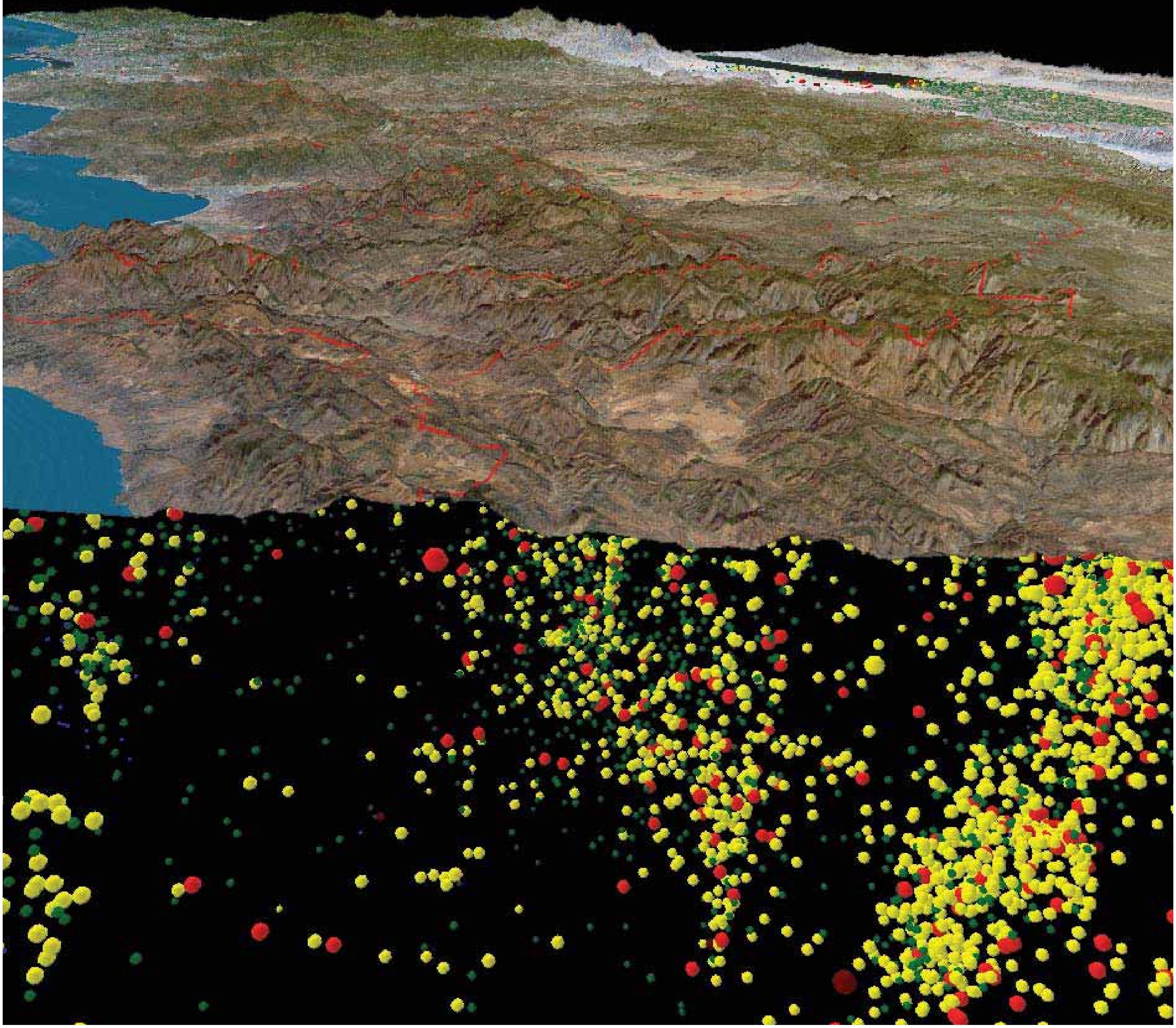
2006 Annual Report

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

SCRIPPS INSTITUTION OF OCEANOGRAPHY, UNIVERSITY OF CALIFORNIA, SAN DIEGO

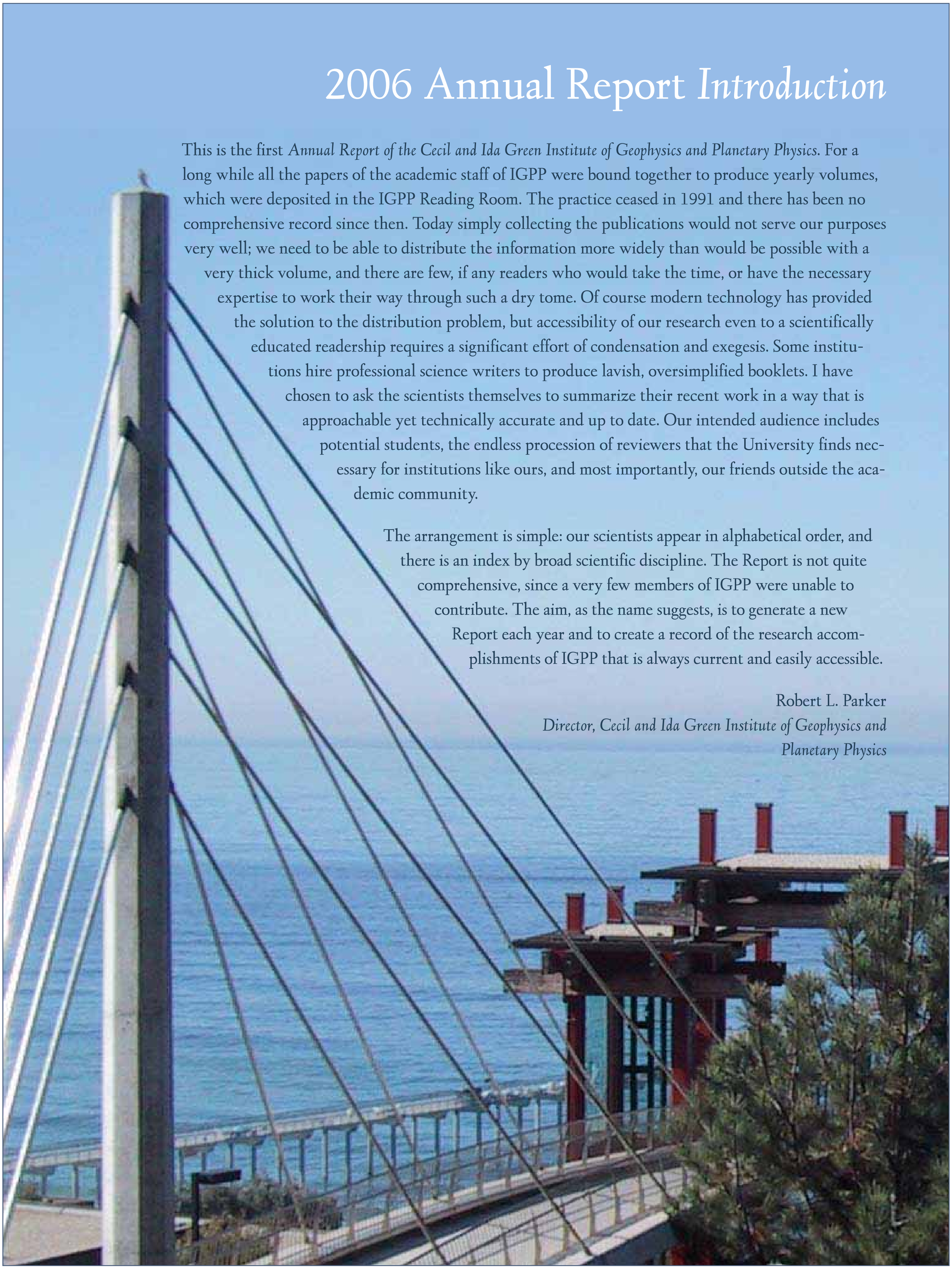


2006 Annual Report *Introduction*

This is the first *Annual Report of the Cecil and Ida Green Institute of Geophysics and Planetary Physics*. For a long while all the papers of the academic staff of IGPP were bound together to produce yearly volumes, which were deposited in the IGPP Reading Room. The practice ceased in 1991 and there has been no comprehensive record since then. Today simply collecting the publications would not serve our purposes very well; we need to be able to distribute the information more widely than would be possible with a very thick volume, and there are few, if any readers who would take the time, or have the necessary expertise to work their way through such a dry tome. Of course modern technology has provided the solution to the distribution problem, but accessibility of our research even to a scientifically educated readership requires a significant effort of condensation and exegesis. Some institutions hire professional science writers to produce lavish, oversimplified booklets. I have chosen to ask the scientists themselves to summarize their recent work in a way that is approachable yet technically accurate and up to date. Our intended audience includes potential students, the endless procession of reviewers that the University finds necessary for institutions like ours, and most importantly, our friends outside the academic community.

The arrangement is simple: our scientists appear in alphabetical order, and there is an index by broad scientific discipline. The Report is not quite comprehensive, since a very few members of IGPP were unable to contribute. The aim, as the name suggests, is to generate a new Report each year and to create a record of the research accomplishments of IGPP that is always current and easily accessible.

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



Institute of Geophysics & Planetary Physics

Duncan Carr Agnew, *Professor of Geophysics* and Frank K. Wyatt, *Principal Development Engineer*

Sofia Akber, *Assistant Professor*

Jeffrey M. Babcock, *Project Scientist*

Jonathan Berger, *Research Geophysicist*

Donna Blackman, *Research Geophysicist*

Yehuda Bock, *Research Geodesist and Senior Lecturer*

Catherine Constable, *Professor of Geophysics*

Steven Constable, *Professor of Geophysics*

J. Peter Davis, *Specialist*

Catherine de Groot-Hedlin, *Project Scientist*

Matthew Dzieciuch, *Project Scientist*

Yuri Fialko, *Associate Professor*

Helen Amanda Fricker, *Associate Research Geophysicist*

Alistair Harding, *Research Geophysicist*

Michael A.H. Hedlin, *Research Geophysicist*

Glenn Ierley, *Professor*

Catherine L. Johnson, *Associate Professor*

Graham Martin Kent, *Research Geophysicist*

Deborah Lyman Kilb, *Assistant Project Scientist*

Anthony A.P. Koppers, *Associate Research Geophysicist*

Gabi Laske, *Associate Research Geophysicist*

Walter Munk, *Research Professor*

Robert L. Parker, *Professor of Geophysics*

David T. Sandwell, *Professor of Geophysics*

Glenn Sasagawa, *Associate Project Scientist*

Peter Shearer, *Professor*

Hubert Staudigel, *Research Geologist, Lecturer*

Frank Vernon, *Research Geophysicist*

Brad Werner, *Professor*

Peter F. Worcester, *Research Oceanographer and Senior Lecturer*

Mark A. Zumberge, *Research Geophysicist*

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

Crustal Deformation (Strainmeters)

A major activity for this year has been constructing and operating longbase laser strainmeters as part of the Plate Boundary Observatory, an activity led by Wyatt, supported by staff members Don Elliott and Stephen Dockter. The first such instrument, installed on the east side of the Salton Sea (Durmid Hill) at 90° to an existing sensor, began operation in June 2005. It has performed very well, showing both small strain changes and a long-term rate that is reasonably consistent with that expected from geodesy—though one significantly higher than is seen on the older instrument, implying a long-term areal strain in the area. Following a somewhat lengthy permitting process, we received permission to begin constructing the second pair of instruments near Salton City in December 2006, and began immediately under Wyatt's supervision. These instruments began operation on 1 October 2006, on time and on budget—though meeting this deadline demanded considerable effort. Wyatt and Agnew also invested substantial time in searching for and locating a site for the next installation in the Cholame region of California, including the compilation of geographic data for the area. Fortunately we have been successful in finding a suitable site with a landowner willing to allow its use; we expect to start construction at this location late in 2006.

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). Part of this software development was the design of a filter suitable for converting 1-Hz strainmeter data to a lower sampling rate. Agnew, working with Dr. K. Hodgkinson of PBO, developed a minimum-phase FIR filter tailored to this particular application.

PBO wishes to augment the small community of strainmeter researchers with new (and younger) researchers. To help with this, UNAVCO has sponsored a set of short courses on how to use such data, which Agnew helped chair and also supplied notes and lectures on Earth tides, on noise and its estimation, sources of deformation, and data analysis. He also made available portable and documented versions of the analysis programs used in our group (PIASD) and an updated version of his ocean-loading programs (SPOTL).

Most of the strainmeters being installed by PBO are borehole systems, which must be calibrated *in situ* using theoretical models, usually of the Earth tides. Agnew has analyzed data from the first instruments installed by PBO (coastal installations aside) and finds that the data cannot be fit by the simple models that PBO has planned to use for relating internal to external strains.

The non-PBO laser strainmeters at Piñon Flat Observatory, Durmid Hill, Glendale, and Yucca Mountain have all continued to operate satisfactorily, not showing any significant departures from previous behavior. The vacuum control systems on the older instruments were largely brought up to the standard of the newer ones, allowing better control and fewer disturbances to the data. Improved analysis of the PFO data by Wyatt and Barbour has reduced errors caused by miscounting in some of the interferometers and given a clearer picture of deformations before and after the Anza earthquake of June 2005; as shown in Figure 1, this event had substantial postseismic strain, unusual and unexpected for an earthquake of this size (magnitude 5.1).

In a classic case of serendipity, Agnew, with UCLA researchers J. Elkhoury and Dr. E. Brodsky, found that the long-running water-height records from two of the wells at PFO show a

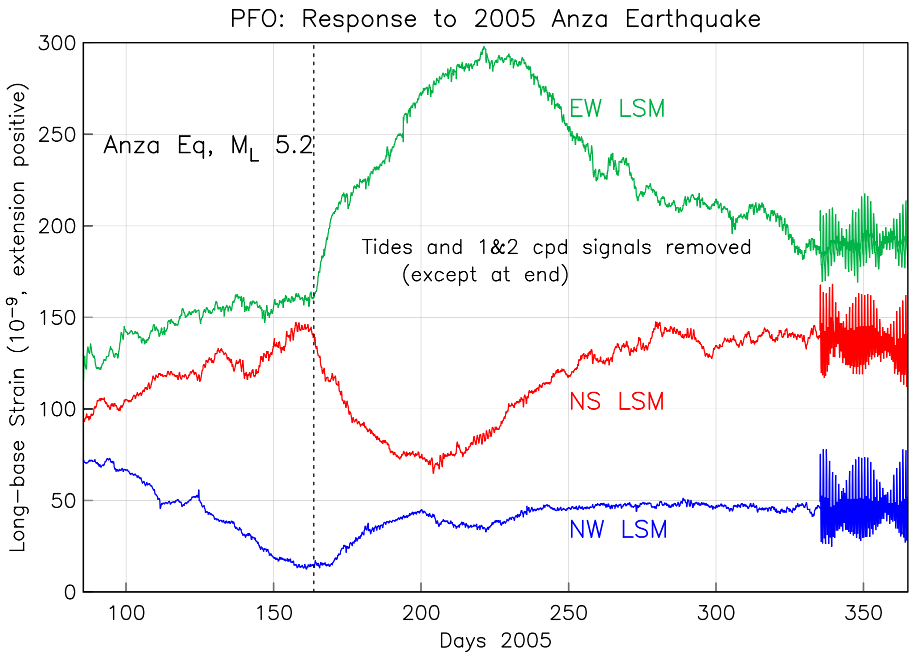

Figure 1

significant change in their tidal behavior at times of strong shaking, with the tidal response moving to a new value and then decaying back to its previous value over the succeeding weeks or months. The shift in response is correlated with the amount of shaking. This can be interpreted as a transient change in permeability induced by shaking, a result with possible implications for earthquake triggering.

Crustal Deformation (GPS)

Agnew, working with Dr. Z.-K. Shen (UCLA) and Dr. R. W. King (MIT) has continued to work on the SCEC Crustal Motion Map. A major extension this year has been the inclusion of data from throughout California to produce a statewide set of interseismic velocities in support of the Working Group on California Earthquake Probabilities.

The network first observed in 1998 for determining deformation in the San Diego area has been reobserved as planned. Analysis of these and other data should provide improved geodetic estimates of the slip rate on the Rose Canyon fault.

As part of an analysis of high-rate GPS data, Agnew and Dr. K. Larson (U. of Colorado) collaborated on a study of the repeat time of the GPS constellation, termed the aspect repeat time (Agnew and Larson 2006).

Relevant Publications

Meltzner, A. J., K. Sieh, M. Abrams, D. C. Agnew, K. W. Hudnut, J.-P. Avouac, and D. H. Natawidjaja, "Uplift and subsidence associated with the great Acech-Andaman earthquake of 2004," *J. Geophys. Res.* (2006) **111**, B02407, doi:10.1029/2005JB003891.

Elkhoury, J. E., E. E. Brodsky, and D. C. Agnew, "Seismic waves increase permeability," *Nature* (2006) **441** 1135-1138.

Agnew, D. C. and K. M. Larson, "Finding the repeat times of the GPS constellation," *GPS Solutions* (2006), doi:10.1007/s10291-006-0038-4

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

Earth materials influence and respond to 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; additonally, 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). Sofia and colleagues investigated the energetics of aluminum substitutions into perovskite in order to determine Al solubility into and partitioning among lower mantle minerals. From this they evaluated the effects of aluminum on the elasticity of these minerals. Additionally they created 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. Sofia continues to work on understanding the configurational entropy of aluminum mixing in $MgSiO_3$ and $CaSiO_3$ perovskites to improve her model of Al partitioning in the CaO-MgO-Al_2O_3-SiO_2 lower mantle assemblage. Lastly, Sofia and colleagues estimated the partitioning of aluminum at the newly discovered $MgSiO_3$ perovskite to post-perovskite phase transition, and examined the effects of aluminum on the depth and sharpness (and hence seismic visibility) of the phase boundary (Figure 2).

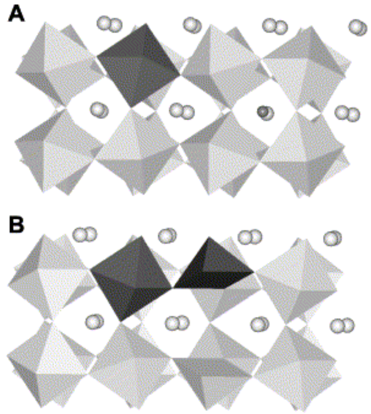

Figure 1: A: charge coupled substitution of Al into MgSiO3 perovskite. B: oxygen vacancy forming substitution. The light gray spheres represent magnesium (Mg) atoms, the light gray octahedra contain silicon (Si) atoms in their centers and oxygen (O) atoms at the corners. The dark gray sphere represents an aluminum (Al) atom, and the dark gray octahedron contains an aluminum atom in its center.

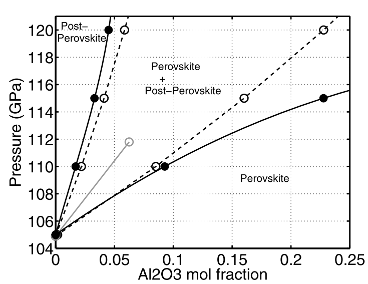

Figure 2: Phase diagram of $MgSiO_3$, for MgSi $\rightarrow$ AlAl substitution. The dashed curves are derived from Henry's Law, whereas the solid black curves are from regular solution theory. The gray curve corresponds to the pseudo-univariant phase transition. A temperature of 2500 Kelvin was assumed.

