2014 Annual Report

SIO Earth Section

Scripps Institution of Oceanography
Earth Section
Annual Report 2014

The Earth Section of the Scripps Institution of Oceanography includes researchers whose primary area of study is the solid Earth. Many of them have provided reports, included here in alphabetical order, summarizing their research over the last year; the aim has been to present this at a level that should be accessible to a broad scientific audience. We hope that you will find this booklet a useful description of our work.

The research done by the members of the Earth Section spans topics in geology, geophysics, chemistry, biogeosciences, and climate science. This research includes observations, measurements, and collection of samples and data on global, regional, and local scales, using shipboard operations, ground-based methods, and satellite remote sensing. Extensive laboratory work often follows these sampling programs, while theory and modeling guide data interpretation and the design and implementation of experiments and observations.

Awards and Honors

Yehuda Bock was elected a fellow of the Explorers Club.

Cathy Constable received the 2013 Gilbert Award from the Geomagnetism and Paleomagnetism Section of the American Geophysical Union.

James Day received the 2014 Nier Prize from the Meteoritical Society and the 2013 Houtermans Medal from the European Association of Geosciences.

Neal Driscoll was awarded the USCG Arctic Service Medal in 2013.

Kerry Key received the 2014 Palomar College Alumnus of the Year Award.

Bernard Minster became a fellow of the American Association for the Advancement of Science.

Lisa Tauxe received the 2014 Benjamin Franklin Medal from the Franklin Institute for Earth and Environmental Science and the 2014 Arthur L. Day Medal from the Geological Society of America.

Transitions

In 2014 the Earth Section gained two new faculty members, Kerry Key, appointed Acting Associate Professor, and Anne Pommier, appointed Assistant Professor, Robin Matoza joined us as a Project Scientist. We had three retirements amongst the academic staff, as Peter Worcester, Guenter Lugmair, and Hubert Staudigel retired from the Research series – though all are remaining active in RTAD status.

A sadder transition was the passing of Professor J. Freeman Gilbert in August 2014, ending a 53-year association with SIO that began when he was appointed Professor in 1961. As one of the leading theoretical seismologists of the 20th century, as a promoter of both global seismic networks and supercomputers, and as an outstanding teacher and administrator, Freeman brought a great deal to the earth sciences at SIO, and will be much missed.

Duncan Agnew, Head, Earth Section

Cover: GPS instrumented stone on Racetrack Playa, Death Valley National Park.
Photo by Mike Hartmann; see report by R. D. Norris or this paper.

Earth Section Academic Personnel

Duncan Carr Agnew, *Professor*
Lihini Aluwihare, *Associate Professor*†
Andreas Andersson, *Assistant Professor*
Laurence Armi, *Professor*†
Gustaf Arrhenius, *Research Professor*∗
Luciana Astiz, *Specialist*†
George Backus, *Professor Emeritus*†
Jeffrey Bada, *Research Professor*∗
Katherine Barbeau, *Professor*
Jon Berger, *Research Scientist*∗
Wolf Berger, *Research Professor*∗
Donna Blackman, *Research Scientist*
Yehuda Bock, *Research Scientist*
Adrian Borsa, *Assistant Research Scientist*
Kevin Brown, *Professor*†
James Brune, *Professor Emeritus*†
Steven C. Cande, *Research Professor*∗†
Paterno Castillo, *Professor*
C. David Chadwell, *Research Scientist*
Christopher Charles, *Professor*†
Catherine Constable, *Professor*
Steven Constable, *Professor*
Geoffrey Cook, *Associate Lecturer*†
Joseph Curray, *Professor Emeritus*†
J. Peter Davis, *Specialist*
James Day, *Associate Professor*
Catherine Degroot-Hedlin, *Research Scientist*
Leroy Dorman, *Professor Emeritus*
Neal Driscoll, *Professor*
Matthew Dzieciuch, *Project Scientist*
Peng Fang, *Specialist*†
Yuri Fialko, *Professor*
Robert P. Fisher, *Emeritus Research Scientist*†
Helen Amanda Fricker, *Professor*
Jeffrey Gee, *Professor*†
Jennifer Haase, *Associate Research Scientist*†
Alistair Harding, *Research Scientist*
Richard Haubrich, *Professor Emeritus*†
James Hawkins, *Professor Emeritus*†
Michael Hedlin, *Research Scientist*
David Hilton, *Professor*
Glenn Ierley, *Professor Emeritus*†
Miriam Kastner, *Distinguished Professor*
Kerry Key, *Associate Professor*
Deborah Lyman Kilb, *Project Scientist*
Gabi Laske, *Professor-in-Residence*
Peter Lonsdale, *Professor*†
Gunter Lugmair, *Research Scientist*∗†
Douglas J. Macdougall, *Professor Emeritus*†
Todd Martz, *Assistant Professor*†
Guy Masters, *Distinguished Professor*†
Robin Matoza, *Assistant Project Scientist*
Bernard Minster, *Distinguished Professor*
Walter Munk, *Research Professor*∗
Richard Norris, *Professor*
John Orcutt, *Distinguished Professor*†
Robert L. Parker, *Professor Emeritus*
Anne Pommier, *Assistant Professor*
William Riedel, *Emeritus Research Scientist*†
David Sandwell, *Distinguished Professor*
Annika Sanfilippo, *Specialist* ∗
John G. Sclater, *Distinguished Professor*
Peter Shearer, *Distinguished Professor*
Alex Shukolyukov, *Project Scientist*∗†
Len Srnka, *Professor of Practice*
Hubert Staudigel, *Research Scientist*∗
David Stegman, *Associate Professor*
Lisa Tauxe, *Distinguished Professor*
Michael Tryon, *Associate Research Scientist*†
Frank Vernon, *Research Scientist*
Martin Wahlen, *Professor Emeritus*†
Edward L. Winterer, *Professor Emeritus*†
Peter Worcester, *Research Scientist*∗
Mark Zumberge, *Research Scientist*

