inversions of geodetic data. In the presence of a kilometer-wide damage zone with the reduction of the effective shear modulus of a factor of 2, inversions that assume a laterally homogeneous model tend to underestimate the amount of slip in the middle of the seismogenic layer by as much as 20%.

Prof. Fialko and his students also studied deformation due to the M7.3 Altai earthquake that occurred on the Russia-China in 2003 (Barbot et al, 2007b). Analysis of postseismic deformation over 3 years following the earthquake demonstrated that most of the observed signal can be explained by a shallow fault slip (including aftershocks and aseismic creep). Surprisingly, the space geodetic data showed that there's been relatively little, if any, poroelastic deformation due to migration of pore fluids at depth. The data also rule out a robust viscoelastic relaxation in the lower crust. These findings indicate that the postseismic response following major crustal earthquakes may not be readily predictable, and likely involves multiple mechanisms.

Recent publications:

Hamiel, Y., and Y. Fialko, Structure and mechanical properties of faults in the North Anatolian Fault system from InSAR observations of coseismic deformation due to the 1999 Izmit (Turkey) earthquake, J. Geophys Res., 112, B07412, doi:10.1029/2006JB004777, 2007.

Barbot, S., Y. Hamiel, and Y. Fialko, Space geodetic investigation of the co- and post-seismic deformation due to the 2003 Mw 7.1 Altai earthquake: Implications for the local lithospheric rheology, J. Geophys Res. (in press).

Barbot, S., Y. Fialko, and D. Sandwell, Effect of a Compliant Fault Zone on the Inferred Earthquake Slip Distribution, J. Geophys Res. (in press).

Fialko, Y., Fracture and frictional mechanics - Theory, *Treatise of Geophysics*, vol.4, Earthquake Seismology, Edt. G. Schubert (in press).

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

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

Antarctic subglacial water: Helen's most significant contribution in 2006-07 was the discovery of active subglacial water systems under the fast-flowing ice streams of Antarctica. She 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. The region where signals were first found was the Mercer and Whillans ice streams (former Ice Streams B and C) in West Antarctica (Figure 1).

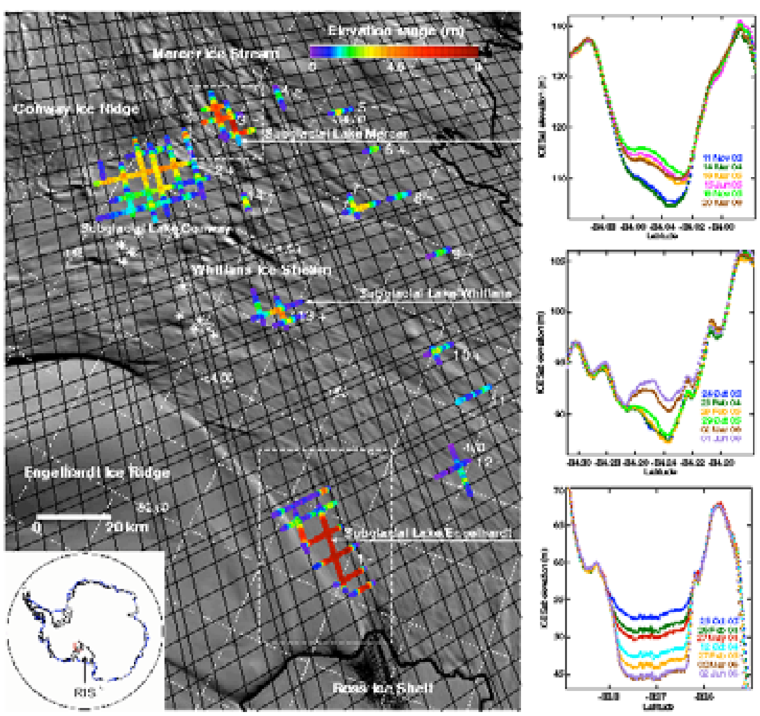

Figure 1. Left panel: Locations of elevation change events identified through repeat-track analysis of ICESat data. Straight black lines show the reference ground tracks and colored track segments show range in elevation amplitude for each elevation change event. Events cluster into 14 elevation change regions which are either rising (+), falling (-) or oscillating (~). Ice flow is from top left toward lower right. Background is MODIS Mosaic of Antarctica and inset map shows its location. Bold black line is the break-in-slope associated with the grounding zone of the Ross Ice Shelf. Right panels: ICESat elevation profiles across examples of each type of region (+, -, ~).

This was not the first time that subglacial water transport was observed under Antarctica – just 6 months earlier some UK researchers had used ERS radar altimetry to detect one flooding event in East Antarctica. However these lakes were not under ice streams therefore had no direct implication for ice stream dynamics. Once the water gets under the ice streams, it lubricates the base and the ice should flow faster. The fact that water moves so rapidly in such large volumes implies that ice stream dynamics can change rapidly also, which affects how fast the ice flows from the continent. 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. The ICESat results were supported by a new image differencing technique developed by Ted Scambos at the National Snow and Ice Data Center in Boulder, CO. The results were documented in a 5-page Research Article in *Science* and received a great deal of media attention.

Ice shelf grounding zones: In 2006-07, Helen has also used ICESat data to map the grounding zones of the ice shelves - the dynamically-active transition zones between grounded and floating ice. Grounding zones (GZ) 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 the GZ is therefore an important part of ice sheet change detection, the primary objective of the ICESat mission. Her analysis of data from repeated tracks, sampled at different phases of the ocean tide, has shown that ICESat can "see" the tide-forced flexure zone between fully grounded continental ice and fully floating ice shelf ice, identifying the landward and seaward limits of ice flexure, providing accurate GZ location and width information for each track. Helen and her group have used this new technique to map the GZ for large parts of the ice sheet. This, combined with surface elevation at the grounding lines will contribute to improved calculations of the ice sheet's mass balance.

Ice shelf rifting: In 2006-07 Helen managed two successful field seasons on the Amery Ice Shelf (2005-06 and 2006-07) to study ice shelf rift propagation. These were the final 2 years of a 4-year field program during which GPS and seismic instruments have been integrated to monitor rift activity on Amery Ice Shelf, East Antarctica. These measurements have shown that rift propagation is episodic and occurs in discrete events separated by approximately 2 weeks.

Relevant Publications 2006-07

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The rifting of continental lithosphere and the transition to seafloor spreading is a long standing problem in Earth science and has been the subject of numerous theoretical and observational studies of the years. However, complete profiles had not been collected across the conjugate margins of young rifted basins. Complete profiles are critical because complexities on one margin cannot be explained away by assigning missing features to the unexplored conjugate margin (e.g. "Upper plate paradox" *Driscoll & Karner*, 1998). Exploring young rifts is important because the style of rifting as well as segment-to-segment changes in extension can be linked more confidently back to conditions in the lithosphere and mantle at the initiation of rifting.

The Gulf of California is a young, highly-oblique rifted continental margin with large variations in rifting style from south to north. The southern segments of the Gulf, which includes the Alarcón Basin have organized seafloor spreading but are sediment starved. The central and northern segments of the Gulf starting at the Guaymas segment, are buried under thick sediments from the Colorado river, while the northernmost segments such at the Wagner and Delfin basins exhibit diffuse extension. The Farallon subduction zones on the western margin of Baja California began to falter around 15 Ma and ceased completely by 12 Ma, initiating the capture of the Baja peninsula by the Pacific plate. In the conventional tectonic history of the Gulf of California, the rifting clock begins at 12 Ma with major strike-slip motion on the Tosco-Abreojos fault in the Pacific margin of the Baja peninsula and slow E-W extension within the proto-gulf (*Oskin & Stock*, 2003). However, there are records of marine excursions within the gulf as early as 14 Ma, some extension may occurred soon after the subduction zones began to falter. The majority of Pacific-North American relative plate motion is known to have switched into the Gulf no later than 6 Ma.

With funding from the NSF MARGINS program, the PESCADOR experiment collected three complete seismic profiles across the Gulf of California, one across the Guaymas Basin, one across the Alarcón Basin, and a third across the mouth of the Gulf from the Cabo block on the southern tip of Baja to just south of Puerto Vallarta. The aim of the experiment was to investigate the origin of the different rifting styles within the Gulf of California. The seismic dataset for each profile was comprised of multi-channel seismic reflection data and refraction data recorded by ocean bottom seismographs (OBSs) and land stations. This large, coordinated land and marine two-ship experiment was a cooperative venture involving principal investigators from Georgia Tech, Scripps Institution of Oceanography, University of Wyoming, CICESE, UCLA, and Northern Arizona University.

The Alarcón Profile

Investigators from IGPP at Scripps took the lead on the analysis of the data from the Alarcón profile, a 881-km-long profile that started just south of Loreto in Baja California, cross the Alarcón spreading center and finished on the mainland in the Trans-Mexican Volcanic Belt just south of Tepic, Figure 1. The submarine portion of the profile is approximately 750 km long, of which only 135 km is oceanic crust formed at the Alarcón Rise and the rest is extended continental crust.

A total of 64 instruments along the Alarcón profile successfully recored refraction arrivals from densely spaced air gun shots produced by the *R/V Ewing* over the interval between 167 & 767 km along profile. This shooting program excluded the shallowest waters closest to shore on either side of the gulf. MCS reflection data was recorded over the same 600-km-long interval.

Crustal Extension in the Alarcon Basin: Tomography Data

Approximately 45,000 Pg, PmP, and Pn travel time arrivals from the Alarcon profile were inverted initially using the method of *Zelt and Smith* (1982), and the resulting model was refined using the to-

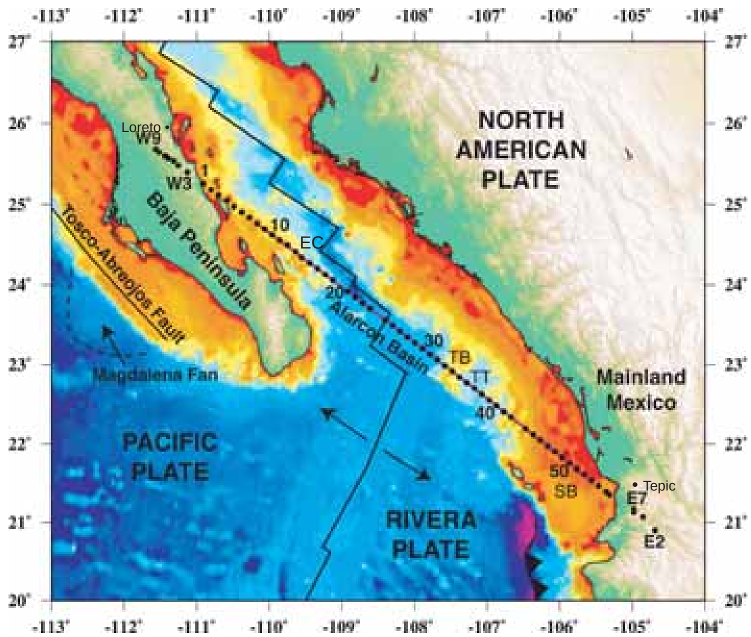

Figure 1: Map of the southern Gulf of California showing the Alarcón transect. Instruments 1-56 are ocean bottom seismographs with 2 Hz vertical seismometers: W9-W3 & E7-2 are IRIS-PASSCAL instruments. TB- Tamayo Bank, TT - Tamayo Trough, SB - San Blas Basin, EC - East Cerralvo Basin.

mography methods of *Van Avendonk et al*. (2004). Data quality for instruments in the center of the profile was generally excellent with Pn arrivals often being detectable to beyond 60 km, although maximum offsets were severely reduced in the shallow waters of the San Blas basin due to the presence of strong water multiples.

The velocity model for the Alarcon profile, Figure 2, shows a general tapering of the extended continental crust on both margins but is also notable for very thin extended crust beneath the Tamayo Trough, a thick keel beneath the Tamayo Bank, and distinct steps in the Moho topography beneath the Baja margin. Tomographic inversions starting from a range of Moho structures reproduced essentially the same Moho structure over the interval with reversed refraction coverage, indicating that the preserved Moho structure is required by the data. The preservation of Moho structure indicates that the lower crust/upper mantle is cold as there has not been significant lower crustal flow since the creation of the structures.

Another notable feature of the model is the general absence of high seismic velocities within the extended continental crust that would indicate underplating or intrusion of significant volumes of mafic material. A more detailed tomographic inversion, Figure 3, of the central, oceanic, part of the profile and extending over both continent-ocean transitions reveals evidence for a minor mafic intrusion and corresponding magnetic signal beneath the Tamayo Trough , and more significant underplating beneath the rifted western edge of the Tamayo Bank. The magnetic anomalies suggest that an initial spreading center may have been established immediately to the west of the Tamayo Bank before jumping to its present location at the Alarcon Rise. A reconstructed crustal section, Figure 3 lower, suggest that prior to final rifting extension was nearly symmetric about the Tamayo Bank with large, extended basins on either side. Then rifting and dike intrusion, coupled with positive thermal feedback happened to select the Alarcon Basin as the locus of final breakup of the Alarcon segment, which transitioned, relatively quickly, to producing normal thickness oceanic crust, perhaps aided by northwards propagation of more fertile Pacific asthenosphere (Lizarralde et al, 2007). The rift-to-drift transition in the Alarcon is relatively simple: the continental ocean transitions on either side of the oceanic crust are narrow, no more than 30-60 km wide.

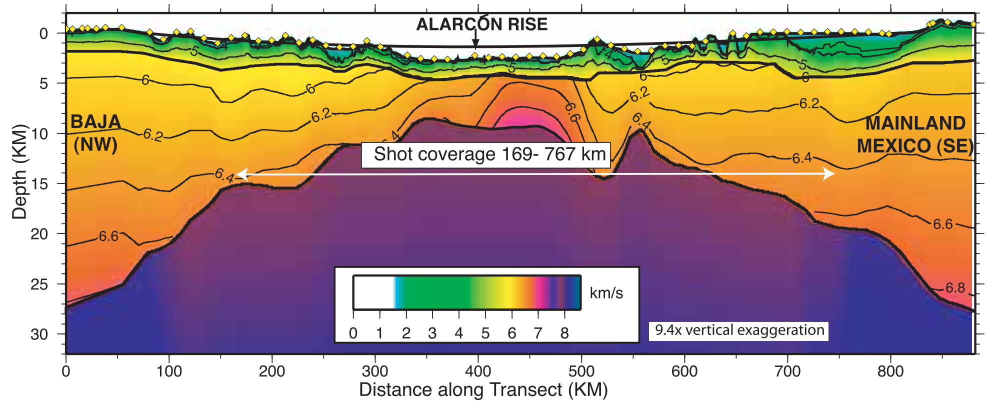

Figure 2 Velocity model of the Alarcón transect based on forward modeling.