High pressure petrology

In order 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.

Recent 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).

Panero, W. R., S. Akber-Knutson, and L. Stixrude, Al_2O_3 incorporation in $MgSiO_3$ perovskite and akimotoite. *Earth Planet. Science Lett.*, (in press).

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.

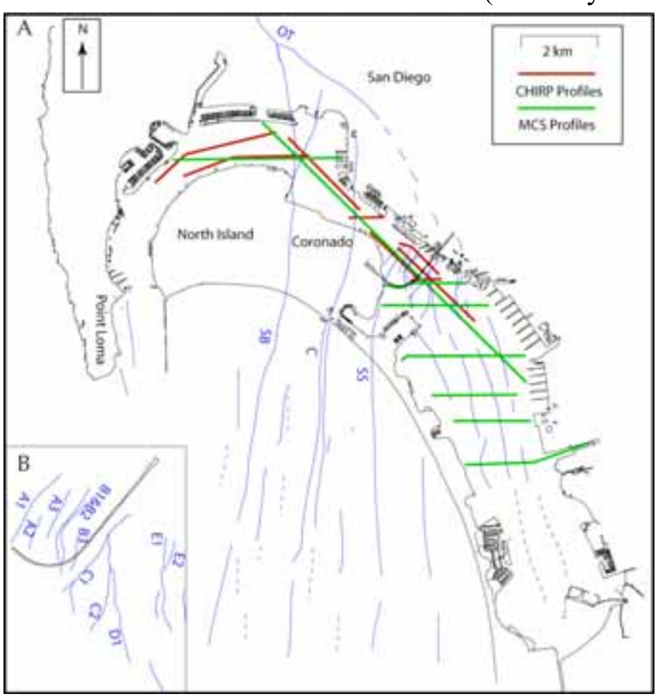

Figure 1: Location of faults and seismic profiles in San Diego Bay. San Diego Bay is an extensional depression formed by a right-step in the Rose Canyon Fault to the offshore Descanso Fault. Major faults in the basin are the Spanish Bight (SB), Coronado (C), Silver Strand (SS), South Coronado Bridge 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.

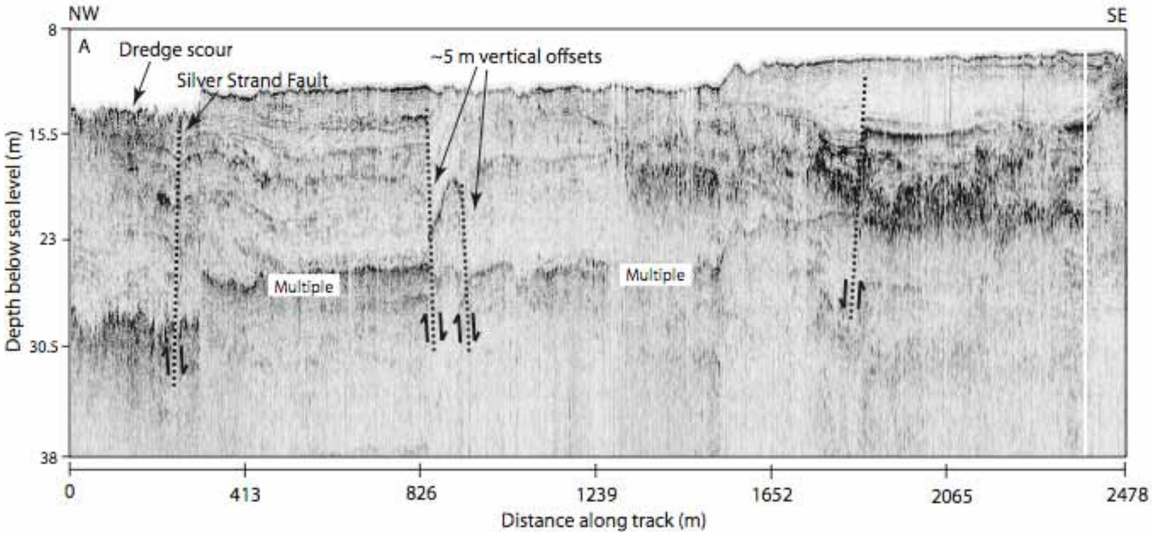

Figure 2: NW-SE trending chirp profile showing significant fault related deformation. Chirp profiles help locate potential sites for sediment cores.

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.

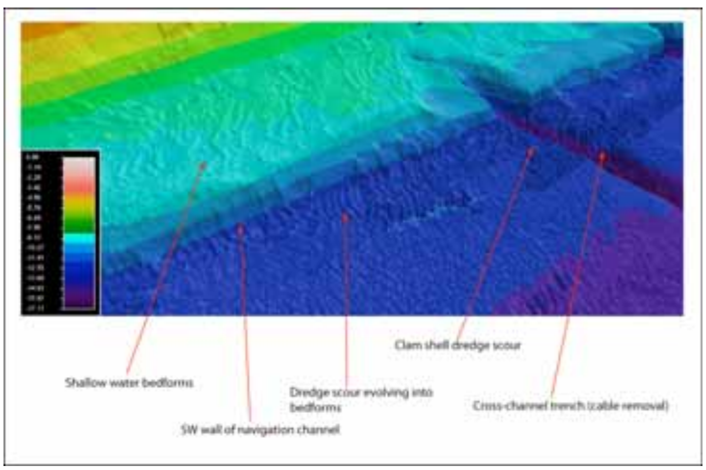

Figure 3: Shallow water bedforms near the Coronado side of the channel (looking east).

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: Global seismological observations , Geophysical instrumentation, , Deep ocean observing platforms, Global communications systems.

In the decade since the last comprehensive model of ambient earth noise was published (Peterson Low Noise Model, Peterson, *1993*), observations of ambient earth noise from the IRIS Global Seismographic Network of widely distributed, similarly equipped, and well-calibrated stations have become available. We have analyzed data from the 118 GSN stations operating during the year July 2001 through June 2002. Based upon over 738,000 hourly spectral estimates computed from these stations' data, we have developed a robust noise model that exhibits significant differences from previous models both in the normal mode and body-wave bands. The left panel of Figure 1 shows our results for the various percentile distributions of the spectral estimates of GSN noise levels. Over most of the bandwidth covered by the GSN, the 1st-percentile spectral values are significantly lower than those of the Peterson Low Noise Mode (PLNM). The exception to this is for periods less than about 0.4 seconds. Here the minimum spectral values of the GSN Noise Model are significantly higher than those for the PLNM. As Peterson (*1993*) noted in his analysis, there was inadequate data to determine the noise for periods shorter than 0.5 seconds - the data set from the latter two stations consisted of a single 4096–sample section. stations consisted of a single 4096–sample section.

The minimum horizontal component noise levels are less than the vertical component noise levels through the microseism band but considerably higher for periods longer than about 30 seconds. There is no systematic bias between the levels of the two directions of horizontal noise. At long periods, some of the horizontal component noise may be caused by local atmospheric pressure fluctuations but a more likely source is thermally induced tilts. The lowest horizontal-component

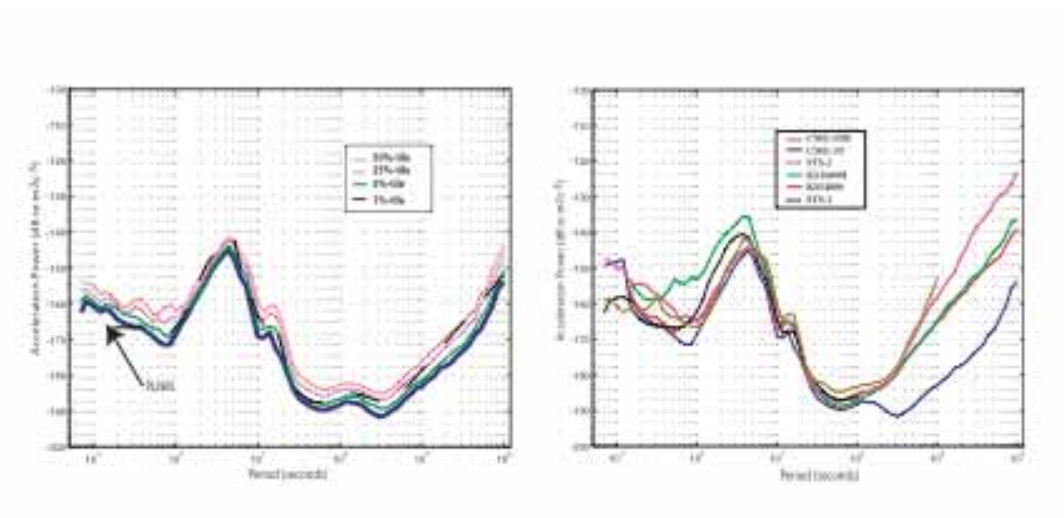

Figure 1. The left panel shows the GSN minimum noise levels at the 1st, 5th, 25th, and 50th noise

levels are observed at stations where the seismometers (all STS-1) are located in tunnels or very well insulated vaults. All minimum noise levels, both horizontal and vertical, are observed on STS-1 seismometers for periods longer than 1.4 seconds. At periods longer than about 120 seconds, the observed vertical component minimum noise levels are lower than the theoretical KS54000 seismometer instrument noise. At periods longer than about 300 seconds, the observed vertical component noise levels are close to the theoretical STS-1 seismometer noise. These results point to the need for improved seismometers at many of the stations. These results point to the need for improved seismometers at many of the stations.percentiles for all station and channels with the Peterson low noise model for comparison. The right panel shows the noise as a function of sensor type.

As the superior STS-1 seismometers are no longer manufactured, we (Mark Zumberge, Erhard Wielandt, and Jose Otero) have designed and build a new observatory-class sensor that uses optical fiber interferometry to record the motion of an inertial mass. The use of optical fiber interferometry rather than traditional electronic displacement transducers affords significant advantages, including: a linear, high-resolution displacement sensor; displacement measurement referenced to the wavelength of light, providing continuous calibration; increased dynamic range and bandwidth; minimum electronics in the sensor — only optical fiber connection to the seismometer — minimizing heat from electronics in the sensor package and noise pickup from connecting electrical cables; and a smaller package — our design will be applicable to both vault and borehole installations and should be relatively easy to manufacture. The prototype is currently under test at the new underground facility at Pinon Flat Observatory

Figure 3: Optical Fiber seismometer under test at the Pinon Flat Observatory

Relevant Publications

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

Berger, J, Davis, P, and Ekstrom, E., Ambient Earth noise: A survey of the Global Seismographic Network, *J.Gophys.Res.* 109, B11307-11317.

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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 form the core of my research. The approaches used vary both by design and in response to opportunities for seagoing experiments. In 2005/2006 my analyses incorporated data/results from deep sea drilling, shipboard mapping, gravity modeling, and seismic refraction. Recent computer simulations provide insights into patterns of crustal deformation near the intersection of a spreading center and a transform fault.

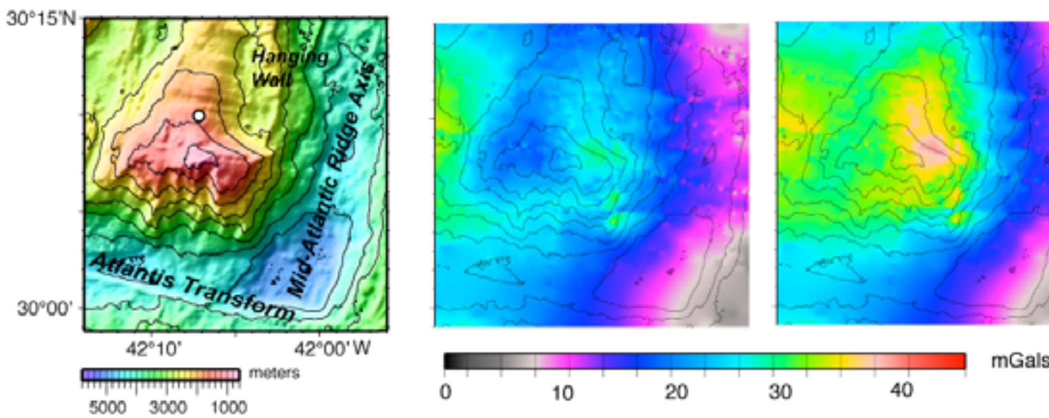

Figure 1: Comparison of gravity models for the oceanic core complex at the Mid-Atlantic Ridge – Atlantis Transform intersection. Seafloor depth map shows shallow domed footwall capped by corrugated detachment fault and down-dropped hanging wall. Circle shows location of 1.4 km deep IODP drill hole where we obtained core and geophysical logs (left). Residual gravity anomaly map of same area. A 3-D processing approach shows that a low density hanging wall and high density footwall can explain much of the gravity signal (middle). 2D processing method produces residual gravity anomaly map that implies remaining high density body within footwall (right).

As chair of the NSF Ridge 2000 program, 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. This year we designed and helped carry out several national and international workshops. New scientific results from Pacific spreading centers were the main emphasis, but modeling of the linked geo-hydro-bio systems was also included; plans for future investigations were discussed. A new aspect of my involvement with the R2K program has been working with colleagues in Education and Outreach.

Collaborative work on seismic anisotropy this year involved linked models of mantle flow, the development of lattice preferred orientation of mantle minerals, predictions of seismic anisotropy, and comparison with observed shear wave polarization directions and splitting. The western US was a main region of emphasis. Cruise planning for a funded experiment in the Lau Basin progressed; scheduling in 2008 is expected. A collaborative proposal was submitted to study mantle structure and anisotropy across the Baja California rift, a component of the NSF Margins program.

Hydroacoustic work this year has involved planning for a year-end cruise in the Southern Ocean which has involved obtaining ship time, arranging gear shipments to New Zealand, checking environmental procedures so our work does not impact marine mammals, after assessing possible distribution in the area, and, looking forward to seeing Antarctica (!)

Relevant Publications

Becker, T.W., Chevrot, S. Schulte-Pelkum, V. and Blackman, D.K., Statistical properties of seismic anisotropy predicted by upper mantle geodynamic models, *J. Geophys. Res.*, in press 2006.

Becker, T. W., Schulte-Pelkum, V., Blackman, D. K., Kellogg, J. B., and O'Connell, R. J., Mantle flow under the western United States from shear wave splitting, *Earth Planet. Sci. Lett.*, 247, 235-251, 2006.

Blackman, D.K., Ildefonse, B., John, B.E., Ohara, Y., Miller, D.J., MacLeod, C.J., and the Expedition Scientists, Proc. IODP, 304/305: College Station TX (Integrated Ocean Drilling Program Management International, Inc.), 2006.

Ildefonse, B., Blackman, D. John, B.E. Ohara, Y. Miller, D.J. MacLeod, C.J. and Expeditions 304-305 Scientists, IODP Expeditions 304 and 305 Characterize the Lithology, Structure, and Alteration of an oceanic core complex, Scientific Drilling, 3, in press 2006.

Van Wijk, J.W. and Blackman, D.K., Deformation of oceanic lithosphere near slow-spreading ridge discontinuities, *Tectonophysics* 407, 211-225, 2005.

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Research Interests: space geodesy, crustal deformation, natural hazards, GIS, GPS seismology

Yehuda Bock's research focuses on space geodetic innovations, which he applies to a wide range of geophysical studies. He also directs the Scripps Orbit and Permanent Array Center (http://sopac.ucsd.edu) and the California Spatial Reference Center (http://csrc.ucsd.edu).

Yehuda has studied since 1989 the role of oblique subduction and interseismic strain segmentation on the earthquake cycle at the Sumatra subduction zone, site of the devastating 26 December 2004, *Mw* 9.1 Sumatra-Andaman and 28 March 2005, *Mw* 8.7 Nias-Simeulue earthquakes (Figure 1). Using survey mode GPS data spanning a 15-year period (1991-2006), continuous GPS data, and vertical deformation recorded by coral microatolls and remote sensing satellites, Yehuda, Linette Prawirodirdjo (at IGPP), and colleagues have observed the end of one earthquake cycle and the beginnings of a new one. The interseismic, coseismic and postseismic phases of this earthquake cycle reveal that the Sumatra megathrust is highly segmented, probably a long-lasting characteristic of this subduction zone. The Nias-Simeulue earthquake ruptured the same region that ruptured in 1861, a 300-km-long segment of the Sumatra subduction zone directly SE of and abutting the rupture zone of the Sumatra-Andaman earthquake. The Mentawai segment of the Sumatra megathrust that ruptured in an *Mw* 8.8 earthquake in 1833, between 0.5°S and 5°S, is fully locked and is flanked by two freely slipping regions, the Batu Islands in the NW and Enggano Island in the SE. Observations of coral heads and modeling of current interseismic deformation on the Mentawai segment of the megathust that last ruptured in 1833 suggests that the occurrence of a similar event in the near future is inevitable.

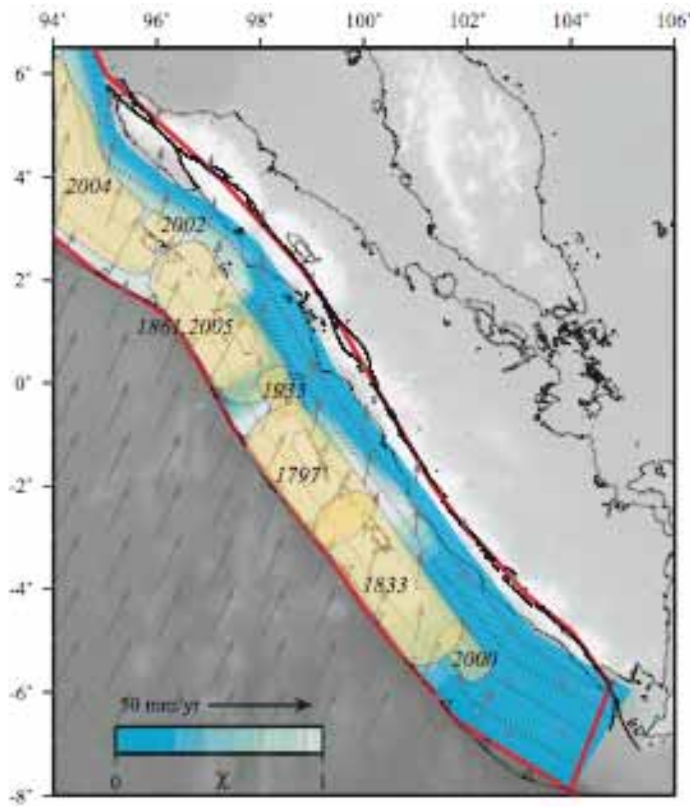

Figure 1: Modeled current interseismic velocity field (arrows) in Sumatra. Shading on the forearc represents the value of the seismic coupling coefficient χ used in model. Yellow patches show estimated rupture zones of significant subduction earthquakes.