∗ RTAD (Return to Active Duty): retired, but with active research program
† no report received

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Frank K. Wyatt, Prin. Dev. Engin., RTAD
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Research Interests: Crustal deformation measurement and interpretation, Earth tides, Southern California seismicity.

Both to understand all phases of the seismic cycle and to monitor possible aseismic events, we have used long-base laser strainmeters to collect continuous deformation data at locations close to the two most active faults in Southern California. Pinyon Flat Observatory (PFO, operating since 1974) is 14 km from the Anza section of the San Jacinto fault (2-3 m slip accumlated slip since the last large earthquake) and Salton City (SCS, since 2006) within 15 km of the same fault further SE. Two other sites (Cholame, or CHL, since 2008, and Durmid Hill, or DHL, since 1994) are within three km of the San Andreas fault (SAF): CHL, at the N end of the segment that ruptured in 1857, and DHL at the S end of the Coachella segment (4-6 m accumulated slip). Surface-mounted laser strainmeters (LSM's), 400 to 700 m long and anchored 25 m deep, provide long-term high-quality measurements of strain unmatched anywhere else: though in geological settings ranging from weathered granite to clay sediments, the LSM's record secular strain accumulation consistent with continuous GPS, something not otherwise possible. The LSM's record signals from 1 Hz to secular; at periods less than several months, they have a noise level far below that of fault-scale GPS networks.

Over periods of months and longer the LSM sites near the San Andreas Fault show strain-rate fluctuations of up to 20 percent of the long-term rate. These sites have observed strain events unassociated with seismicity, lasting hours to days; at CHL these short-term signals have also been observed on borehole strainmeters (BSM's), and there and at DHL they appear to be a few km deep. Aseismic signals observed at PFO are associated with local or regional earthquakes, and are nearer to seismogenic depths on the SJF. Further interpretation is hampered by not having similarly good measurements nearby.

LSM data have been used to rule out possible strain signals, often in ways relevant to short-term hazard, as at times of earthquake swarms close to DHL or following large regional events. The CHL data tightly limit aseismic strains at times of deep tremor. And the PFO data rule out large coseismic strains seen on nearby borehole strainmeters.

Operating these observatories shows that patience and persistence are needed to learn about the Earth: only a multiyear program captures interesting signals and properly characterizes the Earth's behavior. But this is difficult to do over geophysically useful timescales.

