The Earth Section of the Scripps Institution of Oceanography comprises the Geosciences Research Division (GRD) and the Cecil H. and Ida M. Green Institute of Geophysics and Planetary Physics (IGPP). This report summarizes research conducted by investigators in the Earth Section over approximately the last academic year, with the goal of presenting a description of our activities that is accessible to a broad audience.

Our work spans a broad range of subject matter in geology, geophysics, chemistry, biogeosciences, and climate science. Observations, measurements, and collection of samples and data are accomplished on global, regional, and local scales by extensive shipboard and ground-based operations and also include remote sensing by satellites and the use of wide-ranging instrument networks. Extensive laboratory work often follows our sampling programs, while theoretical developments and modeling play a strong role in data interpretation and guide the design and implementation of experimental work.

The Earth Section welcomed a new faculty member this year, Andreas Andersson whose research centers on ocean acidification and its effect on biogeochemical processes in marine environments. A number of members of the Earth Section received recognition for their research, with David Sandwell being elected to the National Academy of Sciences and Lisa Tauxe being elected as a Fellow of the AAAS. Guy Masters received the Beno Gutenberg medal and Wolf Berger the Milutin Milankovich medal from the European Geosciences Union and Miriam Kastner received the Francis Shepard medal from Society for Sedimentary Geology (SEPM).

Thanks to Jennifer Matthews for her efforts in compiling and producing this report. It is our hope that you will find this a useful description of our ongoing work.

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Background Image: Computer simulation of crater formation during an explosive volcanic eruption. The translucent surfaces represent ash and gas, while the opaque surface is rock (see report by D. Ogden).
**Research Interests:** Global environmental change owing to both natural and anthropogenic processes, mainly ocean acidification and its effects on biogeochemical processes in coastal and coral reef ecosystems, but also the effect on the overall function, role, and cycling of carbon in marine environments.

At present time most of my research effort is focused on the Bermuda ocean acidification and coral reef investigation (BEACON) [Figure 1] with co-PIs Nick Bates and Samantha dePutron of the Bermuda Institute of Ocean Sciences (BIOS). BEACON aims to improve our understanding of the potential consequences of ocean acidification to coral reef ecosystems including the effects on individual marine organisms, biogeochemical processes (e.g., calcification and CaCO₃ dissolution), and the cycling of carbon through coral reefs. Bermuda serves as an important and highly suitable location to study ocean acidification and coral reefs owing to a number of factors. For example, there are no major industries or sources of pollution in Bermuda. Consequently, any observed changes over time are most likely due to large-scale changes such as rising temperature and ocean acidification. Natural gradients in seawater CO₂ chemistry across the coral reef platform provide a natural laboratory to conduct experiments. Furthermore, the presence of the Bermuda Atlantic Time-series Station (BATS) makes it possible to carefully characterize differences between offshore and inshore biogeochemical parameters and consequently the processes controlling these parameters on the reef.

*Figure 1:* Overview of the various components of the Bermuda ocean acidification and coral reef investigation (BEACON) supported by grants from NSF and NOAA.
During the past year, the focus of BEACON has been to characterize the natural variability in seawater CO₂ chemistry across time and space over the Bermuda coral reef platform concurrent with measurement of in situ calcification rates of individual coral colonies as well as rates of net ecosystem calcification. Results to date show that the benthic community exerts a very strong control on seawater CO₂ chemistry with implications for individual organisms and processes such as calcification (Coral Reef Ecosystem Feedback hypothesis; Bates et al., 2010). While the Bermuda coral reef deposit large amounts of CaCO₃ for most part of the year, in the wintertime, it is close to a condition where dissolution exceeds calcification. As the ocean continue to absorb anthropogenic CO₂, resulting in a decrease in calcification and an increase in CaCO₃ dissolution, it is anticipated that the magnitude and duration when the Bermuda coral reef is undergoing net dissolution will progressively increase. Interestingly, calcification rates of individual coral colonies do not follow the trend of net ecosystem calcification, which points to complex relationships and interactions between seawater chemistry, biology and physics that need to be considered in the context of ocean acidification.

Additional research initiatives during the past year involve investigating a number of properties across the Bermuda coral reef platform and environmental gradients such as pore water CO₂ chemistry, rates of sediment dissolution and average Mg-calcite composition; cellular, physiological, and mineralogical differences in corals (with Drs. Eric Tambutté and Alex Venn, Centre Scientifique de Monaco); bioerosion rates (Dr. Aline Tribollet, IRD, New Caledonia); characterizing seawater residence time based on ⁷Be as a tracer (Drs. D. Kadko and C. Langdon, and PhD candidate A. Venti, University of Miami); the effect of ocean acidification on gene expression in corals (with Dr. J. Loram, BIOS); and development of a coupled physical-biogeochemical circulation model representative of the Bermuda coral reef platform (with Dr. R. Johnson, BIOS).

Relevant Publications


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Research Interests: chemistry, biological availability and ecological effects of bioactive trace metals in the marine environment

The Barbeau group continues to investigate the biogeochemical cycling of trace metals in marine systems. Graduate student Kelly Roe is completing her thesis on iron uptake and cycling by the nitrogen-fixing cyanobacterium Trichodesmium and representative strains of Trichodesmium-associated heterotrophic bacteria, and plans to defend in early 2012. She currently has a couple papers submitted or nearly so. Graduate student Randie Bundy participated in several research cruises this past year, including in August a California Current cruise led by Ken Bruland of UC Santa Cruz. Randie successfully defended her thesis proposal this past spring and continues to make progress on her thesis research, exploring the use of multiple analytical windows in competitive ligand exchange-adsorptive cathodic stripping voltammetry (CLE-ACSV) analysis to study the chemical nature of iron- and copper-binding ligands in seawater. 2nd year graduate student Shane Hogle was awarded a prestigious NSF Graduate Research Fellowship this past year. Shane is working on a recently funded collaborative NSF project with SIO marine biologist Bianca Brahamsha to study the molecular mechanistics of heme iron acquisition by marine bacteria as an iron recycling pathway. A major bonding experience for the lab this year was the participation of Kathy, Randie, Shane and undergraduate summer fellow Wendy Plante in the California Current Ecosystem Long Term Ecological Research (CCE LTER) program process cruise, from mid-May to mid-June. While on the cruise, the group deployed for the first time a new trace metal sampling rosette system (Figure 1, left panel). This new sampler promises to greatly expand our trace metal profiling capability, which will be particularly useful in our ongoing studies of the biogeochemistry of iron in the Southern California Current region.

A recent publication from our lab, authored by former graduate student Andrew King (King and Barbeau 2011), demonstrates the value of studying iron biogeochemistry in the well-characterized Southern California Current area, where a wealth of time series data exists and ongoing interdisciplinary programs like CCE-LTER provide unique platforms for studying trace metals in a wider marine ecosystem context. This publication presents the distribution of dissolved iron in the southern California Current System (sCCS) from seven research cruises between 2002 and 2006. Dissolved iron concentrations were generally low in most of the study area (<0.5 nM), although high mixed layer and water column dissolved iron concentrations (up to 8 nM) were found to be associated with coastal upwelling, both along the continental margin and some island platforms. The most significant supply of iron to the region, as identified in previous studies along the central and northern California coast, is probably from the continental shelf and bottom boundary layer. With distance offshore, mixed layer dissolved iron concentrations decreased more rapidly relative to nitrate in a transition zone 10 – 250 km offshore during spring and summer, resulting in relatively high ratios of nitrate:dissolved iron (Figure 1, right panel). Higher nitrate:dissolved iron ratios could be the result of iron utilization and scavenging in addition to an overall lower supply of iron relative to nitrate in the offshore transition zones. The low supply of iron leads to phytoplankton iron limitation and a depletion in silicic acid relative to nitrate in the coastal upwelling and transition zones of the sCCS. Occurrences of silicic acid depletion relative to nitrate were examined in the historical California Cooperative Oceanic Fisheries Investigations (CalCOFI) data set.
Figure 1. (Left) Shane, Wendy, Kathy, and Randie participated in the CCE-LTER process cruise in May-June 2011, deploying a new trace metal rosette sampling system. (Right) Mixed layer nitrate: dissolved Fe ratio (μM:nM) versus density (sigma t) for CalCOFI cruises in November 2002 (green circles), February 2003 (blue circles), April 2003 (cyan squares), July 2003 (red triangles), April 2004 (blue squares), and July 2004 (magenta triangles) (from King and Barbeau 2011).

Most Recent Publications


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

In collaboration with Mark Zumberge, I have been working on the development of new sensors to replace the obsolete and no longer available broadband sensors used in the Global Seismographic Network. We are funded to deploy a 3-component borehole model at the USGS Albuquerque Seismological Lab next year. The current prototype includes a new in-line vertical suspension which will not require leveling while the horizontal component sensors consist of a simple pendulum suspended by a monolithic, electrical discharge machined flexure.

I have also been working with the OBSIP group at IGPP in developing a system that will allow us to deploy seismological observatories in the deep ocean and relay data to shore in near real-time. We have been successful in obtaining an NSF Major Research Instrumentation grant that will allow us to try out these ideas over the next two years.

We propose to develop an autonomously deployable, deep-ocean seismic system to provide long-term and near-real-time seismographic observations from sites far offshore. Building upon two proven technologies, autonomous wave-powered surface floats and ocean bottom seismometers, the proposed new generation instrument will, if successful, provide a means of increasing global coverage not only of seismic observations, but also of a variety of ocean bottom observables in an affordable, practical, and sustainable way. In this effort, we are teamed with a small company, Liquid Robotics, which has developed a new, breakthrough technology for deep ocean observations and telemetry. The Liquid Robotics Wave Glider technology comprises a surfboard-sized surface float tethered to a submerged glider, which converts wave motion into thrust and thereby propels itself. Equipped with acoustic and satellite telemetry systems, this platform will provide a communications gateway between an ocean bottom instrument and shore. Combining the Liquid Robotics technology with the technology developed for the US Ocean Bottom Seismograph Instrument Pool, the key features of this new instrument will be its capability to telemeter sensor data from the seafloor to shore without a cable or moored surface buoy, and to be deployable without a ship.
The overall concept is illustrated above. The Liquid Robotics Wave Glider surface float is equipped with solar panels, a satellite modem, GPS, and a small processor to provide commands to steer the system via a rudder on the glider. The Wave Glider has demonstrated the ability to “swim” thousands of kilometers across the open ocean and to hold station in a very small watch circle. Further, the Wave Glider has the capability to tow properly designed, low-drag loads with little loss of speed. Optimal speed performance will be reduced when towing objects, but persistent forward thrust will be maintained. Tests conducted by Liquid Robotics proved that towing an object 2 ft. in diameter and 11 ft. long behind a Wave Glider is practical. Leveraging the talents and strengths of Liquid Robotics and the SIO OBS team, we propose to develop the technology to tow a suitably designed ocean bottom seismic package to the desired site, deploy it, and then circle the launch site with the Wave Glider acting as a surface gateway between the acoustic transmission through the ocean column and the satellite transmissions to shore.

Relevant Publications


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Research Interests: tectonic and magmatic processes that occur along plate boundaries, with emphasis on oceanic spreading centers; deformation of minerals and the development of seismic anisotropy during upper mantle flow.

Geophysical investigations of oceanic spreading center processes remain a main focus of my research. In 2010/2011 my research followed three avenues at Atlantis Massif, an ocean core complex just west of the Mid-Atlantic Ridge axis, where detachment faulting has unroofed intrusive crustal rocks and at least lenses of mantle peridotite. The first avenue involved detailed refraction analysis of the top kilometer of the lithosphere. Grad student Ashlee Henig completed application of the Synthetic Ocean Bottom Experiment (SOBE) method to multi-channel seismic (MCS) data in this area and she refined models of magmatic intrusion and faulting as the core complex developed. Working with co-PI Alistair Harding who was instrumental in developing SOBE, we’ve been able to document the magnitude and scale of lateral heterogeneity throughout Atlantis Massif.

Figure. Seismic velocity structure of Atlantis Massif (from Henig et al. in prep). Map shows rift valley of the Mid-Atlantic Ridge (MAR, blue shades) at intersection with Atlantis transform fault (ATF). The Southern Ridge (red shades), Central Dome just to the north, and the hanging wall block, to the east, are shown with MCS lines overlain. Schematic illustration of drill/dredge/submersible sample locations uses symbols on/in seismic models (rock type in legend). Dashed lines indicate where MCS lines cross.
Secondly, synthesis of drill core analyses at the Central Dome IODP site and regional geophysical results were used in assessing the key factors in igneous, structural, and metamorphic evolution of Atlantis Massif, as reported in a JGR paper this year. Thirdly, looking ahead, Alistair and I will begin working with postdoc Adrien Arnulf to apply waveform inversion techniques to further refine knowledge of the seismic structure of the massif. A brief borehole study will be conducted at the Central Dome, to document local seismic properties that can anchor the regional seismic inversions.