Yehuda has been researching the use of real-time GPS networks as a basis for early warning systems for seismic, tsunami, and volcano hazards. He leads the development of the California Real Time Network (CRTN - http://sopac.ucsd.edu/projects/realtime/), a 1 Hz continuous GPS network for seismic monitoring. Yehuda and Jeff Genrich at IGPP have characterized the noise characteristics of 10-50 Hz GPS data collected in real-time over local and regional scales. IGPP graduate student Fan Yang and Yehuda have developed a Kalman filter to combine in real-time accelerometer data (250 Hz) and GPS data (50 Hz) for measuring displacement seismograms and monitoring structures, and have tested it on a to-scale 7-story structure on UCSD's outdoor shake table at Camp Elliot. Yehuda is applying the results of this research to hazards monitoring of the Etna and Stromboli volcanoes, tsunami warning systems in the Pacific Northwest and the island of Java, Indonesia, seismic hazards mitigation in southern California, and structural monitoring of bridges, buildings and dams.

Yehuda and his group at SOPAC/CSRC are leading a multi-institutional information technology project funded by NASA to develop an on-the-fly data analysis and modeling portal for the Earth Sciences. The focus of this project is to enable direct interaction between modelers and data/data-product providers using Web services, within a unified portal architecture. Modeling applications include, for example, time series analysis of continuous and real-time data, and fault structure. Community resources include access to extensive infrastructure and distributed data archive holdings at SOPAC, an on-line map server/client linked to a GIS database, and a "GPS Explorer" data portal that is extensible to heterogeneous data sets.

Relevant Publications

Bock, Y., S. Wdowinski, A. Ferretti, G. Cecconi and G. Savio, Subsidence of the Venice Lagoon from continuous GPS and InSAR permanent scatterers, submitted to GRL. 2006.

Briggs, R. W., K. Sieh, A. J. Meltzner, D. Natawidjaja, J. Galetzka, B. Suwargadi, Y.-J. Hsu, M. Simons, N. Hananto, I. Suprihanto, D. Prayudi, J.-P. Avouac, L. Prawirodirdjo and Y. Bock, Deformation above and slip on the Sunda megathrust during the giant Nias-Simeulue (Indonesia) earthquake of March 2005, *Science*, *311*, 1897-1901, doi: 10.1126/science.1122602, 2006.

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Genrich, J. F. and Y. Bock, Instantaneous geodetic positioning with 10-50 Hz GPS measurements: Noise characteristics and implications for monitoring networks, *J. Geophys. Res., 111,* B03403, doi:10.1029/2005JB003617, 2006.

Hsu, Y.-J., M. Simons, J.-P. Avouac, J. Galetzka, K. Sieh, M. Chlieh, D. Natawidjaja, L. Prawirodirdjo, and Y. Bock, Frictional afterslip following the Mw 8.7, 2005 Nias-Simeulue earthquake, Sumatra, *Science 312*, 1921-1926, doi: 10.1126/science.1126960, 2006.

Langbein, J. and Y. Bock, High-Rate Real-Time GPS Network at Parkfield; Utility for Detecting Fault Slip and Seismic Displacements, *Geophys. Res. Lett., 31*, doi:10.1029/2003GL019804, 2004.

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Subarya, C., M. Chlieh, L. Prawirodirdjo, J.-P. Avouac, Y. Bock, K. Sieh, A. J. Meltzner, D. H. Natawidjaja, and R. McCaffrey, Plate boundary deformation associated with the great Sumatra-Andaman earthquake, *Nature*, *440*, doi:10.1038/nature04522, 46-51, 2006.

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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 2006 has built on her interests in geomagnetism and paleomagnetism, particularly in recent and long term secular variations of the geomagnetic field. Other work includes using satellite magnetic field data to study mantle conductivity, 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. Side interests have been work with **Hubert Staudigel** analyzing long time series of temperature data from Vailulu'u seamount and with Andy Jackson (ETH, Zurich) on algorithm development for modern magnetic field modeling.

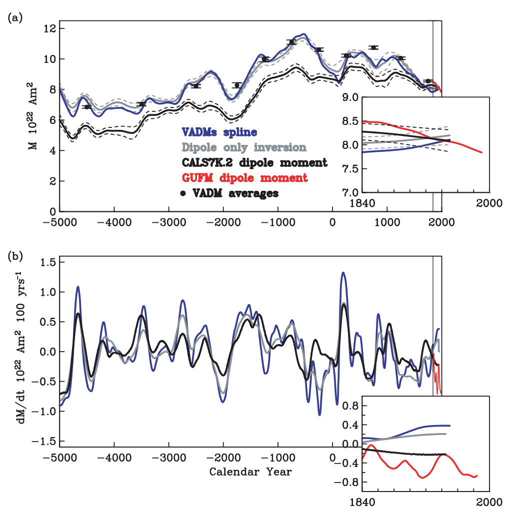

Figure 1:
(a)Various dipole moment estimates for the past 7 kyr - the new field model CALS7K.2 is considered most reliable. Note the good agreement in the time interval overlapping with the historical model GUFM.

(b) Rates of change associated with the dipole moment estimates in (a). The current rate for CALS7K.2 and other paleoestimates is not unusual compared with other activity over the 0-7ka interval.

Much of our understanding about the geomagnetic field comes from paleomagnetic data of various kinds which are needed to sample the longer term changes on thousands to millions of years, that are an intrinsic part of field behavior and can include geomagnetic excursions and reversals. The development of a global view from sparsely distributed paleomagnetic data of rather low accuracy (compared with direct observations) has evolved rather slowly. A major recent accomplishment (in collaboration with Monika Korte of GeoForschungsZentrum, Potsdam) is the global syntheses of paleomagnetic data from the past 7 thousand years to provide a global time-varying description of field. This work showed that flux-lobes seen in the historical magnetic field and often thought to be a manifestation of thermal influences at the core-mantle boundary are not fixed structures: they change positions and relative strengths over time; however, they seem to a quasi-permanent feature of the field and there are particular regions, such as beneath the central Pacific, that they rarely venture to occupy. Analysis of the field has shown that the geomagnetic dipole moment varies on shorter time scales than previously documented, and that the current trend of decreasing dipole moment is a temporary feature when viewed in the context of millennial scale magnetic field variations. See Figure 1. These millennial scale magnetic field models are being used for a broad range of further applications including paleoclimate studies based on radionuclide variations, reconstructing historical voyages of exploration, and magnetostratigraphic applications in archeological and geological settings. The current models have become an essential tool for assessing quality and consistency of new archeomagnetic and paleomagnetic data sets.

Lisa Tauxe, Hubert Staudigel, **Catherine Johnson** and Cathy Constable have continued their work on the analysis of paleomagnetic samples from lava flows in the age range 0-5 Ma from globally distributed locations, using the resulting paleodirectional and paleointensity data to elucidate the second order structure of the geomagnetic field, and determine whether the above mentioned features in the historical record persist over geological time scales. Such data sets also form the basis for a statistical approach to models of paleosecular variation, a topic that has occupied the group at SIO for several decades now. In recently published work, graduate student Kristin Lawrence analyzed a comprehensive new data set drawn from lava flows at latitudes around 20° to show that the long term field structure is not adequately described by any of the current global models. A preliminary power spectrum for geomagnetic dipole moment variations ranging from periods of centuries to tens of millions of years is described in the publication by Constable & Johnson (2005). The spectrum will aid development of statistical paleosecular variation models by allowing a sensible temporal covariance to be introduced: the covariance cannot be obtained directly from lava flows whose temporal relationships are not well defined, so the temporal dependence is currently lacking in these models, limiting their capabilities to provide ground truth for the output of numerical geodynamo simulations. Graduate student Leah Ziegler is also investigating the feasibility of extending time-varying field models to much longer (million year) time scales.

Other work (with **Steven Constable**, former postdoc Nicola Richmond and PhD student Joseph Ribaudo) is concerned with using satellite magnetic data to derive electrical conductivity profiles that can assist seismologists and mineral physicists in inferring the temperature and composition of Earth's mantle. Models of mantle conductivity have been largely based on magnetic observatory data, many of which are located on or near the coast and suffer contamination from the large conductivity contrast between the continents and oceans. The satellite observations not only have better coverage, but a better average view because of their significant elevation above Earth's surface. Earlier analyses have set the stage for work of this kind using data from the now dated Magsat mission. Improved data collected by the Ørsted satellite have allowed us to explore non-uniformity in spatial structure of the external source field whose time variations induce the secondary field in the mantle: the results are leading to new algorithms for evaluating Earth's electromagnetic response. However, the movement of the satellite through the temporally varying field it is measuring complicates separation of primary and induced signals. Unraveling these effects will ensure that the satellite induction problem remains a challenging one for the next few years.

Further information can be found at *http://igpphome.ucsd.edu/ cathy/Projects*

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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.

Korte, M., & C.G. Constable, Continuous geomagnetic models for the past 7 millennia II: CALS7K, *Geochem. Geophys. Geosyst.*, 6(2), Q02H16 DOI 10.1029/ 2004GC000801, 2005.

Constable, C.G., & C.L. Johnson, A Paleomagnetic Power Spectrum, *Physics Earth Planet. Inter.*, 153, 61–73 doi:10.1016/j.pepi.2005.03.015, 2005.

Constable, C.G., & M. Korte, Is Earth's magnetic field reversing?, *Earth Planet. Sci. Lett.*, 246, 1–16, doi: 10.1016/j.epsl.2006.03.038, 2006.

Lawrence, K., C. Constable, & C. Johnson, Paleosecular variation and the average geomagnetic field at $\pm$ 20° latitude, *Geochem. Geophys. Geosyst.*, 7, Q07007, doi:10.1029/2005GC001181, 2006.

Steven Constable
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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 now consists of postdoctoral scholars Kerry Key, Yuguo Li, and James Behrens 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 the NSF. Besides marine EM, Constable has been working this year with student Ashley Medin and professor Bob Parker on estimating temperature and water content in Earth's mantle using conductivity measurements (see **Robert Parker**) and student Joseph Ribauldo, postdoc Nic Richmond, and professor Cathy Constable on estimating Earth conductivity from satellite magnetometer measurements (see **Catherine Constable**).

Work has been ongoing this year to interpret and publish results from the APPLE project (Figure 1), a marine EM experiment designed to study anisotropy in the oceanic mantle of the northeast Pacific, and magnetotelluric (MT) and marine controlled source EM (CSEM) results from the spreading ridge at the East Pacific Rise (Figure 2).

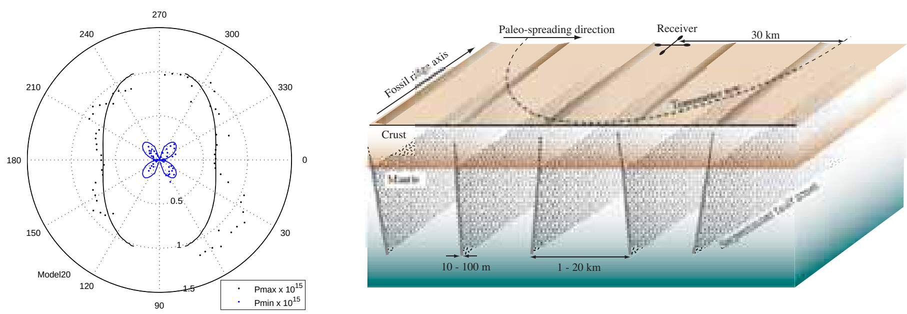

Figure 1. CSEM data from a circular transmitter tow around a central EM receiver, expressed as major (black) and minor (blue) axes of the polarization ellipse as a function of direction to the transmitter (left). The cloverleaf shape of the minor axis and the elongation of the major axis indicates anisotropy, which we model (solid lines) and interpret as serpentinized faults in the upper mantle (right).

Several new projects were initiated this year, starting with a 50-site marine MT survey for BP America in the Gulf of Mexico in October 2005, designed to map the 3D structure of a salt body using marine MT. Seismic methods sometimes have difficulty determining the boundary of the salt, especially if there are steeply dipping roots. Salt is much more resistive than the surrounding sediments, so electrical methods can often image the edge and base of salt quite well.

In May this year we carried out some instrument tests in the San Diego Trough, designed to evaluate advanced methods for imaging deep hydrocarbon reservoirs (funded by ExxonMobil) and to evaluate a controlled-source MT technique that would boost the MT signal for seafloor sites in the band 10 Hz to 0.1 Hz, where the natural MT signal is often too small to measure (funded by AGO/Schlumberger). During the cruise we collected MT and CSEM data over the Catalina Crater structure, whose origin is not known; it could either be an impact crater or a volcanic feature.

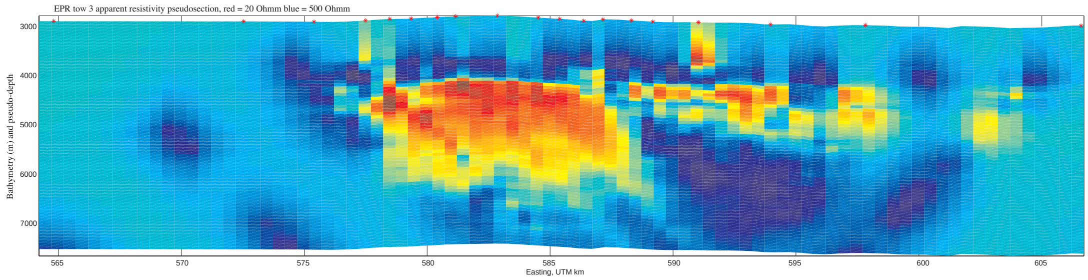

Figure 2. Apparent resistivity pseudo-section of CSEM data collected over the East Pacific Rise, showing a large conductivity anomaly (red) where the crustal magma chamber is thought to be.

Our third and last cruise was in July, in which 5 days of U.C.–funded shiptime on the R.V. Roger Revelle was used to carry out an electromagnetic tomography experiment over Loihi Seamount, the southernmost eruptive edge of the Hawaiian volcanic chain. In this innovative experiment, twenty EM receivers were deployed in a circle around the rim of the vocano about 1,000 m below the summit, and the newly commissioned 500 A transmitter (SUESI-500) was deeptowed around the ring of instruments, transmitting through the volcano to all the receivers.

Karen Weitemeyer continued to work on her CSEM and MT data set from Hydrate Ridge, Oregon, publishing some preliminary results in various forums. We are in the process of planning further EM studies of seafloor gas hydrate deposits in the Gulf of Mexico. Yuguo Li and Kerry Key released 2-dimensional forward modeling codes for marine MT and CSEM studies. These codes incorporate new algorithms for refining a 2D finite element mesh made up of unstructured triangles, as well as a MATLAB interface for creating the model meshes and imaging the results. This work was supported by BP America, along with the Seafloor Electromagnetic Methods Consortium, which now consists of over 20 sponsors.

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

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Weiss, C.J., and S. Constable, Mapping thin resistors in the marine environment, part II: Modeling and analysis in 3D, *Geophysics*, in press, 2006.

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Constable, S., and C.J. Weiss, Mapping thin resistors (and hydrocarbons) with marine EM methods: Insights from 1D modeling, *Geophysics*, 71, G43–G51, 2005.

J. Peter Davis

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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 40 seismographic and geophysical data collection stations distributed among 24 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. Peter Davis's recent work involved using the free oscillations of the Earth excited by the 2004 Sumatra-Andaman Islands earthquake to evaluate the accuracy of instrument response information published by the GSN. Investigators use this information to remove from recorded data the effect 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. The Sumatran earthquake provided a rare opportunity to use the Earth to test independently the accuracy of information derived from laboratory experiments.

That extraordinarily large quake caused the planet to vibrate at very low frequencies detectable by modern seismometers. These resonant vibrations were observed at many stations around the world, in some cases for several months afterward. One oscillation called ${}_0S_0$ has a unique attribute that was particularly useful for this study: to a close approximation, ${}_0S_0$ has the same properties (frequency, amplitude and phase) when observed from any point on the Earth's surface. Peter Davis lead a study to measure this oscillation's properties at all stations of the GSN. If the response information provided by IDA and other GSN network operators were correct, these measurements would be consistent from station to station.

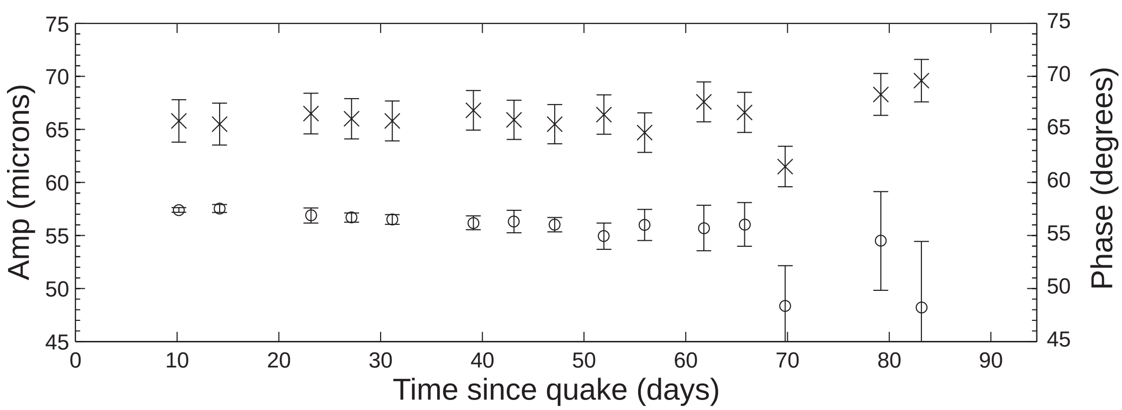

Figure 1: Measurements of the amplitude (o) and phase (x) of the mode ${}_0S_0$ observed at a single station, TLY (Talaya, Russia). This mode remained observable nearly three months following the Sumatra-Andaman earthquake that excited it.

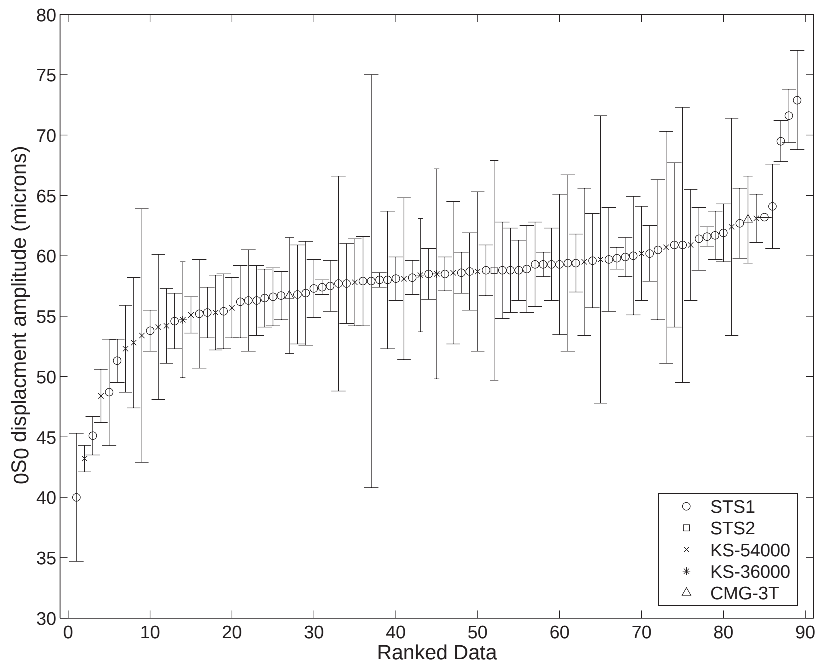

Figure 2: Composite results of $_0S_0$ amplitude measurements for the entire GSN.