Recent Publications

D. C. Agnew and F. K. Wyatt (2014). Dynamic strains at regional and teleseismic distances, *Bull. Seismol. Soc. Am.*, **104**, 1846-1859, 10.1785/0120140007

D. C. Agnew (2014). Variable star symbols for seismicity plots, *Seismol. Res. Lett.*, **85**, 775-780, 10.1785/0220130214

A. J. Barbour and F. K. Wyatt (2014). Modeling strain and pore pressure associated with fluid extraction: The Pathfinder Ranch experiment, *J. Geophys. Res.*, **119**, 5254-5273, 10.1002/2014JB011169

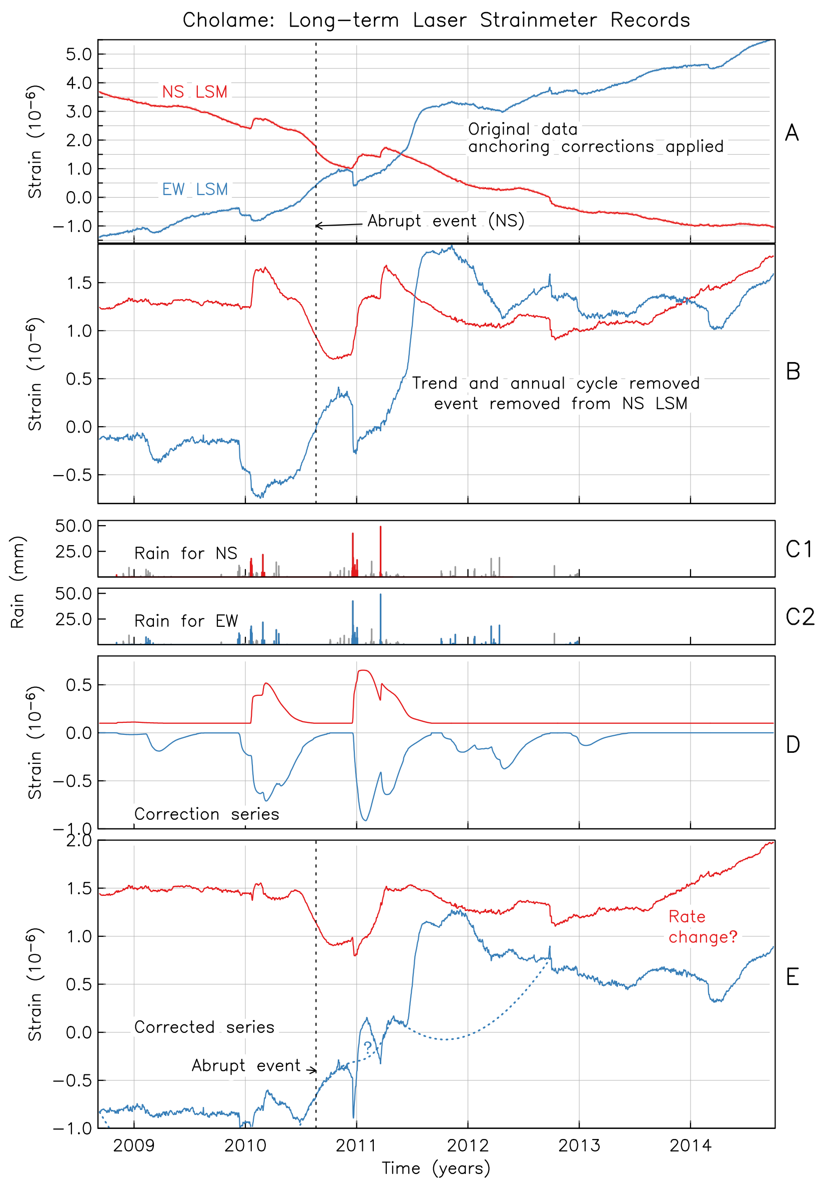

Figure 1: Records from Cholame LSM's, showing empirical corrections for rain effects. Frame A is the data, showing the long-term rate. Frame B is after removing an annual cycle and trend, both based on the data through the end of 2009. Frame C shows the rainfall (gray) and the amounts above a threshold (colored), which are convolved with an empirical correction function to produce a correction series (D). Applying this to the data in (B) gives E; note the change in rate (slowing) on the NS starting in fall 2013.

Andreas J. Andersson

Assistant Professor of Oceanography

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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. Find out more at: www.anderssonoceanresearch.com