The extension of the Alarcon transect was accomplished primarily through pure shear of the entire crust. Up until final rifting, the extension was nearly symmetric about the Tamayo Bank, which formed an unextended keystone at the center. Total crustal extension can be estimated for the Alarcón profile, assuming that present day crustal thicknesses at the profile ends are representative of the average unextended crust. Extension on the Baja margin is 135-150 km, while on the Mainland margin it is 175-210 km. The slight asymmetry in the extension between margins can be attributed to partitioning of the

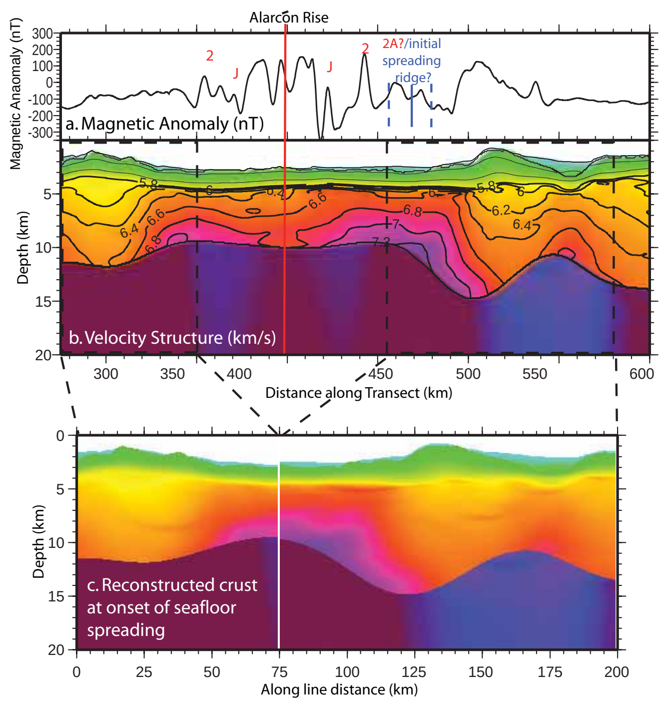

Figure 3: Comparison of magnetic anomaly (top) and central part of the tomography velocity model (middle) allowing identification of the oceanic crust formed at the Alarcón Rise and a reconstruction of the crustal structure prior to the start of seafloor spreading (bottom). Seafloor spreading began no later than 2.5 Ma. There is evidence of minor mafic intrusions beneath the Tamayo Trough but of much more extensive intrusions to the west of the Tamayo Bank associated with breakup.

Tamayo Bank to the mainland side. When the 135 km of oceanic crust is included, the total extension along transect is 445-495 km.

Timing of Rifting: MCS Reflection Data

Constraints on the history of extension was obtained from seismic stratigraphic analysis of sediment deposits within the major basins. In many basins only small-offset basement faults are visible, and a master or bounding fault responsible for the formation of the basin is absent. Summing all the fault offsets visible in the MCS profiles yields total extensions of 28 km and 52 km for, respectively, the Baja and Mainland margins. Even allowing for the underestimation of extension from MCS images, this is much smaller than the whole crustal extension estimated from refraction profile. However, if all the space occupied by the major basins is assumed to have been created by upper crustal extension then the results are in much closer agreement with the whole crustal estimate.

The absence of visible major bounding faults in some basins can be explained by the presence of basement covering, non-sedimentary layer along much of the profile. In many basins, a discontinuous reflective sequence can be identified beneath the sedimentary layers. Investigation of the velocity structure of this sequence using refraction arrivals recorded at longer offsets by the MCS data, resolves a distinct 250-500 m thick layer at the top of the basement with relatively low velocities of 2.5-2.8 km/s. These velocities would be consistent with a volcanic ash or tuff layer that post-date basin formation, mantling the basement and obscuring the original faulting. Although there are a number of possible origins for this layer, the most likely source is the Comondú formation which erupted between 20-11 Ma and forms 1-2 km thick sequences on Baja California. If this is the case, then major basins within the Alarcón profile would have formed before 11 Ma, the end of the Commondú eruptions.

Another bound on the basin age can be obtained from the thickness of the sedimentary deposits and estimated sedimentation rates. The deeper basins such as the East Cerralvo, Tamayo Trough and San Blas have estimated ages of 10-14+ Ma, while the smaller basins are 4-7.5 Ma. Taken together, these estimates indicate that the locus of major extension switched between basins as extension progressed prior to final breakup at and establishment of seafloor spreading no later than 2.5 Ma, Figure 3.

The estimated ages of the basins along the Alarcon profile point to major oblique extension beginning in the southern Gulf of California much earlier than generally believed, perhaps as early as 14 Ma when the first marine incursions were recorded. The transfer of the majority of Pacific-North American plate motion into the Gulf could not have been delayed until as late as 6 Ma, as the Pacific-North American rates have held nearly constant at around 48 mm/yr: the 445-495 km of total extension of estimated for the Alarcon profile would require at least 9-10 Ma. If extension began as early as 14 Ma, this would require 200 km of dextral slip on the Tosco-Abreojos fault system, less than usually assumed but more in line with recent estimates of offsets the Magdalena fan (*Fletcher et al,* 2007), Figure 7. The estimated total extension across the Alarcon of 495 km is in accord with a recent reconstruction of plate motions within the western America (*Wilson et al*, 2005).

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Sutherland, F. H., A. J. Harding, G. M. Kent, D. Lizarralde, P. J. Umhoefer, J. M. Fletcher, G. J. Axen, N. W. Driscoll, W. S. Holbrook, A. Gonzalez-Fernandez, P. Lonsdale, Seismic crustal structure across conjugate margins in the southern Gulf of California, to be submitted to *J. Geophys. Res.*, 2007.

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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.

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

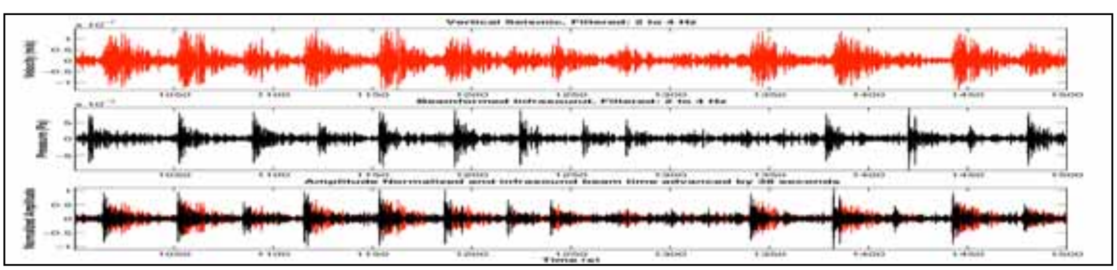

Figure 1: Seismic and infrasound signals from Mt St Helens are shown in the upper two traces. The two records are plotted together (bottom) after advancing the infrasound record 38 seconds to account for the propagation delay. The infrasound and seismic signals clearly have a common source within the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

Rocket experiments: Controlled sources (i.e. well known in terms of yield, 3-D location and time) can be used to study the propagation of infrasound through our turbulent atmosphere. Over the past two years we have collaborated with a number of other institutions across the United States to detonate 50-pound charges of high explosives at altitudes ranging up to 50 km. Such small charges detonated at high altitudes disturb a large volume of air, due to low confining pressure, and generate infrasound waves. We are presently modeling recordings of these explosions to improve our ability to locate infrasonic sources, and to study atmospheric structure.

Miscellaneous studies: 1) Bolides: The global infrasound network will be used to collect statistics on large meteors entering our atmosphere. We believe that this direct measure of the influx of meteors will provide the raw data for developing statistics on the largest meteors – the ones that might devastate large regions on impact. This field is in its infancy as we are just building the global network. These impulsive events are also useful for studying atmospheric structure. We are currently analyzing signals from a large bolide that exploded ~ 30 km above Seattle. **2) Ocean noise**: Using data from our permanent array in the Anza-Borrego desert we detect surf noise from along the coast of California. Infrasonic waves from the crashing surf propagate through the stratosphere to our station approx. 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 study ocean storms remotely, and can be used to probe atmospheric structure**. 3) Mine Blasts**: Our group is studying infrasound and seismic signals from mine blasts in Russia and the US to learn more about the physics of these sources and how waveform data can be used to discriminate these events from earthquakes and nuclear tests.

Field operations: Our group has built two permanent infrasound arrays in the US and has just completed a third in Africa. In the past year we deployed infrasound arrays across the southwestern US to record signals from high-altitude explosions. We currently operate two arrays near Mount Saint Helens. A typical temporary array comprises 4 aneroid microbarometers spanning an area 100 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 G4 and G5 computers. All data from the field is archived on a 1.3 TB RAID. All computers, and supporting peripherals such as printers, are linked via a broadband communications network.

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Continuing in the area noted in 2006, I have been implementing the programming required to solve a certain problem in "upper bound" theory, by which means one will obtain rigorous bounds for turbulent flows. The focus in this work is on a classic problem known as "plane Couette flow" (in honor of the French rheologist Maurice Couette), which is perhaps the simplest imaginable flow, albeit not so easy to realize in the laboratory. Fluid is confined between parallel plates and these are then slid in opposite directions (in practice one can hold one plate stationary and move the second only). Fluid near either plate moves at nearly the velocity of that plate while fluid near the interior reaches some value midway between the two extremes.

Historically this flow has been the subject of an enormous literature because it proves to have a seemingly paradoxical character. While laboratory realizations of such flow give rise to turbulence once the plates exceed some critical velocity, the equation derived from the first theory of how turbulence would arise (the so-called Orr-Sommerfeld equation) predicts the flow will never be turbulent. Only quite recently with the development of certain ideas through the mid 1980s and later have we come to a more nuanced understanding of the origins of turbulence, and one can say that at least the problem of explaining the general basis for transition is in fairly good shape. Understanding subsequent behavior as the turbulence becomes more intense remains, as with nearly all other turbulent flows, much less well understood.

While upper bound theory has been turned to this end in the past, the results to date, though rigorous, have been disappointingly far from observation. And so while we can say with mathematical certainty that the dissipation of the turbulent flow must surely be less than a predicted value, the true answer, though indeed less, is very very much less. The hope is that by adding more physics to the bounding problem, this bound can be brought into close proximity of experiment. In so doing, one would then also have a better sense of the amplitude controlling processes that are critical in shear flow turbulence quite generally (even though the model problem is the idealized case of plane Couette flow).

The calculation is sufficiently elaborate and the numerical formulation nonstandard that several more months will be required before some first numbers emerge. In the meantime, beginning last January, I turned some attention to a new project on modeling the geomagnetic field, prompted by the interest of Dr. Philip Livermore in coming to IGPP to work with Professor Cathy Constable and me as a postdoctoral fellow. Happily, a proposal to NSF for his support has been funded and he has joined us as of this past August. Dr. Livermore came prepared with a very interesting problem to use observational data of the Earth's field in conjunction with a well known dynamical constraint in order to find bounds not dissimilar from those noted above. In this case the bound, if sufficiently tight, may be able to tell us which among competing theories of the early thermal history of the Earth is correct (or which is at least not incorrect). A byproduct of this study will be a fully three-dimensional magnetic field which, it is hoped, will be representative of that part of the Earth's magnetic field which remains forever hidden from direct observation, the "toroidal field".

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Catherine Johnson's research (http://igpphome.ucsd.edu/~cljohnson/) focuses on the internal structure and evolution of terrestrial (silicate rock) planetary bodies. On the Earth, her interests are mainly in understanding the behavior of the Earth's magnetic field over the past few million years. This involves developing models to explain records of paleointensity and paleodirection of the magnetic field. Over the past year, her non-Earth research has been focused in 3 main areas: understanding where, when and why deep moonquakes occur, and understanding the magnetic field histories of Mars and the Moon. Catherine has been involved in several planetary missions, including the Magellan mission to Venus (1989-1994) and the Mars Global Surveyor mission (1999-present). Two of the current lunar studies are described below.

Deep Moonquakes: During the 1960s and early 1970s, seismometers were installed at five of the six Apollo landing sites. At four of these sites, the seismometers successfully recorded data, spanning the period 1969-1977. Approximately 12,000 events were recorded, the majority of which are moonquakes that occur at great depths: between 700 and 1200 km depth. During the Apollo era, it was recognized that these deep quakes occur with monthly (tidal) periodicities; however detailed studies of these events were not possible due to computational limitations. Current computing power means that it is now possible to store and analyze the complete Apollo seismic waveform data set.

Together with PhD student Renee Bulow (see http://mahi.ucsd.edu/rbulow/RESEARCH/) Catherine has been working on several aspects of deep moonquakes. The first study takes advantage of the observation that deep moonquakes appear to originate from a few specific source regions, and that events from a given source region have repeatable waveforms. By implementing a new technique in which waveforms for a known source region are stacked and then and cross-correlated with the entire continuous time series it has been possible to identify 503 previous undiscovered quakes (a 36% increase) at 8 of the largest near-side source regions.