Figure 1 shows the measurements made for an outstanding IDA station, Talaya, Russia. Located in Siberia far from oceanic noise sources, TLY recorded $_0S_0$ for almost three months. The very long recording period permitted the properties of $_0S_0$ to be measured very precisely. The same procedure was repeated for all other GSN stations. The summary of those measurements is shown in Figure 2. Stations whose measurements fall on the tails of the distribution (to the left and right) will be subjected to further testing to check if their sensor's behavior is properly characterized.

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

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Park, J., T.-R. Song, J. Tromp, E. Okal, S. Stein, G. Roult, E. Clevede, G. Laske, H. Kanamori, P. Davis, J. Berger, C. Braitenberg, M. Van Camp, X. Lei, H. Sun, H. Xu and S. Rosat, Earth's free oscillations excited by the 26 December 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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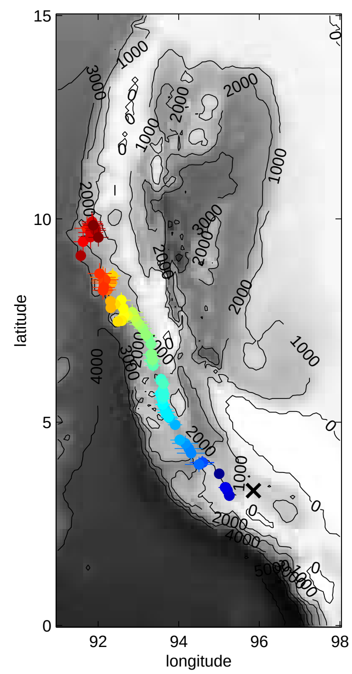
Research Interests: Analysis of hydroacoustic signals from sub-oceanic earthquakes and their use in determining rupture properties; propagation modeling of infrasound signals generated by mining and atmospheric explosions and their use in nuclear test-ban verification.

Hydroacoustics: Submarine earthquakes shake the seafloor, generating sounds that can travel through the water for thousands of kilometers. Although various properties of an earthquake source can be inferred from the analysis of the low frequency acoustic waves produced by the source, the analysis of these sound waves has primarily been limited to deriving source epicentral locations. This changed with a recent analysis of hydroacoustic signals generated by the Great Sumatra earthquake of Dec 26, 2004; that rupture tore through a nearly 1300 km section of fault where the Indian tectonic plate plunges beneath the Sunda plate, generating sound waves along the entire rupture path.



Hydroacoustic waves from by this rupture were recorded at hydrophone stations operated by the Comprehensive Nuclear-Test Ban Treaty (CTBT) Organization in Vienna and analyzed by several groups, including my group at IGPP. The results showed that the locus of the sound source, which followed the fault rupture, moved slowly to the northwest along the Sunda trench where the fault between the two tectonic plates lies. The acoustic data indicate there were two phases of fault rupture; the first phase started from a point near the rupture nucleation point and progressed northwest at a rate of about 2.4 km/s along a nearly 600km segment of the plate boundary. The acoustic source locations were somewhat less certain for points further north, but suggest that the rupture slowed to approximately 1.5 km/s as it advanced to the northwest.

Further work is progressing on deriving properties of small-scale sub-oceanic earthquakes from the hydroacoustic signals they generate; results of this work have the potential to impact tectonic studies over the sparsely instrumented areas of the world's oceans.

Infrasound: The study of infrasound, or low frequency sound waves, is invaluable for nuclear monitoring efforts. Infrasound can generated by a wide variety of naturally-occuring events (volcanoes, earthquakes, surf noise, or bolides), as well as man-made explosions, including mining blasts. The means by which sound energy is excited by sources at or below the Earth's surface, *e.g.*, volcanoes or mining blasts, is a topic of active research interest by our group at IGPP; we are currently developing modeling methods to improve our ability to predict the infrasonic arrivals at stations near volcanoes, and known mining areas. The propagation of sound through the atmosphere is strongly affected by winds and turbulence; we are also developing modeling and inversion methods to improve our ability to locate sources of infrasound.

Relevant Publications

de Groot-Hedlin, C.D., and Orcutt, J.A., "Synthesis of earthquake-generated T-waves", Geophys.

Res. Lett., **26**, 1277-1230 (1999).

de Groot-Hedlin, C.D., and Orcutt, J.A., "Excitation of T-phases by seafloor scattering", J. Acoust. Soc. Am., **109**, 1944-1954 (2001).

de Groot-Hedlin, C.D., "Criteria for discretization of seafloor bathymetry when using a stairstep approximation: application to computation of T-phase seismograms", J. Acoust. Soc. Am., **115(3)**, 1103-1113 (2004).

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., "Modeling infrasound waveforms in a windy environment", Inframatics, **10**, September (2005).

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Research interests: ocean acoustic tomography, signal processing

Matthew Dzieciuch's research focuses on understanding sound propagation in the ocean. Specifically low-frequency sound that 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. In my particular area of interest, ocean acoustic tomography, 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. The goal of this work is to understand how this happens and to determine the validity of the ray approximation.

An example of why this is important are the non-geometric shadow zone arrivals recently measured in the NPAL 2004 experiment. A simulated example of this is shown in the top panel of Figure 1. The arrow points to an arrival at a reciever 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.

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.

Although we still have much to learn from the application of the full-wave kernel to ocean sound propagation, this new tool has shed much light on the scattering physics involved.

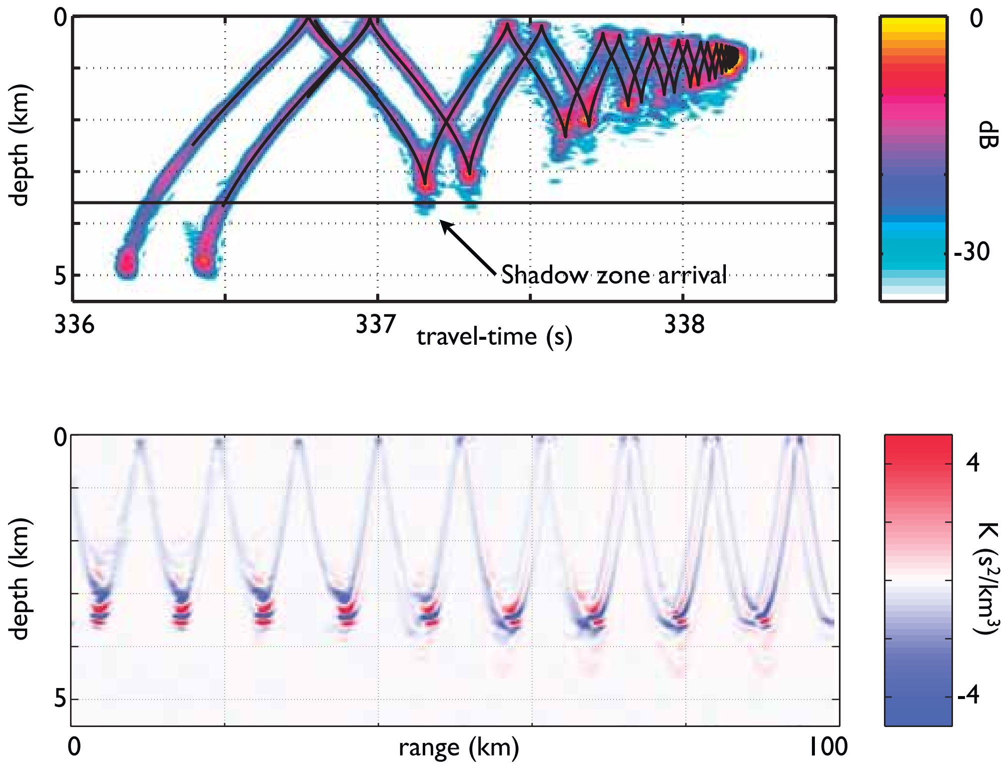

Figure 1: shadow zone tsk.

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).

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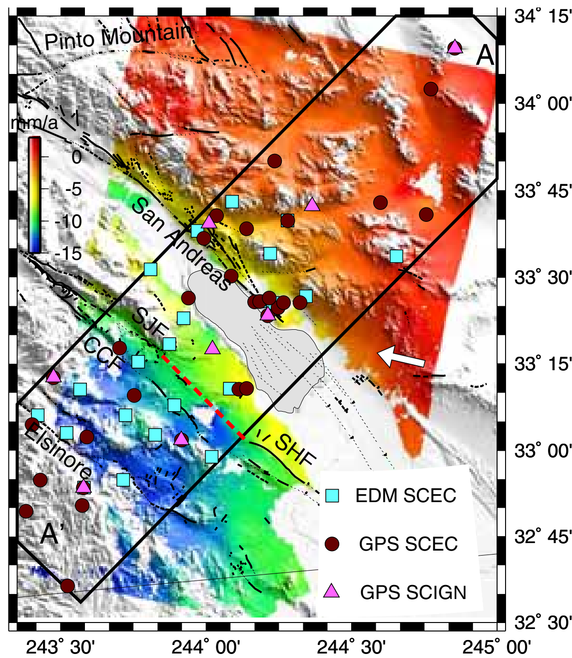
Research interests: earthquake physics, crustal deformation, space geodesy

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. Over the last year, Fialko studied interseismic strain accumulation on the southern San Andreas Fault (SAF) system using the the spatially and temporally dense Interferometric Synthetic Aperture Radar (InSAR) data collected between 1992 and 2000, and point measurements of surface velocities representing a time interval between 1985 and 2005 (Figure 1). Space geodetic data shown in Figure 1 demonstrate that the southern SAF is accumulating significant elastic strain, as indicated by a broad area of high gradient in the LOS velocity field on the eastern side of the fault. A prominent feature of strain accumulation on the southern San Andreas fault that was not recognized in previous studies is a significant asymmetry in the velocity gradient with respect to the fault trace. This asymmetry may be due to dissimilar elastic properties of rocks on different sides of the fault. Given the measured slip rate of 25 ± 2 millimeters per year, the minimum amount of slip deficit accrued on the southern SAF over the last 300 years is of the order of 6-8 meters, close to, or in excess of a maximum interseismic slip deficit ever documented on the fault by paleoseismologic studies. These results imply that the southern SAF is in the late phase of interseismic loading.

Another earthquake-related project that involved the use of space geodetic data was a study of coseismic deformation due to the M_w6.6 Bam earthquake in Iran. Fialko derived the full vector displacement field due to the Bam earthquake using Advanced Synthetic Aperture Radar data from the Envisat satellite. Analysis of surface deformation indicated that most of the seismic moment release along the 20 km-long strike-slip rupture occurred at a shallow (4-5 km) depth, yet the rupture did not break the surface. The Bam event is therefore an end-member case of the shallow slip deficit model postulating that the coseismic slip in the uppermost crust is systematically less than that at the seismogenic depth (4-10 km). The 3D coseismic displacement data from the Bam and other large shallow earthquakes suggest that the uppermost section of brittle crust may undergo a distributed failure (thereby accumulating little elastic strain) in the interseismic period. Prof. Fialko also studied relationships between the present-day topography and kinematics of motion on the San Andreas fault system to address a long-standing question of the magnitude of shear stress at which major crustal faults operate throughout the earthquake cycle. This work takes advantage of the fact that the major bends of the San Andreas fault in California are associated with significant variations in the along-fault topography. Fialko showed that the topography-induced perturbations in the intermediate principal stress may cause the fault rotation with respect to the maximum compression axis provided that the fault is non-vertical, and the slip is horizontal. The progressive fault rotation may produce additional topography via thrust faulting in the adjacent crust, resulting in a positive feedback. The observed rotation of the fault plane due to the along-fault variations in topography was used to infer the magnitude of the in situ differential stress. Fialko's results suggest that the average differential stress in the upper crust around the San Andreas fault is of the order of 50 MPa, implying the effective fault strength that is about a factor of two less than predictions based on the Byerlee's law and the assumption of hydrostatic pore

Figure 1: LOS velocity (color) from a stack of radar interferograms from the ERS track 356 spanning a time interval between 1992 and 2001. The velocity map is draped on top of the SRTM digital topography. Black wavy lines denote the active Quaternary faults. Color symbols denote positions of the GPS and EDM (electronic distance measurement) sites within the profile. Data from these sites are provided by the Southern California Earthquake Center (SCEC) and Southern California Integrated GPS Network (SCIGN).



pressures. Other recent research involved studies of the effects of melting on the dynamic faults friction during earthquakes, the origin of kimberlitic magmas, and precise locations of mining-induced earthquakes using satellite imagery.

Recent publications:

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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.

ICESat calibration: To calibrate ICESat, Helen (together with graduate student Adrian Borsa) led an expedition to the salar de Uyuni in Bolivia, the flattest surface on Earth, where they used GPS to make a precise Digital Elevation Model (DEM) of the surface and compared this DEM to the ICESat data (Fricker et al., 2005a). This is part of ongoing ICESat Science Team duties.

Ice shelf rifting: In 2005-06, Helen and her research group (including graduate student Jeremy Bassis) have continued to study **rifts** at the front of the ice shelves. Rifts are fractures which cut to the base of the ice shelves and eventually lead to tabular iceberg calving. Iceberg calving accounts for 2/3 of the total mass loss from Antarctica, yet little is known about the processes involved in rift propagation, and we do not know how these processes will respond to climate change. To address this deficiency, Helen's group and their colleagues study the propagation and evolution of active rifts using a combination of fieldwork and satellite remote sensing (see http://eqinfo.ucsd.edu/~helen/amery_rift. Satellite imagery acquired over a 6 year time series has revealed important information about rift propagation, on longer time-scales, showing that propagation is faster in the summer than in winter (Fricker et al., 2005a). For four consecutive field seasons, 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.

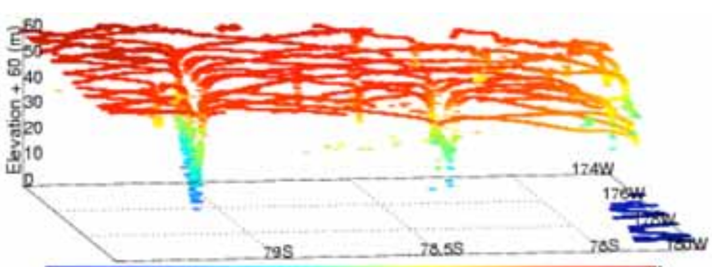

Figure 1: 3-d rendition of ICESat elevation profiles across rifts on the Ross Ice Shelf.

In 2005-06 Helen has used ICESat data to study the vertical structure of rifts and the mélange which fills them, revealing that mélange accounts for about 30% of the entire ice shelf thickness (Fricker et al., 2005c; Figure 1). Ice shelf rifts are the subject of a SIO-led International Polar Year (2006-08) project CRAC: Collaborative Research into Antarctic Calving.

Ice shelf grounding zones: In 2005-06, 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 (Figure 2). Helen will use 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.

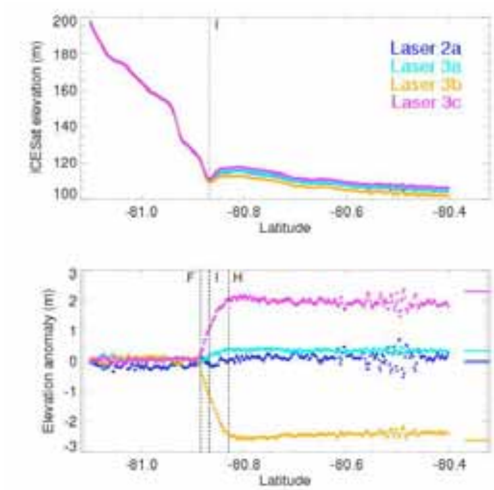

Figure 2. a) ICESat elevation profiles vs latitude for the four valid repeats of Track 218 and b) elevation anomaly values for each repeat. Horizontal lines at right are the equivalent anomalies based on tide predictions from a tide model. I is the break-in-slope; F is the limit of flexure and H is the seaward limit of the GZ**.**

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Fricker, H.A., A Borsa, B Minster, C Carabajal, K Quinn, B Bills. Assessment of ICESat performance at salar de Uyuni, Bolivia, *Geophys. Res. Lett.,* 32, L21S06, doi:10.1029/2005GL023423, 2005b.

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One of the primary goals of mid-ocean ridge studies is to identify and quantify the variables that control crustal accretion and the structure of the oceanic crust. The primary variable is spreading rate: fast spreading ridges, such as the East Pacific Rise, are characterized by steady state magma chambers and an axial high, while slow spreading ridges, are characterized by axial rift valleys and intermittent magma chambers. At intermediate spreading rates, ~50-100 mm/yr full rate, the state of the ridge is sensitive to both spreading rate and magma supply as measured by crustal thickness. Current work in the Lau back-arc basin, an integrated study site for the NSF sponsored Ridge 2k program, allows us to look systematically at another crustal accretion variable - proximity to the volcanic arc, and the influence of the metasomatized mantle wedge that lies above the subducting Pacific plate, Figure 1. The Lau basin is spreading at intermediate rates and one result from our multichannel seismic (MCS) data and other geophysical datasets, is that as expected the state of the ridge axis, rift or axial high, is sensitive to crustal thickness, which in turn reflects the productivity of the mantle wedge.

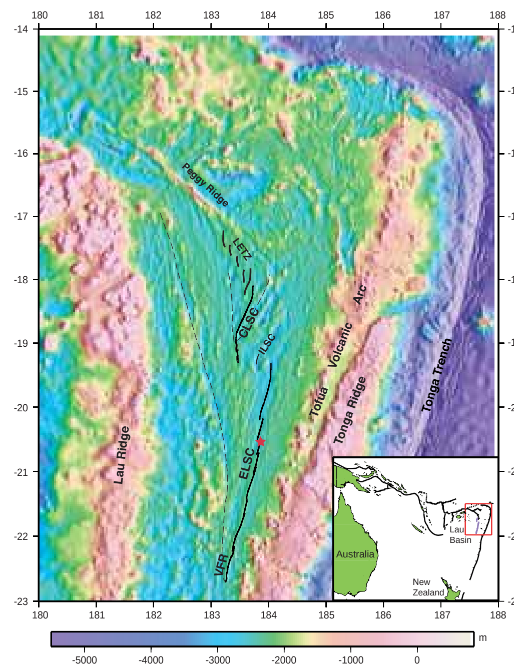

Figure 1 The Lau back-arc basin with major spreading centers, the central Lau spreading center (CLSC), the eastern Lau spreading center (ELSC) and the Valu Fa ridge (VFR). South of the transition segment at 20° 30' S (red star) the structure of ELSC/VFR exhibits progressively stronger subduction zone influenced as it approaches the Tofua volcanic arc.

A more systematic look at upper crustal velocity structure by graduate student, Allison Jacobs, Dr. Graham Kent and myself reveals other systematic trends in crustal structure associated with the volcanic arc. MCS data, bathymetry and petrology reveal that the arc influence arrives abruptly over a short 25 km segment at 20° 30’ S, where the ridge transitions from a rift to an axial high, a steady state magma chamber is recovered and the erupted lavas become significantly more silicic. At the same time upper crustal seismic velocities drop discretely and continue to drop southwards as the arc is approached and the lavas become progressively more silicic and viscous. At the southern end of the system, the Valu Fa Ridge magmas are basaltic-andesites to andesites. Although part of the seismic velocity drop can be attributed to changes in chemistry, analysis indicates that a more significant fraction is the result of increased porosity due, perhaps, to the presence of volatiles in the erupted magma.