In the Lau Basin, last November I helped recover an array of ocean bottom seismometers (OBS), that had been deployed for a year to record earthquakes generated during subduction of the Pacific plate at the Tonga trench. These data will be used to document seismic anisotropy in the mantle wedge between the trench and backarc spreading centers. While our colleagues on the project emphasize S-wave splitting measurements, we are moving ahead with linking models of mantle flow along 3 transects across the basin with quantitative predictions of anisotropy. Grad student Rachel Marcuson is in the process of conducting this initial numerical investigation. As analysis of the OBS data proceeds, we’ll work with our collaborators to determine what flow parameters need to be adjusted so that model predictions match observed mantle anisotropy patterns.

A modest mapping project along four spreading segments that extend north from the Chile Triple Junction combined morphology data from two 2010 cruises. A systematic pattern of clockwise rotation of volcanic chain and fault scarp trends in the southern portion of 3 of the segments suggests that either regional tectonic forces or a persistent pattern of mantle upwelling may influence detailed axial morphology. We (Stegman and I with GRD colleagues Castillo, Day, & Cande) have designed additional mapping and lava sampling that could test between different models of plate-driven versus flow-driven evolution of the plate boundary and associated magma chemistry in this region.

Finally, I continued efforts in community planning for future drilling of the oceanic lithosphere and associated geophysical studies that could maximize the advances that deep core samples would provide. This was done mainly via participation in meetings for the ocean drilling (IODP) and ocean bottom seismic (OBSIP and R/V Langseth) programs.


Research Interests: geochemistry and petrogenesis of magmas produced within and along divergent and convergent margins of tectonic plates; magmatic and tectonic evolution of continental margins; mantle geodynamics

My research activities during the last several years focus on the origin of oceanic intraplate magmatism, specifically, the origin of ocean island basalts (OIB) that form linear volcanic island chains and aseismic ridges. A widely accepted explanation for these volcanic features is the hotspot or plume hypothesis, which calls for the occurrence of fixed, hot, upwelling plumes consisting of primitive and recycled Earth materials from the lower mantle; these stationary plumes generate and deposit OIB on the surface of moving oceanic plates. Although the hotspot hypothesis has remained popular for more than four decades, continuous accrual of data shows difficulties in reconciling the observables with the presence of deep and/or primitive mantle reservoir for the source of OIB. The main alternative hypothesis is the plate stress hypothesis, which calls for the origin of linear volcanic island chains and aseismic ridges through lithospheric rupturing processes. In this scenario, the upper mantle consists of a ubiquitous though random mixture of small to moderate scale (1–100 km) enriched, crustal lithologies embedded in a depleted mantle matrix; such enriched lithologies are injected into the upper mantle through plate subduction.

To verify whether lithospheric rupturing processes can generate OIB or not, my colleagues and I analyzed lavas from non-linear oceanic volcanoes such as seamounts near the East Pacific Rise and ridges along fossil spreading centers. These volcanoes form along lithospheric ruptures and generate lavas that are very similar to those that form linear volcanic chains (i.e., OIB-like). In other words, the bulk of the lavas are alkalic and geochemically more enriched in incompatible trace elements and radiogenic isotopes than normal mid-ocean ridge basalts (MORB). For the near-ridge seamount investigation, our specific objectives were to constrain the source of near-ridge seamount lavas and if these lavas contain He/4He ratios higher than those of normal MORB; high 3He/4He ratios are a hallmark feature of OIB from prominent linear volcanic chains such as Hawaii, Galapagos, Samoa, and Iceland. Our results show that the source of OIB-like seamount lavas is indeed the heterogeneous upper mantle, similar to that proposed for the source of OIB by the plate stress hypothesis. However, the lavas do not have high 3He/4He ratios. Thus, the high 3He/4He of OIB cannot be simply coming from dispersed, heterogeneous lithologies in the upper mantle; the mantle source of high 3He/4He OIB is unique to linear volcanic chains and likely resides in the deeper mantle.

Results of our investigation of the OIB-like lavas from fossil spreading centers in the eastern Pacific show that the spreading center lavas also originate from the heterogeneous upper mantle. This is again consistent with to the proposed source of OIB by the plate stress hypothesis. However, results also show that, together with petrologic and geochemical data for near-ridge seamounts, intraplate volcanoes that do not form linear volcanic chains in the eastern Pacific define a compositional continuum ranging from normal MORB-like to OIB-like. The data indicated to us that the entire compositional spectrum of these intraplate lavas in the eastern Pacific results from variations in the degree of partial melting of a common, compositionally heterogeneous mantle source consisting of more easily melted, geochemically enriched components of varying sizes and amounts embedded in a
depleted lherzolitic matrix. Large degree and more voluminous partial melting produces normal-MORB-like melts represented by some near-ridge seamount lavas whereas small degree produces OIB-like lavas represented by some fossil spreading center lavas. This is very similar to the main idea of the plate stress hypothesis for generating OIB that form linear volcanic chains. However, similar to the results of our near-ridge seamount study, our new fossil spreading center data suggest that the source of OIB that form linear volcanic island chains and aseismic ridges is unique and likely resides in the deeper mantle.

Recent publications:


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

Major research interests over the past year have been (i) the behavior of the geomagnetic field behavior on millennial timescales during the Holocene time period (in collaboration with Monika Korte of GeoForschungs Zentrum, Helmholtz Center, Potsdam); (ii) the magnetic field on million year time scales (PhD student Leah Ziegler); (iii) development of modeling and data processing tools for global electromagnetic induction studies using magnetic field observations from low-Earth-orbiting satellites (PhD students, Joseph Ribaudo and Lindsay Smith-Boughner); (iv) the development with Anthony Koppers (Oregon State University) and Lisa Tauxe of flexible digital data archives for magnetic observations of various kinds under the MagIC (Magnetics Information Consortium) database project. (v) continuing work with postdoctoral researcher Christopher Davies (now at Leeds University, U.K.) and research associate David Gubbins on the compatibility of numerical geodynamo simulations with paleomagnetic results.

Figure 1 Time averages of CALS10k.1b for the radial component of the field at the core mantle boundary. Aitoff projection centred on 0 and 180°E.

(i) Holocene Geomagnetic Field Behavior: We have extended time-varying spherical harmonic geomagnetic field models to span the (0-10 ka) Holocene interval (see Figure 1). An updated global compilation of paleomagnetic records from rapidly accumulated sediments, archeological artifacts and young lava flows, allows the recovery of substantial structure in the southern hemisphere. For the past 400 years, twin magnetic flux lobes bordering the inner core tangent cylinder in both northern and southern hemispheres dominate the geomagnetic field and appear more or less fixed in location. In contrast, the millennial scale view shows that such features are quite mobile and subject to morphological changes on time scales of a few centuries to a thousand years, possibly reflecting large scale reorganization of core flow. The lobes rarely venture into the Pacific hemisphere, and average fields over various time scales generally reveal two or three sets of lobes, of diminished amplitude. Thus millennial scale models are suggestive of thermal core-mantle coupling generating a weak bias in the average field rather than a strong inhibition of large scale field changes. Persistent structure in the equatorial Pacific region is the subject of further study.

(ii) Magnetic Field Variations on Million Year Time Scales: The recovery of 0–2Ma variations in dipole moment (Ziegler et al., 2011) allows frequency domain analysis to search for characteristic
time scales for core dynamics that might be associated with excursion and reversal rate, time taken for reversals, or any signs of control by Earth’s orbital parameters. The spectrum is characteristically red for the time interval 0—160 Ma, suggesting non-stationarity associated with average reversal rate changes, probably reflecting the impact of superchrons and a continually evolving core. Distinct regimes of power law decay with frequency may reflect different physical processes contributing to the secular variation. Evidence for non-stationarity at shorter time-scales is present in dipole moment variations over 0–2 Ma with average growth rate faster than the decay process. Details can be found in Ziegler & Constable (2011).

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

Items (1) and (2) above are studied using commercial software FlexPDE for flexible 3-dimensional forward modeling to accommodate arbitrary spatial and temporal variations in external source fields and 3D conductivity variations inside the earth (Ribaudo et al., 2011). Forward modeling can be conducted in either the time or frequency domain: the former is particularly useful for satellite observations where motion of the satellite through a time-varying field can produce spatio-temporal aliasing, and the method can also accommodate the effects of Earth rotation, which are significant. Work continues on item (3), exploring the use of multi-taper spectral estimation explicitly designed to recover frequency-domain response function estimates from data series with inconvenient gaps. Current work involves the extension of the methods described in Smith-Boughner et al. (2011) to cross-spectral techniques for response function estimates.

Relevant Publications


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

Steven Constable directs the SIO Marine EM Laboratory along with assistant researcher Kerry Key. As the name suggests, much of the Lab’s work is involved in developing and using marine EM methods. The two main techniques are controlled-source EM (CSEM), in which a deep-towed EM transmitter broadcasts energy to seafloor EM recorders, and magnetotelluric (MT) sounding, in which these same receivers record natural variations in Earth’s magnetic field. We currently have 5 PhD students, a postdoc, a project scientist, and a research associate working in the group.

Figure 1. Phase of CSEM electric fields at three frequencies (0.75 Hz, 1.75 Hz, and 3.25 Hz) over the Scarborough gas field (outlined in black) at a fixed source–receiver offset of 3,000 m.

In 2009 we collected a large CSEM data set over the Scarborough gas field, on the Northwest Shelf of Australia, under sponsorship from BHP-Billiton. This project forms part of David Myer’s PhD studies, and we are beginning to obtain results from the data analysis. One innovation we employed during this experiment was a new transmitter waveform that allows us to simultaneously collect a broad spectrum of frequencies, described in Myer et al. (2011). In Figure 1 we show the phase difference between the transmitter and seafloor receivers for three frequencies at a fixed source–receiver range of 3,000 m. Over the gas reservoir, which is slightly more resistive than the host rocks, the phase difference is less because EM fields propagate better in resistive rocks and so the apparent phase velocities are higher. The effect increases with increasing frequency because the skin depth, or EM propagation constant, gets shorter at higher frequencies, allowing a bigger difference in phase to accumulate at the fixed range. The data clearly illuminate the reservoir, and we are using geophysical inversion to recover the thickness and extent of the gas.

Last year we reported results from our efforts to map marine gas hydrate using CSEM methods. This year we have been working on measuring the electrical properties of methane hydrate in the laboratory. This is not a trivial task because the hydrate has to be kept under high pressure methane to be stable and to mimic the conditions in 1,000 m water depth, where it occurs naturally. We built a high pressure conductivity cell and made the first measurements of methane hydrate conductivity as a function of temperature. This work is reported in Du Frane et al. (2011) and described in Karen Weitemeyer’s annual report entry, along with some comparisons between the Hydrate Ridge EM results and a seismic survey (Weitemeyer et al., 2011).

This year we finally worked up and published a MT data set collected off Japan in May 2000 (Key and Constable, 2011). These data were some of the first collected on the modern generation of instruments, and to this day represent the deepest deployments we have made (up to 5,400 m). The analysis took advantage of recently developed modeling code which allowed us to understand more fully the effect of coastlines, which have a very large impact on data such as these. Kerry describes this work in his annual report entry.
In April and May last year we carried out the SERPENT experiment, collecting MT and CSEM data to study the geology of the Nicaraguan subduction zone. Kerry reports on the MT and CSEM data sets, but in Figure 2 we show the results of a novel experiment in which the EM transmitter is towed in a 30 km diameter circle around extra-sensitive instruments in order to study anisotropy, or changes in conductivity with direction. On the abyssal plain (red data) the size of the electric field does not vary very much with the direction to the transmitter. On the outer rise, however, there is a strong increase in fields when the transmitter is NW or SE of the receiver (blue data). Paradoxically, this means that the crust is more conductive in this direction, almost certainly because of the faulting associated with plate bending. Further work will quantify the amount and depth of the faults.

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

Figure 2. Polarization ellipse maxima as a function of transmitter–receiver direction for 30 km circular CSEM tows on the abyssal plain (red) and outer rise (blue) offshore Nicaragua.

Recent Publications


Zhdanov, M.S., L. Wan, A. Gribenko., M. Cuma, K. Key, and S. Constable, Large-scale 3D inversion of marine magnetotelluric data: Case study from the Gemini prospect, Gulf of Mexico, Geophysics, 76, F77-F87, 2011.
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Research interests: Tectonics and geological history of NE Indian Ocean and Southeast Asia.

Joseph R. Curray, Professor Emeritus, spent part of the past year applying results of some of his previous years of basic research to practical problems of the modern world. He served as a scientific advisor for the legal team presenting the case for the claim of Bangladesh for offshore areas in the Bay of Bengal in its dispute with its neighbor, Myanmar. He was a part of the team of American, British and Bangladesh attorneys and politicians at the United Nations Law of the Sea Tribunal in Hamburg, Germany during September 2011.

Law of the Sea conventions are written by attorneys and not scientists. They have redefined for their own purposes age-old geomorphic and geologic terms, such as “continental shelf, continental margin, etc. The legal Law of the Sea “continental shelf”, for example, is 250 nautical miles wide, beyond the limits of the “territorial waters” claim of a coastal state. The “outer continental shelf” extends a variable but specified distance beyond 250 miles by “natural prolongation”.

Curray has devoted most of the past forty years to study of the sediments, geological history and tectonics of the region in and around the Bay of Bengal, northeastern Indian Ocean, including Sri Lanka, India, Bangladesh, Myanmar, the Andaman Sea and Islands, Sumatra and Java. He had previously donated data to and had assisted Sri Lanka and Bangladesh in establishing offshore claims in the Bay of Bengal under the international agreements of the Law of the Sea conventions and tribunals.