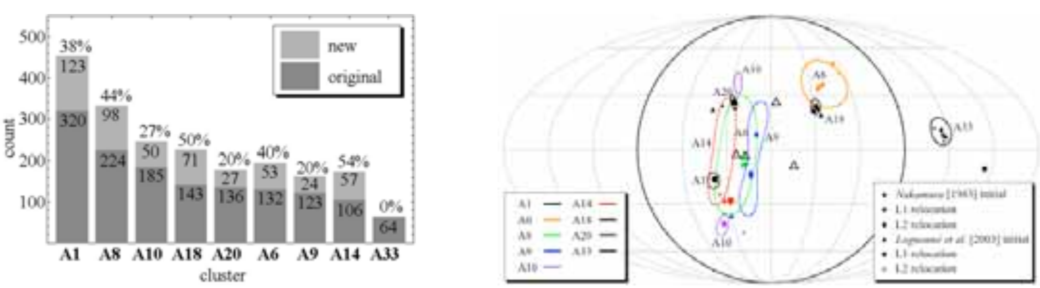

Figure 1: Left – number of deep moonquakes in each of the 8 largest near side clusters, and the one known far side cluster. The dark gray boxes indicate the number of quakes known previously, and light gray boxes indicate the number of new moonquakes identified. Right – locations of the deep moonquake source regions. The grid intervals are 30° in latitude and longitude, the center of the map is the center of the near side of the Moon. The different colors represent different source regions: symbols are different estimates of the source location, and the colored lines are the 95% confidence interval on one of the location estimates. The four open triangles denote the locations of seismic stations at Apollo landing sites 12, 14, 15 and 16.

The new data set of deep moonquakes has enabled investigation of the locations and temporal characteristics of these seismic events (the "where" and "when"), which have in turn permitted modeling their cause (the "why"). Uncertainties in source region locations are critical to understand because they trade off with estimates for internal seismic velocity structure (which in turn reflects the thermal and compositional structure of the lunar interior). Spectral analyses of the occurrence times of deep moonquakes in the new data set show not only the 1-monthly tidal periodicity, but are able to distinguish distinct forcing periods at 27.21 and 27.55 days.

The underlying cause of deep moonquakes is still not well understood. A large part of Renee's thesis has been the development of models for tidally driven elastic stresses in the moon, and examination of these stresses at the times and locations of deep moonquakes.

Magnetic Field History of the Moon: Samples returned from the Apollo missions showed a surprising result: rocks with approximate ages in the 3.9 – 3.6 Ga range have high paleointensities, suggesting that they acquired a magnetization in global lunar magnetic field. A second record of crustal magnetization on the Moon comes from magnetic field measurements made in orbit by the Lunar Prospector satellite. These data show weak magnetic fields over a few regions. Several difficulties present themselves in understanding the Moon's magnetic field history. The first is the quality of existing paleointensity measurements – almost all were performed in the 1970s using now inferior laboratory methods. The second challenge is reconciling the sample-based record with the satellite-based observations. The third is in postulating a plausible thermal evolution scenario for the Moon that allows a dynamo in the 3.9 – 3.6 Gyr period. PhD student Kristin Lawrence (http://titan.ucsd.edu/~klawrence/) and Catherine are attempting some new paleointensity measurements on several Apollo samples. In addition, Kristin is assessing the satellite and rock magnetic records and examining lunar magnetic field histories consistent with both types of data.

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This past year, we undertook two separate seismic CHIRP surveys located at Fallen Leaf Lake (Tahoe basin) and the Salton Sea to study recent ruptures along the West Tahoe fault and San Andreas fault/Brawley Seismic Zone, respectively. In this annual report, however, for brevity, we will only highlight some of our research on tectonic deformation in the Salton Trough. The Salton Trough is a critical structure that separates spreading center dominated deformation in the Gulf of California and dextral strike-slip deformation along the San Andreas Fault System (SAF). To date, however, a critical portion of this tectonic system remains poorly understood, in large part, due to a lack of geophysical subsurface data in the Salton Sea. We (Daniel Brothers, Neal Driscoll, Graham Kent, Jeff Babcock, Alistair Harding) acquired > 350 line-km of CHIRP data in spring 2007 to define the fault architecture in the Salton Sea. For the first time, we have documented NE-SW oriented compression in the Salton Sea as evidenced by ramp-flat thrusting across the Extra Cross Fault Zone (ECFZ) with southward vergence (Figure 1).

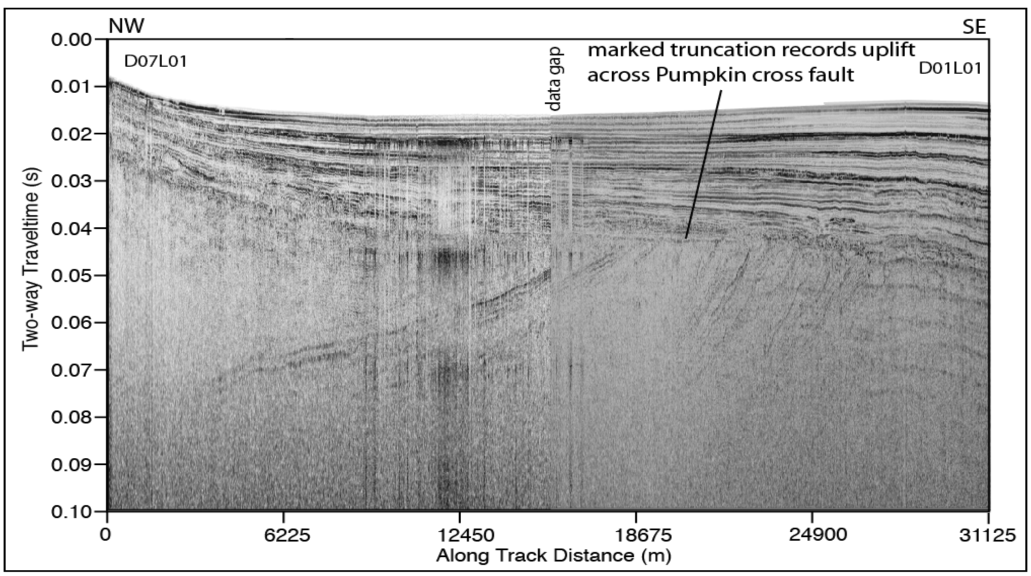

Figure 1. *CHIRP profile offshore Durmid Hill imaging a pronounced angular unconformity beneath the modern Lake Cahuilla sediments that we interpret to record uplift along the Extra Fault. The deformation exhibits a ramp – flat geometry with an upthrown northern block.*

North of ECFZ at Bombay Beach the SAF steps to the west engendering transpression along the cross faults in this portion of the dextral-slip system. To the south, the Brawley Seismic Zone (BSZ) connects the SAF and the Imperial Fault (IF) across a ~15 km releasing step that causes transtension across the cross faults. En echelon normal faults are observed along the western edge of the BSZ (Figure 2). Based on the orientation of the en echelon normal faults, it appears they accommodate transtensional strain via the right-step between the SAF and the IF.

Our group (Jeffrey Dingler, Neal Driscoll, Graham Kent) also have acquired new terrestrial laser scanner data from Mecca Hills, California to constrain fault offset and paleoearthquake magnitude for the southern San Andreas Fault (SAF). The sixteen scanner-derived drainage offset measurements revealed four distinct offset peaks at 1.35, 5.10, 7.17, and 7.79 m. Based on our interpretation, the first peak at 1.35 m records aseismic creep since the most recent event (MRE). If correct, then the remaining 3.75 m interval between the first and second peak records coseismic slip during the ~1676 MRE.

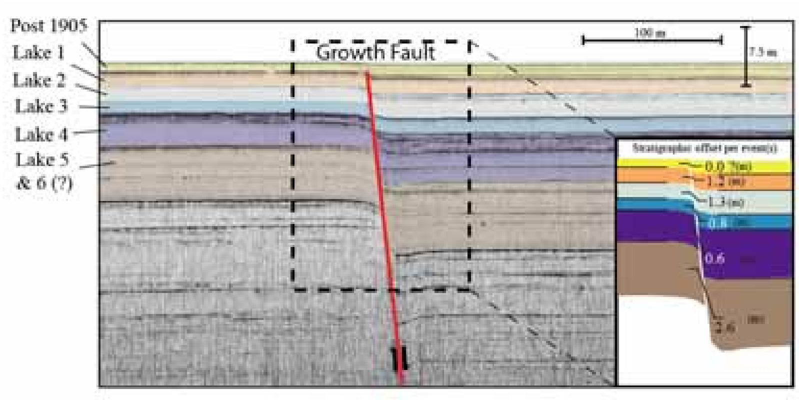

Figure 2. CHIRP profile crossing a down-to-the-east normal fault in the BSZ. Note the growth along the fault with offsets diminishing upsection. Slip appears to occur abruptly with a characteristic offset (~1 m) associated with each earthquake. Preferential filling east of the fault reflects the creation of coseismic accommodation.

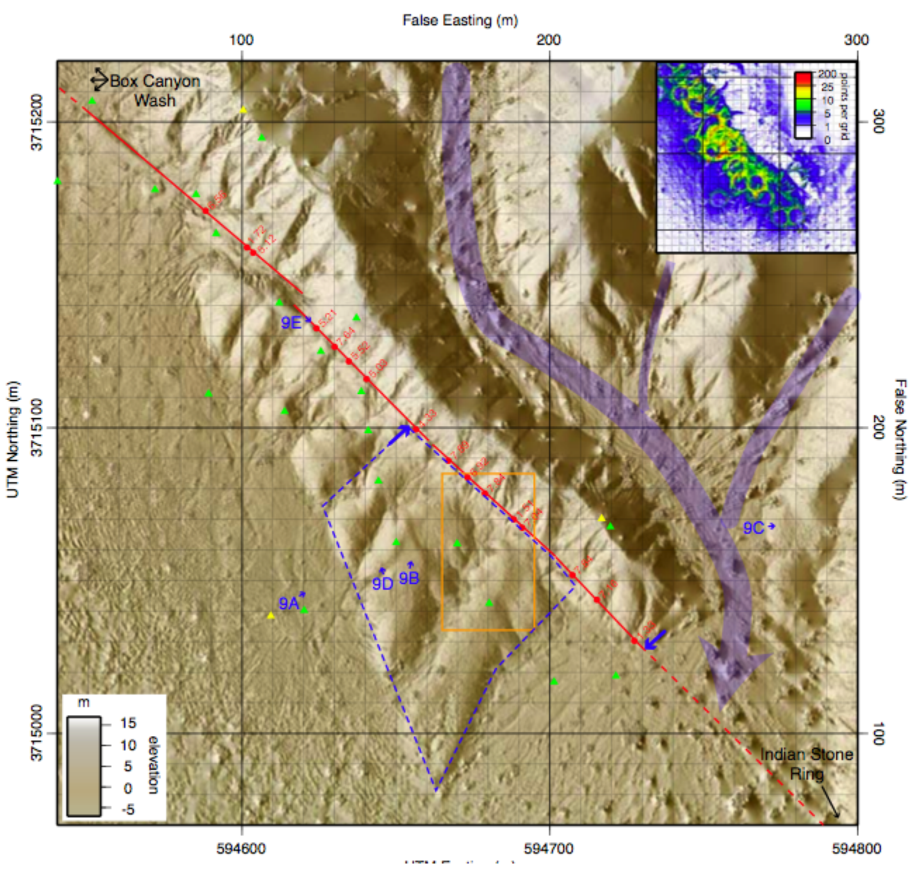

Figure 3. 2007 Lidar survey of the Mecca Hills. Red lines show location of the San Andreas Fault with offset of gullies across the fault labeled.

If a relationship exists between quiescence period and rupture magnitude as purported by the slip-predictable earthquake model, then the ~3.75 m of coseismic offset for the MRE, together with the long modern ~325 yr a quiescent period that is ~50% longer than the average recurrence interval, implies a future rupture that would exhibit 5.3 – 7.0 m of coseismic slip at the surface or a greater displacement of 6.9 – 8.4 m at depth.

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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. To investigate these topics, Kilb uses statistical and visualization tools, which help examine the spatial and temporal behavior of earthquakes, properties of an earthquake's seismograms and spectra, as well as issues of catalog completeness and uncertainties.

The Temporal Lag Between a Mainshock and the First Aftershocks: Aftershocks are often obscured by the large decaying amplitude of the mainshock's seismic waves (coda), making it difficult to identify early aftershocks. Working with IGPP's Drs. Vernon and Martynov, Kilb examined the temporal lag between the mainshock and the first aftershocks in the Anza 2001, southern California, sequence (Figure 1). The results show that the size of the magnitude differential between a mainshock and its largest aftershock is likely dictated by a combination of factors that include the mainshock energy release, directivity of rupture, and complexity of the fault system, in addition to the elapsed time from the previous large earthquake in the region (Kilb *et al.,* 2007).

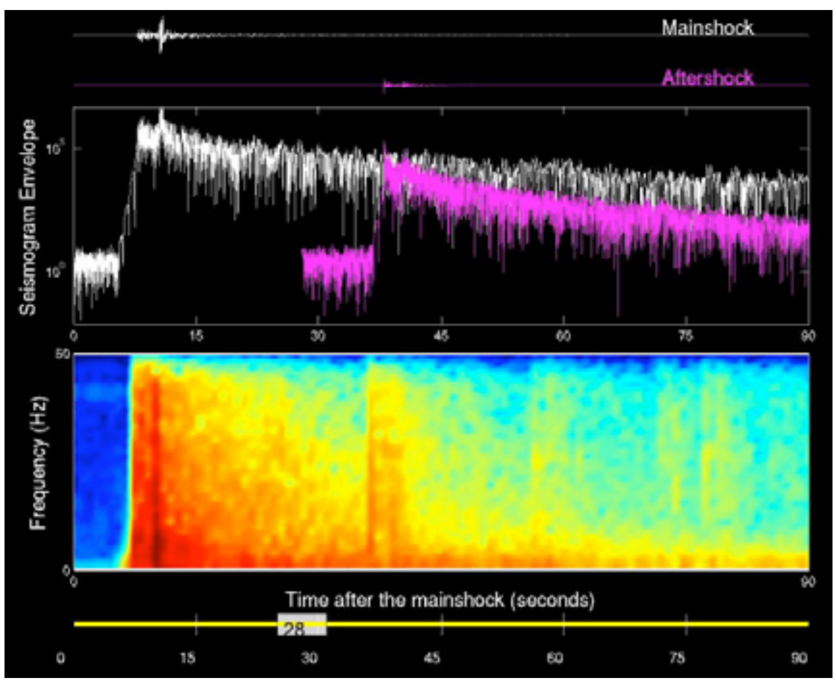

Figure 1. To quantify when early aftershocks are identifiable within the mainshock coda, we linearly add seismograms from a magnitude 3.2 earthquake to the continuous waveform data of the Anza 2001 sequence. We interactively reduce the lag time between the two events and assess when the magnitude 3.2 earthquake is no longer visible within the mainshock coda. An example of a 28 second lag is shown for: seismograms (top), seismogram envelopes (middle) and spectrograms (bottom).