Another line of reasoning that leads to the same conclusion comes from measuring the ratio of the thickness of erupted volcanic pile to the depth of the magma chamber. For mid-ocean ridges this ratio is relatively constant over a broad range of magma chamber depths (Figure 2), and reflects a simple balance between the buoyancy of the erupting magma and the overburden pressure on the magma chamber. The volcanic piles along the arc-influenced part of the Lau basin are unusually high, defining their own trend, but are readily achievable if exsolution of volatiles during eruption adds to the buoyancy of the magma.

These results begin to quantify the effects of arc influence on crustal accretion. The changes in structure and geochemistry affect other parts of the ridge system such as hydrothermal circulation and biology. They are also of interest because many ophiolites, obducted pieces of oceanic crust, are thought to have formed in back-arc basins, thus it is of interest to quantify systematic changes in structure associated with this setting as opposed to standard mid-ocean ridges.

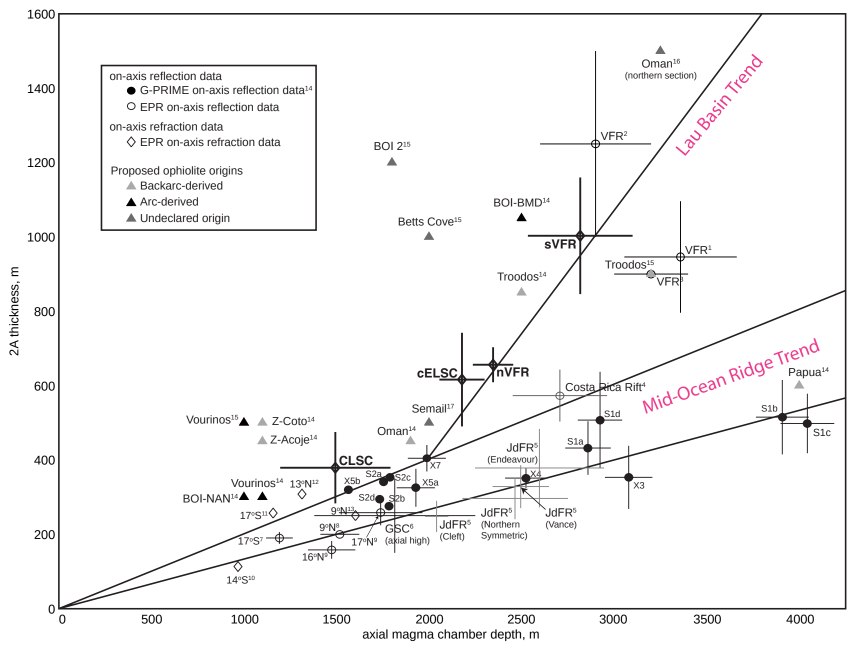

Figure 2 Ratio of erupted extrusives, layer 2A to magma chamber depth showing the mid-ocean ridge trend and the distinctive Lau basin trend south of the transition segment as the possible result of volatile exsolution during eruption. Ratio for ophiolites are plotted for comparison

References:

Axial crustal structure of the Lau back-arc basin from velocity modeling of multichannel seismic data, A. M. Jacobs, A. J. Harding, G. M. Kent, submitted to *Earth Planet. Sci. Lett.*

Lau basin 3D visualizations at *http://ridgeview.ucsd.edu/index_lau.html*

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

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

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

Volcano acoustics: We believe that to properly characterize activity within volcanoes it is necessary to study the entire wavefield – that is downgoing seismic and upgoing acoustic energy. We anticipate that infrasound will also emerge in the next few years as an important tool for closely monitoring volcanoes for ash releases that might threaten aircraft and might not be detected on other monitoring systems, such as seismic networks and satellites. Following the recent eruptive activity at Mount Saint Helens (MSH), our group joined forces with the Geological Survey of Canada to deploy two infrasound arrays near this volcano. One 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.

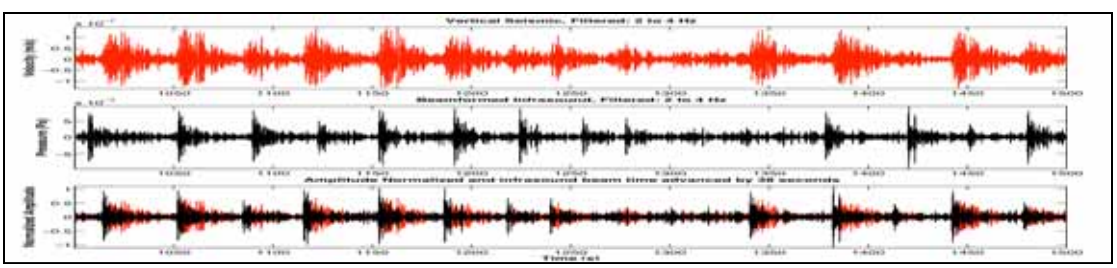

Figure 1: Seismic and infrasound signals from Mt St Helens are shown in the upper two traces. The two records are plotted together (bottom) after advancing the infrasound record 38 seconds to account for the propagation delay. The infrasound and seismic signals clearly have a common source within the 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 is currently building 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. Data from most arrays are telemetered in realtime to our lab in La Jolla. Our research is conducted on several 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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While the power of numerical computing grows exponentially, with consequences apparent in the literature, it is less appreciated that specific tools of analysis have experienced a nearly commensurate increase. A theme common to nearly all of the research I have pursued over the past decade, which exploits this analytic capacity either as a significant adjunct to the development of numerical means of exploration, or in purely its own right, is a focus on precisely stated theses and precisely constructed solutions. The setting for this work has generally consisted in the determination of rigorous bounds on turbulent processes, such as convection and shear flow.

There are many computer simulations of turbulent flow, but the dynamic range accessible with "direct numerical simulation" (DNS), i.e. accurately solving the fundamental equations believed to describe the motions on all length scales, remains small. In the notable case of geophysical flows, as in the atmosphere and ocean, the regimes of interest are many orders of magnitude removed from the possibility of such simulation. Various approximations are used to permit solution beyond the range of DNS but the influence of such approximations on the solutions obtained is in most cases not well enough understood to permit any intrinsic error estimates. For this reason, it is useful to have independent means by which one can give definite bounds for various mean properties of turbulent flows; bounds that the fundamental equations must certainly satisfy and bounds that, moreover, can be accurately determined for arbitrarily large values of the relevant governing parameter.

While on sabbatical in July of 2002, I began what grew into a major collaborative effort with Dr. Richard Kerswell at Bristol University and his doctoral student Steven Plasting to bound the heat transported by convection in a fluid of infinite Prandtl number as a function of the vertical temperature gradient across a horizontal layer,[1] a problem previously the subject of considerable study by S. K. Chan in 1971. Our own work was completed in January 2006.

The Prandtl number is a dimensionless ratio of the fluid viscosity to its thermal conductivity. For large values of this ratio—as in the case of mantle convection in the Earth—there is a striking simplification in the equations governing the fluid motion because a key nonlinear term drops out. Paradoxically, it emerges that the same simplification actually complicates determination of an upper bound on the heat flux since the associated variational method by which such bounds are determined is found to yield equations of a highly singular nature.

The general method for obtaining bounds has been successfully applied to a wide range of fluid problems, but this singularity has not elsewhere been encountered.[2] By the same token, however, these other bounds, though mathematically rigorous statements about the nature of turbulence, are generally not very tight, that is, in the range for which comparison is possible, all lie disappointingly far from results obtained variously through laboratory measurement, field observation, and direct numerical simulation.

The physics of infinite Prandtl number convection, and its mathematical expression

[1] more precisely as a function of the "Rayleigh number," a nondimensionalized version of the temperature gradient

[2] Though it can now be anticipated in related problems, such as doubly diffusive systems also at infinite Prandtl number.

in the form of a singular variational bound, is such that a qualitatively tighter relation between bound and "data" should obtain. Strictly, no real fluid can have an infinite Prandtl number so any comparison with data is necessarily restricted to three-dimensional DNS computations. Nonetheless laboratory results do indicate that convection at large, but finite, Prandtl number closely parallels the foregoing bound. From the standpoint of wishing to obtain the tightest possible bounds on turbulent processes, convection at infinite Prandtl number is thus a model problem of more than usual interest.

One question to which this apparent convergence naturally leads is how one might systematically tighten other bounds when the tightening is not fortuitously brought about by singularity. I have been engaged since midyear working in this direction, with shear flow as the setting.

Recent publications:

Plasting, S. C. and Ierley, G. R., Estimates of heat transport in infinite Prandtl number convection. Part 1: Conservative bounds, *J. Fluid Mech.*, 542, 343-363, 2005.

Ierley, G. R., Kerswell, R. R., and Plasting, S. C., Infinite Prandtl number convection. Part 2: A singular limit of upper bound theory, *J. Fluid Mech.*, 560, 159-227, 2005.

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Research Interests: planetary geophysics, geomagnetism

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.

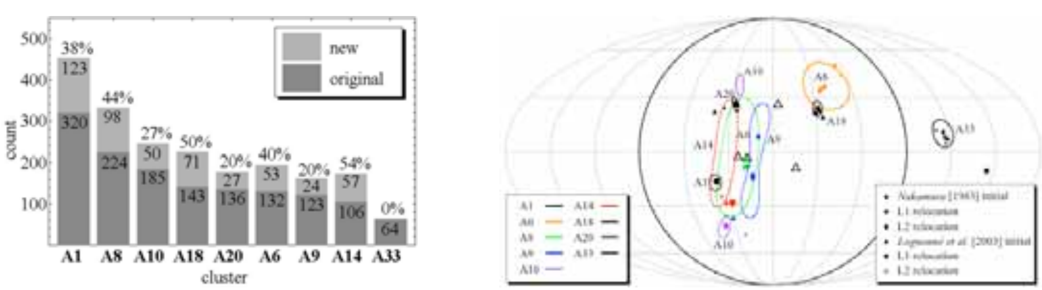

Figure 1: Left – number of deep moonquakes in each of the 8 largest near side clusters, and the one known far side cluster. The dark gray boxes indicate the number of quakes known previously, and light gray boxes indicate the number of new moonquakes identified. Right – locations of the deep moonquake 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.

Relevant Publications

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Research Interests: reflection seismology, mid-ocean ridge dynamics, rifted margins, fault hazards, paleoseismology, Walker Lane tectonics, Lake Tahoe, immersive visualization

Recent offshore characterization of the Tahoe basin (*Kent et al*., 2005) has demonstrated that significant tectonic strain is accommodated across three active faults: the West Tahoe, North Tahoe/Stateline and Incline Village faults, listed in order of decreasing slip-rates of at least 0.6, 0.45 and 0.1-0.2 mm/yr, respectively. Although these results have been instrumental in a significant revision of the previous de facto active fault map (Nevada Bureau of Mines, 2000; Schweikert, et al., 2000) and have been incorporated into the latest active fault map (California Geological Survey, 2005; Saucedo et al., 2005), paleoseismic information concerning these faults is sparse. In 2004, we were able to obtain the first paleoseismic results for the Tahoe basin from an integrated fault-specific on and offshore investigation of the Incline Village fault. Here, we were able to use offshore hi-res seismic CHIRP imaging (Fig. 1) to confidently target an onshore fault trace where a paleoseismic field effort was possible (Fig. 2) with a low probability of failure. This multi-method approach has developed into a powerful tool because characterizing active faults in the Tahoe basin environment is limited when only on or offshore methods are used. Onshore mapping alone has proven to be fraught with uncertainty concerning the ability to identify active fault traces and continuity, and offshore seismic surveys do not yet deliver the specific fault behavior parameters needed for seismic hazard assessments. The reasons that onshore fault mapping has proven to be so challenging are largely related to the mountainous environment that has experienced a Pleistocene/Holocene glacial geomorphic overprinting that has resulted in many linear fault-appearing scarps that are indeed fluvial and glacial landform scarps. Additionally, coverage with dense forests makes aerial image analysis and field observations more difficult and requires a higher level of fieldwork than arid, less vegetated environments. Now that it is clear that the Tahoe basin includes several faults that are active and capable of M7 range earthquakes, it is also clear that conventional field methods may have limited success because of the widespread water coverage over the portions of the faults that are

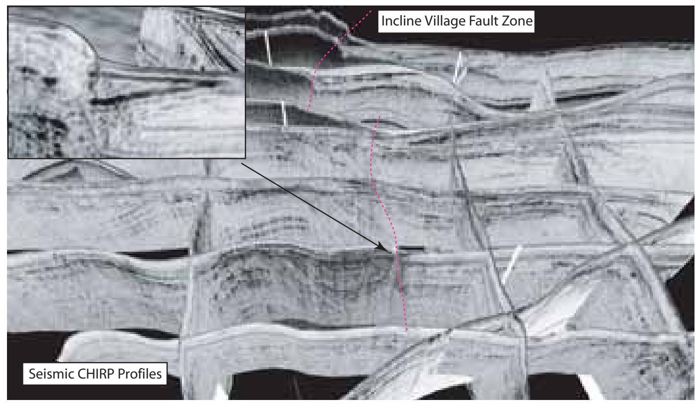

Fig. 1 Seismic CHIRP profiles highlight fault structure (magenta), offshore Incline Village, view to the north. This criss-crossing network of profiles allowed proper identification of the Incline Village Fault scarp, which ran onshore and through the local elementary school, where the 7+ meter-deep trench was dug. Colluvial wedge from most recent event (MRE), 500 B.P., is seen in CHIRP profile (see inset).

Fig. 2 Photo of a colluvial wedge in the Incline Village Trench, highlighting coarse-grained debris that define the most recent and penultimate colluvial wedges. This characteristic triangular wedge-shape deposit has also been recognized in CHIRP profiles (see Fig. 1).

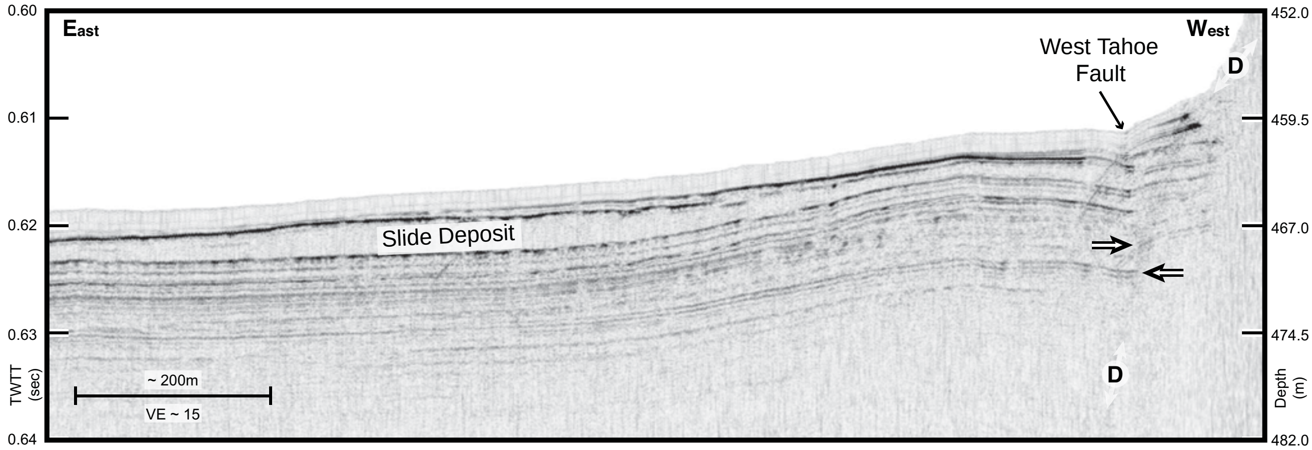

Fig. 3 A seismic CHIRP profile showing the most recent rupture of the West Tahoe fault, along the west shore of Lake Tahoe. Arrows highlight at least 2-3 m of vertical displacement across sedimentary horizons, with lesser offsets near the lake floor indicating growth faulting. This seismic profile also images a distinct slide deposit that may have been triggered during this large event.

most active. Hence, we have adopted a multi-method approach that integrates offshore and onshore methods to arrive at a more comprehensive fault characterization. To characterize the most active of the Tahoe basin faults, the West Tahoe fault, scientists at Scripps-IGPP, in collaboration with researchers at UC Davis, SDSU and UNR, used a diverse set of oceanographic remote sensing tools in the summer of 2006 to map the southernmost offshore portions of the West Tahoe fault in both Lake Tahoe and Fallen Leaf Lake. Hi-res seismic CHIRP profiling, complemented with decimeter-resolution side-scan sonar imagery, was able to extend our knowledge of the West Tahoe fault through successfully mapping this feature where it crosses Fallen Leaf Lake, some 5 km south of Lake Tahoe. On land mapping of suspected fault scarps have been confirmed through this offshore mapping campaign, extending the potential rupture length of the West Tahoe fault from 30 km to over 55 km in length. Subbottom imagery has also revealed that the last rupture along the West Tahoe fault is overlain by a few meters of sediment, suggesting inactivity for ~3,000-5000 years (Fig. 3), or about a recurrence interval for this fault system (*Kent et al.*, 2005). Onshore trenching of the West Tahoe fault is slated for the summer of 2008, in hopes of better defining the history of past ruptures along the main bounding fault within the Tahoe basin, which in turn will allow a more comprehensive seismic hazard assessment of the Tahoe basin.

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Kent, G. M., J. A. Babcock, N. W. Driscoll, A. J. Harding, G. G. Seitz, J. A. Dingler, J. V. Gardner, C. R. Goldman, A. C. Heyvaert, P. Gayes, R. Karlin, L. A. Mayer, C. W. Morgan, L. A. Owen, R. C. Richards, A 60 k.y. record of extension across the western boundary of the Basin and Range Province: Estimate of slip rates from offset shoreline terraces and a catastrophic slide beneath Lake Tahoe, Geology, 33, 365-368, 2005.

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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 the earthquake's seismograms and spectra, as well as issues of catalog completeness and uncertainties (e.g., Figure 1).

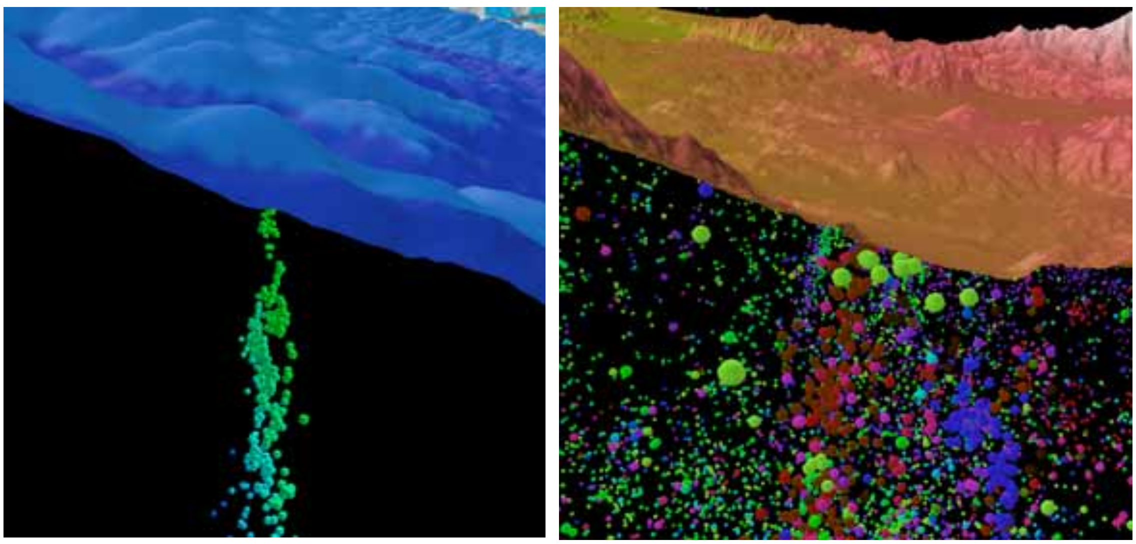

Figure 1. Seismicity distributions (spheres & cubes) color-coded by time. Contrast the knife-edge fault defined by seismicity along the San Andreas Fault near Parkfield California (left) with the drastically different complex fault structure along the San Jacinto Fault near Anza in Southern California (right).