For purposes of presenting the Bangladesh claim for its “Outer continental shelf”and “natural prolongation” Curray introduced the term and concept of the “Bengal Depositional System”. The Bengal Depositional System is defined as the continuum of sedimentary processes and sedimentary environments of the confluent Ganges and Brahmaputra Rivers derived from the rising Himalayas and Tibetan Plateau, extending from the fluvial system in Bangladesh and the Bengal Basin, through the Bengal Delta to the continental shelf and slope and to the Bengal submarine Fan flooring the Bay of Bengal. This concept has not yet been introduced into the geological literature, but it is now an established term and concept in the legal literature of the Law of the Sea.

It was an interesting and rewarding experience to see the results of years of basic academic research applied to a problem of modern society.
My research responsibilities at IGPP center upon managing the scientific performance of Project IDA’s portion of the Global Seismographic Network (GSN), a collection of 42 seismographic and geophysical data collection stations distributed among 26 countries worldwide. IDA is currently upgrading the core data acquisition and power system equipment at all stations using stimulus funding provided by NSF through the IRIS Consortium. A map of the network showing upgraded systems denoted by orange triangles is shown in Figure 1.

![Map of the Global Seismographic Network](image)

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

The GSN has been fully deployed for only a short time: during this new phase of operation, IDA’s staff is working to fine tune the network’s performance. One method for accomplishing this tuning is comparing the GSN’s recordings to those of instruments from other networks designed primarily for geodetic or tidal research. Key phenomena such as Earth tides and some normal modes should register the same on these fundamentally different geophysical tools. To the extent that measurements made with multiple instruments, which have been calibrated in very different fashions, match, we may have greater confidence that the instrument response information IDA distributes with GSN waveform data is accurate. Investigators use this information to compensate for the frequency-dependent sensitivity of sensors so that they may study true ground motion and its underlying physical causes.

Although they occur infrequently, very large earthquakes like those that took place in Japan and Chile recently, afford scientists an excellent opportunity to verify the accuracy of instrument responses. Figure 2 shows a spectrum from two different instruments that recorded...
the 2011 Tohoku quake. One is from the GSN seismometer at Sutherland, South Africa; the other, from a superconducting gravimeter in Germany. Prominent in both recordings are spectral peaks associated with the Earth’s gravis
test normal modes. We expect the amplitudes of many of these modes to differ at the two locations, but one, the mode 0S0, should be excited to a uniform amplitude globally. The amplitude difference of 0S0 here indicates inaccuracies in the instrument response of the seismometer that needs to be corrected.

Figure 2. Spectrum of the 2011 Mw=9.0 Tohoku, Japan earthquake observed at IRIS/IDA station SUR (blue dashed line) and a superconducting gravimeter at Germany’s Black Forest Observatory BFO (red line). The GSN produced spectacular data for this large event, including clear evidence of splitting of 0S2 at single stations such as in these cases. Mode 0S0 can be used to assess the quality of the network’s published instrument responses.

Relevant Publications
Research Interests: Solar System formation and evolution; planetary differentiation processes; mantle geochemistry; igneous and metamorphic petrology and volcanology

How did planets in our Solar System form and subsequently transform into the bodies that we observe today? This is the fundamental puzzle that drives my current research and has implications for seemingly disparate fields of study in the astronomical, earth, and life sciences. Indeed, this question is also motivating construction of a new state-of-the-art isotope geochemistry laboratory at Scripps to address planetary accretion (formation) and differentiation (transformation) processes in the Solar System. We will provide more information on this project in the coming years.

Our recent efforts to address planetary formation and transformation include detailed study of martian meteorites (Riches et al., 2011; Basu Saradhikari et al., 2011), and studies of plate tectonic processes and mantle geochemistry in Earth (Day et al., 2010; Riches et al., 2010; Füri et al., 2011). Below, I consider two specific areas of on-going research into the origins of our planet and our Solar System.

Bling, bling, bling! Gold is one of society’s most prized elements. Yet it would probably surprise most people that the abundance of this element in the rocky (crust and mantle) portion of Earth is much higher than expected. This is because gold, along with other highly ‘siderophile’ (iron-loving) elements, such as osmium, platinum and palladium, should have drained into the center of the Earth during metallic core formation. Recently, we (Bottke et al., 2010) proposed that the cause of the high and variable abundances of highly siderophile elements observed in Earth, Moon, and Mars today are the consequence of a few variably sized and huge (100’s to 1000’s km diameter) bodies that impacted the planets shortly after their major differentiation (silicate mantle-metal-core formation) events, and soon after the formation of the planets themselves. We dub this event ‘stochastic late accretion’ (Figure 1). Such an event(s) may also have been responsible for the addition of volatiles (e.g., water!) to the planets.

![Figure 1.](image-url)
Un-mixing Earth’s Mantle: The mantle is the huge volume of rock that lies between the thin skin of crust that we reside on and the enormous metallic core that exists in the centre of Earth. Despite the thin crust (<10 km in some portions of the ocean), it is surprisingly difficult to get material from the mantle, and so our understanding of this important terrestrial reservoir is restricted. One way to indirectly observe the composition of the mantle is to study lavas that erupt on the surface and that come from melting of the upper portions of the mantle. In a recent study (Day & Hilton, 2011), myself and Prof. Dave Hilton (Scripps) investigated lavas from the Canary Islands of El Hierro and La Palma to understand the composition of mantle in this region. We found a correlation between oxygen isotopes (a proxy for alteration of lavas at Earth’s surface) and helium isotopes (a measure of primordial gases trapped within Earth) for the islands indicating preservation of ancient recycled crust in Earth’s mantle (Figure 2). We propose that some of the isotopic heterogeneity in El Hierro and La Palma may reflect lithological (rock type) variation in Earth’s mantle, combined with reservoirs that have seen limited modification in the mantle for billions of years. Our work suggests that Earth’s mantle is highly heterogeneous, but that it may be possible to ‘un-mix’ the composition of Earth’s mantle using oceanic island basalt lavas such as those in the Canary Islands to unravel the complex dynamics of plate tectonics and mantle convection driven - ultimately - by terrestrial heat loss.

Recent Publications


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

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

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

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

Figure 1. (left) A map of the configuration of the USArray seismic network in June 2007 (circles), also showing the source location (diamond) and sites of infrasound arrays (triangles). Signals at sites within 600 km of the source (dark circles) were analyzed. (right top) Observed celerities (=horizontal range/time). (right bottom) Predicted celerities.
The presence of the transportable USArray in this region provides this study with a much broader and denser array of sensors than would otherwise be available. Arrival times, predicted using standard atmospheric specifications that give variations in wind and sound speed with altitude, indicate that the arrivals are multi-pathed; the earlier arrivals are ducted within the thermosphere, later ones are refracted within the stratosphere. An unexplained observation is the presence of high frequency infrasound arrivals, near the acoustic frequency band. This suggests that propagation may be non-linear at upper altitudes, where non-linear steepening of the sound waves can take place to maintain the higher acoustic frequencies. Propagation algorithms to explain this phenomenon are under development.

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

**Relevant Publications**


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Research Interests: Landscape and seascape evolution in response to tectonic deformation, sea-level fluctuations, and climate; neotectonics and geohazards

Large earthquakes and consequent tsunamis in Sumatra (2004) and Japan (2010) have brought into sharp focus geohazards along actively deforming margins. My research group uses a variety of instruments to study geohazards by imaging fault offset and defining earthquake recurrence intervals. We examine both direct (fault offset, divergence and rotation) and indirect (tsunami deposits, debris flows, and turbidites) evidence for tectonic deformation. Recent studies have examined the Southern San Andreas Fault (Brothers et al., 2011) as well as fault systems in Pyramid Lake and the Great Salt Lake.

Much of the topographic relief in the southwestern US is caused by active tectonic deformation. The Salton Sea covers a structural boundary at the southern end of the San Andreas Fault (SAF) where it takes a southwestward step to the Imperial Fault. ECSZ – Eastern California Shear Zone; SJF – San Jacinto Fault; EF – Elsinore Fault, S.N. Sierra Nevada

Southern California’s Salton Trough, once a large natural lake fed by the Colorado River, may have played an important role in the earthquake cycle of the southern San Andreas Fault and may have triggered large earthquakes in the past. By examining displacement indicators preserved in sedimentary deposits, we have reconstructed the earthquake history and found evidence for coincident timing between flooding of the ancient Salton Sea and fault rupture in the sea. Rupture on these newly discovered step over faults in the sea has the potential to trigger large earthquakes on the southern San Andreas Fault. Lateral stepover zones often segment large strike-slip faults, like the San Andreas Fault. Movement on smaller faults within a stepover zone could perturb the main fault segments and potentially trigger a large earthquake. The southern San Andreas Fault has not experienced a large earthquake for approximately 300 years, yet the previous five earthquakes occurred at ~180-year intervals - many experts purport that it is ~100 years overdue. We conclude that rupture of the stepover faults, caused by...
periodic flooding of the paleo-Salton Sea and by tectonic forcing, had the potential to trigger earthquake rupture on the southern San Andreas Fault. Extensional stepover zones are highly susceptible to rapid stress loading and thus the Salton Sea stepover may be a nucleation point for large ruptures on the southern San Andreas Fault (Brothers et al., 2011).

CHIRP profile acquired in Pyramid Lake showing how stratal geometry can help define basin deformation. The increasing dip with depth in the divergent package indicates that sedimentation was occurring during the deformation. High-resolution seismic data together with geologic sampling allows us to define the timing and magnitude for the most recent event (MRE) along fault systems as well as the earthquake recurrence interval.

Selected Recent Publications:
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Research interests: earthquake physics, crustal deformation, space geodesy, volcanology

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

A particular area of Prof. Fialko interests is the Southern San Andreas Fault system. The San Andreas Fault (SAF) is a mature continental transform fault that accommodates much of the relative motion between the North American and Pacific plates. The southernmost section of the SAF has not produced major earthquakes in historic time (over more than 300 years), as it is currently believed to be late in the interseismic phase of the earthquake cycle. Estimates of seismic hazard on the SAF as well as on other major faults in Southern California critically depend on the present-day strain rates and the degree of fault locking in the seismogenic crust (i.e., the presence and extent of fault creep). Both factors can in principle be evaluated with help of precise spatially dense measurements of surface deformation. In collaboration with colleagues from IREA (Italy), Prof. Fialko used a large set of ERS-1 and ERS-2 acquisitions spanning the southern part of San Andreas Fault system (Figure 1). The new results are an improvement on previously published velocity data (Fialko, 2006, Nature, vol. 441, pp. 968-971) due to better temporal and spatial coverage. In particular, the new data extend to the central and northern sections of the San Jacinto fault (Figure 1). One can clearly see a regional deformation pattern due to interseismic strain accumulation on major faults (in particular, the San Andreas and San Jacinto faults). Prof. Fialko and his students are combining these data with sophisticated models of interseismic deformation to place robust constraints on slip rates and locking depths of major active faults in the area. This work may ultimately result in better understanding of seismic hazards in Southern California.

On April 4, 2010, a major earthquake hit Southern California near the US-Mexico border. The $M_w 7.2$ El Mayor-Cucapah earthquake was the largest earthquake to strike the region in the last 18 years. In collaboration with colleagues from SIO and CICESE (Mexico), Prof. Fialko is studying the aftermath of this event. The El Mayor-Cucapah earthquake was well imaged by several space-borne InSAR missions, including ENVISAT and ALOS. Among the initial results of this research is evidence for surface slip on multiple faults in the Imperial Valley triggered by the main shock (Wei et al., 2011). Analysis of InSAR data showed small (centimeter-scale) co-seismic offsets on the San Andreas, Superstition Hills, Imperial, Elmore Ranch, Wienert, Coyote Creek, Elsinore, Yuha, and several minor faults near the town of Ocotillo at the northern end of the mainshock rupture. Field measurements of slip on the Superstition Hills Fault were shown to agree with InSAR and creepmeter measurements to within a few millimeters. Dislocation models of the InSAR data from the Superstition Hills Fault confirmed that creep in this sequence, as in previous slip events, is confined to shallow depths (less than 3 km).

Another area of interest of Prof. Fialko is the origin, evolution and extent of damage around major crustal faults. Over the last year Prof. Fialko worked with Postdoctoral Scholar Yoshi Kaneko on a problem of inelastic yielding of the host rocks during dynamic rupture, and the effects of yielding on surface deformation. Evidence for such yielding
is emerging from geologic, seismic and geodetic observations. This work showed that the amount of shallow slip deficit (that is, coseismic slip appears to decrease towards the Earth surface) is proportional to the amount of inelastic deformation near the Earth surface. The largest magnitude of slip deficit in models accounting for off-fault yielding is 2-4 times smaller than that inferred from kinematic inversions of geodetic data. However, assumptions implicit in the kinematic inversions may bias the inferred slip distributions. Inelastic deformation in the shallow crust reduces coseismic strain near the fault, introducing an additional “artificial” deficit of up to 10 per cent of the maximum slip in inversions of geodetic data that are based on purely elastic models. The largest magnitude of slip deficit in elasto-plastic rupture models combined with the bias in inversions accounts for up to 25 per cent of shallow slip deficit, which is on the low end of deficit inferred from kinematic inversions.