My group's research mainly focuses on the effects of ocean acidification on coral reefs and the cycling of carbon in these ecosystems (**Fig. 1**). To address this problem we need to understand how seawater CO_2 chemistry on coral reefs will change as a result of increasing atmospheric CO_2 concentrations, and how marine organisms and biogeochemical processes will be affected by these changes. Perhaps this would have been straightforward if it wasn't for the fact that the net reef metabolism, i.e., the sum of primary production, respiration, calcification and $CaCO_3$ dissolution, has a significant influence on the overlying seawater CO_2 chemistry. The extent to which reef metabolism modify seawater CO_2 chemistry is a function of a wide range of parameters including, for example, light, temperature, nutrients, flow regime, and community composition. The aim of our research attempts to address the relative importance and control of these parameters on reef biogeochemistry as well as the interactions between physics, chemistry, and biology. We utilize chemical measurements of seawater at different spatial and temporal scales to "take the pulse" of a given reef system in order to monitor its biogeochemical function and performance in the cycling of carbon. We complement this with controlled experiments in aquaria and mesocosms as well as numerical model simulations. We also study $CaCO_3$ dissolution, and especially the susceptibility and rates of dissolution of Mg-calcite mineral phases to changing seawater CO_2 chemistry.

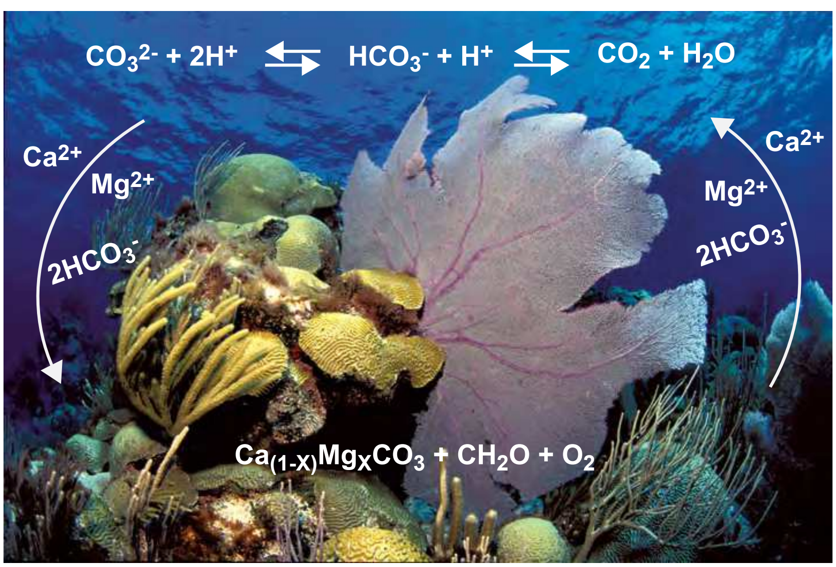

Figure 1. Illustration of the coupled organic and inorganic carbon cycles on coral reefs via photosynthesis, calcification, respiration and calcium carbonate dissolution.

In 2014, we have continued our work on characterizing the controls and variability of near-shore carbonate chemistry in both coral reef and Southern California environments. We have shown that biogeochemical processes on coral reefs exert strong control on the local seawater carbonate chemistry and that projected changes to coral reefs can to some extent counteract changes in seawater chemistry arising from ocean acidification (Andersson *et al*., 2014). Furthermore, we have observed a coupling between variations in reef biogeochemistry and local acidification events on the Bermuda coral reef with offshore processes that ultimately are linked to the North Atlantic Oscillation. These observations served as the foundation for a proposal recently funded by NSF Ocean Acidification program to explore the connection between inshore and offshore biogeochemical processes. Our near-shore work in California has taken us to a saltmarsh north of San Diego, which contrary to expectations raises seawater pH during outgoing tides due to a large export of total alkalinity. We hope to investigate this observation further to find the source and mechanism for this alkalinity production and export. This year, we have also dedicated increasing efforts to study $CaCO_3$ mineral dissolution in the context of ocean acidification and we are hopeful a number of important publications will result from these efforts (e.g., Eyre *et al.*, 2014).

Some of our collaborators in 2014 included Drs. Rod Johnson, Nick Bates and Samantha de Putron at the Bermuda Institute of Ocean Sciences (BIOS) investigating coral reef biogeochemistry in Bermuda; NOAA PMEL monitoring seawater CO_2 on the Bermuda coral reef; Drs. Eric Tambutté and Alex Venn, Centre Scientifique de Monaco (CSM), investigating how chemical and environmental parameters affect cellular, physiological, and mineralogical properties in corals; Drs. Bradley Eyre and Tyler Cyronak, Southern Cross University, Australia, studying the effect of ocean acidification on $CaCO_3$ sediment dissolution; and Drs. Paul Jokiel and Ku'ulei Rodgers at Hawaii Institute of Marine Biology (HIMB) investigating the interactions between coral reef benthos and overlying seawater chemistry.