Quantifying the Remote Triggering Capabilities of Large Teleseismic Earthquakes: Kilb and graduate student Deborah Kane are establishing new techniques to quantify the remote triggering capabilities of large teleseismic earthquakes. They search the ANZA network catalog for evidence of remote triggering, using three statistical tests (Binomial, Wilcoxon Rank-sum, and Kolmogorov-Smirnov) to determine the significance of quantity and timing of earthquakes in southern California before and after large teleseismic events. They find minimal differences between the spectral amplitudes and maximum ground velocities of the local triggering and non-triggering earthquakes. Similar analysis of remote earthquakes shows that the related ground motion regularly exceeds that of local earthquakes, both at low frequencies and in maximum velocity. This evidence weakly suggests that triggering requires larger amplitudes at high frequencies and that a maximum ground velocity alone is not the primary factor in remote triggering. Our results are complex, suggesting that a triggering threshold, if it exists, may depend on several factors. (Kane *et al.,* in press 2007).

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

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

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

Relevant Publications

Kane, D.L., D. Kilb, A. S. Berg & V. G. Martynov, "Quantifying the Remote Triggering Capabilities of Large Earthquakes Using Data From The ANZA Seismic Network Catalog (Southern California)", *J. Geophys. Res.*, (In Press, 2007).

Kilb, D., V. G. Martynov, & F. L. Vernon, "Aftershock Detection Thresholds as a Function of Time: Results from the ANZA Seismic Network following the 31 October 2001 *M*L 5.1 Anza, California, Earthquake," *Bull. Seism. Soc. Am.*, 97780–97792, doi: 10.1785/0120060116, 2007.

Kilb, D. & J.L. Hardebeck, "Fault Parameter Constraints Using Relocated Earthquakes: A Validation of First Motion Focal Mechanism Data," *Bull. Seism. Soc. Am.*, 96, 1140-1158, doi: 10.1785/0120040239, 2006.

Jiracek, G.R., V. M. Gonzalez, T. G. Caldwell, P. E. Wannamaker, & D. Kilb**,** "Seismogenic, Electrically Conductive, and Fluid Zones at Continental Plate Boundaries in New Zealand, Himalaya, and California-USA", *AGU Geodynamics Monograph*, (In Press, 2007).

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

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Research interests: seismic surface waves and global seismology; regional-scale seismology; tomographic imaging and geodynamical implications; global propagation of ocean noise; natural disasters and global change

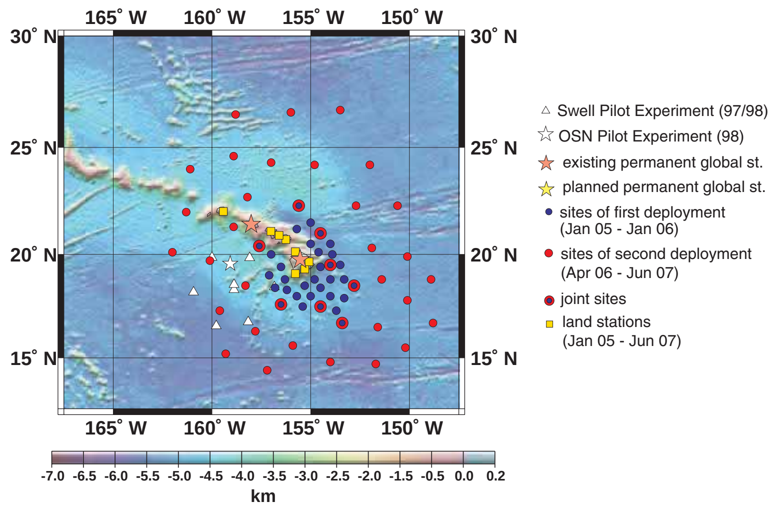
Gabi Laske's main research area is the analysis of seismic surface waves, on global and regional scales.

Free oscillations, global and regional tomography: Free oscillation parameters provide invaluable constraints on Earth's internal structure that remain elusive to other seismic techniques. The great Sumatra–Andaman earthquake allows the measurement of these parameters to unprecedented precision. Some aspects are of this event are discussed by Park and co-workers. Laske and colleagues continue to refine the free oscillation database that will define the new REM (Reference Earth Model).
Laske has maintained a collaboration with Princeton colleagues Ying Zhou and Tony Dahlen to apply and test their finite–frequency formulation (the surface wave equivalent of the Princeton Banana–Doughnut approach) on Laske's global surface wave dataset. The group took into acount the often ignored fact that phase measurements "at fixed frequency" are actually measurements smoothed over a narrow frequency band. While the wavelength of long–period surface waves is probably too long to resolve plume heads, the new research can reliably distinguish between mantle structure beneath fast and slow spreading centers. Laske has been involved in the DESERT project (Dead Sea Rift Transect) to image crustal and mantle structure beneath the Araba Valley south of the Dead Sea. An intriguing aspect of this research is to find the cause for the uplift of the Arabian Plateau east of the Dead Sea Transform Fault. Thermo-mechanical modeling suggests that a plume responsible for the Red Sea rifting could have eroded the Arabian lithosphere though Laske's surface wave study does not appear to support this idea. All other seismic component of this project were either equivocal or inadequate to address this issue.

The PLUME project: Laske is the lead-PI of the multi–institutional, multi–disciplinary Hawaiian **PLUME** project (Plume–Lithosphere–Undersea–Melt Experiment) to study the plumbing system of the Hawaiian hotspot (Figure 1). The project aims to address fundamental issues such as the geographical location of the plume head and conduit and whether or not the plume originates in the lower mantle. So far, little is known about the seismic structure beneath Hawaii due mainly to the fact that the nearly linear alignment of the Hawaiian islands has not allowed seismologists to obtain complete and unbiased images. The PLUME project is driven by seismology and 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 broad–band OBS array which is augmented by a 10–station land array. Occupying a total of over 80 sites and having an aperture of over 1000km, this experiment is one of the largest in the world. It is one of the first large-scale, long-term broad–band OSB deployments.

PLUME is a two–phase project in which two deployments gathered teleseismic events between January 2005 and June 2007. An initial 35–station array with small station spacing and aperture focussed on the island of Hawaii, where the plume head is assumed to be located. A second, wider 38-instrument array reached into the lower mantle and gathered off-swell reference data for the undisturbed Pacific Ocean. While the first deployment was

Figure 1: Deployment plan of the two-stage PLUME experiment. The first deployment was occupied from January 2005 through January 2006. Also shown are existing and planned permanent stations of the global seismic network. The SWELL pilot array collected data on differential pressure sensors between April 1997 and May 1998.



very successful, with an instrument recovery rate of 91%, the second deployment saw a loss of 26% of its instruments, and rescue missions with a submersible are underway. The first deployment collected a a large number earthquakes providing excellent azimuthal coverage. During the summer of 2007, the SIO group has pre-conditioned an extensive long–period surface wave dataset that reveals a clear trend from high seismic velocities to the south-east of the island of Hawaii to slow velocities on the western side of the island chain between Hawaii and Maui. Laske also reanalyzed the data from the 97/98 SWELL pilot experiment that covered an area to the southwest. The study shows conclusively that the Hawaiian lithosphere has undergone a rejuvenation process though the idea of mechanical erosion appears inconsistent with the data.

Recent publications:

Park, J., Song, T.A., Tromp, J., Okal, E., Stein, S., Roult, G., Clevede, E., Laske, G., Kanamori, H., Davis, P., Berger, J., Braitenberg, C., Vam Camp, M., Lei, X., Sun, H., Xu, H. and Rosat, S. Earth's Free Oscillations Excited by the 26 December 2004 Sumatra-Andaman Earthquake, *Science*, 308, 1139-1144, 2005.

Laske, G. and Widmer–Schnidrig, R., Normal Modes & Surface Wave Measurements, *Treatise of Geophysics*, vol.1, Seismology and Structure of the Earth, Ed. B. Romanowicz and A.M. Dziewonski, 2007.

Zhou, Y., Nolet, G., Dahlen, and Laske, G., Global upper–mantle structure from finite–frequency surface–wave tomography, *J. Geophys. J. Res.*, 111, B04304, doi:10.1029/2005JB003677, 2006.

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., (in revision 2007).

Laske, G., The Hawaiian SWELL Pilot Experiment – Evidence for Lithosphere Rejuvenation from Ocean Bottom Surface Wave Data, *GSA Special Paper 430* , doi: 10.1130/2007.2430(11), 2007.

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OBSIP - We are operating the Scripps' Institutional Instrument Center for the NSF Ocean Bottom Seismograph Instrument Pool (OBSIP; http://obsip.ucsd.edu). The other major facility is at Woods Hole and Lamont Doherty Earth Observatory has recently re-joined the OBSIP. The purpose of OBSIP is to serve the entire US marine seismology community by providing instrumentation and expertise in collection of marine seismic data through the standard NSF proposal process. In addition, we have built substantial amounts of identical instruments for initiating similar programs in the United Kingdom (National Oceanography Centre, Southampton) and France (Institut de physique du globe de Paris).

Figure 1: IGPP LC2000 trapped in large, recent lava flow at 9°N on the East Pacific Rise. Several OBSs were lost in the flow and were unrecoverable.

Negotiations are underway with Spain to develop a similar system for use in that country. John Orcutt is the OBSIP PI and Jeff Babcock is the Executive Director. The instrumentation available is extensive.

The current fleet, when recently funded construction is complete, will comprise approximately 55 short period units and 35 long period (or broadband) instruments. The broadband units make use of new 250s natural period Nanometrics accelerometers for recording low frequency and broadband data. These instruments have been used recently in the Hawaii Plume experiment (see the Laske article in this report), the East Pacific Rise at 9°N, the Gulf of California, offshore Oregon, the equatorial East Pacific Rise, Lake Tahoe, Taiwan, and several test trips for instrument testing offshore San Diego. In the spring of 2006, only eight of twelve deployed instruments could be recovered from the East Pacific Rise at 9°N after a year's deployment. Through tows in the area and subsequent visits by the Woods Hole TowCam, photographs determined unambiguously that the four units had been trapped in basalts from a major eruption during the deployment year (see Figure 1).

Cyberinfrastructure – HiSeasNet (http://hiseasnet.ucsd.edu) is a satellite communications network operated by Jon Berger and John Orcutt at IGPP, which is designed to provide continuous Internet connectivity for oceanographic research ships and platforms. Access to the Internet is an integral part of nearly every research lab and office on land; extending this access to oceanographic ships – our seagoing laboratories – broadly impacts seagoing research activities. Scientists have been going to sea in ships now for approximately 250 years. While the nature of ships has changed during that period of time making oceanographic research at sea increasingly productive, future changes in ship design will have only incremental impacts on the field. On the other hand, tools including the use of the global positioning system (GPS) with accuracies at sea now on the order of one meter and the extension of the Internet to sea are highly *disruptive* technologies that change the way oceanography is conducted. In September, Scripps added the 14th ship in the US academic fleet to HiSeasNet comprising all the largest ships as well as most of the intermediate ships. The system relies upon C-Band and Ku-Band antennae located on the roof of UCSD's San Diego Supercomputer Center. Real-time position and photographs from the R/V Roger Revelle can be viewed at http://mercali.ucsd.edu/rtapps/rtimbank.php?camera=SIO_Revelle_Axis2 .

The NSF Ocean Observatories Initiative (OOI) comprises three types of interconnected observatories spanning global, regional and coastal scales. The global component addresses planetary-scale problems via a network of moored buoys linked to shore via satellite. A regional cable observatory will wire a single region in the Northeast Pacific Ocean with a high speed optical and power grid. The coastal component of the OOI will expand existing coastal observing assets, providing extended opportunities to characterize the effects of high frequency forcing on the coastal environment. The OOI Cyberinfrastructure (CI) constitutes the integrating element that links and binds the three types of marine observatories and associated sensors into a coherent system-of-systems (http://ooici.ucsd.edu/).

John Orcutt is the Project Director for the CI component of the OOI and Frank Vernon serves as Deputy Project Director. Matt Arrott, at Calit2, is the CI Program Manager. The Coastal and Global Scale Nodes are a collaboration with Woods Hole (lead) and Oregon State University. John Orcutt is a member of a three-member Leadership Team, Jon Berger is the Engineer for the Extended Depth Platform (EDP; see Figure 2), and Carolyn Keen is the Deputy Project

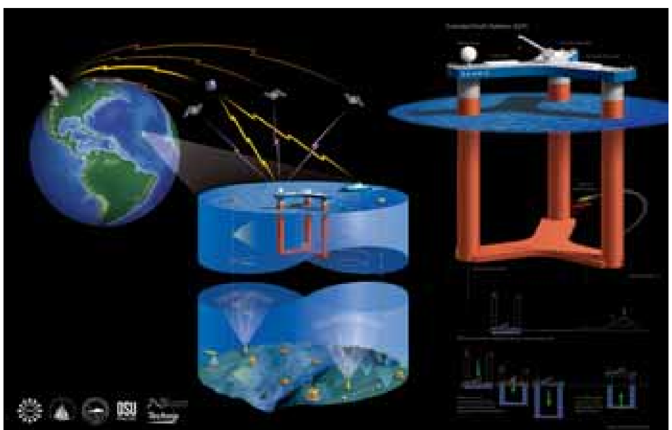

Figure 2: IGPP/Technip Extended Depth Platform shown deployed in the Mid-Atlantic.

Manager with responsibility for the program at Scripps. The Ocean Observatories Initiative is funded for $331M for a period of six years.