Recent publications:


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Research Interests: application of paleomagnetic and magnetic anomaly data to crustal accretionary processes at mid-ocean ridges and past geomagnetic field variations; origin and significance of magnetic fabrics in igneous rocks.

Paleolatitude record of Louisville hotspot trail: From December 2010 to February 2011, Expedition 330 of the Integrated Ocean Drilling Program (IODP) drilled six sites along the older portion of the Louisville seamount chain (Fig. 1). The 4300 km long Louisville Seamount trail is the South Pacific counterpart of the much better studied Hawaii-Emperor chain. Both chains are thought to reflect motion of the Pacific plate over persistent mantle melting anomalies although the stationarity of these hotspots, and thus their suitability as a reference frame for Pacific plate motions, remains uncertain. Drilling at the Emperor Seamounts documented an ~15° southward shift of the Hawaiian hotspot between about 80 and 50 Ma. IODP Expedition 330 targeted Louisville guyots with ages comparable to those sampled in the Emperor Seamounts, with a primary goal of documenting the paleolatitudes of seamounts with ages comparable to those drilled in the Hawaii-Emperor chain. Because of the abundance of volcaniclastic material recovered, estimating the paleolatitude for the Louisville guyots is less straightforward than for the sites on the Hawaii-Emperor chain, where a sequence of discrete (primarily subaerial) lava flows was recovered. Studies of the Louisville drillcore samples are ongoing but analysis of shipboard magnetic data reveals inclinations that are generally compatible with formation near the present-day location of the Louisville hotspot (~51°S) rather than undergoing a large southward shift as did the Hawaiian hotspot.

Figure 1: Bathymetric map of the northern end of the Louisville hotspot trail, from the Kermadec Trench to a bend in the chain at 169°W. 40Ar/39Ar ages are from dredge samples collected during the site survey cruise (Koppers et al., 2011) for IODP drilling. Drilling during IODP Expedition 330 sampled volcanic basement at five of six sites (U1372-1377).
Jurassic geomagnetic field behavior recorded in the Dufek layered intrusion: Links between geomagnetic field intensity, reversal frequency and directional variability (secular variation or excursions) provide an important, but poorly understood, constraint on the temporal dynamics of the geodynamo. These relationships should be most pronounced and easiest to document in rocks that record the extremes of geomagnetic field behavior. Our ongoing study of the ~182 Ma Dufek layered intrusion in Antarctica is focused on characterizing one such interval with frequent reversals and postulated low field intensity. Samples from the lowermost ~500m exposed in the Dufek intrusion, reveal the presence of multiple polarity components, with many samples having two or three well-defined components evident in thermal demagnetization. A second section approximately 800m higher in this same section reveals even more complex remanence behavior, with as many as five or more polarity intervals recorded in a single sample. Thermal modeling (Fig. 2) indicates that these two reversal records can be reconciled if the ~2km intrusion was emplaced near the surface and cooled during a period of rapid reversals. We have also been able to determine ancient field intensities for a significant fraction of these samples by the modified Thellier absolute intensity method and a new method based on thermal demagnetization of a laboratory thermoremanence. The Dufek intrusion preserves a record of a large number of polarity intervals and low field intensity, in many cases comparable to values found during excursions or reversals, suggestive of a weak (perhaps fibrillating) field that differs markedly from more recent records of the geomagnetic field.

Figure 2: Thermal model of remanence acquisition in the Dufek intrusion during an interval with geomagnetic field reversals every 20 kyr. The temperature range of corresponding normal polarity (red) and reversed polarity (blue) magnetization components in the 2km-thick intrusion is determined by the polarity interval length and cooling rate.

Recent Publications


Michael A.H. Hedlin  
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*Research Interests:* Analysis of acoustic signals from large-scale atmospheric phenomena; study of seismo-acoustic phenomena, 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.

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

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

**Miscellaneous studies:** 1) **Ocean noise:** Using data from our permanent array in the Anza-Borrego desert and two more arrays near San Diego we detect surf noise from along the coast of California. Infrasonic waves from the crashing surf propagate through the stratosphere to our stations up to 200 km away. We see further avenues for research in this area in that lower frequency signals, known as microbaroms, are known to propagate 1000’s of km and can be used to probe atmospheric structure. 2) **Natural hazards:** Our group is using infrasound energy to detect and monitor emerging hazards (such as volcanic eruptions, major storms at sea, tornadoes).
We are particularly interested in the use of infrasound sensors to monitor volcanoes, such as Mount Saint Helens, that have a history of releasing ash into the stratosphere. 3) **Study of seismo-acoustic phenomena:** The Earth’s free-surface is rich in sources that generate both downgoing seismic and upgoing acoustic energy. We believe to properly characterize such sources it is necessary to study the entire seismo-acoustic wavefield. We have recently completed a study of Mount Saint Helens using both types of sensors (Robin Matoza, PhD thesis). Studies of other seismo-acoustic sources (such as shallow earthquakes) are currently underway.

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

**Relevant Publications**


Research Interests: Noble gas and major volatile isotope geochemistry of subduction zones, mantle hotspots, groundwaters and geothermal systems.

We continue to investigate the volatile systematics – particularly noble gases and major volatiles such as CO$_2$ - of various tectonic environments. New publications this year include work on oceanic basalts from three different regions of the ocean basins – the Central Indian Ridge– Réunion Island hotspot track (Füri et al., 2011), the northern section of the Lau Basin in the western Pacific (Tian et al., 2011a) and fossil spreading ridges off Baja California, Mexico in the eastern Pacific (Tian et al., 2011b). We targeted these locations to study the interaction history of different mantle sources such as enriched material, often associated with mantle plumes, and depleted material, representing ambient mantle matrix.

A related study involves the Canary Islands in the eastern Atlantic (Day and Hilton, 2011). At this location, we present new helium isotope ($^{3}$He/$^{4}$He) data that show remarkable correlations with oxygen isotope ($^{18}$O/$^{16}$O) variations on the same phenocryst suites. These correlations allow us to identify compositionally and lithologically heterogeneous mantle sources (e.g., pyroxenite, eclogite, peridotite) containing recycled oceanic crust and lithosphere entrained within upwelling high-$^{3}$He/$^{4}$He (plume) mantle that has been severely diluted by interaction with depleted mantle. Consequently, we propose that the noble gas systematics of HIMU-type lavas, and ocean island basalts (OIB) in general, are most simply interpreted as being controlled by the most gas-rich reservoir involved in mixing to generate the mantle sources.

We present new He isotope data on mineral separates from Rungwe Volcanic Province at the southernmost extreme of the Kenya Dome. Spectacularly, and most unexpectedly, $^{3}$He/$^{4}$He ratios are as high as 14.9 RA (RA = air $^{3}$He/$^{4}$He) – the first report of such high values (> upper mantle as sampled by mid-ocean ridge basalt) anywhere south of the Turkana Depression which separates the Ethiopia and Kenya domes (Hilton et al., 2011). Previous work has only found MORB-like or lower values (see Figure) and these observations have given rise to the hypothesis that the Kenya Dome is supported by convection restricted to the upper mantle only. Our finding removes this constraint, and we suggest that both Ethiopia and Kenya domes are formed by deep (lower) mantle upwelling associated with the African Superplume. Our work also reveals why the fundamental misconception of two scales of convection below East Africa has arisen: over-reliance on geothermal fluids as a He sampling medium particularly in regions where old crust dominates the bedrock geology.

Finally, we present a new review paper on the applications of helium to groundwater studies (Kulongoski and Hilton, 2011).
Figure. The East African Rift System (EARS) showing the Ethiopia and Kenya domes. The highest $^{3}\text{He}/^{4}\text{He}$ ratios (R/R_A notation) are plotted for different segments of the EARS, using circles (lavas), squares (geothermal fluids) and triangles (xenoliths). In the Kenya Dome region, $^{3}\text{He}/^{4}\text{He}$ ratios do not exceed the canonical MORB value ($8 \pm 1$ R_A) with the exception of Rungwe at 9°S (Hilton et al., 2011). The most southerly locality in the Ethiopia Dome region to have $^{3}\text{He}/^{4}\text{He} >$ MORB is Shalla (13.9 R_A) located at 7°N in the Main Ethiopia Rift. High $^{3}\text{He}/^{4}\text{He}$ ratios (up to 19.6 R_A) extend through the Afar region to the Gulf of Aden, the Red Sea and Yemen.

New Publications


Kerry Key

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Research Interests: Marine electromagnetic exploration, subduction zones, mid-ocean ridge, margins, hydrocarbon exploration, numerical methods, marine geophysical instrumentation.

SERPENT: Serpentinite, Extension and Regional Porosity Experiment across the Nicaraguan Trench: In last year’s annual report I described our research cruise to characterize the electrical structure of the subduction zone offshore Nicaragua (Figure 1); this year we share some preliminary results. The controlled-source EM (CSEM) data reveal that when the seafloor bends and fractures at the trench due to subduction, it is accompanied by a significant decrease in electrical resistivity at crustal depths; this is likely due to conductive seawater penetrating into the porous extensional faults (Figure 1). My collaborator Steven Constable shows in his annual report entry another EM data set that constrains the conductivity increase to be anisotropic in a fault parallel geometry, furthering our evidence that it is due a porosity increase from faulting. Graduate student Samer Naif is analyzing the magnetotelluric (MT) data to see how this influx of seawater affects deeper conductivity in the upper mantle and the subsequent generation of partial melts after the hydrated plate has been subducted.

Figure 1. Marine EM survey of bending faults in the subduction zone offshore Nicaragua (left). Seafloor EM receivers (white dots) deployed across the Middle America Trench recorded EM transmissions from an electric dipole deep-towed across the array (black line). (A) Electrical resistivity model obtained from inversion of the CSEM data. The lateral variation of resistivity is more readily seen after normalization by an average vertical profile (B).

Adaptive Finite Element Modeling: In Key and Ovall (2011) we developed a 2.5D electromagnetic modeling code (2D model with a 3D source) that automatically generates and refines an unstructured modeling grid until the solution achieves the desired accuracy, thereby enabling even novices to obtain reliable modeling results for complicated electrical conductivity models with dipole or plane-wave EM sources. Our parallel implementation allowed us to run this code on a cluster computer using 1000 CPUs, where results were computed in only a few seconds to tens of seconds instead of the minutes to hours required when using only a single CPU.

MT Survey offshore Japan: In Key and Constable (2011) we finally published an analysis of some very unusual magnetotelluric data we acquired back in 2000 when I was a PhD student (Figure 2). This pilot experiment was carried out to study the electrical structure of the seismogenic zone.
offshore Japan using our then newly developed broadband MT receiver. The data exhibited unusual cusps and extreme phase variations that our new modeling 2D code (Key and Ovall, 2011) revealed to be due to strong inductive coupling at the edge of the conductive ocean, leading to the normally downward diffusing MT plane-wave instead diffusing back up beneath the margin slope (Figure 2A). 2D inversion of this data constrains the thickness of conductive forearc sediments and the underlying high resistivity associated with the mantle wedge and subducting oceanic lithosphere (Figure 2B). Although we only interpreted a 2D subset of this data due to 3D complexities at long periods, pending analysis of the entire data set will help us constrain the distribution of fluids along the plate boundary and how these may be related to nearby source region of the great 2011 Tohoku earthquake.

Figure 2. Marine MT survey of the subduction zone offshore northeastern Japan where the Pacific plate subducts beneath the island arc. Eight seafloor MT stations (orange squares) were acquired in June 2000 along the margin slope about 200 km north of the location of the 2011 Tohoku earthquake (star). (A) EM Poynting vectors (white lines) showing the direction of diffusion for the MT plane wave and colors show the corresponding TE mode phase. (B) Electrical resistivity model obtained from 2D MT inversion.

Recent Publications


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

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

A Comparison of Spectral Parameter Kappa from Small and Moderate Earthquakes Using Southern California ANZA Seismic Network Data: Kappa is a one-parameter estimator of a seismogram’s spectral amplitude decay with frequency (Kilb et al., 2011a). Low values (~5ms) indicate limited attenuation of high frequency energy whereas higher values (~40ms) indicate high frequency energy has been removed (Figure 1). Kappa is often assumed to be a site term and used in seismic designs. Kilb and her co-authors address two key questions about kappa: (1) How to identify source, path, and site contributions to kappa; and (2) Can kappa estimates from smaller earthquakes, and more readily accessible weak-motion recordings, be reasonably extrapolated to estimate kappa of larger earthquakes? The use of small earthquakes (magnitudes < 1) presents many challenges and requires new approaches. Kilb and her team developed estimates of kappa for seismograms from 1,137 small earthquakes recorded by the ANZA seismic network in southern California, and they compare these to results from the stronger recorded shaking generated by 43 earthquakes of magnitude 3.5 or greater inside the network. They found kappa from small earthquakes predicts the relative values of kappa for larger earthquakes (e.g., measurements at stations PFO and KNW are small compared with those at stations TRO and SND). For SND and TRO data, however, kappa values from small earthquakes over-predict those from moderate and large earthquakes. Although site effects are most important to kappa estimates, the scatter within kappa measurements at a given station is likely caused by a significant contribution from near the source, perhaps related to near source scattering. Because of this source-side variability, care is recommended in

Figure 1: Data from a magnitude 3.6 earthquake. (a) Seismogram recorded at ANZA station KNW (located on hard rock). Elongated rectangles identify the time windows of the noise window (left) and S-wave signal (right). (b) As in (a) for a seismogram recorded at the ANZA station SND (located within the San Jacinto Fault Zone). (c) Velocity spectra (blue line) and model fit (black dashed line) for station KNW and noise spectra (green line). (d) As in (c) but for data recorded at station SND. Note the enriched high frequency energy at the more distant station KNW (hypocentral distance: 30 km; kappa=6.6), in comparison with that at station SND (hypocentral distance: 15 km; kappa=49), which is counter to what is expected.
using individual small events as Green’s functions to study source-time effects of moderate and large events.