Ability for Large Earthquakes to Trigger Mud Volcano Eruptions: In collaboration with Dr. Mellors (SDSU), and a number of Russian geoscientists, 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., in press 2006).

Accuracy of Earthquake Focal Mechanisms: Kilb, working with Dr. Hardebeck (USGS, Menlo Park), studied the accuracy of earthquake focal mechanisms (i.e., earthquake fault orientations and direction of movement). The quality of fault orientation parameters in focal mechanism catalogs are difficult to quantify because the true fault plane orientations are often unknown. To avoid this difficulty, Kilb and Hardebeck use relocated earthquakes that delineate well defined faults and apply principle component analysis to determine fault orientations to within ±1°. They compare these observed orientations with two different focal mechanism catalogs: one generated with the standard FPFIT method and the other generated with the new HASH method. They find the overall higher percentages of acceptable mechanisms, and the usefulness of the formal uncertainty in identifying quality mechanisms, validate the HASH approach of testing for mechanism stability. This indicates that focal mechanisms computations should always account for uncertainties in the velocity structure (Kilb & Hardebeck, 2006).

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 (southern California) 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. Other studies have revealed remote triggering in many volcanic locations, yet Kilb and Kane find no clear evidence that remote triggering is occurring in southern California. The statistical portion of this work is being conducted in collaboration with UCSD mathematics graduate student Arthur Berg (Kane et al., in review 2006).

The Temporal Lag Between a Mainshock and the First 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. 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, complexity of the fault system, in addition to the elapsed time from the previous large earthquake in the region (Kilb et al., in review 2006).

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 may be very important in the earthquake nucleation process (Jiracek et al., in review 2006).

Estimating the Relative Complexity of Aftershock Sequences Using Waveform Cross-Correlation Measurements: In collaboration with graduate student German Prieto, Kilb is estimating the relative complexity of aftershock sequences using waveform cross-correlation measurements. They find the relatively low correlations found in their study regions in Tien Shan, Central Asia, and the eastern California shear zone result from either complex earthquake source processes within the sequence (*i.e.,* variable fault orientations or rupture directivity) or an extremely heterogeneous fine scale velocity structure in the source region (Kilb et al., paper in preparation).

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

Relevant Publications

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, 2006.

Mellors, R., D. Kilb, A. Aliyev, A. Gasanov & G. Yetirmishli "Correlations between Earthquakes and Large Mud Volcano Eruptions," *Journal of Geophysical Research*, In Press, 2006.

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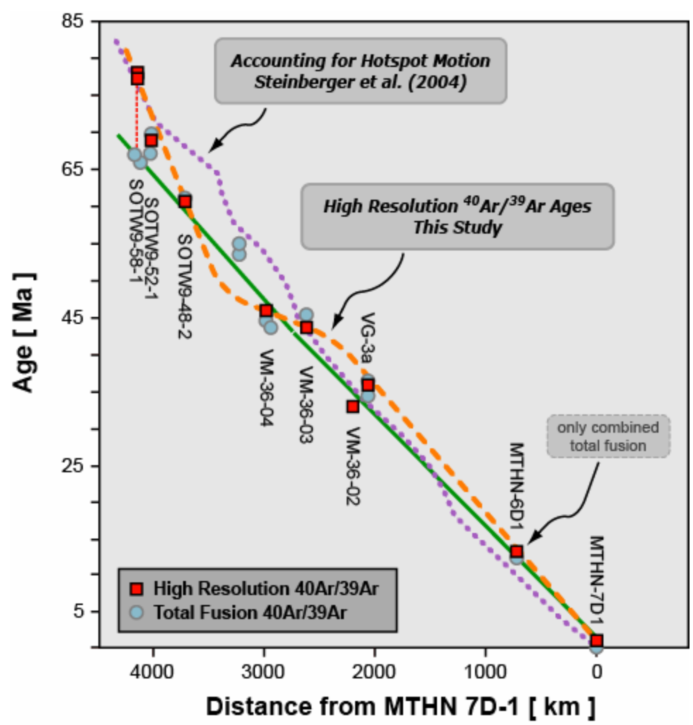
Hotspot Volcanism and $^{40}Ar/^{39}Ar$ Geochronology

Hotspots and their linear age-progressive volcanic chains have been amongst the most convincing observations supporting plate tectonics with fundamental implications for plate motion and mantle-chemical geodynamics. The current research of Dr. Anthony Koppers is focusing on several aspects in this broad field, ranging from $^{40}Ar/^{39}Ar$ geochronology to Sr-Nd-Pb isotope geochemistry of hotspot volcanism to modeling absolute plate motion and the possible motion of hotspots. He has been able to use $^{40}Ar/^{39}Ar$ age dating to test the classical hotspot hypothesis, which has been a cornerstone of plate tectonics over the last 30 years. In these studies he has been able to show that inter-hotspot motion is required to explain the observed $^{40}Ar/^{39}Ar$ age progressions in many of the seamount trails in the Pacific basin (Koppers et al. 2001) and that, in other cases, lithospheric extension needs to be applied as an alternative or secondary process in the formation of these volcanoes (Koppers & Staudigel, 2005). These results seem to disagree with the stationary nature of mantle plumes typically assumed in the hotspot hypothesis, and as a result it has become one of his main science objectives to better understand the "true" nature of intra-plate volcanism.



More recently, Dr. Koppers has been involved in the age dating of the Louisville seamount trail, which next to the infamous Hawaiian seamount trail is one of the primary examples of a textbook hotspot. In a pilot study he has been able to re-date samples from a previously collected sample collection, showing that the presumed linear age progression is not linear after all (see orange line in above Figure). Based on this observation and some plate motion modeling, he could conclude that hotspot motion is required, but in a different direction than observed for the Hawaiian hotspot (Koppers et al. 2004). Together with Peter Lonsdale and Jeff Gee he has carried out a site survey for a future IODP drilling leg on which he is the lead proponent. Over 40 samples have been retrieved during this site survey expedition onboard the R/V Roger Revelle, and will be dated using $^{40}Ar/^{39}Ar$ incremental heating dating over the next year. Dr. Koppers is also involved in project with Hubert Staudigel and Stan Hart to explore the evolution of the Samoan seamount trail and the historically active Vailulu'u underwater volcano (Staudigel et al. 2003; 2006). For long the origin of Samoa has been enigmatic with respect to the hotspot hypotheses, because many of the volcanic islands are covered with post-erosional volcanism, which is up to 3 Myr too young when compared to the predictions of the hotspot model. Together with M.Sc. student Jamie Russell more than 25 basalts dredged from the deep flanks of the Samoan islands and seamounts are being dated using $^{40}Ar/^{39}Ar$ geochronology. The ultimate goal of this study is to find and date the onset of shield building volcanism due to the presence of a mantle plume.

Earth Science Cyber-Infrastructure and EarthRef.org

Dr. Koppers has been the head database manager and webmaster for the http://earthref.org website since its beginning in 1999. In collaboration with Hubert Staudigel and John Helly (San Diego Supercomputer Center) he has been the primary architect of this widely used web portal that attracts more than 100,000 users per year. This website contains four nodes that are specialized with a focus on geochemistry (GERM), paleomagnetism and rock magnetism (MagIC), seamount bathymetry and morphology (SBN) and the use of all these scientific data in educational objects (ERESE). These different nodes under the EarthRef.org umbrella are all interconnected through an extensive reference database, user address book and the EarthRef Digital Archive (ERDA). Users can freely search this website, download data of their interest, and they can add their own scientific data by uploading it into EarthRefs online Oracle databases or the ERDA digital archive. Currently Dr. Koppers is working together with Daniel Staudigel and Rupert Minnett on an implementation of "Google Maps" for seamounts.

Relevant Publications

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Staudigel, H., S.R. Hart, A. Pile, B.E. Bailey, E.T. Baker, S. Brooke, D.P. Connelly, L. Haucke, C.R. German, I. Hudson, D. Jones, **A.A.P. Koppers**, J. Konter, R. Lee, T.W. Pietsch, B.M. Tebo, A.S. Templeton, R. Zierenberg, C.M. Young, 2006. Vailulu'u Seamount, Samoa: Life and Death on an Active Submarine Volcano. Proceedings National Academy of Sciences, 103(17), 6448-6453. ARTICLE# 06-00830.

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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

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

Global tomography: In the past few years, it has been recognized that the use of ray based theories may hamper seismic tomography to resolve fine details in global images. Laske has maintained a collaboration with Princeton colleagues Ying Zhou and Tony Dahlen to apply and test their newly developed finite frequency formulation (the surface wave equivalent of the Princeton Banana–Doughnut approach) on Laske's global surface wave dataset. In the tests as well as in the real inversions, they took into account the fact that phase measurements "at fixed frequency" are, in fact, measurements smoothed over a narrow frequency band, a fact that is usually ignored when inverting for structure at depth. When taking finite frequency effects into account, the kernels are three–dimensional and become dependent on source effects. The inversion then becomes computationally intensive but can be done on a PC cluster. Special attention has been given to adequately address effects from crustal structure which cannot be resolved by a global long-period surface wave dataset. Compared to the model resulting from a classical inversion using ray–based theory, the new upper mantle model resolves structure more accurately where data coverage has been poor (e.g. in the Eastern Pacific Ocean). 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.

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). This project is driven by seismology – including co-PIs from SIO (Laske, Orcutt), WHOI (Collins, Detrick), U. Hawaii (Wolfe), DTM (Solomon) – but also has a geodynamical (Bercovici from Yale Univ.) and a geochemical (Hauri from DTM) component. 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. So far, little is known about the Hawaiian plume due mainly to the fact that the nearly linear alignment of the Hawaiian islands has not allowed seismologists to obtain complete and unbiased images of seismic velocities and discontinuity topography in the greater area beneath the Hawaiian Swell. 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. The project will also investigate what causes the uplift of the swell.

This is a two–phase project in which two deployments gather teleseismic events over a total period of two years. During the first deployment, the group gathered a large dataset between January 2005 and January 2006 with a dense 35–station array that focussed on the island of Hawaii, where the plume head is assumed to be located. A second, wider array was deployed in May 2006 to collect data for another year. The data from this deployment will facilitate the study of deeper Earth structure. With 33 of 35 instruments recovered, the recovery of the first deployment was very successful. This deployment saw a wealth of large

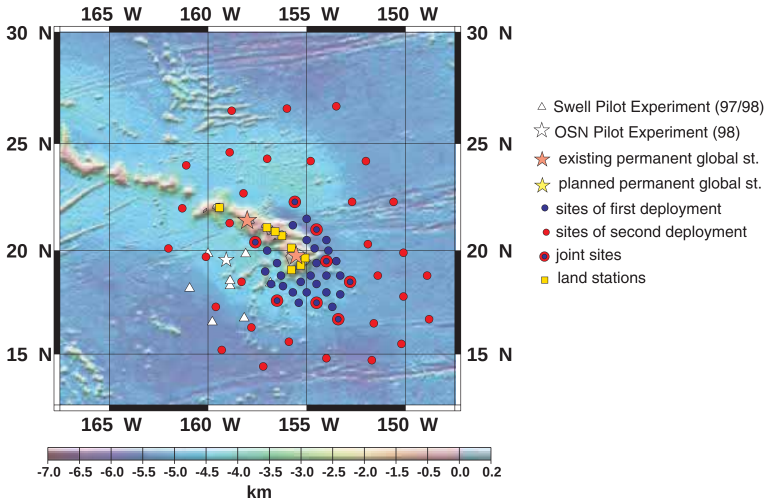

Figure 1: Deployment plan of the PLUME experiment. The first deployment was occupied from January 2005 through January 2006. The second deployment is planned to record from April 2006 through May 2007. The land stations will operate through the end of the second deployment. Also shown are existing and planned permanent stations of the global seismic network. The SWELL pilot array collected data on differential pressure sensors between April 1997 and May 1998.

earthquakes providing excellent azimuthal coverage. This includes two large earthquakes off the U.S. West Coast covering azimuths that are usually hard to obtain. An initial data quality assessment shows that we collected an excellent long–period surface wave dataset. We will also be able to conduct a detailed shear–wave splitting analysis and obtain long–period receiver functions that can constrain the topography of the discontinuities of the transition zone, a key study to assess the plume's origin. In preparation of the project, Laske and Babcock analyzed the data from a test deployment off the coast of San Diego, the first deployment of the new SIO OBSIP instruments. Laske reanalyzed the data from the 97/98 SWELL pilot experiment that covered an area that is covered by the second deployment and is still collecting data. The excellent data quality from that experiment has allowed Laske to estimate the extent of a possible plume–lithosphere interaction.

Recent publications:

Zhou, Y., Dahlen, F.A., Nolet, G. and Laske, G., Finite–frequency effects in global surface wave tomography, *Geophys. J. Int.*, 163, 1087–1111, 2005.

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. and Widmer–Schnidrig, R., Normal Modes & Surface Wave Measurements, *Treatise of Geophysics*, vol.3, Seismology and Structure of the Earth, Edt. G. Schubert (submitted July 2006).

Laske, G. and Babcock, J. Wide–Band Seismic Signal and Ambient Noise on OBSs in the California Borderland, *J. Geophys. Res.*, (submitted May 2006).

Laske, G., The Hawaiian SWELL Pilot Experiment – Evidence for Lithosphere Rejuvenation from Ocean Bottom Surface Wave Data, *GSA Special Paper*, (submitted Sep 2006).

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Research Interests: Ocean Acoustics and Physical Oceanography.

OCEAN ACOUSTICS. The focus remains on the North Pacific Acoustic Laboratory (NPAL) led by Peter Worcester (references 2-8). My chief contribution has been to quantify spicy fronts as a major source of noisy scattering (reference 1). These fronts populate the surface mixed layer in fall and winter, and they cause a degradation of the signal comparable to internal waves. A study now underway by Rudnick and me indicates that the penetration of the abyssal shadow zone is caused by reflections from a remarkably sharp boundary at the bottom of the mixed layer. (This would explain the *phantom arrivals* which have been known since early SOSUS days.) For fifty years the emphasis has been on the dramatic *finale* of the SOSUS message; from the oceanographic (and ASW) point of view it is the *overture* with its surface to bottom rays which is crucial.

PHYSICAL OCEANOGRAPHY. I have continued efforts to interpret the role of tides in the crucial mixing of the pelagic oceans (reference 9). The variation of the obliquity (between 22.5 and 24.5 degrees, now 23.5 degrees) with a period of 41,000 years is the result of the gravitational pull of other planets, principally Jupiter (because it is so massive) and Venus (because it is so close). Bruce Bills and I have reported on the resulting fluctuations in the amplitude of the principal tides, and the associated modulations in pelagic mixing and poleward heat transport. We propose a role in the cause of ice ages; this is very speculative.

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3. Howe, B. M., B. D. Cornuelle, B. D. Dushaw, M. A. Dzieciuch, D. Menemenlis, J. A. Mercer, W. H. Munk, R. C. Spindel, D. Stammer, P. F. Worcester, and M. Zarnetske (2004) Acoustic remote sensing of large-scale temperature variability in the North Pacific Ocean. *OCEANS'04, MTS/IEEE Techno-Ocean '04*, Kobe, Japan, 1504–1506 [DOI: 10.1109/OCEANS.2004.1406343].

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6. Voronovich, A. G., V. E. Ostashev and The NPAL Group (J. A. Colosi, B. D. Cornuelle, B. D. Dushaw, M. A. Dzieciuch, B. M. Howe, J. A. Mercer, W. H. Munk, R. C. Spindel, and P. F. Worcester) (2005) Horizontal refraction of acoustic signals retrieved from the North Pacific Acoustic Laboratory billboard array data. *J. Acoust. Soc. Am.* **117**: 1527-1537.

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9. Munk, W. and B. Bills (2005) Tides and the climate; some speculations. *J. Phys. Oceanogr.*, *in press*.

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

In the 2006 academic year, Bob Parker's research concentrated on understanding and developing techniques for solving the nonlinear inversion problems associated with electromagnetic induction. The central question is that of deducing the interior electrical conductivity of the interior from measurements of electric and magnetic fields at the surface or, as has become increasingly important, at the bottom of the ocean in the search for natural resources. This topic has become particularly important to IGPP with research programs headed by Prof. Steve Constable in marine electromagnetic sounding, and in the extraction of planet-wide electrical responses from magnetic field measurements made by recently launched satellites, a project of Prof. Cathy Constable.

The starting point for the new work is the observation that none of the current inversion and modeling methods for nonlinear inverse problems are capable of providing trustworthy uncertainties for their solutions. The range of answers consistent with the measurements is hazy at best. In some cases, (e.g. inversion for seismic parameters) the range of plausible solutions permitted by geological or physical constraints is relatively small and so linear approximations may be adequate.

But the electrical problem is more difficult: conductivities span many orders of magnitude within short distances, so that the linear approximation at the heart of most traditional methods, like the Backus-Gilbert theory, must break down. More troublesome is the fact that the actual uncertainly may be arbitrarily large, but the one found by linearization may be small, thus seriously misleading the investigator. To overcome these difficulties, a radical new approach is required that avoids linear approximations. In his new theory Parker treats the inverse problem as a very large constrained optimization problem. The things that are known about the system, such as the data values, the fact the electric and magnetic fields obey Maxwell's equations, and so on, are the constraints: they are the conditions that every solution must obey. Quantities of interest, in particular the average value of the conductivity in specified region, are functions to be maximized and minimized. In this way upper and lower limits are calculated for these properties of the model, subject to the restriction that the model is consistent with observation and other possible considerations from physics or geology.