The EDP is a collaboration between a large French company, Technip, with offices in Paris and Houston and Scripps/IGPP. The EDP is a large platform (approximately 31m between tips of the triangular deck in Figure 2) that can be towed to site and erected entirely while at sea. The system will provide a nominal 500W to instruments on the seafloor and in the water column while using HiSeasNet to transmit at least 64kbps to shore (several Mbps are possible). The instrumentation includes a broadband borehole seismometer, an acoustic source for thermometry, 2-3 meteorological stations, atmospheric LIDAR, high-frequency acoustic imaging of ocean waves and turbulence to a kilometer from the EDP, 3-D platform motion from GPS and accelerometers, upward and downward looking acoustic Doppler current profilers (ADCP) and ocean profilers throughout the water column.

Observatories in the ocean represent a major change in the way oceanography will be conducted in the future. It's possible to think of Earth as a Connected Planet:

- Beginning of an epoch - **Instrumented Earth**
- A globally accessible **Continuous Signal**
- Representing the **Now State** of the Earth System
- Informing our understanding of its - **Past, Present and Predicted Future**
- Signal scales exponentially for the foreseeable future - **Quantity, Resolution, Coverage and Utility**

The core capabilities and the principal objectives of ocean observatories are collecting real-time data, analyzing data and modeling the ocean on multiple scales, and enabling adaptive experimentation within the ocean. A traditional data-centric CI, in which a central data management system ingests data and serves them to users on a query basis, is not sufficient to accomplish the range of tasks ocean scientists will engage in when the OOI is implemented. Instead, a highly distributed set of capabilities are required that allow:

- end-to-end data preservation and access
- end-to-end, human-to-machine and machine-to-machine control of how data are collected and analyzed
- direct, closed loop interaction of models with the data acquisition process,
- virtual collaborations created on demand to drive data-model coupling and share ocean observatory resources (e.g. instruments, networks, computing, storage and workflows),
- end-to-end preservation of the ocean observatory process and its outcomes, and
- automation of the planning and prosecution of observational programs

This future model of continuous streams of data compared to the extraction of files from a data archive changes enormously how scientists will work with data and the associated networks or resources.

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Research Interests: Inverse theory, geomagnetism, spectral analysis, electromagnetic sounding

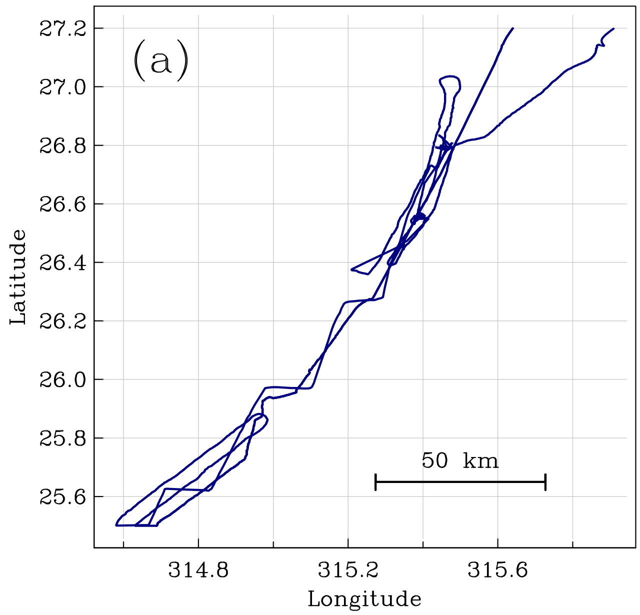
Bob Parker has worked in a number of his research areas during the 2007 academic year, including the inverse theory of geomagnetic sounding with his student Ashley Medin and Steven Constable, work partially described in the 2006 Annual Report. We completed the study and obtained for the first time firm bounds derived from geomagnetic time series on the average conductivities in three regions: the upper mantle, the transition zone, and the top of the lower mantle. Our results (published in *PEPI*) preclude the presence of significant amounts of water in the transition zone conjectured in the geodynamics literature. Work on the two-dimensional extension of the inversion technology continues.

Another broad topic occupying Parker this year with several specific applications is estimation of power spectra from time series, or spatial profiles. Modern methods of spectral estimation are based on the *multitaper method* introduced in 1982 by David Thomson, now at Queens University. The basic idea is that many independent estimates are computed from the record by applying a set of orthogonal weight functions (called tapers), finding the periodogram, and performing a weighted average. In the now classic approach devised by Thomson the tapers are computed to minimize broad-band bias, which is the tendency for power from strong peaks to spread into neighboring frequency intervals of lower power; this undesirable tendency is called ''spectral leakage.'' To achieve maximum suppression of random variability, the multitaper must average the true spectrum over a designated frequency interval, introducing a second form of bias which flattens out the strong peaks. Parker worked with student German Prieto, and colleagues David Thomson and Frank Vernon to study this issue. We have found that by estimating the covariance matrix of the multitaper spectra it is possible to calculate two derivatives of the spectrum with respect to frequency, and in this way estimate the true curvature of the spectrum which is normally lost during the standard averaging procedure. Thus the peaks can be recovered, and the true spectrum more faithfully rendered. This work is described in a paper accepted for publication in the *Geophysical Journal International*.

The multitaper method is a form of nonparametric estimation, intended for situations in which no simple equations known to describe the shape of the power spectrum. Sometimes, however, a simple mathematical expression works very well. Such a situation arises in a study underway by Professor David Sandwell and his student Joseph Becker who are making maps of seafloor roughness down to the one-kilometer scale based on ship tracks. In some areas where the coverage is very dense one discovers that the power spectrum of long straight profiles of bathymetry is quite accurately described by the equation

$$P(k_x) = \frac{b}{(1 + k_x^2/k_0^2)^{\mu - \frac{1}{2}}}$$

where the three constants b, k_0 and μ depend on the region; here k_x is the along-track wavenumber, or reciprocal wavelength. Mixing of the ocean waters by tidal motions is strongly influenced by the bottom roughness, and a global assessment of this effect is currently impossible because of sparse coverage of the ocean bathymetry. Sandwell and Becker aim to fill this gap, but to do so they must rely in many places on a few scattered ship tracks on which to base an estimate of $P(k_x)$; see Figure 1a. We need not only values for the three unknowns in the equation, but some estimate of the accompanying uncertainties in the estimates, and for these purposes the nonparametric approach is not optimal. Parker has shown



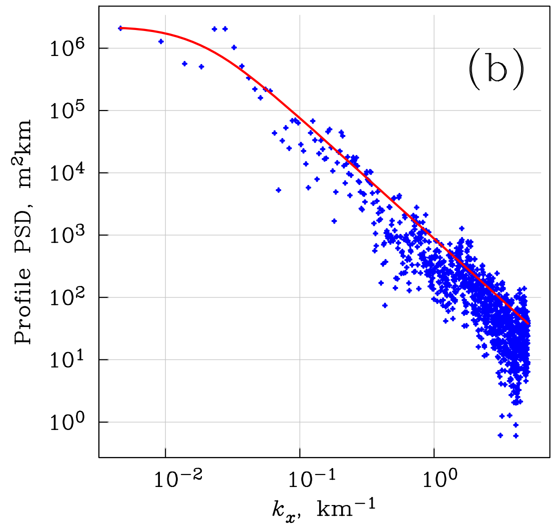
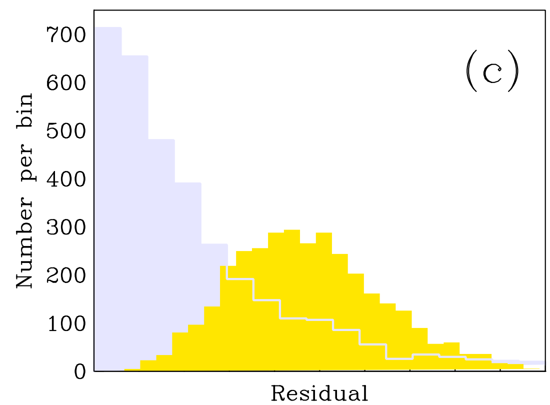


Figure 1: (a) Ship tracks available for analysis in a 175-km square in the Pacific; (b) The unsmoothed power spectrum and best-fitting parametric model spectrum; (c) Blue: histogram of residuals; yellow: histogram after stretching.



that to obtain reliable values with uncertainties it is better not to calculate a smooth spectrum as a starting point. Instead, we form estimates at many frequencies with large individual variances as in Figure 1b, and let the functional form of P to do the smoothing. The parameters in the equation are found by a nonlinear least-squares fit, but the distribution function of the residuals is far from Gaussian, causing bias. To remedy that defect, the spectrum (and the model) are subjected to cube-root stretching before fitting: this mapping transforms the usual chi-squared error distribution into an excellent approximation of the normal distribution; see Figure 1c. Other problems we have dealt with include combine short-wavelength estimates from many short pieces of track, and calculating the distortions caused by track curvature. With these various ideas we are able to obtain reliable seafloor spectral parameters in almost every one degree square of the oceans.

Relevant Publications

Medin, A., Parker, R., and Constable, S., Making sound inferences from geomagnetic sounding, *Phys. Earth & Planet. Int.*, v 160, 51-9, doi:10.1016/j.pepi.2006.09.001, 2007.

Prieto, G. A., Parker, R. L., Thomson, D. J., and Vernon, F. L., The Quadratic multitaper spectrum, *Geophys. J. Internat.*, accepted, June, 2007.

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Research Interests: Geodynamics, global bathymetry, crustal motion modeling

During the 2007 academic year, Dave Sandwell's research was focused on solid Earth Geophysics with an emphasis on understanding the dynamics of the crust and lithosphere. Most of his research funding is for improving global bathymetric maps by combining dense satellite altimetry measurements of the ocean surface topography (geoid height) with sparse ship soundings. These practical activities "pay bills" but more important they provide improved data for understanding geodynamics processes in the oceanic lithosphere. Graduate students J.J. Becker, Karen Luttrell, and Meng Wei as well as Post Doc. Bridget Smith-Konter, perform most of the research and are therefore first author on most of the publications.

Radar Interferometry - After one year in orbit, the L-Band synthetic aperture radar interferometer aboard the Japanese ALOS spacecraft is performing beautifully and is providing global interferometric crustal motion measurements (Figure 1). Dave Sandwell, David Myer, Yuri Fialko, and Meng Wei are using radar corner reflectors deployed at Pinon flat observatory to calibrate the radar measurements. Graduate student David Myer is working with David Sandwell and the Geodesy group at the University of Hawaii to measure vector crustal deformation at the Kilauea volcano on Hawaii (Myer et al., 2007).

Global Bathymetry - David Sandwell and Water Smith (NOAA - Silver Spring Maryland) continued their collaboration on retracking the raw radar altimeter waveforms from ERS-1 and Geosat to further improve the accuracy and resolution of the global marine gravity field (*Sandwell and Smith*, 2005). In addition they continue to advocate a new altimeter mission with a 5-fold improvement in accuracy (*Sandwell et al.,* 2006). J.J. Becker has designed a program for editing the 40-year archive of ship soundings and has used the edited data 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*, 2007). This research helps to resolve the issue of, where and how, deep-ocean mixing occurs.

Crustal Motion Modeling - Bridget Konter-Smith 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 measurements (*Smith and Sandwell*, 2006). 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.

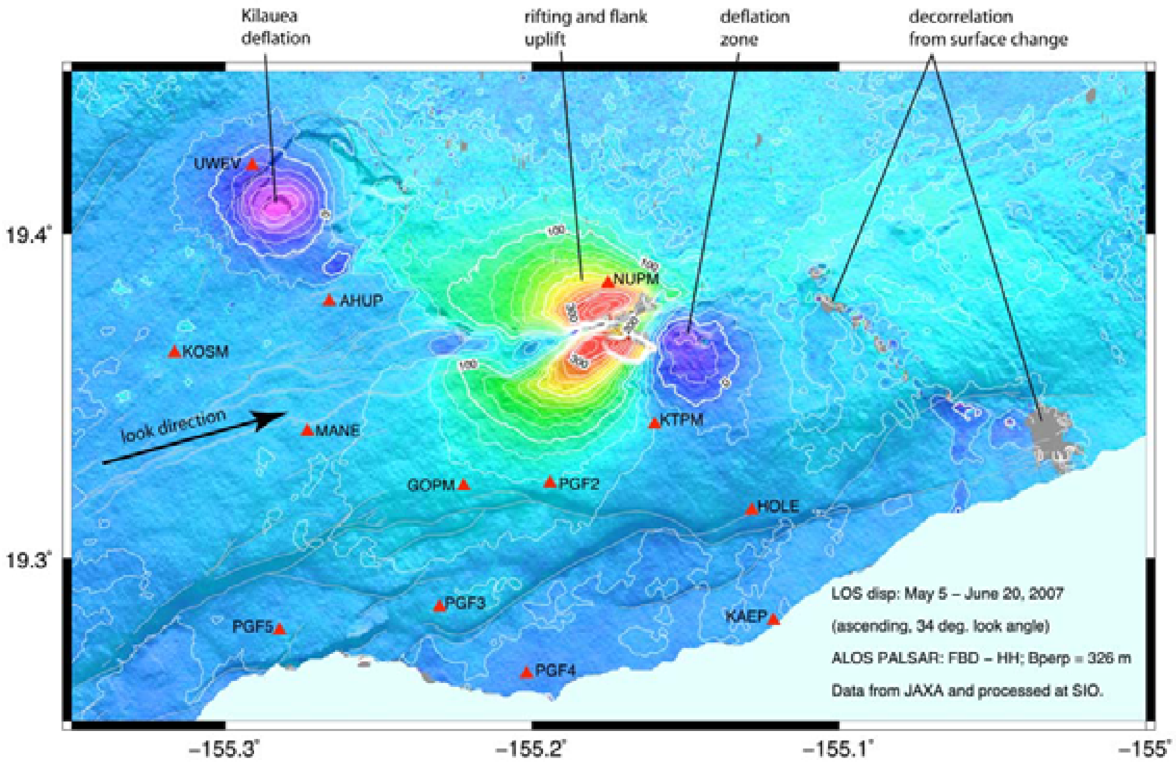

Figure 1. Between June 17 and 20, 2007, the East Rift of Kilauea Volcano opened approximately 2 meters. This displacement map, constructed from ALOS PALSAR acquisitions on May 5 and June 20, reveals the details of the rift opening and rift-flank uplifts as well as the deflation of the Kilauea caldera. Crustal deformation of the rifting event was monitored in real time using GPS stations (red triangles).