**Potential triggers for large ruptures along the southern San Andreas Fault:** In a collaborative project with past SIO graduate students Daniel Brothers and Karen Luttrell, in addition to professors Neal Driscoll and Graham Kent, Kilb explores why the southern San Andreas Fault (SSAF) in California has not had a large earthquake in approximately 300 years, yet the average recurrence for the previous five ruptures is about 180 years. Key in this work is the observation that a 60 km section of the SSAF has periodically been submerged during high lake levels of the large late-Holocene Lake Cahuilla (LC), and emerging evidence indicates coincident timing between LC flooding and fault displacement. As a large SSAF earthquake appears imminent, it is important to understand how crustal stress perturbations can promote or inhibit fault failure(s) in this region. In this work, Kilb and co-workers assess the potential for LC to act as a catalyst in triggering a sequence of large earthquakes. They find calculated static stress perturbations from LC flooding and/or rupture of secondary faults beneath LC are sufficient (i.e., reaching levels above an assumed triggering threshold of 0.1 MPa) to potentially trigger large earthquakes on the SSAF. Since the current lake level is relatively stable, any future interaction between the faults under today’s Salton Sea and the SSAF will depend solely on tectonic loading, without any perturbing stresses from lake level changes. In general, these results highlight the importance of including lake loading and secondary fault ruptures in seismic hazard assessments, as both have the potential to modulate earthquake cycles on major plate boundary faults such as the SSAF (Brothers et al., 2011).

**Listen, Watch, Learn:** The increased popularity of YouTube videos has changed the format of how information is distributed and assimilated, highlighting the importance of including auditory information in videos. Videos that include sound are also permeating the research community as evidenced by their recent increase within on-line supplements to journal articles. Tapping into this new approach of information exchange, Kilb and her co-workers are creating a seismic data video repository. These videos augment visual imagery (seismograms and associated spectragrams) with the associated auditory counterparts (Kilb et al., 2011b; Peng et al., 2011). We term these ‘SeisSound’ video products, which are presented in movie format to indicate how the data evolves with time. Concepts that can be more easily discussed and investigated by incorporating sound include: categorizing seismic wave attenuation with distance from the source, identifying aftershock rates and recognizing site effects including reverberation in basins. SeisSound products can also be useful in discriminating complicated seismic signals from multiple sources, such as aftershocks within the coda of large earthquakes, remote triggering of earthquakes and tremor.

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

**Recent Publications**


Gabi Laske
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Research interests: regional and global surface wave seismology; seismology on the ocean floor; observation and causes of seismic noise; natural disasters and the environment

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

Global and regional tomography: Laske’s global surface wave database has provided key upper mantle information in the quest to define whole mantle structure. Graduate students Christine Houser and Zhitu Ma as well as students from other universities have used her data to compile improved mantle models. Laske has collaborated with Guust Nolet at GeoAzur, U. Nice, France and his students to image upper mantle structure beneath North America and to analyze a new set of free oscillation splitting matrices.

Global reference models: With CRUST5.1 and CRUST2.0, Laske and collaborators Masters and Mooney produced the most widely used global crustal models that found application in a wide range of disciplines in academia and industry, and sometimes reached into quite unexpected fields such as the search for Neutrinos. Laske collaborates with Masters, graduate student Zhitu Ma and Michael Pasyanos at LLNL to compile a new global crustal and lithosphere model, LITHO1.0. A prototype 1-degree crustal model, CRUST1.0 is close to public release for initial testing (Figure 1). The new model is based on most recent models of topography and ice cover, an improved version of Laske and Masters’ global sediment map as well as an updated compilation of Moho depths. Initial adjustments have been made to improve the fit to Ma’s new group velocity dataset. Collaborating with Masters, she currently works on refining estimates of Earth’s inner core differential rotation.

The PLUME project: Laske is the lead-PI of the Hawaiian PLUME project (Plume–Lithosphere–Undersea–Mantle Experiment) to study the plumbing system of the Hawaiian hotspot. The project aims at resolving the fundamental question whether a deep-reaching mantle plume or other mechanisms feed Hawaii’s extensive volcanism. The PLUME team includes co-PIs from SIO (Laske, Orcutt), WHOI (Collins, Detrick), U. Hawaii (Wolfe), DTM (Solomon, Hauri) and Yale Univ. (Bercovici). During two 1-year deployments in 2005 through 2007, the team collected a unique large seismic dataset from the world’s largest network of broadband ocean bottom seismometers (OBS).

The body wave study provided conclusive evidence that Hawaii’s volcanism is indeed fed by a deep-reaching mantle plume rather than from passive magmatism resulting from a cracking plate. A surprisingly thick and large body of anomalous mantle material appears to pond at depths below 200 km. The surface wave study, on the other hand, imaged a relatively narrow low-velocity feature in the asthenosphere to the west of the island of Hawaii which likely provides the pathway for plume material to reach Hawaii’s magma chambers (Figures 2 and 3). The Hawaiian lithosphere has undergone a thermal rejuvenation process with no extensive mechanical erosion. The group found no evidence for a broad and thin pancake spreading beneath the lithosphere as is predicted by some geodynamical models. The seismic low-velocity anomalies are consistent with a marked temperature anomaly of roughly 250°C and perhaps 1-2% of partial melt. The PLUME crustal receiver function study (Leahy et al., 2010) found extensive crustal underplating beneath the Hawaiian Swell, thereby supporting the anomalies imaged by the surface waves. Graduate student Paula Chojnacki currently conducts a detailed study of surface wave azimuthal anisotropy to con-
Figure 1: The prototype crustal model CRUST1.0. Top: updated crustal types; Bottom: thickness of the crystalline crust including sediment cover. The input crustal thickness was compiled using existing active source data as well as receiver functions and some gravity data.

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

strain patterns of mantle flow and fabric.

Recent publications:


Research Interests: Origin and evolution of the solar system - isotopic studies on extraterrestrial materials; extinct radionuclides; cosmochronology; nucleosynthesis; impact structures and impact deposits on Earth.

The principal aim of our work is to improve our understanding of the earliest evolutionary period of our solar system (i.e. the first tens of millions of years). We continue to explore its chronology by using mostly short term chronometers (based on extinct radioactive nuclei), the bearing of short-lived nuclei on planetary heating and differentiation, and the addition of 'exotic' nuclei to solar system matter to help constrain models of nucleosynthesis. We have shown that the $^{53}\text{Mn}$-$^{53}\text{Cr}$ system ($T_\frac{1}{2}(^{53}\text{Mn}) = 3.7$ Ma) is a powerful tool to obtain relative ages of meteorite formation and, more general, of early solar system processes with a time resolution of ~1 Ma or less. The use of a precise absolute Pb-Pb age of the angrite NWA 4801 - our new time marker - and the $^{53}\text{Mn}$/$^{55}\text{Mn}$ ratio in this meteorite at the time of its solidification allowed us to map the relative Mn-Cr ages of other meteorites to an absolute time scale. In particular, we dated various classes of chondrites, achondrites, and unusual meteorites, determined the timing of planetary differentiation and other processes within early planetary bodies.

Our main instrument in these investigations is high precision thermal ionization mass spectrometry.

In the last year we conducted the study of the metachondrite Northwest Africa 3133 (NWA 3133). Several new groups of stony meteorites have been recently recognized. These meteorites have no chondrules, but have elemental and oxygen isotopic compositions and textures suggesting that they were altered by metamorphism and/or partial melting from precursor carbonaceous chondrites. These metachondrites include examples related to CR, CV and CO types and possibly to yet unknown types of carbonaceous chondrites. The re-crystallization has completely erased textural evidence of chondrules and CAI, although chemical and modal mineralogical inhomogeneities remain in the resulting metachondrites.

This work was a continuation of our effort to improve our understanding of the early evolutionary period of the solar system by applying $^{53}\text{Mn}$-$^{53}\text{Cr}$ systematics to NWA 3133. The other important goal of this work was to determine a characteristic $^{54}\text{Cr}$/$^{52}\text{Cr}$ ratio for this unusual meteorite in order to test the proposed genetic link between this meteorite and carbonaceous chondrites.

We have measured $^{53}\text{Cr}$/$^{52}\text{Cr}$ and $^{54}\text{Cr}$/$^{52}\text{Cr}$ ratios and Mn and Cr abundances in chromite (Chr), silicates (Sil), and total rock (TR). The results are presented in Figure 1. The data points in the figure represent the average of repeat $^{53}\text{Cr}$/$^{52}\text{Cr}$ measurements versus $^{55}\text{Mn}$/$^{52}\text{Cr}$ ratios. The relative abundances of $^{53}\text{Cr}$ in TR, Chr, and Sil are $+1.24\pm0.18\ \varepsilon$, $+1.28\pm0.18\ \varepsilon$, and $+1.31\pm0.18\ \varepsilon$, respectively, and are essentially the same. The average from all three fractions is $+1.28\pm0.11\ \varepsilon$. 


From the slope of the isochron we calculate a $^{53}\text{Mn}/^{55}\text{Mn}$ ratio of $(1.96\pm0.39) \times 10^{-6}$ at the time of isotope closure. Using our new absolute time marker, the angrite NWA 4801, we calculate an absolute age. The Pb-Pb age of NWA 4801 is $4558.0\pm0.13$ Ma and the corresponding $^{53}\text{Mn}/^{55}\text{Mn}$ ratio is $(0.96\pm0.04) \times 10^{-6}$. We obtain a metamorphic age of NWA 3133 of $4561.8\pm0.5$ Ma.

The excess of $^{54}\text{Cr}$ (+$1.28\pm0.11\ \varepsilon$) in NWA 3133 clearly indicates that the precursor of this meteorite was a carbonaceous chondrite material since only this class of meteorites is characterized by elevated relative abundances of $^{54}\text{Cr}$.

The excess of $^{54}\text{Cr}$ in NWA 3133 (+$1.28\pm0.11\ \varepsilon$), however, is clearly larger than in CV chondrites. It is similar to the relative $^{54}\text{Cr}$ abundance in the CM chondrite Murray: $+1.13\pm0.21\ \varepsilon$. We also note that the excess of $^{53}\text{Cr}$ in the bulk sample (TR) of NWA 3133 (+$0.41\pm0.07\ \varepsilon$) is considerably larger than in the bulk Allende: $+0.10\pm0.09\ \varepsilon$ and is similar to that in the bulk samples of the CI chondrites Orgueil and Ivuna: $0.40\pm0.10\ \varepsilon$.

Thus, the Cr isotope systematic may imply that the precursor of the metachondrite NWA 3133 was a complex conglomerate of different carbonaceous chondrite lithologies or represents a yet unknown type of carbonaceous chondrite.

Another direction of our work is the use of the Cr isotopic composition as a tracer of extraterrestrial material on Earth. Our investigations of the $^{53}\text{Mn}-^{53}\text{Cr}$ isotope system during the last decade have shown that all meteorite classes studied so far have relative $^{53}\text{Cr}$ abundances that are clearly different from terrestrial and are characteristic for individual classes of meteorites. Thus, based on measurements of the Cr isotopic composition, we can unambiguously demonstrate an extraterrestrial component in geological samples on Earth that contain a significant proportion of meteoritic Cr.

Using the Cr isotopes isotopes and cosmic ray ages together with impact crater and ejecta chemistry we recently proposed that the Brangane asteroid family is a result of the disruption of a large H-chondrite parent body. The paper on this subject was published in 2011.

Relevant Recent Publications


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Research Interests: Large-scale diversification of biodiversity, Paleogene and Cretaceous warm climates, evolutionary and ecosystem dynamics in pelagic organisms, impact of human society on marine ecosystems.