Five Recent Publications

Andersson, A. J., Yeakel, K., Bates, N. R., and de Putron, S., 2014. Partial offsets in ocean acidification from changing coral reef biogeochemistry. *Nature Climate Change,* 4, 56-61.

Eyre, B., Andersson, A. J., Cyronak, T., 2014. Benthic coral reef calcium carbonate dissolution under ocean acidification. *Nature Climate Change*, DOI:10.1038/NCLIMATE2380.

Andersson, A. J., 2014. The oceanic $CaCO_3$ cycle. In: Holland H.D. and Turekian K.K. (eds.) Treatise on Geochemistry, Second Edition, vol. 8, pp. 519-542. Oxford: Elsevier

Venti, A., Andersson, A. J., and Langdon, C., 2014. Multiple driving factors explain spatial and temporal variability in coral calcification rates on the Bermuda platform. *Coral Reefs*, DOI: 10.1007/s00338-014-1191-9.

Parson, R. J., Nelson, C. A., Carlson, C. A., Denman, C. C., Andersson, A. J., Kledzik, A. L., Vergin, K. L., McNally, S. P., Treusch, A. H., and Giovannoni, S. J., 2014. Marine bacterioplankton community turnover within a seasonally suboxic sub-tropical sound: Devil's Hole, Bermuda. *Environmental Microbiology,* doi:10.1111/1462-2920.12445

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Research Interests*:* biogeochemistry. cosmochemistry, materials science

Our recent research has concerned the origin of life and experimental investigation of synthesis mechanisms , plausible under natural conditions, that produce precursors of information-carrying biomolecules, primarily RNA.

A related question is when and where this could have happened and our investigations during the last year have focused on potential life indicators in the (at 3.8 billion years) oldests preserved sediments on Earth. In these rocks time, temperature and pressure have led to the complete obliteration of any microfossil shapes by crystallization to graphite.

Graphite also occurs in forms of inorganic origin – precipitated from crustal fluids containing methane and carbon monoxide. Another source of "inorganic" graphite is disproportionation of ferromanganese carbonate. In this case the oxidized carbonate carbon is reduced to elemental form by the divalent iron-and manganese cations. These "inorganic" forms of the mineral may be confused with the graphite produced by decomposition of organic matter unless physical criteria can be found that distinguish between the genetically different types.

Graphite crystallizes in two modifications – one metastable with rhombohedral layer stacking ABC …, the other, the stable hexagonal end member with stacking sequence ABAB….Our previous work led to the discovery that the graphite in the Earth's oldest (3.8 billion years) preserved sedimentary rocks from the Isua region in Greenland that for other reasons are thought likely to be of biogenic origin, have a high proportion of rhombohedral graphite. We also know that the highly disordered graphite nanocrystals in younger rocks, growing from organic matter initially inherit hydrogen and heteroatoms like nitrogen , oxygen and sulfur from the source organics and we postulate that these impurity atoms until they are gradually expelled stabilize the rhombohedral structure that largely survives into old age, slowly converting to the stable hexagonal form and bearing witness to the live origin of this carbon.

Seeking support for this hypothesis we have this year separated and analyzed the biogenic carbon from rocks, at 3.4 byr. geologically "slightly" younger and with remaining recognizable organic matter.
The results, illustrated in Fig.1, confirm that the immature biogenic and heteroatom containing proto-graphite shows proportionally higher diffracted energy from rhombohedral- than from hexagonal lattice planes, confirming the high proportion of the rhombohedral structure in biogenic graphite and a direct indication of the presence of life on Earth 3.8 billion years ago in the Isua carbonaceous shale since the rhombohedral content also is high there.

With the Earth formed 4.6 byr ago an 800 million year initial period is left from which no record has yet been found on our planet and during which life must have formed here or arrived from elsewhere.