Relevant Publications

Becker, J. J., D. T. Sandwell, Global Estimates of Seafloor Slope From Single-Beam Ship Soundings, submitted to *J. Geophys. Res. Oceans*, January, 2007.

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.

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Research Interests: Seafloor geodetic measurements and nanoscale instrumentation.

Glenn Sasagawa's research focuses on the design, development, and deployment of scientific instrumentation to investigate geodetic questions in the marine environment. In the 2006-2007 academic year, two marine geodetic surveys were completed, data analysis for a continuously recording seafloor instrument was ongoing and work continued on a nanoscale instrument for chemical detection in seawater. Additionally, development of a prototype seafloor pressure reference was initiated. The geodetic research is a group effort that includes Mark Zumberge.

2007 Snohvit/Ormen Lange During the summer of 2007, a seafloor gravity survey was conducted in cooperation with researchers at Statoil of Norway. The Snohvit gas field is located in the Barents Sea and came on-line in 2007. As natural gas is extracted, seawater infiltrates beneath the seafloor to replace it. The subsequent vertical deformation and gravity changes can be used to improve reservoir models, which are essential to efficient production strategies. A seafloor gravity meter called the ROVDOG (Remotely Operated Vehicle deployable Deep Ocean Gravimeter) was developed in 1998. The instrument is a Scintrex land gravity meter, which has been extensively modified for remote operation on the seafloor. This survey is the first or baseline survey. Future surveys will provide "snap-shot" or time-lapse data on the gravity changes in the field, as well as vertical height changes using differential pressure gauge measurements. The instruments and techniques developed to date are now capable of providing 0.005 mGal repeatability in the surveys (1 mGal = 10^{-3} cm/s^2 = 10^{-5} m/s^2) .

Another gas field to the south was surveyed for the first time in the summer of 2007. The Ormen Lange field is at an average depth of order 900 m; the average depth at Snohvit is of order 300 m.

Continuous Seafloor Gravity: A modified ROVDOG gravimeter (TIDEDOG) was deployed from the Troll field natural gas platform, in order to collect a long tidal gravity time series. The tidal gravity models in the open ocean are not well tested, but are critical to correcting the data collected in the seafloor surveys. A continuously recording system can provide the data to verify and improve tidal models. The TIDEDOG gravity meter was connected via an underwater cable to the platform for power and data transfer. The data was then transmitted via microwave link to shore. Recording ended in November of 2006, and the data analysis is ongoing. Initial results show the solid earth and ocean loading models agree well with the observations, but seafloor pressure models do not sufficiently predict the observed seafloor pressure signal.

Nanoscale Chemical sensors: In conjunction with Miriam Kastner at SIO and Michael Sailor of the UCSD Chemistry department, we are investigating the feasibility of nanoscale porous silicon as a low-cost chemical sensor for marine science. Porous silicon wafers are fabricated by etching silicon wafers to form nanoscale optical structures. The presence of chemical vapors causes a shift in the resonant frequency of the optical cavity, which can be seen as a color change with the naked eye. We are investigating the possibilities of using the same techniques in seawater. Such sensors would be relatively low cost. Real-time chemical sensors in the oceans are still limited in capability, and represent an unmet need for the scientific community. This particular investigation, if successful, could lead to a new class of scientific instrumentation for oceanographic research.

Seafloor Pressure Standard: Continuously recording seafloor pressure gauges have been used to monitor episodic vertical deformation on the seafloor. However, the instrument readings slowly drift in time, masking any slow signals due to seafloor deformation. We are building a laboratory prototype that could provide a stable pressure reference signal for geodetic applications. A fixed mass resting on a precisely machined hydraulic cylinder provides a known and stable pressure signal; standard pressure calibration systems use this technique. A seafloor pressure gauge could periodically measure, in situ, the reference pressure signal. In turn the pressure gauge drift would be determined and the uncontaminated slow deformation signals would be extracted without ambiguity.

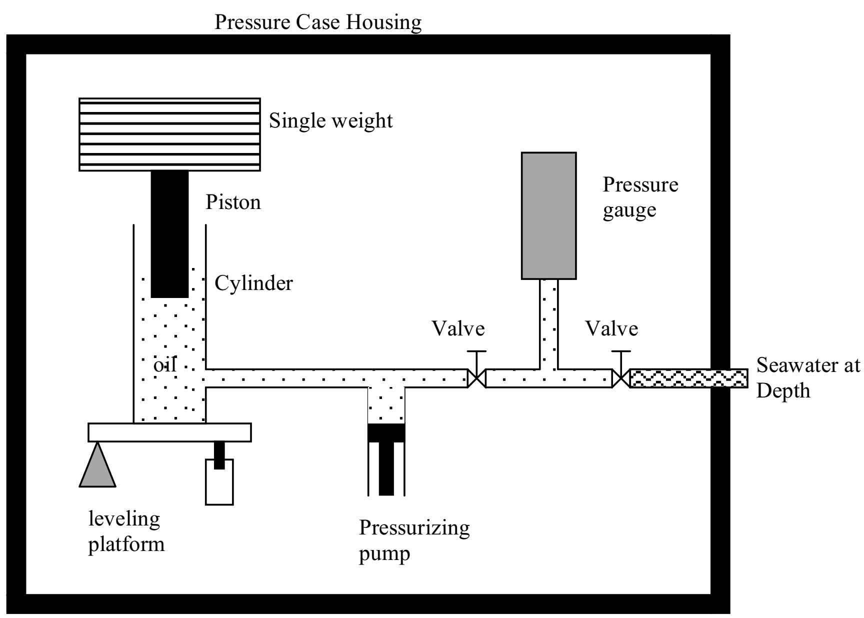

Figure 1: A pressure gauge is used to measure either seawater pressure or a reference pressure, as selected by a set of valves. When the reference pressure is selected, the pump pressurizes the cylinder until the piston can lift and float the mass; the piston and mass are rotated to reduce the static friction between the piston and cylinder. To first order, the reference pressure P_0 depends upon the mass M, the area of the piston A, and gravity g. Thus $P_0 = Mg/A$ and is stable with time. Periodic measurements of P_0 will determine the instrumental drift of the pressure gauge.

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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. His global seismology research has involved the development of new analysis approaches to handle efficiently the large digital data sets that have emerged from the global seismic networks during the last 15 years or so. In particular, he has applied stacking (averaging) methods to improve signal-to-noise ratios and make visible features in the waveforms that are not obvious on single records. This approach has proven particularly useful in studying the upper-mantle discontinuities and mapping their topography and other properties. Recent work with postdoc Jesse Lawrence analyzed a variety of mantle discontinuity phases to obtain globally averaged velocity and density profiles through the transition zone (*Lawrence and Shearer*, 2006). Models obtained using a nonlinear inversion method have smaller contrasts in density and velocity than most previous studies.

Shearer's southern California work has focused mostly on improving microearthquake locations using robust methods and waveform cross-correlation. Graduate student Guoqing Lin (now a postdoc) is also involved in this research and calculated detailed relocations for the 1983 Coalinga earthquake sequence, contributing to a structural study of the Coalinga anticline (*Guzofski et al*., 2007). Lin also developed and tested a new method for estimating local *Vp*/*Vs* ratios within similar event clusters using the precise times from waveform cross-correlation (*Lin and Shearer*, 2007) and released a software package that implements the source-specific station term (SSST) location algorithm *(Lin and Shearer*, 2006), a method that has similarities to double-difference locations but with computational advantages for large data sets. Shearer and Lin's relocated earthquake catalogs for southern California are now used by a number of researchers, including *Vidale et al.* (2006), who studied earthquake swarms in southern California and Japan, which are of great interest because they appear to be driven by fluids or aseismic slip episodes rather than simple tectonic loading.

A mysterious boom rattled windows across San Diego in 2006 and sparked a number of media inquiries. Postdoc Elizabeth Cochran worked with Shearer to show that this event was one of a number of offshore infrasound events that can be detected and located using continuous data from the Southern California Seismic Network. The events are mostly recorded in the winter and spring when atmospheric conditions trap acoustic energy near the Earth's surface. These results suggest that data from seismic networks can supplement observations from infrasound arrays for Comprehensive Test Ban Treaty monitoring and other geophysical applications.

Recently, Shearer and graduate students Germán Prieto and Bettina Allmann have been analyzing earthquake source spectra to estimate stress drops and other source properties. Allmann studied seismicity at Parkfield, California, both before and after the 2004 M6 Parkfield earthquake (*Allmann and Shearer*, 2007). Using an empirical Green's function approach, she was able to isolate the earthquake source contributions to the observed spectra from path effects and differences in site response and estimate stress drops for over 4000 individual earthquakes and identify patterns of high and low stress-drop regions along the fault. She found, somewhat surprisingly, that to first order the high and low stress-drop patterns were unchanged by the mainshock (see Figure 1). However, through careful analysis she was able to identify small changes in average stress drop caused by the mainshock and areas of increased seismic attenuation near the fault. Allmann won a "Best Student Paper" award for a presentation of this work at the 2007 SSA meeting in Hawaii. Prieto has been working (with Drs. Parker, Vernon and Thomson) to improve confidence intervals and uncertainties in earthquake source spectrum and parameter estimation and tested the results on the 2001 M5.1 Anza earthquake and borehole records from Cajon Pass (*Prieto et al.*, 2006, 2007).

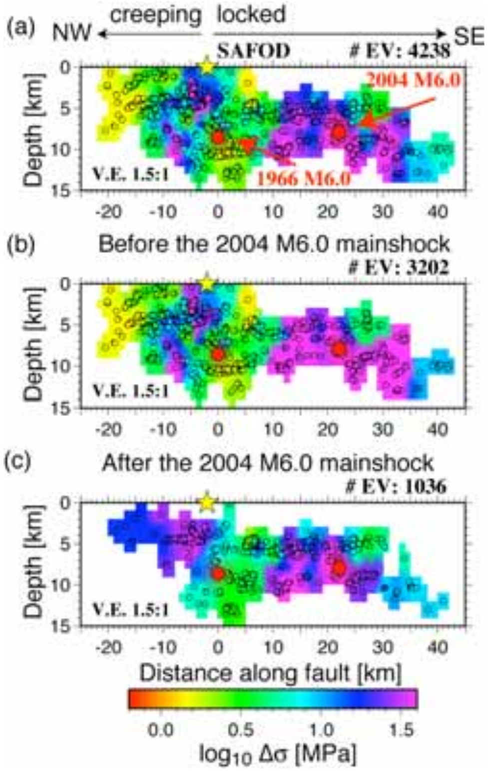

Figure 1. Spatial and temporal stress drop variations along the San Andreas Fault at Parkfield. Black circles show all events projected onto the fault plane. The 1966 and 2004 hypocenters are shown as big red circles. (a) Spatial stress drop variations over the whole time period from 1984 to June 2005. (b) Stress drop variations before the 2004 M6.0 mainshock. (c) Stress drop variations after the 2004 M6.0 mainshock. From *Allman and Shearer* (2007)

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Cochran, E.S., and P.M. Shearer, Infrasound events detected with the Southern California Seismic Network, *Geophys. Res. Lett.*, **33**, L19803, doi:10.1029/2006GL026951, 2006.

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Lin, G. and P. Shearer, The COMPLOC earthquake location package, *Seismol. Res. Lett.,* **77**, 440-444, 2006.

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

Seamounts have been a central theme in Hubert Staudigel's research since his PhD work on the seamount series of La Palma, Canary Islands (Staudigel and Schmincke, 1984). Since then he has worked on numerous aspects of seamount science, from petrology and isotope geochemistry to their Mn encrustations, macrobenthic communities and microbiology, their magnetic properties, density distribution (gravity) and seismic structure. Over the last couple of years most of his seamount research focused on the geochronology, isotope geochemistry and the microbial communities colonizing them, in particular around active hydrothermal vents. Recent papers include: the geochronological (2) and isotope geochemical (2) of the Samoan islands and seamounts (with, Hart, Koppers and (former) graduate students, Workman, Jackson (2), Konter, Russel (1)) demonstrated the age progressive nature of the island chain (in particular Savaii) and helped us fundamentally understand the geochemical makeup of the earth's mantle through the discovery of the most radiogenic (extreme) EM II composition of Samoa; (3) An isotopic investigation of previously dated seamount samples in the Western Pacific (Konter and Barry Hanan SDSU) showed that three recently active hot spot volcanoes in the Cook-Austral island chain have been consistently producing isotopically extreme magmas suggesting an origin by long-lived hot spots.

Hubert Staudigels' involvement in volcanology includes interests in submarine volcanism and dike intrusions and he also teaches a class in volcanology whereby the next class will be in 2008 (http://earthref.org/ERESE/courses/HVFT/2005/index.html). Recent volcanological studies include the discovery of potentially the oldest ophiolite on earth in the Isua Supracrustal Belt (Furnes et al., 2007) and volcano-based paleomagnetic research in Antarctica in the McMurdo volcanic series (http://earthref.org/ERESE/projects/GOLF182/index.html, in collaboration with Lisa Tauxe and Cathy Constable). The key objective of the latter is to study the fine scale (secular) variation of the magnetic field, where HS explores field relationships and the potential for volcano-tectonic disturbance of a paleomagnetic signal.

Hubert Staudigel collaborates with Brad Tebo, Alexis Templeton and graduate students Brad Bailey and Lisa Sudeck (Haucke) to study the chemical and biological controls of water-rock interaction during seafloor alteration of the oceanic crust. Current work focuses on the characterization and isolation of microbes that facilitate these processes (Templeton et al., 2005) and the mechanisms by which microbes may dissolve in paricular volcanic glass. In collaboration with H. Furnes (U. Bergen, Norway) and others Hubert Staudigel studied characteristic corrosion that is imposed by microbial activity on natural basaltic glass, and they could show that the majority of glass alteration is caused by microbial activity, in the upper 300m of the oceanic crust of all ages in the ocean basins, back through time to almost 3.5 Ba (Staudigel et. al., 2006). Hubert Staudigel's particular interests aim at low temperature geochemical fluxes of major and trace elements (Ca, Sr, K, Rb, Cs, REE, Th, U, Pb), and redox reactions of Fe and U.