The past year, my laboratory group has focused on biological evolution, paleoecology, and climate change in the oceans. We have studied the ecological recovery from the Cretaceous-Paleogene mass extinction including work on geochemistry, fish teeth, and microfossils. On-going work concerns the response of mid-level consumers (small pelagic fishes) to the extinction, and work on sedimentation rates through the recovery interval based upon extraterrestrial helium isotope fluxes. Another topic has been the use of fish teeth to interpret the history of fishing pressure in reef environments. My climate studies include work on extreme warm periods in the Paleogene by my student, Sandra Kirtland, and a statistical analysis of modern reef biomes by my student, Lauren Freeman, and fellow professor, Art Miller. Finally, I have recently been named co-Chief of Expedition 342 to drill the “Titanic Site” near the Grand Banks of Canada. This expedition will focus on studies of Eocene and Oligocene drift sediments and oceanographic history of the North Atlantic in Summer 2012. Two examples of my lab’s work are described below:

**Reef fish teeth as indicators of pre-European fishing impacts in the Caribbean.** Student Lauren Freeman and I traveled to the Dominican Republic in March 2011 to sample Holocene reef sediments in the Enriquillo Valley. These reefs are amazingly well preserved and are accessible through a series of canyons cut through the reef core. We collected bulk samples of reef sand, dissolved it in acid and recovered suites of 300 to >1200 teeth per sample. Our goal is to assess the population abundance and structure of reef fishes before widespread human impacts on coastal reef environments. Preliminary results suggest that most of the fish communities in the back reef lagoons and the reef core consist of ~40-95% predatory fish species, including micropredators. Sharks and other long-lived species are rare, but present, in the assemblages whereas most of the tooth assemblage is composed of small, short-lived species. Qualitatively, the results from these 5000-9000
year old reef communities are similar to modern sand samples from Bimini, suggesting that major human impacts on reef fish populations are very recent (post 1950’s) and post date even our “modern” samples.

*Ecological Recovery of Pelagic Ecosystems after the Cretaceous-Paleogene Mass Extinction*

Ecological modeling suggests that during large extinctions the top of the food chain is both disproportionately hammered and recovers much more slowly than the basal parts of the food chain. Work with former graduate student, Celli Hull (now a post doc at Yale) and new graduate student Elizabeth Sibert, shows that there was a major turnover in marine plankton after the Cretaceous-Paleogene extinction, with a drastic drop in calcareous nanoplankton production, a massive increase in planktonic foraminifera production, and little, if any, change in fish productivity. Our studies (partly reflected in Hull et al. 2011a, b), suggest that the existing models of ecological recoveries do not capture the true complexity of these events. Indeed, our results suggest that each part of the food chain shows individualistic behavior with some groups crashing, others booming, and still others managing to maintain similar levels of productivity. These results are not expected given the prevailing view that the K-Pg extinction nearly eliminated the top of the food chain in a cascading series of extinctions that followed a global shutdown in photosynthesis. We conclude that the true story is both more complicated and more interesting than current simplistic models would suggest.

Figure 2: History of the mass accumulation rate of nannoplankton (primary producers) foraminifera (unicellular consumers) and small pelagic fishes (mid level consumers). Note the different responses of each species following the extinction (yellow line). Note also that the seemingly most vulnerable group (the fish) increase production in the several million years following the extinction. We suggest that the boom of fish production is related to the extinction of top predator fishes as documented elsewhere

*Some Recent Publications*


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I specialize in adapting cutting edge computational models to address research problems in geosciences. My interests are process oriented with a focus on fluid dynamics. I primarily apply this work toward explosive volcanic eruptions. The two major themes of my current work are linking acoustic signals generated by eruptions to physical processes in the eruption column and the interaction of eruptions with the surrounding rock. I am also involved in projects related to volcano seismicity, laboratory experiments of volcanic jet analogs, and connecting volcanic processes to mass extinction.

In explosive volcanic eruptions, rapidly expanding particulate-laden gases decompress through erodible and brittle vents. The shape of the vent can change in response to the stresses applied by the fast-moving expanding gas, which, in turn, is controlled by the vent shape. In particular, the degree of curvature undergone by fluid in the vent has a strong influence on the pressures and velocities of the eruptive fluid, which can have dramatic effects on eruption dynamics (Ogden, 2011). With collaborators at Los Alamos National Laboratory (LANL), I use computational simulations to determine the effect of vent formation on the evolution of an eruption column through time. These projects include both the theoretical aim of more fully understanding the dynamics of supersonic turbulent flow at volcanic scales and the practical goal of quantifying these effects for application to volcanic hazards analysis. Our simulations indicate that vent shape is more strongly dependent on eruptive dynamics than the rheology of the surrounding rock. However, higher resolution and longer simulations are required to test this theory.

Infrasound (acoustic signals with frequencies below that of human hearing) provides a means to detect the atmospheric oscillations from volcanoes at distances of meters to thousands of kilometers from the source. Recent infrasound recordings of volcanic jets have frequency spectra similar to the acoustic signal produced by man-made jets (jet noise). For the past 60 years, aeroacoustics has studied the relationship between the flow properties of man-made jets and the acoustic signal produced. Our long-term objective is to reverse this concept by determining the flow properties of volcanic jets based on the infrasound signal produced by the eruption. As a first step toward that goal, my research group is using a combination of analytical and numerical simulations to study the interaction of volcanic jets with the surrounding atmosphere.
computational models to adapt empirical man-made jet noise results from aeroacoustics to the more complex volcanic jet system.

This past year saw expansion of my research into exotic volcanism, i.e., eruptions that are not common on the Earth’s surface in the present day. In collaboration with Norm Sleep at Stanford University, I explored the feasibility of explosive interaction of coal and basalt as a mechanism for the End Permian mass extinction (Ogden & Sleep, 2011). Around the time of this extinction, large amounts of basaltic volcanism occurred in Siberia, forming what is now known as the Siberian Traps. However, there was no robust physical mechanism linking this relatively local volcanism to mass, global extinction. Basaltic volcanism is not capable of injecting matter high enough into the atmosphere to produce global climate change and ocean acidification. We proposed that the basalt may have interacted explosively with local coal beds, which would produce enough thermal and kinetic energy to drive large amounts of particulates and greenhouse gasses high into the atmosphere. This injection would result in rapid climate change, ocean acidification and loss of biota on land and in the ocean.

Relevant Publications


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

Bob Parker has continued to study theoretical problems in electromagnetic induction. After the horizontally or radially layered systems, the simplest electrical structures to understand are 2-dimensional. Then the magnetotelluric (MT) induction problem naturally decomposes into two modes, one in which the driving magnetic field is parallel to the lineation, Transverse Magnetic (TM) induction, the other where the field is perpendicular to it, Transverse Electric (TE) induction. In his recent work (ref 1 below), Parker investigates TE in a degenerate structure comprising conductors that are extremely thin compared to their width, a model often used for representing the oceans in large-scale modeling, or for fluid-filled cracks and rifts. He discovers a large class of such conductors with a strange property: the electromagnetic response possess a single (imaginary) resonant frequency. The response, defined as the $E_x/\omega B_y$, of every known 2-dimensional system until now, exhibited infinitely many such resonances.

In the well-understood 1-dimensional inverse problem for MT, conductivity profiles with finitely many resonances play a central role, and they too consist of thin layers embedded in an insulator. Although mathematical analysis the 2-dimensional inverse problem is almost completely lacking, there is reason to believe that best-fitting models may also be built from thin conductors with a finite number of resonances, so that the new class of solutions to the TE induction problem could play a part in a fully-developed 2-dimensional inverse theory.

Another role for these models is in validating numerical codes, which are at present almost our sole means of exploring induction in dimensions higher than one. Thin layers represent a considerable challenge to finite difference and (to a lesser extent) finite element programs. Exact solutions for the new models are readily found using analytic functions of complex variables.
The diagram above gives contours of $E$, where the electric field into the page is $E_y(x, z, t) = E(x, z) e^{i\omega t}$, around a simple 2-dimensional system of conductors, shown in red. The base is a perfect conductor and the thin vertical conductor has a specially designed conductance profile, $\tau(z) = a \tau_0/(a^2 - z^2)^{1/2}$ that yields a single resonance for this geometry. The contours are also lines of magnetic force.

**Recent Publications**


Research Interests: Geodynamics, global bathymetry, crustal motion modeling

During the 2011 academic year, Dave Sandwell's research was focused on solid Earth Geophysics with an emphasis on understanding the dynamics of the crust and lithosphere. Our group comprises three graduate students Karen Luttrell, Meng Wei, and Xiaopeng Tong. Our research is mostly supported by three grants; two are from the National Science Foundation with titles Observations and Modeling of Shallow Fault Creep Along the San Andreas Fault Zone and High-Resolution Gravity, Topography, and Seafloor Roughness while the third is from NASA to perform Geodetic Imaging and Modeling of the San Andreas Fault System.

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

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

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

More information is provided at http://topex.ucsd.edu.
Figure 1. Radar interferometry of the 2010 M8.8 Maule, Chile Earthquake. Nine tracks of ALOS ascending interferograms and two tracks of ALOS descending interferograms cover a wide area from the coastline of central Chile to the foothills of the southern Andes.

Relevant Publications


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Research Interests: Radiolarian evolution, taxonomy and stratigraphy, magnetobiostratigraphic chronology and correlation of Cenozoic marine sequences, extinction and diversification associated with climate change during the Paleogene.

Continuation of work stimulated by the World Registry of Marine Species (WoRMS) and the Encyclopedia of Life (EOL) has lead me to join a team of radiolarian colleagues in an effort to produce an illustrated catalog of Cenozoic radiolarian genera including type species, revision of genera, discussions of descriptions and synonmies. A project started last year to re-examine the gradual evolution in a known Eocene radiolarian lineage using more sophisticated digital data gathering techniques to collect morphological evidence is starting to show progress that might some day yield the answer to the hypothesis that morphological variation is distributed continuously across the range of possibilities. I have accepted an invitation to join the Scientific Committee of InterRad 13 which will be held in Spain 2012, to review abstracts and scientific papers submitted to the next meeting of international radiolarists.

My paleontological research and interest are intimately linked to the geological collections and their proper curation. As the curator for the U.S. West Coast Repository for the DSDP/ODP Micropaleontological References Centers, I continue to inventory new radiolarian slides that are periodically added to the collection. Slow progress is being made toward revitalization and inventory of unique, retired and/or orphaned paleontological collections acquired by SIO Geological Collections as an important contribution to future paleontologists.

Relevant Publications


Peter Shearer

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Research Interests: seismology, Earth structure, earthquake physics

Peter Shearer’s research uses seismology to learn about Earth structure and earthquakes, both globally and in California, and has involved the development of new analysis approaches to handle efficiently the large digital data sets that are now emerging from the global and regional seismic networks. Recent work with former postdoc Catherine Rychert (now at the University of Bristol, U.K.) applied seismic receiver function analysis in a comprehensive study of the lithosphere-asthenosphere boundary (LAB), showing that it is a globally pervasive feature that varies in depth depending upon the tectonic environment. Receiver functions provide information only near seismic stations, limiting studies to continents and excluding most of the oceanic crust and lithosphere. SS precursor studies provide more complete global coverage, but traditionally have been used only to image interfaces deeper than the LAB, such as the 410 and 660-km discontinuities, which appear as distinct SS precursor phases. Rychert and Shearer (2011) show that subtle differences in SS waveform stacks can be used to resolve the LAB under the Pacific. The depth to the discontinuity varies from 25 to 130 km and correlates with distance from the ridge along mantle flow lines. This implies that the depth of the oceanic lithosphere-asthenosphere boundary depends on the temperature of the underlying asthenosphere.

A wealth of new seismic data is available from the USArray project, enabling increased resolution for studies of the lithospheric and deeper structure of the North American continent. Graduate student Janine Buehler analyzed Pn arrival times from the transportable stations of USArray to resolve crustal thickness and uppermost mantle structure (Buehler and Shearer, 2010). Her crustal thickness map generally agrees with previous results but differs in some details. High upper-mantle seismic velocities are found beneath eastern Washington and northern Idaho, and lower velocities near the California-Mexico border, the Sierra Nevada, the northern coastal California region, and the greater Yellowstone area. These results should complement other seismic studies (e.g., body- and surface-wave tomography and shear-wave splitting) to provide information about composition, temperature, and tectonic processes in the western United States.

Shearer’s southern California work has focused on improving earthquake locations using robust methods, waveform cross-correlation, and the development of new crustal tomography models to account for 3D velocity variations. Work with former student Guoqing Lin (now at the University of Miami) developed a relocated catalog of southern California seismicity from 1981 to 2005 (the LSH catalog) that is now being widely used by other researchers. Smith-Konter, Sandwell and Shearer (2011) used this catalog to estimate locking depths along major faults from the maximum depth of seismicity and compared these results to geodetic constraints on locking depths. The methods agree in most areas, with the notable exception of the Imperial, Coyote Creek and Borrego fault segments. These differences have important implications for the accuracy to which future major earthquake magnitudes can be estimated. Graduate student Xiaowei Chen examined seismicity in the Salton Trough, in particular the behavior of the numerous seismic swarms that are common in this region. She found that all of the swarms exhibited spatial migration of seismicity, with migration velocities characteristic of hydraulic diffusion for swarms near geothermal sites (Chen and Shearer, 2011). Swarms with faster migration velocities cannot be explained by the diffusion curve, rather, their velocity is consistent with the propagation velocity of creep and slow slip events. Thus, these variations in migration behavior allow us to distinguish among different swarm driving processes.
Figure 1. Pacific bouncepoint caps with well-resolved depths to the lithosphere-asthenosphere boundary (LAB). Circle colors correspond to the depth of the discontinuity. Background pastel colors show seafloor age from young (0–35 Myr in yellow) to old (140–175 Myr in magenta). Note the generally shallower LAB under young regions. From Rychert and Shearer (2011).