To start with the simplest system Ashley Medin, Parker's student, re-examined an analysis performed by Steve Constable to learn about the deep electrical structure of the Earth, based on ground stations and satellite measurements. In this model only variations with depth were permitted, leading to a so-called one-dimensional system. Ashley, working with Prof. Philip Gill of UCSD's Math Department, implemented the problem in SNOPT, a general-purpose nonlinear optimization code that permits the imposition of inequality constraints and takes advantage of the sparse nature of the matrices. One condition it is vital to include is the fact that conductivity must be positive. But it is almost certainly true that conductivity always increases with depth, and imposing this condition improves the quality of the solution considerably. In this problem, mineral physics suggests there are three distinct regions of interest: the upper mantle, a transition zone, and the lower mantle. Therefore Ashley computed bounds on

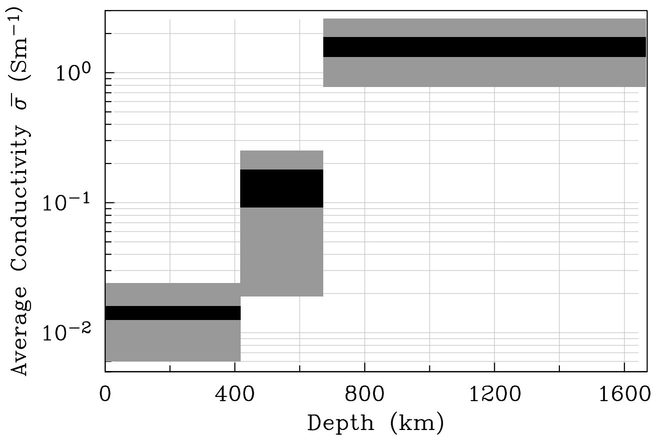

Figure 1: Strict limits on conductivity model averages from geomagnetic sounding data.

the average conductivity in these zones, though it turns out to be impossible to say anything about the lowest part of the mantle. Figure 1 shows the results. The black areas give the limits when the conductivity cannot decrease with depth, in the grey areas this condition is lifted. The transition zone provides the most interesting conclusion: we have shown that the electromagnetic induction data are incompatible with recent models based on mineral properties that propose a high water content for the layer. Parker, his student, Gill and another colleague in Math, Prof. Randy Bank, are currently extending the technique to two-dimensional systems, for application to marine experiments under way in IGPP.

Parker has also been involved in a study to understand the uncertainties in parameters that characterize earthquakes: the source moments and magnitudes. The lead here was taken by a student, German Prieto, in applying a number of statistical methods, most importantly multi-taper spectral estimation and mean-square error minimization, to a problem that has largely escaped any statistical treatment until now.

Relevant Publications

Medin, A., Parker, R., and Constable, C., Making sound inferences from geomagnetic sounding, *Phys. Earth & Planet. Int.*, submitted, March, 2006.

Prieto, G. A., Parker, R. L., Vernon, F. L., Shearer, P. M., and Thomson, D. J., Uncertainties in earthquake source spectrum estimation using empirical Green functions, in *Radiated Energy and the Physics of Earthquake Faulting*, in press, 2006.

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Research Interests: Geodynamics, global bathymetry, crustal motion modeling

During the 2006 academic year, Dave Sandwell's research was focused on solid Earth Geophysics with an emphasis on understanding the dynamics of planetary lithospheres. 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.

Geodynamics - Anthony Watts was on sabbatical leave at SIO for the 2005-2006 academic year and collaborated on a project to investigate the global distribution of seamounts and their isostatic compensation (*Watts et al.,* 2006). Karen Luttrell developed a theory to explain why the topography of Jupiter's ice-covered moon Europa appears smooth on large scales but rough on small scales (*Luttrell and Sandwell,* 2006). Meng Wei used the principles of conservation of energy and thermal expansion to estimate the global heat loss from the cooling oceanic lithosphere without invoking a particular heat transfer mechanism (*Wei and Sandwell,* 2006). This new estimate of global heat flow is twice the value of an estimate published in 2005 by a Washington University group but it is in accordance with earlier estimates so our understanding of global heat loss does not need to be revised.

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*, 2006). This research helps to resolve the issue of, where and how, deep-ocean mixing occurs.

Crustal Motion Modeling - Bridget Smith-Konter 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 (Figure 1). 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.,* 2006). The L-Band synthetic aperture radar interferometer aboard the Japanese ALOS spacecraft had a successful launch in January 2006 and is now providing interferometric crustal motion measurements. Dave Sandwell, Yuri Fialko, and Meng Wei are using radar corner reflectors deployed at Pinon flat observatory to calibrate the radar measurements.
More information is provided at http://topex.ucsd.edu.

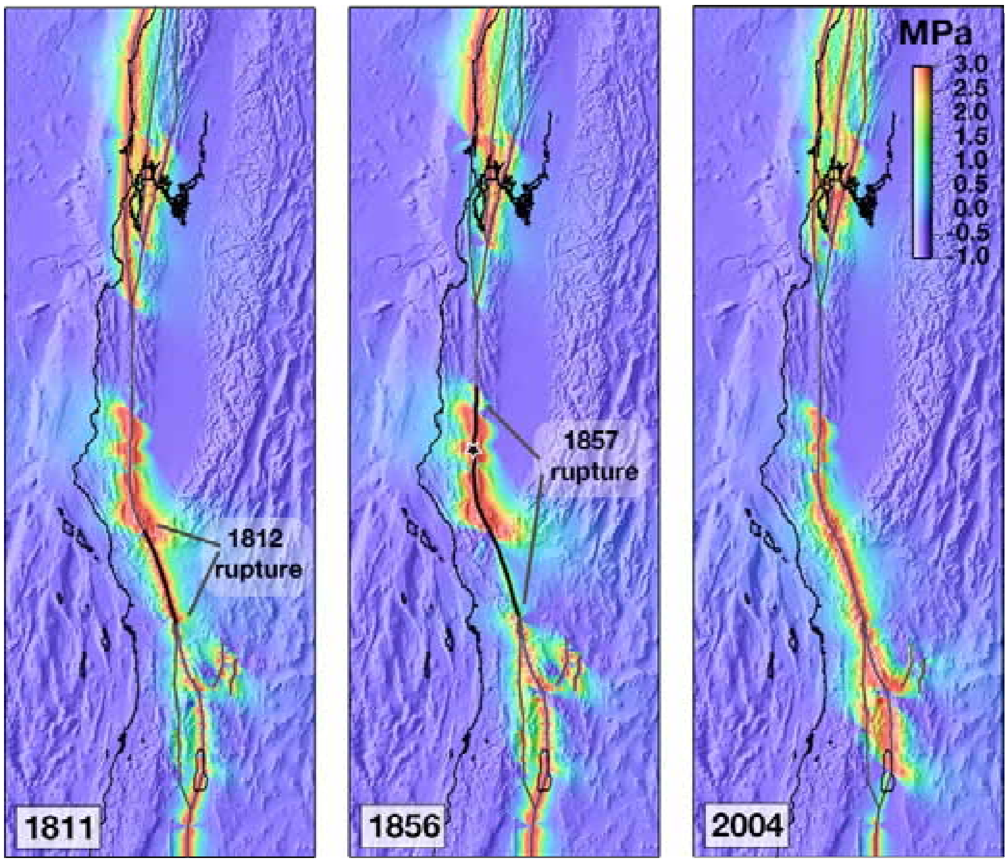

Figure 1: Crustal stress at seismogenic depth along the San Andreas Fault System for three snapshots in time. (left) 1811 calendar year prior to the 1812 M~7 Wrightwood Earthquakes. (center) 1856 calendar year prior to the M7.9 1857 Great Fort Tejon Earthquake. (right) 2004 calendar year model, representing present-day stress (*Smith and Sandwell*, 2006). Stress is highest today on in the Salton Trough area of the San Andreas Fault.

Relevant Publications

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Sandwell, D. T., and W.H.F. Smith, Retracking ERS-1 Altimeter Waveforms for Optimal Gravity Field Recovery, *Geophys. J. Int., 163*, 79-89, 2005.

Sandwell, D. T., Smith, W. H. F., S. Gille, S., Kappel E., Jayne S., Soofi K. , Coakley B., and L. Geli, Bathymetry from Space: Rationale and requirements for a new, high-resolution altimetric mission, *Comptes Rendus de l'Académie des Sciences, in press, 2006*.

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Wei, M. and D. Sandwell, Estimates of Ridge-Axis Heat Flow from Depth and Age Data, submitted to *Tectonophysics, 417,* p. 325-335, 2006.

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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, a continuously recording seafloor instrument was deployed, and work continued on a nanoscale instrument for chemical detection in seawater. The geodetic research is a group effort that includes Mark Zumberge and Scott Nooner.

2005 Troll During the summer and fall of 2005, a seafloor gravity survey was conducted in cooperation with researchers at Statoil of Norway. The Troll gas field is one of the largest offshore gas fields in the Norwegian sector, west of Bergen, Norway. 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. The 2005 survey is the fourth survey in a series going back to 1998. These surveys 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) .

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 is connected via an underwater cable to the platform for power and data transfer. The data is then transmitted via microwave link to shore. To date, the TIDEDOG has been operating for over a year.

2005 Sleipner Survey: During the same 2005 Troll survey, a seafloor gravity survey was conducted over the Sleipner CO_2 sequestration field. Sleipner is also a natural gas field, in which the natural gas has a relatively high concentration of CO_2. Prior to export, the CO_2 is chemically scrubbed and, rather than released to the atmosphere, is re-injected into a caprock formation for sequestration. This pilot project is important for determining the effectiveness of geological sequestration as a means of reducing industrial carbon emissions. Time-lapse seismic surveys are used to determine the location and migration of the sequestered CO_2. However, the CO_2 density in the reservoir is not well known, which adds uncertainty to seismic interpretation. As part of a larger overall project, gravity measurements can provide constraints on the CO_2 density.

2006 Midgaard Survey: The prior results at Troll and Sleipner have proven useful for geophysical exploration. As proof of that, a new time-lapse survey was initiated at the Norwegian Midgaard field.

Graviluck 2006: The ROVDOG technology, originally developed for exploration geophysics, has also been leveraged for basic scientific research. The French Graviluck expedition, lead by Valerie Ballu of the University of Paris, was targeted at collecting a deformation time series of the Lucky Strike Volcano, located on the mid-Atlantic Ridge west of the Azores. The Graviluck 2006 expedition used a single ROVDOG unit in a heavy pressure case rated to 4500m depth. The submersible *Nautile* was used to deploy the ROVDOG during 11 dives, for a total of 55 station measurements. This particular cruise, however, faced a number of technical problems with the instrument. The cruise also conducted seafloor photography and extensive water column sampling.

Figure 1. The ROVDOG instrument being deployed from the Nautile submersible. This image is from the expedition website, http://www.insu.cnrs.fr/web/article/art.php?art=1869.

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 a unmet need for the scientific community. This particular investigation, if successful, could lead to a new class of scientific instrumentation for oceanographic research.

Relevant Publications

Stenvold, T., O. Eiken, M.A. Zumberge, G.S. Sasagawa, S.L. Nooner, High-Precision Relative Depth and Subsidence Mapping from Seafloor Water-Pressure Measurements, *Soc. Petroleum Engineering J.*, **11**, 380-389, 2006

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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 shows that global receiver function mapping of the 410- and 660-km discontinuities is in agreement with *SS* precursor studies (*Lawrence and Shearer,* 2006). Lawrence also used a new waveform cross-correlation method to study upper-mantle attenuation structure beneath North America (*Lawrence et al*., 2006), a technique that is ideal for large-scale analysis of the volumes of seismic data expected from the USArray experiment.

Work with postdocs Miaki Ishii and Kris Walker led to development of a back-projection method to image high-frequency radiation from large earthquake ruptures. *Ishii et al.* (2005) uses the Japanese Hi-Net data to show that the M 9.1 December 2004 Sumatra-Andaman earthquake ruptured about 1300 km to the north at a nearly constant average rupture velocity (see Figure 1). *Walker et al.* (2005) shows using both Hi-Net and global seismic network data that the M 8.7 March 2005 Sumatra earthquake involved bilateral rupture. Because the imaging method is computationally efficient and requires few assumptions about the fault geometry, it is suited for rapid calculations, and Shearer and Walker are currently working with Paul Earle at the National Earthquake Information Center (NEIC) to implement a near-real-time system.

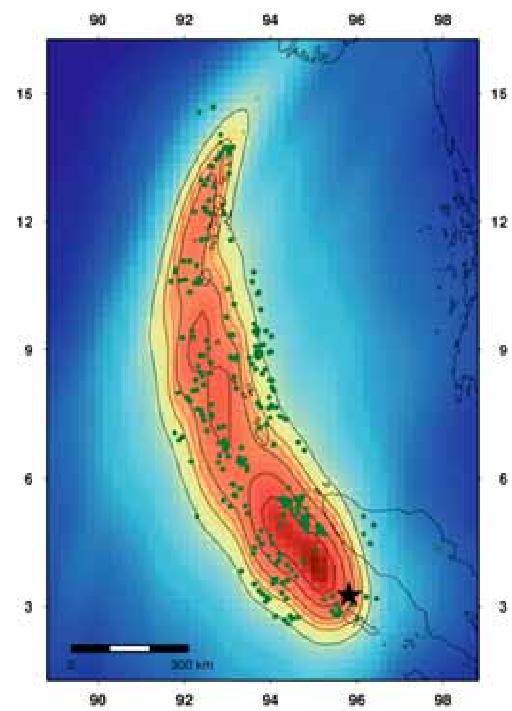

Figure 1: Seismic energy from the 2004 Sumatra-Andaman earthquake, integrated over 600 seconds after initiation. The epicenter is the black star. Note the good agreement between the 1300-km-long rupture zone and the locations of the first month of aftershocks (dark green circles).

Shearer's southern California work has focused mostly on improving micro-earthquake locations using robust methods and waveform cross-correlation. The latter method is computationally intensive but is becoming practical for large-scale use owing to improvements in computer speed and storage capacity. This work recently culminated in the relocation of the entire southern California catalog of over 300,000 earthquakes from 1984 to 2002 (*Hauksson and Shearer*, 2005; *Shearer et al.*, 2005). Graduate student Guoqing Lin is also involved in this research and performs synthetic tests in *Lin and Shearer* (2005) to validate the accuracy of the relocation methods and shows in *Lin et al.* (2006) that remote sensing data can be used to improve the locations of quarry blast events. The new southern California earthquake catalog resolves many seismicity features that have been obscured by scatter in previous catalogs and is now widely used by other researchers. *Vidale and Shearer* (2006) use the catalog to study earthquake swarms in southern California, which are of great interest because they appear to be driven by fluids or aseismic slip episodes rather than simple tectonic loading.

Recently, Shearer has begun taking advantage of the online waveform archive at Caltech to compute and analyze earthquake source spectra. *Shearer et al.* (2006) uses spectral stacking techniques to systematically estimate stress drops for over 60,000 earthquakes in southern California. This is by far the largest earthquake stress-drop study ever performed and shows many interesting spatially coherent patterns, but with no obvious correlation with faulting type or local tectonics. Shearer is currently working with graduate student Bettina Allmann to apply these methods to analysis of seismicity at Parkfield, California. Earthquake spectra can also be used to study crustal attenuation (Q) structure and *Hauksson and Shearer* (2006) describes an inversion for the 3-D Q structure beneath southern California. The relative strength of P and S attenuation suggests partially fluid-saturated crust.

Working with Catherine Johnson and graduate student Renee Bulow, *Bulow et al.* (2005) analyzes lunar seismograms and identifies a number of previously undetected moon quakes. Renee is a co-winner of the 2006 Frieman prize for excellence in graduate student research for this paper.

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Bulow, R.C., C.L. Johnson and P.M. Shearer, New events discovered in the Apollo lunar seismic data, *J. Geophys. Res.*, 110, doi: 10.1029/2005JE002414, 2005.

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Hauksson, E., and P. M. Shearer, Attenuation models (Qp and Qs) in three dimensions of the southern California crust: Inferred fluid saturation at seismogenic depths, *J. Geophys. Res.*, 111, 2006.

Ishii, M., P.M. Shearer, H. Houston and J.E. Vidale, Extent, duration and speed of the 2004 Sumatra-Andaman earthquake imaged by the Hi-Net array, *Nature*, doi:10.1038/nature03675, 2005.

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Lin., G. and P. Shearer, Tests of relative earthquake location techniques using synthetic data, *J. Geophys. Res.*, 110, B4, B04304, doi:10.1029/2004JB003380, 2005.

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Vidale, J. E., and P. M. Shearer, A survey of 71 earthquake bursts across southern California: Exploring the role of pore fluid pressure fluctuations and aseismic slip as drivers, *J. Geophys. Res.*, 111, 2006.

Walker, K.T., M. Ishii and P.M. Shearer, Rupture details of the 28 March 2005 Sumatra Mw 8.6 earthquake imaged with teleseismic P waves, *Geophys. Res. Lett.*, 32, L24303, doi: 10.1029/2005GL024395, 2005.

Hubert Staudigel

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Research Interests: Seamounts, Volcanology, Seafloor (bio-) alteration, Science Cyberinfrastructure and Education

Seamounts: Hubert Staudigel's most recent research on seamounts includes the exploration of Vailulu'u seamount (Samoa) and marine geological, geochemical and geophysical investigations of seamounts in the Pacific: Submersible exploration of Vailulu'u seamount showed that Vailulu'u recently erupted, forming a new, 300m tall cone in its crater floor at 1000 m depth. This new volcanic cone, Nafanua hosts an unexpected large colony of eels at its summit, while the crater surrounding Nafanua was named the "moat of death" due to the abundance of fish carcasses, probably due to poisoning effects of hydrothermal venting Staudigel et al. (2006a). Koppers and Staudigel (2005) studied the geochronology of two characteristic bends in the Gilberts and Tokelau seamount chains and showed that they are asynchronous with the morphologically similar Hawaiian-Emperor seamount bend. These bends cannot be caused by a simple change in plate motion over three stationary hot spots requiring plate extension as a most likely mechanism to explain these bends. Ongoing seamount work with students and collaborators includes a geochronological study of the Samoan Hot Spot track (with colleagues Anthony Koppers and Stan Hart, and MSci student Jamie Russel), an isotopic study of Jasper seamount in the Fieberling- Guadalupe seamount chain (with graduate student Jasper Konter), a microbial study of Vailulu'u seamount (see below) and a range of investigations at Loihi Seamount, Hawaii. The latter includes the recent establishment of a microbial observatory (with Katrina Edwards, Dave Emerson, Craig Moyer and Brad Tebo), a conductivity – tomography experiment (with Steve Constable and Graduate Student Dave Myer).

Volcanology: Hubert teaches a comprehensive, two week field class in volcanology in Hawaii (http://earthref.org/ERESE/courses/HVFT/2005/index.html) jointly with the UC Davis and UC San Diego campus, in collaboration with Peter Schiffmann and Robert Zierenberg. Hubert's scientific interests in volcanology focus on a wide range of structural, hydrothermal, geochemical studies including the seismic monitoring on seamounts (Staudigel et al., 2006a; Konter et al., 2004). Hubert wears the hat of the volcanologist in a range of paleomagnetic investigations involving the sampling of volcanic rocks, together with Lisa Tauxe, Cathy Constable and students. This work lately focuses on high latitude studies in Antarctica and Spitzbergen.