Hubert Staudigel is also involved in efforts creating a Cyberinfrastructure for earth science and science education, in collaboration with A. Koppers, J. Helly, C. Manduca and D. Mogk. Key data base components include the reservoir data base for the Geochemical Earth Reference Model (GERM) initiative, the Seamount Catalog for the Seamount Biogeoscience Network (SBN) and the ERESE project (Enduring Resources for Earth Science Education), all accessible at earthref.org and Hubert Staudigel's website (http://earthref.org/whoswho/ER/hstaudigel/index.html) including his bibliography for references not listed below.

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Research Interests: Time Series Analysis, Earthquake Source Physics, Seismometer Design, Real-Time Sensor Networks, Ocean Observing Systems

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.

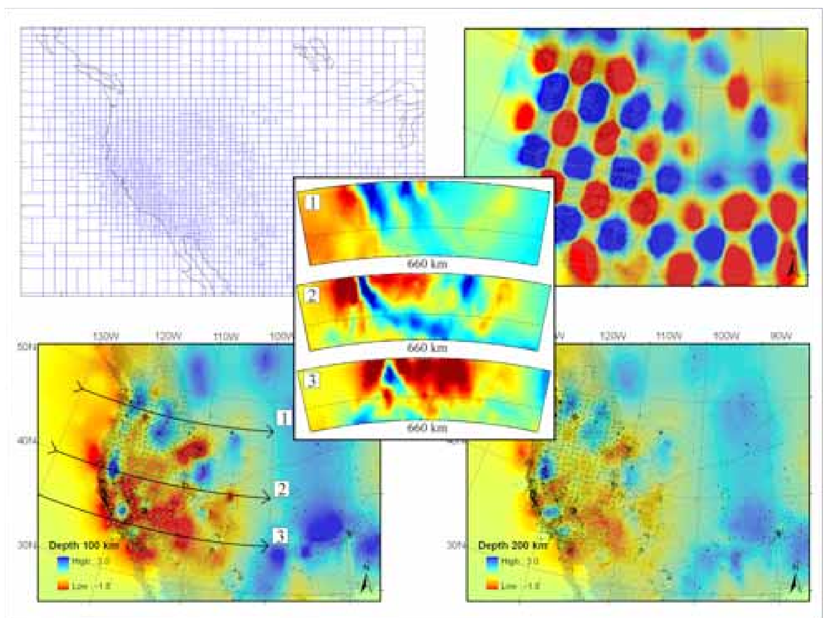

Figure 1. Results from body wave tomographic imaging using USArray. Top left the panels show grid resolution, top right checkboard test, bottom shows map views at 100 km and 200 km depth. The middle panel shows three cross-sections.

Spectral analysis 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.

We have studied the physics of the earthquake source using the data available from the Anza Seismic Network. Given the presence of large numbers of stations close to the very active San Jacinto Fault region we have been able to extract information about the earthquake source. We have analyzed the problem of uncertainties of the earthquake source spectrum using Empirical Green Functions. In order to remove the effects of the propagation of the seismic waves through the earth, it is necessary to use a small earthquake as an approximate Green function, and deconvolve it from the earthquake that we are interested in. But doing this introduces uncertainties and the deconvolved spectrum has larger variability. Using data from the aftershock sequence of the M5.1 2001 Anza Earthquake, we studied the errors associated with EGF methods and introduced techniques to estimate confidence intervals of source parameters and to reduce the uncertainties.

The HPWREN program (http://hpwren.ucsd.edu) is creating a large-scale wireless high-performance data network that is being used for interdisciplinary research and education applications, as well as a research test bed for wireless technology systems in general. HPWREN provides wide area wireless Internet access throughout southernmost California including San Diego, Riverside, and Riverside counties and the offshore regions. Under UCSD's HPWREN program, research is being conducted on building "last kilometer" wireless links and developing networking infrastructure to capture real-time data from multiple types of sensors from seismic networks, hydrological sensors, oceanographic sensors, video sensors as well as data from coastal radar and GPS.

A key research project is the ROADNet program (http://roadnet.ucsd.edu) which is focused on developing the real-time cyberinfrastructure to acquire, process, distribute, and archive data from environmental, oceanographic, geophysical, and structural monitoring sensor nets, many of which are accessed through HPWREN.

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Prieto, G. A., P. M. Shearer, F. L. Vernon, and D. Kilb (2004). Earthquake source scaling and self-similarity estimation from stacking P and S spectra. J. Geophys. Res., 109, No. B8, B08310 10.1029/2004JB003084..

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

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Research interests: complexity, nonlinear dynamics and pattern formation; permafrost terrain; dynamics of human systems and human-landscape interactions; urban landscapes; scientific inquiry; social and economic justice movements; and independent media.

Brad Werner and co-workers Dylan McNamara and Alex Zvoleff in the Complex Systems Laboratory have been working to develop and refine the tools used to investigate complex systems, those systems for which simple and complicated descriptions, and often a range of intermediate representations, can be constructed. The current focus revolves around developing and investigating numerical models for landscape dynamics, information acquisition, storage and flows in human systems, and human-landscape interactions.

Landscape Systems
Thaw lakes form in lowland permafrost, where organic-rich dark summertime waters preferentially absorb solar radiation over surrounding terrain, causing ice-rich permafrost to melt and consolidate. This process gives rise to lakes that expand and deepen, thereby melting permafrost and rendering frozen organics susceptible to decomposition. Our model of this process, incorporating permafrost melting and recovery, lake initiation, expansion and draining, and organic soil decomposition, indicates that for deep lakes, such as in the northern Seward Peninsula of Alaska, enhanced melting of permafrost via thaw lake expansion and consequent greenhouse gas release will significantly lag climate warming. In a preliminary result presented at the 2006 AGU Fall Meeting, the model was used to illustrate the development of thaw lakes in northern Siberia using as input published paleo-temperature and paleo-precipitation time series, and also to project methane release into the future based on a range of climate change scenarios. Current efforts are focused on expanding that study geographically and preparation of a journal article.

Human Systems
Discussions of human systems, ranging from the philosophizing of Deleuze to scientific studies of consciousness, commonly fail to account for the severe constraints that nonlinear dynamics places on their possible states and outcomes. That most human relations, except at the smallest scales, are now governed by profit-seeking, commodifying market dynamics permits remarkable simplification in describing the interaction of billions of people, each of whom potentially could exhibit complicated behavior (Werner and McNamara, 2007). Agent-based models, in which the actions of individual or groups of humans are represented by rule-following agents, capture the intermediate- to long-time-scale behavior of humans as constrained by the market system.

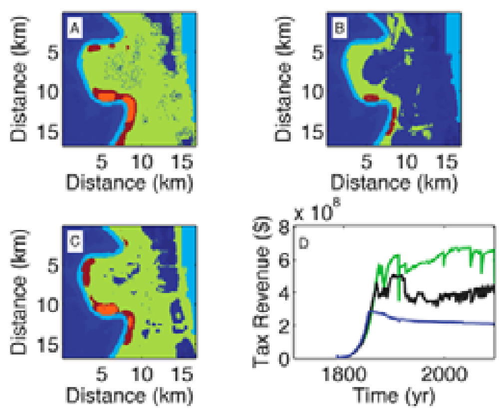
Publicly available information, from that used to make political decisions to personal life choices, largely has been implicitly commodified and is intensely manipulated for various purposes. Much of the regional and national news produced in this information free market and consumed in the United States passes through a handful of large media corporations (e.g., Bagdikian, 2004). In a classic conceptual model, Herman and Chomsky (1988) described and documented the (largely linear) effect of media concentration on filtering information in a biased manner. A preliminary agent-based news model loosely based on this conceptual model reproduces the type of bias that was predicted but also exhibits potential for much richer nonlinear behaviors. The production of scientific information also occurs within a market-based system that controls (with some restrictions) funding, publishing and researcher rewards. A preliminary model derived in part from the structure of the news model suggests that market-based science might inevitably lead to large amplitude fluctuations in information production, as a self-organized constellation of powerful interests operating in the short term use their influence to support prevailing ideas in opposition to long-term trends toward revision and refinement of theories.

The long-term focus of these modeling studies (using the dynamics of complex systems as background) is on how alternative information systems, operating within a dominant information economy, affect information flows. For example, how do blogs, myspace and indymedia interact with and affect the corporate media? What are the dynamics of these alternative information subsystems, for example, the person-to-person contacts of myspace vs. the person-to-community interactions of indymedia? How do alternative information subsystems interact with and strengthen social and economic justice movements? And finally, what strategies might social justice organizers adopt to successfully confront entrenched but adapting information and power systems? These questions are significant not only for investigating the dynamics of human systems, but also for describing how ecosystems and landscapes, severely impacted by human intervention on a global scale, will evolve in the future.

Human-Landscape Interactions

Increasing population, economic development and technological advances have led to interactions between human agency and landscapes, oceanographic and atmospheric systems that are increasing in diversity and strength. The underlying effect of most approaches to studying the human-natural interface has been to suppress the nonlinearities that are a necessary ingredient of the long-term behavior of the coupled system.

The Complex Systems Laboratory currently is investigating human-landscape dynamics by coupling models of landscapes with agent-based models of economic development in five examples. In a model for the interaction of barrier islands with agent-based models of market-driven tourism and resort development, storm damage to resorts and coastal hazard protection measures, market dynamics destabilize barrier island response to rising sea level, giving rise to emergent, episodic boom and bust cycles that alternate in phase alongshore (McNamara and Werner, 2007a-b). At longer time scales, redistribution of sediment used to counteract erosion syncs the boom and bust cycles, leading to regional resort destruction. A spatio-temporal instability also evolves in a model of the urban-wildland boundary in urbanizing mountain catchments, where economically driven residential development competes for space with fires, floods, debris flows and landslides. A model for economic development, river and hurricane-induced flooding, and levee building in New Orleans approximately reproduces historical expansion, flooding and increase in levee heights (with storm surge levees lagging river flood levees), as well as the occurrence of Katrina-scale floods-predicted to continue into the future in the absence of major shifts in economic and political system dynamics (McNamara and Werner, 2007c). Two in-progress modeling projects are examining the interaction between resource development, greenhouse gas emissions and climate and recent widespread development of slums in megacities, largely sited in locations subject to hazards, such as landslides, floods and fires.



Modeled development (red: port services; orange: hotels; yellow: homes) in New Orleans shown in year 2000 under 3 policy scenarios: A. Construct levees (green); B. Tax developers based on future damage costs (blue); C. No levees (black). D. Tax revenue vs. time for the three scenarios (colors as indicated above) illustrating that levee building leads to extensive development punctuated by large disasters, no protection reduces development with frequent, small damage events and taxing developers for future damage costs essentially eliminates flood damage, at the expense of less extensive development.

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--D.E. McNamara & B. T. Werner (2007a) Coupled Barrier Island-Resort Model: 1. Emergent instabilities induced by strong human-landscape interactions, Journal of Geophysical Research-Earth Surface, in review.

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--D.E. McNamara & B.T. Werner (2007c) Flood evolution and human response in a coupled landscape and economic model for New Orleans, Geophysical Research Letters, in preparation.

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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 the propagation of sound in the ocean, including the effects of scattering from small-scale oceanographic variability.

Acoustic Thermometry. Large-scale, range- and depth-averaged temperatures in the North Pacific Ocean were measured by long-range acoustic transmissions over the decade 1996–2006 [*Worcester et al.*, 2005]. Acoustic sources located off central California and north of Kauai transmitted to receivers distributed throughout the North Pacific from 1996 through 1999. The Kauai transmissions resumed in early 2002 and continued until late 2006. The acoustic data are a high signal-to-noise ratio measure of large-scale temperature, with mesoscale variability suppressed in the horizontal averages. Even at these large spatial scales, the ocean is highly variable, with significant changes occurring in a few weeks. For example, a path to the northwest from Kauai (Kauai to k) showed modest warming (shorter travel times) and a weak annual cycle from late 1997, when the transmissions started, until early 2003, when the path cooled abruptly (longer travel times) and a strong seasonal cycle returned. Travel times computed from sound-speed fields derived from the "Estimating the Circulation and Climate of the Ocean" (ECCO) ocean general circulation model show similarities to the measured travel times, but also significant differences, suggesting that the acoustic travel times would provide meaningful constraints on the model behavior. The on-going analysis of these data is closely coordinated with Brian Dushaw (University of Washington).

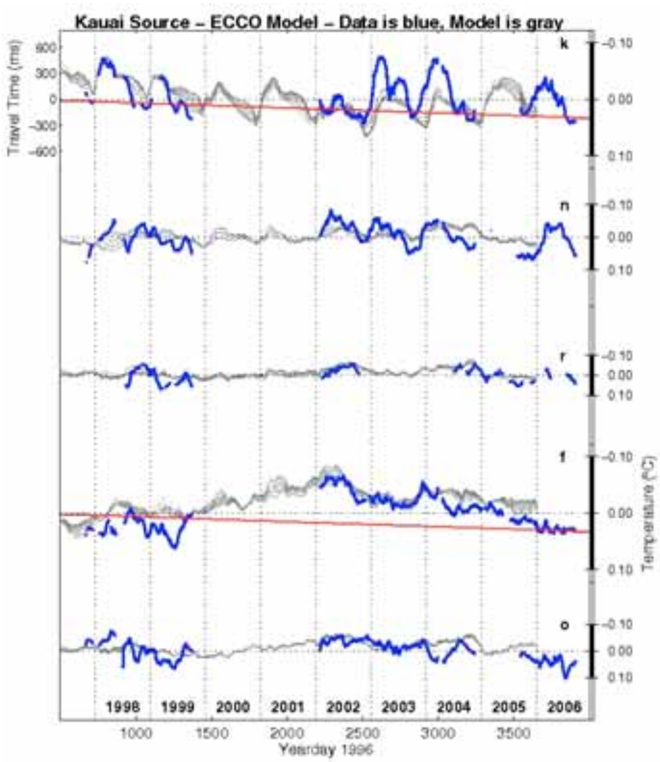

Figure 1. Travel times measured on 1–5-Mm-long acoustic paths from the Kauai source (blue) compared to travel times predicted using the Jet Propulsion Laboratory implementation of the ECCO ocean model (gray). For comparison, the trend in travel time corresponding to a 5 m°C/year change in temperature at the sound-channel axis is shown for two of the paths (red).