Recent Publications


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Research Interests: Seamounts, Mid-ocean Ridges, Water-Rock Interaction, Low Temperature geochemical fluxes, Volcanology, Biogeoscience, Science Education (K-16)

My long-term scientific interests aim broadly at volcanoes, how they work, exploring their impact on the geochemistry of the hydrosphere, and the mantle – crust evolution, and the role they play in biogeosciences. My recent work is described below focusing on two themes, the biogeosciences of seamounts and on the interaction of microbes with volcanoes. My teaching includes a field class in volcanology and I run a NSF funded (GK-12) educational program that brings graduate students into in Middle and High School classrooms in the San Diego Unified School District. References to my broader research interests and other prior work can be found in the bibliography at my website (http://earthref.org/whoswho/ER/hstaudigel/index.html)

Seamounts: Most of my recent field work focused on Loihi Seamount and seamounts in the Samoan Chain including Vailulu’u seamount. I am expecting to dive on Vailulu’u in 2012 using the Pisces submersibles. Over the last three years I coordinated a Seamount Biogeoscience Network and co-edited and wrote papers in a special volume of Oceanography on of “Mountains in the Sea”. All of the articles in this volume are freely available from the website of The Oceanographic Society (http://www.tos.org/oceanography/archive/23-1.html). My papers include in particular contributions regarding the geological history and structure of seamounts (Staudigel and Clague, 2010), their role in subduction systems (Staudigel et al., 2010) and the associated deep-sea metal deposits (Hein et al., 2010). Other recent papers on seamounts include the description of microbial consortia in their hydrothermal systems (Sudek et al., 2009) and the discovery that fungi are common in these submarine systems, not unlike in terrestrial soils (Connell et al., 2009).

Microbes in Volcanoes: I study the biogeosciences of volcanoes using geological and microbiological approaches. In the geological record we study trace fossils of microbes drilling into volcanic glass. This demonstrated that microbes are active in any ocean crust section studied so far and that these fossils can be trace back in time to the time period of the origin of life on earth 3.5 Ga ago (e.g. Staudigel et al., 2008; McLoughlin et al., 2010). Our microbiological work continues at Vailulu’u and Loihi Seamounts with the characterization and isolation of microbes from these settings (Sudek et al, 2009; Bailey et al., 2009) as well as studies of how they colonize rock surfaces and how they may dissolve volcanic glass (Templeton et al, 2010). My work on microbe-basalt interaction now focuses on extreme environments of the McMurdo area in Antarctica, including volcanic terrains in the Royal Society Range, the Dry Valleys, and in particular on Mt Erebus on Ross Island. Details of this work can be found on in an on-line lecture I gave at the Birch Aquarium http://www.uctv.tv/search-details.aspx?showID=16074 and our Antarctica Expedition website (http://earthref.org/ERESE/projects/GOLF439/index.html).

Teaching: Jointly with colleagues from Scripps and UC Davis, I am offering a two-week volcanology field class in Hawaii. In collaboration with Cheryl Peach I am also running a NSF educational program for graduate students to work with K-12 students (“GK-12”). This
program, the “Scripps Classroom Connection” (“SCC”; http://earthref.org/SCC/) offers nine graduate fellowships to Scripps graduate students each year to improve their communication skills by teaching in middle and high school classrooms. Fellows receive full support for an overall 1/3rd effort in SCC, including a four week Summer Institute and the teaching in classrooms during the school year. Fellows are chosen from all science sections at Scripps.

**Recent Publications**


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

My field, geodynamics, aspires to develop a dynamical theory that provides a physical explanation for both the motions of tectonic plates as well as motion of plate boundaries. While I routinely employ some of the nation’s fastest supercomputers to run numerical models that simulate the motions of tectonic plates, this past year afforded me an opportunity to work with Prof Steve Cande on analyzing and interpreting a diverse suite of tectonic observations.

It is well-documented that during the Cenozoic, the Indian plate traveled towards Asia at speeds reaching 18 cm/yr. We have recently attempted to better constrain the details of this extraordinary event and discovered something quite remarkable. The onset of this motion is coincident with the arrival of the Deccan plume head just slightly before 65 Ma as seen in Figure 1. India’s motion prior to 70 Ma is a typical value for a plate that is attached to a subducting slab. However, the superfast speeds that India recorded (18 cm/yr) were only for a very short (1 Myr) burst, followed by sustained plate speeds >11 cm/yr until 55 Ma, before finally fading down to more typical plate speeds by 43 Ma. Yet, even more interesting is that the slow northward motion of Africa appears to have become hindered over the same time period, shown in Figure 1 as dips in the spreading rate. This hinderance is seen in Africa’s spreading histories with South America, North America, and Australia-Antarctica and recorded as S-shaped bends, shown in Figure 2 in the otherwise linear-trending magnetic anomaly patterns in the corresponding South Atlantic, Central Atlantic, and Southwest Indian ocean basins, respectively.
This suggests the Deccan plume head played a major role in both providing the driving force for the sudden onset and sustained plate speeds of India as well as providing a force to temporarily slow Africa’s motion. Because the Deccan plume head was positioned in between India and Africa during this time, straddling their common spreading center, the picture that immediately emerges is that Deccan pushed in all directions, driving India faster away and slowing Africa coming towards it (Figure 3).

Our work thus far provides compelling evidence for the existence of this plume-push force, which if indeed is a new driving force for plate tectonics, has significant importance for reconciling reconstructed plate motions with the underlying mantle dynamics. Although the plume-push force appears to be ephemeral by nature, the new findings (Cande and Stegman, 2010) suggest it can significantly influence global plate motions over 5-20 Myr time-intervals. If the superfast motion of India is caused by the plume-push force, the slowdown of India starting from 55 Ma can be reinterpreted simply as the weakening influence of the plume head as India moves further away from the source in addition to diminishing strength of the plume head over time. Figure 1 shows the implication if the slowdown at 55 Ma was not due to the India-Asia collision, but rather, due to fading of the plume-push force. It is interesting to note that no change in spreading azimuth is recorded until 43 Ma. Such a change in the direction of Indian plate motion almost certainly reflects an India-Asia collision.

**Publications for 2010-2011**

Lisa Tauxe

Distinguished Professor of Geophysics

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Research Interests: Behavior of the ancient geomagnetic field. Statistical analysis of paleomagnetic data. Applications of paleomagnetic data to geological problems.

My research over the past year expanded on our efforts to document the extraordinary geomagnetic field behavior observed in copper mining slags recovered from the 10th Century BCE in Jordan (Ben-Yosef et al., 2009) and Israel (Shaar et al., 2011). These studies document the highest geomagnetic fields ever published using modern paleointensity methods. This year, we carried out two new expeditions to Hawaii and to Cyprus. There we sampled lava flows (Hawaii) and copper mining debris (Cyprus) from the last four millennia, including the period of the so-called “geomagnetic field spike” seen in both Israel and Jordan.

In March 2011, we (L. Tauxe, H. Staudigel and H. Ron) went to Hawaii in search of reliable records of ancient field strength dated by radiocarbon methods (F. Trusdell, pers. comm.) to between two and four thousand years BP. As nearly all Hawaiian lavas give the “wrong answer” when compared to known fields, we developed a new approach, targeting the freshest quenched material available To demonstrate the reliability of the new approach, we also sampled lava flows extruded over the 20th Century (CE) for which the actual geomagnetic field is reasonably well known (e.g., see Figure 1).

Figure 1: Example of quenched material targeted for Hawaiian expedition.
In August, 2011, a team of UCSD, Cypriot and Israeli archaeologists and archeomagnetists, led by myself and T.E. Levy from the Anthropology Dept., UCSD excavated numerous copper mine slag heaps, including one small section thought to be about 8th Century BCE (Figure 2). A brief account of our expedition is available in Ben-Yosef et al. (2011; http://antiquity.ac.uk/projgall/ben-yosef330/).

Figure 1: Excavation in Politico, Kokkinorotsos Archaeological Site, Cyprus thought to be from the 8th Century BCE. (Photo courtesy of Philip Staudigel.)

Relevant Publications


Research Interests: The marine hydrogeology of cold seeps, mud volcanoes, and submerged faults, the physical and chemical processes associated with the structural evolution of convergent margins, and the development of new seafloor instrumentation for investigations of the above processes.

My current research activities include four field projects (West Nile Delta, Muddy Waters (Crete), MEMO (Nankai), and the Chile earthquake response) and two instrument development projects (GEOCE: a seafloor 3-D strain meter, and PUPPI-II: a seafloor piezometer). Mud volcanism is a common phenomenon in accretionary margins and deltaic depositional systems worldwide. Fluid formation and fluidization processes occurring at depths of several kilometers below the seafloor can be monitored in mud volcanoes, acting as natural windows to processes unreachable by other means. To gain a better understanding of deep processes occurring in such environments, I have three ongoing projects.

The Muddy Waters project aims to characterize hydrological processes and the fluid geochemistry of the intermediate loop of the Subduction Factory at the Hellenic Subduction Zone. In March 2011, we carried out a research cruise to deploy flow meters, take gravity cores and collect in situ pore pressure and temperature data at the mud volcanoes and backstop faults. On recovery in 2012 we will use existing geotechnical as well as geochemical data plus those collected during the cruise and from the flow meters to numerically model fluid flow at the boundary between the accretionary complex and its hinterland (i.e. the intermediate loop of the subduction factory between Eurasia and Africa), to test hypotheses regarding physico-chemical processes along the active faults and how they relate to the geochemical findings.

To augment the NanTroSEIZE IODP drilling program, we are carrying out Project MEMO. In the Kumano Basin, arcward of the NanTroSEIZE drilling transect, an active mud volcano field provides evidence for rapid fluid and mud ascent from several km depth and provides such a window to processes unreached by IODP drilling. Given the enigmatic lack of evidence of deep sourced fluids in the toe-ward portion of the Nankai OOST region drilled during NanTroSEIZE stage 1, searching for such evidence arcward is of prime importance in understanding this system. Are all of the fluids generated deep along the subduction thrust passing to the toe region, bypassing the OOST region? This unlikely outcome can be resolved with evidence of low chlorinity fluids with distinctive elemental and isotopic signatures at more arcward locations. During the project we will collect piston and MeBo (seafloor drill rig) cores and install long-term monitoring instruments to test hypotheses regarding physico-chemical processes occurring within the Kumano Basin mud volcano field and its roots at great depth.

In the West Nile Delta area, we have just completed a study on two large mud volcanoes. The project focused on qualifying the chemical and isotopic composition of pore fluids as well as investigations of light volatile hydrocarbon gases and the quantification of the variability of dewatering and degassing through long-term flow rate and chemical flux measurements. A surprising result of this study is that the central area of North Alex MV undergoes rapid (up to 0.5 Hz) vertical ground motion (60-100 cm) due to harmonic oscillation in resonance with the entire conduit feeding the mud volcano. Pore fluids are dominated by seawater due to rapid flushing of the upper sediment column in response to this motion and the rapid volumetric changes in the free gas. Both flow meter and heat flow data indicate downflow of seawater into the sediment dominates the area surrounding the central dome.
The Chile Earthquake Response was an NSF Rapid project consisting of a multibeam bathymetric survey of the rupture zone and deployment of high-resolution pressure sensors to monitor the vertical motion of the subduction zone wedge in response to aftershocks and viscoelastic relaxation after the February 2010 magnitude 8.8 earthquake offshore Maule, Chile. These instruments were recovered in March, 2011, and numerous events of seafloor vertical motion and permanent deformation were recorded associated with aftershocks. In 2012 we will begin the next stage, to deploy a focused array of 10 broadband ocean bottom seismometers outfitted with SIO seafloor flow meters updip of the region of maximum slip to monitor the post-seismic response of the outer accretionary prism. Onshore and offshore seismological data suggest that slip during the main event and in the immediate aftershock period stopped ~30 km downdip of the trench. The lack of a detectable bathymetric change in the outer accretionary complex several months after the earthquake also suggests that the upper part of the megathrust did not slip during the event. This conclusion is consistent with models of the temperature on the megathrust and the transition from velocity weakening to velocity strengthening friction. Based on these observations, we expect that the outer accretionary wedge behaves as a poroelastic medium and adjusts gradually, through multiple faults, folds and volumetric strain, to the change in stress resulting from up to 20 m of slip on the megathrust during the earthquake. The close spacing (~10 km) of our planned array on the lower slope in water depths of 2000-5300 m immediately seaward of the patch of greatest slip during the earthquake should allow us to study a wide range of seismic and hydrological responses that should be occurring as the accretionary complex adjusts to the change in stress caused by the earthquake. In particular, we will look for seismic tremor and for low frequency earthquakes as well as for normal earthquakes in the prism and underlying subducting crust and for slow fluid flow out of the seafloor that can be modeled to derive volumetric strain in the underlying sediments.