Seafloor (Bio-) Alteration: Global chemical fluxes in seafloor alteration focuses is one of Hubert's major long-term interest in seafloor alteration (e.g. Staudigel 2003; Kelley et al., 2005). Recently, however it became clear that microbes are involved in water – rock interaction, probably with profound implications for chemical fluxes, the global distribution of biomass, and maybe the origin of life on planet earth. Hubert is studying microbially mediated water-rock interaction along two main lines of research: In collaboration with H. Furnes, he studies the traces that microbial activity leaves in volcanic glass and could show that this process is extremely common, in all oceans, and in the geological record back at least 3.5 Ba. This find makes these fossils some of the oldest fossils on earth, and allows us to speculate about their role in the origin of life on the planet (e.g. Staudigel et al., 2006b). Hubert also works with geomicrobiologists Brad Tebo, Alexis Templeton, and graduate students Brad Bailey and Lisa Sudeck (Haucke) to identify the main microbial players involved in this process and to help understand the processes involved in microbe-rock interaction (e.g. Staudigel et al., 2004). This biogeoscience group has now isolated a substantial number of microbes that are capable of extracting energy from the oxidation of iron (e.g. Templeton et al., 2005). Reduced iron is very common in basalt. Experimentation with these microbes is done in the laboratory, and in nature, using Vailulu'u and Loihi seamounts as natural laboratories.

Earth Science Cyberinfrastructure and Education: Hubert is also interested in working towards a Cyberinfrastructure for earth science and science education, in collaboration with A. Koppers, J. Helly, M. Helly, C. Massel, D. Miller, C. Manduca and D. Mogk. Key data base components include the reservoir data base for the Geochemical Earth Reference Model (GERM) initiative and the Seamount Catalog for the Seamount Biogeoscience Network (SBN). In 2006, he co-organized international workshops for the SBN in La Jolla http://earthref.org/events/SBN/2006) and for GERM at Columbia University (http://earthref.org/events/GERM/2006). Our education efforts are mostly focused on the ERESE project (Enduring Resources for Earth Science Education), with the creation of web-resources for teachers and two teachers' professional development workshops (in 2004 and 2005; http://earthref.org/events/ERESE/2005). Another educational project involved the participation of three high school seniors in one of his research cruises, the Alia Expedition (http://earthref.org/ERESE/projects/ALIA).

Relevant Publications

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

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.

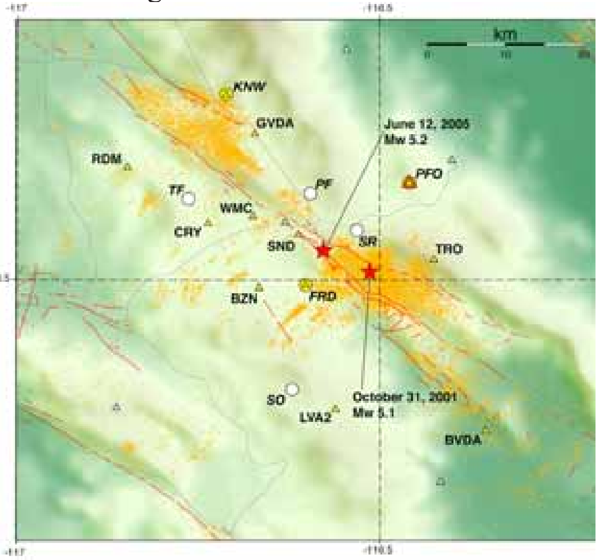

Figure 1. Map of M~5 earthquakes (red stars) and background seismicity recorded by the ANZA seismic network. Seismic stations are triangles or circles.

In early 1998, the first Ocean Seismic Network Pilot Experiment (OSN1 or OSNPE) was carried out at ODP Hole 843B about 225 km southwest of Oahu. The experiment demonstrated the technical capability to deploy borehole systems using wireline re-entry technology. The scientific experience from the Ocean Seismic Network Pilot Experiment indicates that broadband borehole sensors deployed in oceanic basement are: 1) among the best seismic sensors in the world in terms of ambient noise floor from 10 mHz to 100 mHz (vertical component), 2) among the best oceanic sensors (including island and coastal sensors) in terms of ambient noise floor from 100 mHz to 5 Hz (vertical and horizontal components), and 3) the best oceanic sensors for observing short period teleseismic body waves (from ranges greater than 30 degrees). We are currently working on improving this system and readying it for deployment as part of the NSF Ocean Observatories Initiative.

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.

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 over 260 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.

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

Brad Werner and co-workers Dylan McNamara, Nick Magliocca and Alex Zvoleff in the Complex Systems Laboratory are 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 coupling numerical models for particular systems on a range of temporal scales, with applications to 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. Current efforts are directed toward refining the model to produce forecasts and forecast uncertainties for greenhouse gas emissions from particular locations under a range of climate scenarios.

Wind-blown sand dunes are slow to respond to changes in wind forcing and sediment supply; therefore, their patterns store information about the past. To extract quantitative information from currently observed patterns, a continuum model for dune spacing, orientation and defect density (number of terminations per unit length of crestline) was constructed based on previously developed models for the evolution of the means of these quantities in a dunefield. The model permits exploration of the effect of sediment supply and wind regime changes on dune field patterns, with the eventual goal of inverting observed patterns for dune field history. A particularly robust test of the central role of time in the model predictions is offered by compound dunes, where small dunes form and migrate on the backs of larger dunes. Spacing, orientation and defect density changes observed on the backs of megabarchans in the Algodones dune field match model predictions.

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. 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. The production of scientific information also occurs within a market-based system that controls (with some restrictions) funding, publishing and researcher rewards. Because of these simplifying dynamics, production, storage and flows of information in the society as a whole and within the science subsystem are amenable to agent-based modeling. A preliminary 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 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 different information subsystems, for example, the person-to-person contacts of myspace vs. the person-to-community interactions of indymedia? And how do these alternative information subsystems interact with and strengthen social and economic justice movements?

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 (McNamara), market dynamics destabilize barrier island response to rising sea level, giving rise to emergent, episodic boom and bust cycles that alternate in phase alongshore. 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 (Magliocca). A model for economic development, river and hurricane-induced flooding, and levee building in New Orleans approximately reproduces the 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, which are predicted to continue into the future (McNamara). Two in-progress modeling projects are examining the interaction between resource development, greenhouse gas emissions and climate (Zvoleff) and the recent widespread development of slums in megacities, largely sited in locations subject to hazards, such as landslides, floods and fires.

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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 have been 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 (Fig. 1). 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. 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. Even after removing the mean seasonal cycle using historical data, the interannual variability is large compared to any secular trends in the data. Worcester is working with Brian Dushaw (Applied Physics Laboratory, University of Washington) to compare the measured travel times with those calculated using 0–750 m temperature fields generated from satellite altimetry and in situ profile data and with travel times computed from sound-speed fields derived from the Estimating the Circulation and Climate of the Ocean (ECCO) and Parallel Ocean Program (POP) ocean general circulation models.

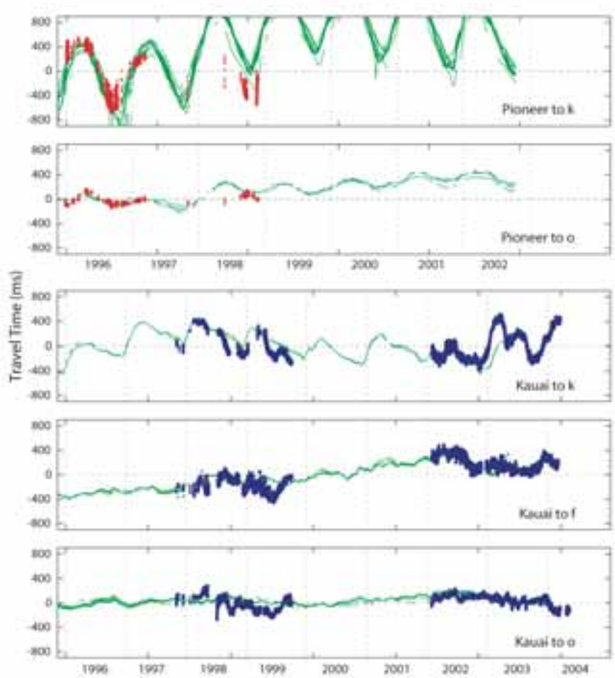

Figure 1. Travel times measured on the 1–5-Mm-long acoustic paths (red and blue) compared to travel times predicted using the JPL-ECCO ocean model (green).

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 receiving arrays, 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 (Fig. 2). Lora Van Uffelen, Worcester's student, 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.

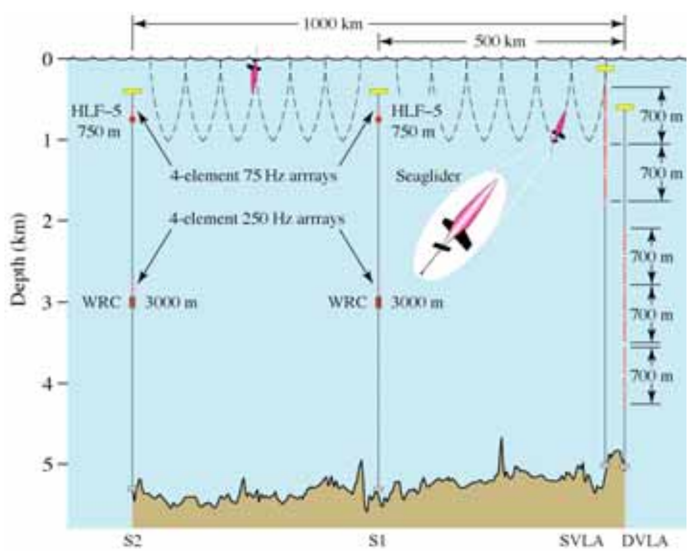

Figure 2: SPICEX experimental geometry. Two transceiver moorings (S1 and S2) were deployed 500 and 1000 km from two autonomous vertical line array receivers (SVLA and DVLA). The Seaglider shown is one of several methods used to obtain the necessary environmental data.

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

Seafloor relative gravity measurements

In 1997, the IGPP gravity group was approached by the Norwegian firm Statoil to develop a gravity technique for monitoring the evolution of a natural gas reservoir beneath the North Sea. Such monitoring will enable increased gas recovery over the 40-year life of the reservoir. The group designed a gravimeter capable of deployment with a remotely operated vehicle (ROV). They have made five surveys in the North Sea. Based on the success of this work (sponsored by the oil industry), they received NSF funding to build a deep ocean version of the instrument to be used in studies of mid-ocean ridges. Surveys have been done on the mid-Atlantic ridge in two separate cruises with manned submersibles. Other interesting applications include the survey of a site of CO_2 sequestration in the North Sea to monitor the stability of the gas stored there, and a survey to assess the quality of ore in sulfide mounds under 1500 m of water off the coast of Papua New Guinea. (Zumberge and Glenn Sasagawa have collaborated on this work).

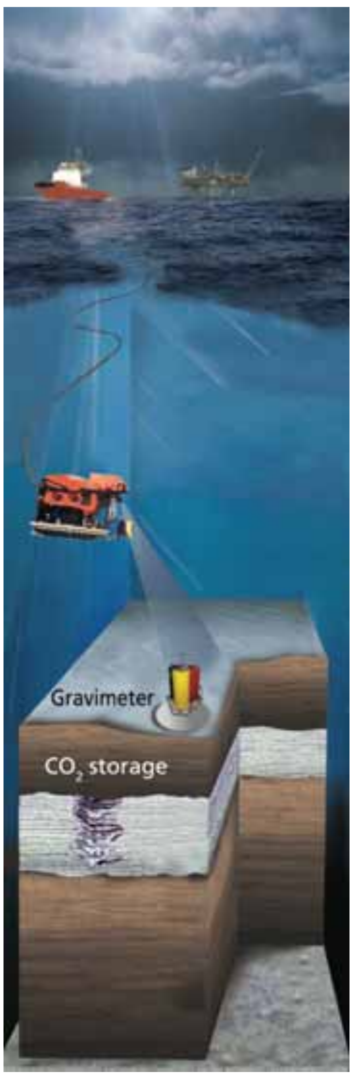


Figure 1: In the sea floor gravity surveys, an ROV carries three gravity meters (to improve the statistics) to sea floor benchmarks—small concrete platforms that facilitate precise relocation of the instruments during repeated measurements. As CO_2 is pumped into an underground reservoir, it displaces water in the pore space, decreasing the average density. This produces a slight but measurable decrease in the strength of Earth's gravity over the reservoir, allowing analysts to track the movement of CO_2 as the reservoir evolves. The goal is to determine if the sequestered CO_2 is safely captured.

Development of fiber optic strainmeters

The group is developing two types of strainmeters that rely on optical fibers to sense deformation in Earth's crust. The first is a seafloor sensor. It is a relatively low resolution strainmeter (about 1 part per million) that is fairly inexpensive and has low power requirements. (Graduate student John Blum is working on the project, which is aimed at monitoring seafloor landslides.)

The second type is a high-resolution (0.1 parts per billion), interferometric sensor, based on a new signal processing technology. In late 2004, the group installed several kilometer-long optical fibers in the SAFOD (San Andreas Fault Observatory at Depth) borehole. Short period signals are very promising — longer period signals are currently contaminated by thermal noise. Efforts to improve this are underway.

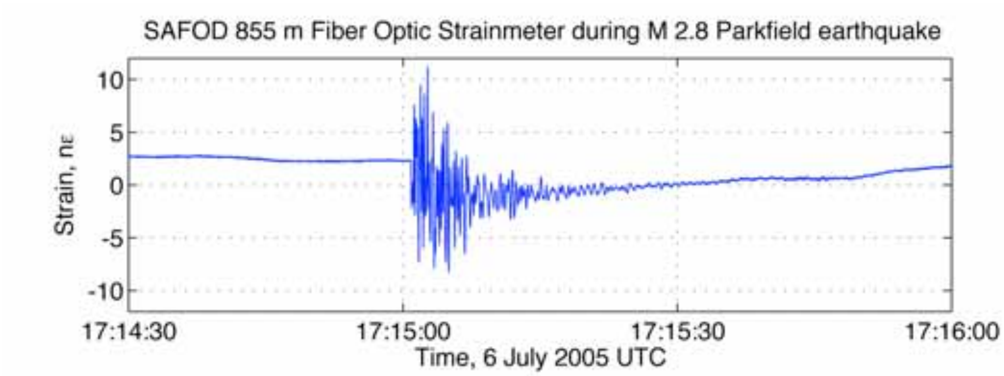


Figure 2. An optical fiber is stretched between the surface and a depth of 855 m in the SAFOD borehole near Parkfield, California. Small earthquakes on the nearby San Andreas fault cause deformations in the ground. This strain ($\Delta z/z$) produces changes in the fiber optic cable's length, which is recorded by analyzing laser light transmitted through the fiber.

Development of an optical seismometer

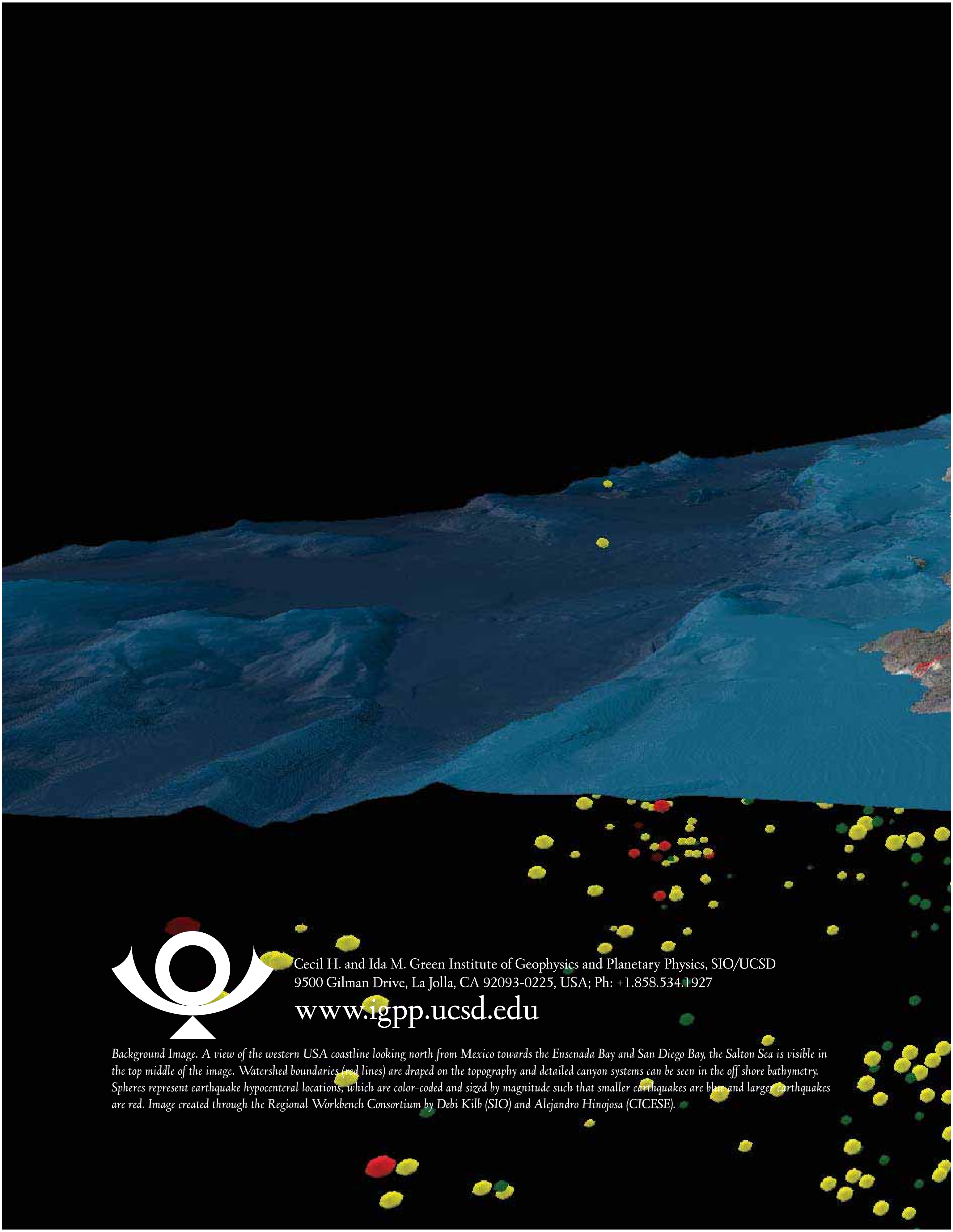
In collaboration with Erhard Wielandt, Jon Berger, and graduate student Jose Otero, Zumberge is experimenting with a new seismometer. It is based on a spring-mass system, as is the case in almost all seismometers, but it uses optics rather than electronics to record mass position. The technology developed for the group's other interferometric sensors provides a displacement transducer that has very wide dynamic range (10^{10}) and very high resolution (10^{-12} m). This combination is perfect for seismic research, and will have certain advantages over conventional electronic seismometers (deep borehole installation, for example).

Relevant Publications

Sasagawa, G., Crawford, W., Eiken, O., Nooner, S. Stenvold, T., and Zumberge, M., A new seafloor gravimeter, *Geophysics*, 68, 544-553 (2003).

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).



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Background Image. A view of the western USA coastline looking north from Mexico towards the Ensenada Bay and San Diego Bay, the Salton Sea is visible in the top middle of the image. Watershed boundaries (red lines) are draped on the topography and detailed canyon systems can be seen in the off shore bathymetry. Spheres represent earthquake hypocenteral locations, which are color-coded and sized by magnitude such that smaller earthquakes are blue and larger earthquakes are red. Image created through the Regional Workbench Consortium by Debi Kilb (SIO) and Alejandro Hinojosa (CICESE).