North Pacific Acoustic Laboratory. The ultimate limits of long-range sonar are imposed by ocean variability and the ambient sound field. Uncertainty due to ocean variability limits our ability to make accurate predictions of acoustic propagation. Scattering due to internal waves and other ocean processes limits the temporal and spatial coherence of the received signal. The objectives of the North Pacific Acoustic Laboratory (NPAL) program are to understand the basic physics of low-frequency, broadband propagation in deep water and the effects of environmental variability on signal stability and coherence. The goal is to determine the fundamental limits to signal processing in deep water imposed by ocean processes. A series of field experiments in the North Pacific over the last 15 years has explored various aspects of long-range propagation in deep water, taking advantage of developments in low-frequency, wideband transducers driven by controlled waveforms and large vertical line array (VLA) receivers, including ones that can store a year or more of data, that finally provide the means to measure the spatial and temporal statistics of the fluctuations needed to advance the development of propagation theory [*Worcester and Spindel*, 2005].

The most recent NPAL experiment ended in June 2005, with the recovery of oceanographic moorings installed the previous year. The experiment consisted of three closely related components, named *SPICEX (Spice Experiment), LOAPEX (Long-range Ocean Acoustic Propagation Experiment),* and *BASSEX (Basin Acoustic Seamount Scattering Experiment)*. Worcester's group had primarily responsibility for *SPICEX*, in which two moorings with 250-Hz acoustic transceivers at depths of about 750 and 3000 m transmitted to two autonomous VLA receivers. Worcester's student, Lora Van Uffelen, is analyzing the 250-Hz data with the goals of understanding the large amount of acoustic energy scattered into the shadow zone below the lowering turning points of the acoustic rays and elucidating the extent to which density-compensated ocean fine structure, named "spice," contributes to acoustic scattering in deep water. Her research involves comparisons of the measured receptions with simulations using advanced parabolic equation acoustic propagation models.

One of the lessons of oceanography, learned again and again, is that it is dangerous to extrapolate from one region to the next. Over the last twenty years we have developed the equipment and methods for conducting long-range, deep-water acoustic transmissions. For largely logistic reasons, the NPAL experiments have been performed almost entirely in the relatively benign eastern and central North Pacific Ocean. We are now making definite plans in coordination with the Office of Naval Research to conduct the next NPAL experiment in the Philippine Sea during 2010–2011, preceded by a Pilot Study/Engineering Test during April-May 2009. The northern Philippine Sea is a highly dynamic region. The Kuroshio Current flows northward on its western boundary. It is modulated by significant eddy variability moving in from the east, with a high level of synoptic kinetic energy and rapid timescales. The background sound-speed field is quite different from that in the eastern and central North Pacific. We expect the character of the transmissions to differ in a profound way from those in the North Pacific.

Relevant Publications

Worcester, P. F., Munk, W. H., and Spindel, R. C., Acoustic remote sensing of ocean gyres, *Acoustics Today*, *1*, 11–17, 2005.

Worcester, P. F., and Spindel, R. C., North Pacific Acoustic Laboratory, *J. Acoust. Soc. Am.*, *117*, 1499–1510, 2005.

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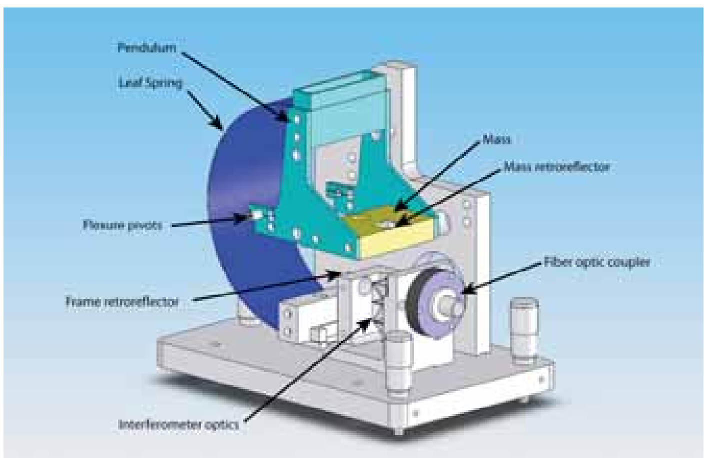
Research Interests: Measurement of gravity in the marine and subaerial environments, development of new seismic instrumentation, optical fiber measurements of strain and pressure

Construction of an interferometric seismometer

In collaboration with a visiting Green Scholar, Erhard Wielandt, our group began investigating a new type of seismic sensor in 2002. Using funds donated by Walter Munk from his Kyoto award, we started studying the possibilities of replacing the electronics in a traditional seismometer with an optical system. The motivation was to allow use of a long-period seismometer in a deep borehole, where noise from anthropogenic sources and natural surface effects are attenuated. We could make use of optical fibers to bring laser light to and from the sensor without the need for electrical cables and downhole circuitry — two problematic features of traditional borehole seismometry. Working



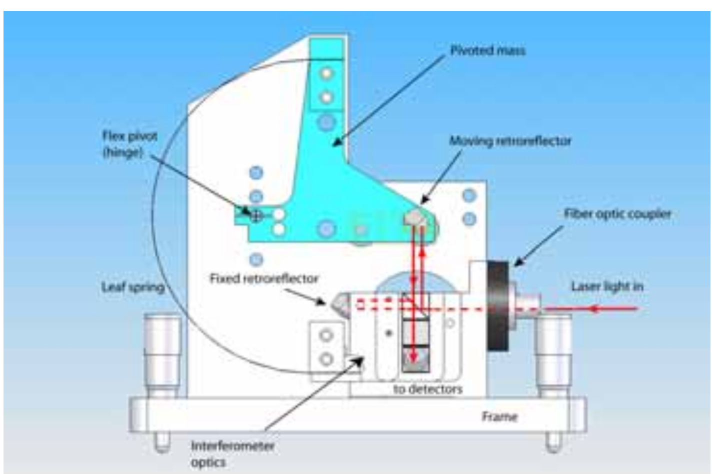


Figure 1: The new seismometer has a mechanical design based on a concept originally formulated by Prof. E. Wielandt who guided us in the design of our new instrument. It consists of a basic leaf spring configuration allowing a long free period (about three seconds). A Michelson interferometer facilitates an extremely sensitive measurement of the mass's displacement while retaining the high dynamic range and linearity required for detecting both distant tremors as well as local earthquakes. New digital signal processing of the interferometer outputs provide displacement digitization with 30 bit resolution (about 1 part per billion). We are currently investigating noise sources in an effort to optimize the sensor's performance.

with graduate student Jose Otero and colleague J. Berger, we have studied the implications of abandoning electronics (including electronic force feedback — long considered a requirement for success in building a seismometer). We have found that the performance of the new seismometer is quite good and approaches that of the best observatory seismometers currently available. Having been awarded a second National Science Foundation grant to pursue this research, refinements to the system are now being made and we plan to deploy several prototypes at seismic observatories here and abroad.

Development of fiber optic strainmeters

The group is investigating a number of strainmeters that rely on optical fibers to sense deformation in Earth's crust. The most successful so far is a high-resolution (0.01 parts per billion), interferometric sensor, based on the same signal processing technology we use in the seismometer. In late 2004, the group installed several kilometer-long optical fibers in the SAFOD (San Andreas Fault Observatory at Depth) borehole near Parkfield, CA. Short period signals are very promising — longer period signals are currently contaminated by thermal noise. Efforts to improve this are underway.

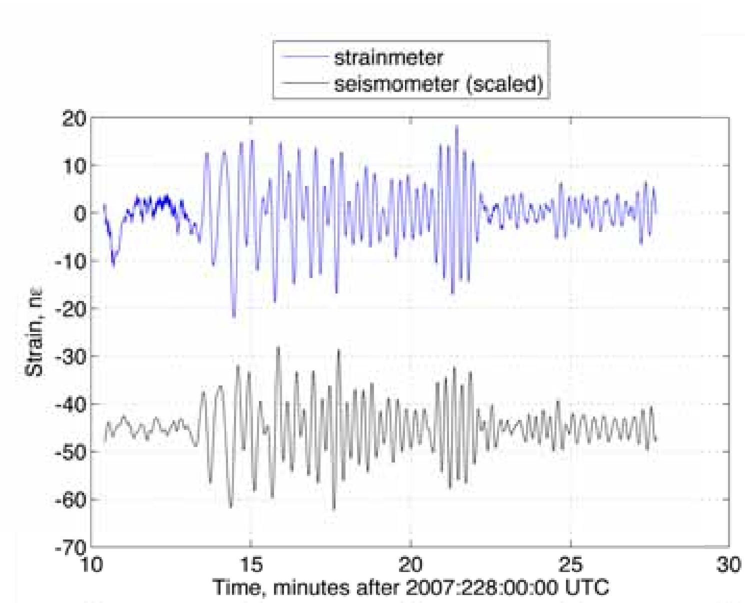


Figure 2. An optical fiber is stretched between the surface and a depth of 855 m in the SAFOD borehole near Park-field, California; its length is recorded interferometrically. The 2007 Peru M8 earthquake provided a valuable signal with which the strainmeter could be tested. Because the waveform from the strain-meter looks very similar to that from a nearby seismometer, we know that coupling to the rock over its 855 m length is good.

Relevant Publications

Zumberge, M., Berger, J., and Wielandt, E., Experiments with an optical seismometer, *Eos Trans. AGU*, 84 (46), Fall Meet. Suppl., Abstract S52C-0144 (2003).

Zumberge, M. A., A Borehole Fiber-Optic Strainmeter, *Eos Trans. AGU*, 2005AGUFM.T21A0440Z, Fall Meet. Suppl., Abstract T21A-0440 (2005).

Blum, J. A., Nooner, S. L., and Zumberge, M. A., Recording Earth strain with optical fibers, *IEEE Sensors Journal*, submitted (2007).

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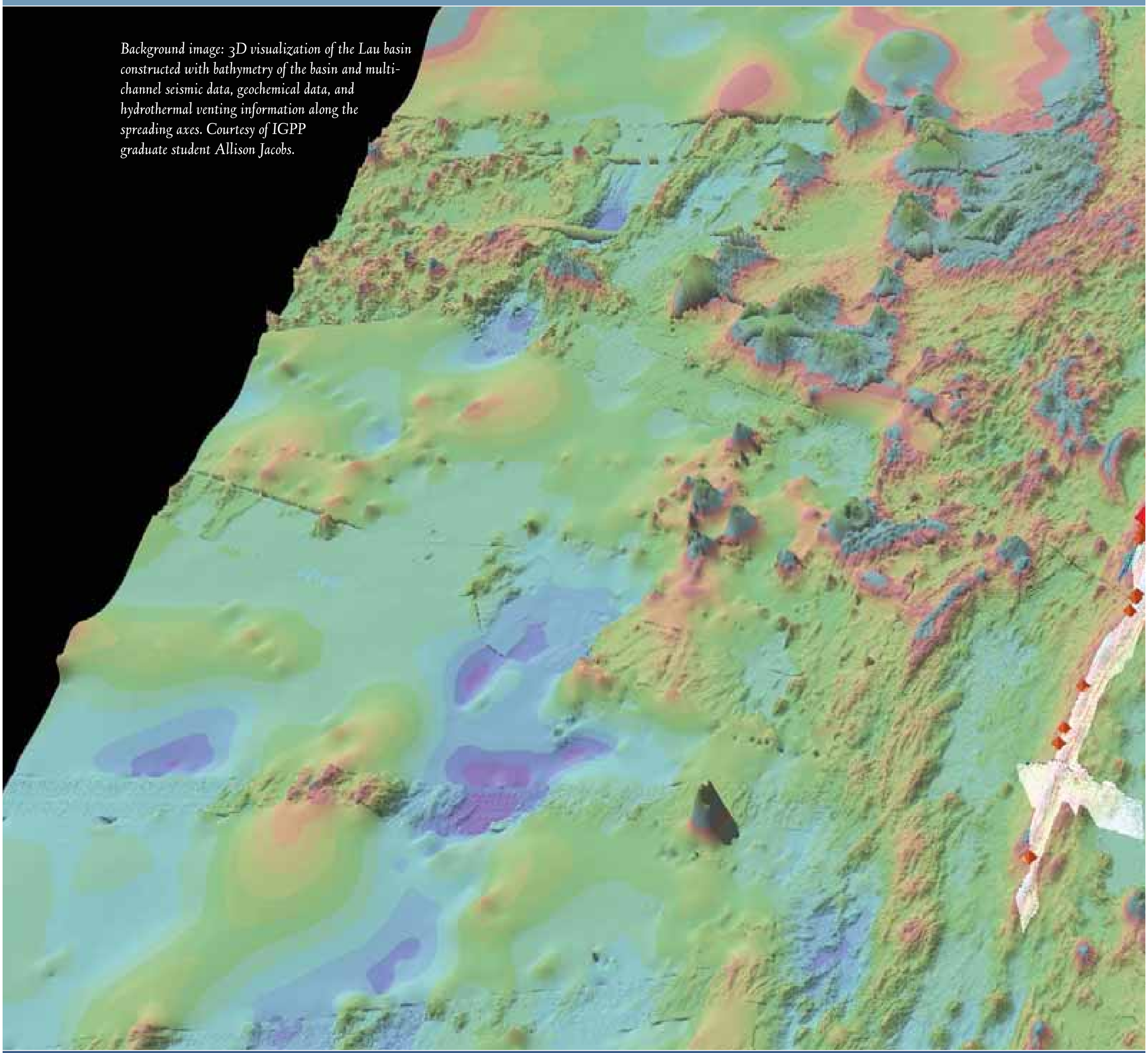

Background image: 3D visualization of the Lau basin constructed with bathymetry of the basin and multi-channel seismic data, geochemical data, and hydrothermal venting information along the spreading axes. Courtesy of IGPP graduate student Allison Jacobs.