I have two instrument development projects ongoing. The first of these is the development of an ocean bottom 3-D strain meter, GEOCE, in collaboration with D. Chadwell and U. Send, both at Scripps. My portion of this project uses high-resolution pressure measurements and a seafloor pressure standard to determine the vertical motion of the seafloor in response to tectonic deformation and/or gravitational sliding. The data from the shallow engineering deployment off Torrey Pines indicates we are near to achieving the goal of 1 cm resolution in 3 dimensions. A final deep test deployment is currently ongoing near Catalina Island. My second instrumentation project is the development of a new generation of seafloor piezometers (PUPPI-II) for both long-term monitoring of the hydrological response to tectonic strain and for geotechnical investigations. Design, modeling, electronics, and construction is completed and the instrument is currently undergoing testing and sea trials. These two instrumentation development programs will allow us to monitor the most critical properties (stress and strain) of continental margins to improve our understanding of the underlying tectonics and for evaluation of their potential for catastrophic failure.

**Recent Publications**


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Research Interests: Atmospheric infrasound, earthquakes, tectonics, array processing, ray tracing

I've been working on several projects in atmospheric infrasound. The most mature of these projects is the creation of the Western U.S. Infrasonic Catalog, ver. 1 (WUSIC-1; Walker et al., in press). The USArray is in an excellent position to discover sources of infrasound in the U.S. as well as investigate problems in infrasonic propagation and atmospheric dynamics using these events in the same way that seismologists use earthquakes to tackle problems in seismology and geodynamics. A key interest is in studying atmospheric phenomena with infrasound. But before this can be done well, we need to validate recent advances in the creation of time-varying atmospheric sound speed models. Arguably the best approach for this is a statistical analysis of hundreds to thousands of events recorded over many months. Toward that goal, undergraduate student Richard Shelby and I used reverse time migration of envelope functions of 1 to 5 Hz acoustic-to-seismic coupled signals recorded by USArray to detect and locate 901 infrasonic sources in the western U.S. (Figure 1). We are now conducting a similar study using the Southern California Seismic Network.

![Figure 1. Two-dimensional histogram showing imaged source locations for 901 events detected by the USArray in 2007-08. Warm areas illuminate repeating sources of infrasound, or “infrasonic hotspots.” The hotspots spatially correlate with areas of military activity (stars). From Walker et al. (in press).](image)

I'm also leading a study of the imaging of the source location of microbaroms. Microbaroms are hypothesized to be the acoustic equivalent of microseisms; pressure signals with frequencies of about 0.2 Hz generated from the interaction of anti-parallel ocean waves. However, there has yet to be a study combining observations and theoretical modeling that has definitely tested this hypothesis. In 2010 I led the installation of two infrasonic arrays in Southern California and Northern California. There are now six infrasonic arrays in the western U.S. states as well as several tens of microphones at USArray sites in Cascadia, all of which are in a good position to record infrasound from microbarom sources in the eastern Pacific during the 2011-12 winter season. Preliminary results from the 2010-11 season suggest that the arrays detect the same source of infrasound quite often, when either the source is in the deep Pacific basin or when the source is close to the coast. Modeling of the microbarom source strength using NOAA Wave Watch 3 model data shows a predicted microbarom source near the coast, in general agreement with the array observations (Figure 2), but more work needs to be done.

I’m also analyzing the infrasonic and strong-motion seismic recordings of the Mw 9.1 Tohoku earthquake, which has presented to date the best opportunity to study global infrasonic emissions from a very large earthquake. An array near Tokyo provided the first infrasonic recordings in the near field (<
500 km) for such a large event. High-frequency infrasound that originated from surface shaking in the epicentral region (the Earth is a speaker) was detected to 5700 km range. A clear relationship exists between amplitude and range for both stratospheric and thermospheric arrivals. Lastly, infrasound recorded by the Tokyo array as well as an array in Kamchatka has been back projected to the source region to illuminate the areas that experienced the greatest intensity of surface shaking. These results correlate with the spatial distribution of maximum shaking defined by the strong-motion network.

I’m working with AOS graduate student Scott DeWolf in the quantification of the self-similarity of outdoor wind turbulence using Optical Fiber Infrasound Sensors (OFISS). Measurements of wind turbulence were made with OFISSs of different lengths in 2009-10. These measurements provide the needed information to develop a quantitative approach for designing the optimum OFIS array for windy locations where the expected signal strength is known a priori (such as in the case of nuclear monitoring).

**Relevant Publications**


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Research interests: Marine EM methods, gas hydrates

Karen Weitemeyer is apart of the SIO Marine EM Laboratory run by Professor Steven Constable along with assistant researcher Kerry Key. Much of Karen’s work is involved in developing and using marine electromagnetic methods for mapping gas hydrates. Gas hydrate, a frozen mixture of water and gas (mostly methane), is extremely important for a variety of reasons. It may be an economically viable source of natural gas, it is a hazard for deepwater drilling, and may be involved in slope failure and rapid climate change, yet we know little about its distribution in seafloor sediments.

Last year’s annual report from Steven Constable described a controlled source electromagnetic (CSEM) data collection cruise to the Gulf of Mexico aimed at mapping gas hydrate deposits. The report also discussed the initial results from Mississippi Canyon block 118 (MC 118) and demonstrated the sensitivity of electromagnetic methods to gas hydrate concentration and distribution. To fully utilize the CSEM field data we have also expanded our knowledge of the electrical properties of gas hydrates by undertaking laboratory electrical conductivity measurements on methane hydrate and methane hydrate sediment mixtures. The success of this has drawn on the expertise of postdoc Wyatt DuFrane (LLNL), Laura Stern (USGS), Jeff Roberts (LLNL), and Steven Constable (SIO). We developed a pressure cell to synthesize gas hydrate while simultaneously measuring the in-situ frequency dependent electrical conductivity. Initial findings were published this year in Geophysical Research Letters which shows that pure methane hydrate is resistive as expected, about 20,000 $\Omega$m at 0°C and has an activation energy of 30.6kJ/mol (~15 to 15°C). These results give a conductivity-temperature relationship of pure methane hydrate that provide a basis for future work on hydrate-sediment mixtures in order to understand mixing relationships. This research will eventually allow us to convert the field electrical resistivity measurements into a hydrate concentration.

A collaboration with Anne Tréhu at Oregon State University allowed us to incorporate a 3D seismic tomography inversion with our 2D CSEM inversion result from Hydrate Ridge. Figure 1 shows the usefulness of examining both seismic and EM data jointly. The seismic inversion shows a low velocity zone that coincides exactly with a high resistive region in the CSEM inversion, suggestive of a free gas zone, likely associated with seismic horizon A, a conduit that carries free gas to the gas hydrate stability zone. There is also agreement between the EM and the seismic inversions in the pattern of the high velocity and the high resistivity associated with the folding of the accretionary complex sediments. The comparison of the 3D seismic tomography inversion to the CSEM inversion as well as comparisons to magnetotelluric data and resistivity well logs were published this summer in Geophysical Journal International.

Relevant Publications


Figure 1. Apparent resistivity pseudosection section for 5 Hz CSEM data collected at Hydrate Ridge shows a pant leg feature associated with a surface conductor, such as brines (top); the 2D CSEM inversion is overlain on seismic line 230 (middle) and has collapsed the pant leg feature into a surface conductor. There is a resistive region hovering above and below the seismic bottom simulating reflector (BSR) suggestive of hydrate above and free gas below. Seismic horizon A is a conduit carrying free gas into the gas hydrate stability zone and is highly resistive. The bottom panel is a slice through a 3-D seismic P-wave velocity model, for which velocities were constrained to be above 1.5 km/s beneath the seafloor. Without this constraint, the low velocity zone beneath the western flank is more compact and the minimum velocity within it decreases. This anomaly is interpreted to indicate the presence of free gas associated with horizon A. Higher velocities are associated with folded accretionary complex sediments. These apparent folds in the velocity model correlate well with high resistivity zone in the CSEM model. Seismic line 230 is from Tréhu and Bangs (2001); the 2D CSEM inversion was done in collaboration with G. Guozhong and D. Alumbaugh at EMI-Schlumberger; and seismic inversion is from Arsenault et al. (2001).

Further information can be found at the lab’s website, http://marineemlab.ucsd.edu/
Acoustic Propagation in the Philippine Sea. Over the last twenty years, long-range, deep-water acoustic propagation experiments have been performed almost entirely in the oceanographically benign northeast and north central Pacific Ocean [e.g., Colosi et al., 2010; Van Uffelen et al., 2009, 2010]. The North Pacific Acoustic Laboratory (NPAL) Group recently conducted a series of acoustic experiments in the northern Philippine Sea to study deep-water propagation in a much more oceanographically energetic and variable region. A short-term Pilot Study/Engineering Test was conducted during April-May 2009 (PhilSea09). The 2010–2011 NPAL Philippine Sea Experiment, consisting of six acoustic transceivers and a new water-column spanning Distributed Vertical Line Array (DVLA) receiver, was deployed during April 2010 and recovered one year later, during March-April 2011 (PhilSea10).

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

Figure 1. Overall mooring geometry of the 2010–2011 Philippine Sea Experiment, consisting of six 250-Hz acoustic transceivers (T1, T2, ... T6) and a new DVLA receiver. The array radius is approximately 330 km.

Finally, the one-month Ocean Bottom Seismometer Augmentation of the 2010–2011 NPAL Philippine Sea Experiment (OBSAPS) was conducted during April-May 2011, immediately following the PhilSea10 mooring recovery cruise. For this experiment, a low-frequency acoustic source
suspended from shipboard transmitted to six Ocean Bottom Seismometers (OBS) and a Near-seafloor DVLA. The OBSAPS experiment was motivated by similar observations made during the 2004–2005 NPAL Experiment in the central North Pacific, during which four OBS were deployed around a Deep Vertical Line Array receiver. Broadband transmissions with a center frequency of about 75 Hz from a ship-suspended source revealed a new class of arrivals in long-range ocean acoustic propagation that were named Deep Seafloor Arrivals (DSA), because they were the dominant arrivals observed on the OBS, but were either undetected or very weak on the deepest Deep VLA hydrophone (Stephen et al., 2010).

**Fram Strait Tomography Experiment.** The Fram Strait, with a sill depth of 2600 m and a width of nearly 400 km, is the only deep connection where exchanges of intermediate and deep waters take place between the North Atlantic and Arctic Oceans. It is therefore a key location to study the impact of the Arctic Ocean on global climate change. The Nansen Environmental and Remote Sensing Center (NERSC) in Bergen, Norway, with assistance from Worcester’s group, installed an ocean acoustic tomography array in Fram Strait during summer 2010, with final recovery planned for summer 2012. The goal is to improve the accuracy of estimates of the heat, mass, and freshwater transports through Fram Strait by combining the acoustic measurements with data from gliders and oceanographic moorings and a high-resolution ice-ocean model through data assimilation.

![Figure 2. Overall mooring geometry of the 2010–2012 Fram Strait Tomography Experiment, consisting of three 250-Hz acoustic transceivers (A, B, C) and a small vertical receiving array (D), superimposed on an Advanced Synthetic Aperture Radar (ASAR) satellite image. The gray/white areas correspond to sea ice; the darker areas are open water.](image)

**Relevant Publications**


A new suspension for a vertical optical seismometer
(In collaboration with Jon Berger)

Technologies for seismology, geothermal energy research, and nuclear test monitoring require advancements in seismometers capable of achieving the resolutions of existing sensors which operate in underground vaults but with the capability to operate in boreholes and, in some instances, at high temperature. Electronics-based sensors are problematic when installed in boreholes, especially very deep ones because normal silicon–based electronics encounter problems above 150 °C, a temperature reached in boreholes a few km deep or in shallower ones in geothermal regions.

Figure 1: Most modern vertical seismometers use a leaf spring design in which a mass is attached to a horizontal beam that rotates around a hinge. A leaf spring connecting the pivoted mass to the frame provides a restoring force to center the beam. Careful design of the spring geometry leads to a long free period and hence high sensitivity as a seismic sensor. Such suspensions, however, are very sensitive to alignment with the local vertical. If the sensor becomes slightly tilted, the geometry is spoiled and the seismometer no longer operates properly. We have adopted a design first invented by Erhard Wielandt at the University of Stuttgart which uses leaf springs to provide a long free period while the mass moves in a straight line rather than an arc. The resulting sensor makes adaptation to a borehole much simpler.
We are pursuing an alternative to electronics for acquiring downhole seismic records. The emergence of new optical fibers with metal and/or advanced polymer coatings which can withstand temperatures up to 600 °C, and the success we have achieved using optical fiber sensors in seismometers and tiltmeters in vaults, enables complete elimination of electronics from the downhole sondes without loss of sensitivity. Such devices will allow precise observation of geophysical parameters in high temperature boreholes encountered in geothermal monitoring environments.

The in-line geometry of the sensor depicted in Figure 1, when adapted to a borehole, will operate even when tilted. Our optical displacement transducer’s wide dynamic range will accommodate the shift in vertical position of the mass that will accompany small tilts. Elimination of leveling motors in the borehole sonde will be a significant simplification.

*Figure 2.* Installation of the first in-line optical seismometer at our test vault at Piñon Flat Observatory.

**Relevant Publications**

Background Image: Pahoehoe lava flow top from 2010 Hawaiian eruption showing typical glassy surface that was the target of a project to estimate ancient geomagnetic field intensity (see report by L. Tauxe).