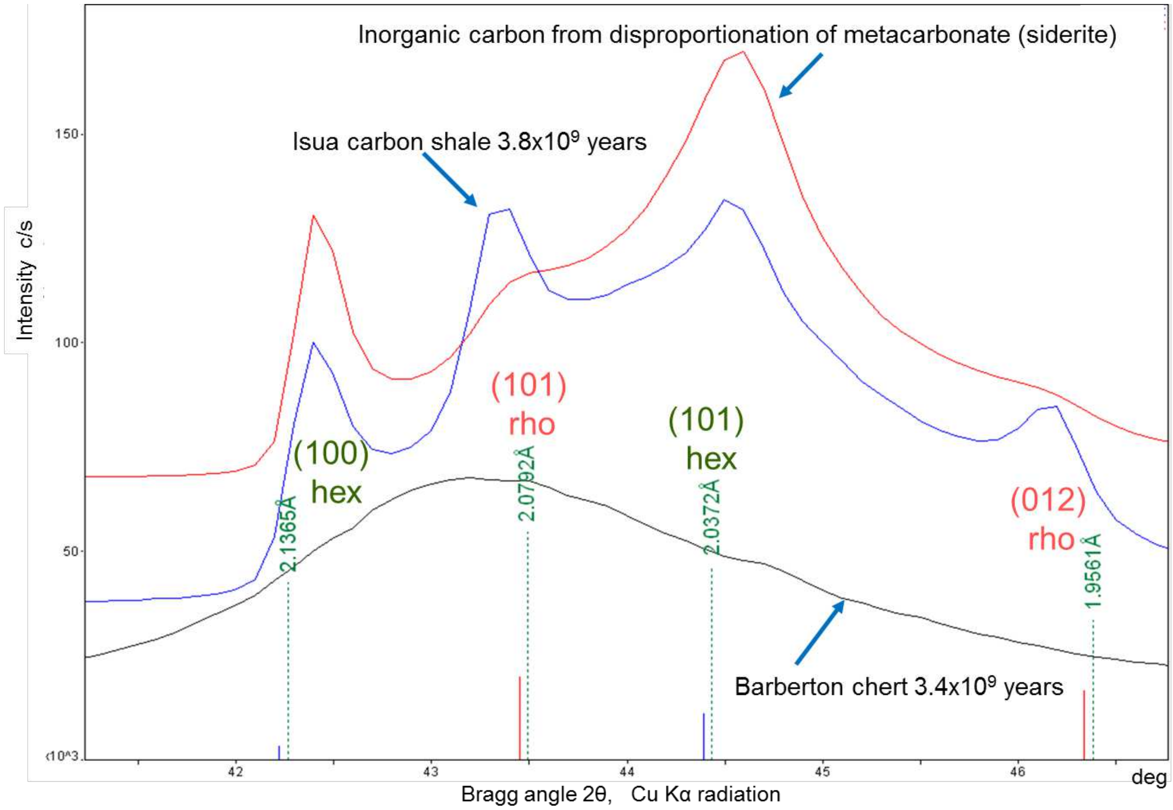

Figure 1. Diffractogram of biogenic carbon from the 3.4 billion year old Barberton chert (black curve) compared to graphite from the oldest known sedimentary rock, the carbonaceous shale from Isua,

Greeenland (blue curve), and to graphite formed by disproportionation of ferrous carbonate, an inorganic carbon forming process (orange curve).

Numbers in parentheses are Miller indices for the respective diffraction lines, here broadened into bands, identifying the inverse three-dimensional coordinates and thus the orientation of individual atomic planes in the crystal with interplanar distances shown in Ångström units on the vertical index lines. Indices marked in red and labeled "rho" derive from rhombohedraal crystals, black "hex" from the hexagonal phase.

Small crystallite size and structural disorder causes broadening and overlap of the diffraction lines into bands. The Barberton carbon, retains a substantial intergrown component from the organic source matter, inserting distorting heteroatoms and substituting hydrogen in the graphite structure. This leads to broadening of the diffraction lines, in this case into a single unresolved band . The diffraction maximum in his band occurs at the Bragg angle for the (101) rhombohedral plane, confirming the relative dominance of rhombohedral graphite in Barberton. This is also characteristic of the graphite in the Isua sediment but reversed in the inorganic metacarbonate carbon, that is dominated by hexagonal and, as deposited from crustal fluids at high temperature, relatively well ordered graphite.

These observations may be taken as material support for the circumstantial interpretation of the Isua deposit as organogenic and thus indicating the existence of life as early as 3.8 billion years ago

Recent Publications

No publications are available from these recently recorded results.

Name: Jeffrey Bada

Title: Distinguished Research Professor, Distinguished Emeritus Professor

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Research Interests*:* My research deals with 3 general topics: How the ingredients for the origin of life where synthesized on the primitive Earth and elsewhere; the geochemically plausible synthesis of simple peptides on the early Earth; and the limits to living organisms in the deep sub-surface of the Earth.

How the ingredients for the origin of life where synthesized on the primitive Earth:

Stanley Miller, whose famous experiment first published in 1953, showed how a spark discharge experiment could be used to study the synthesis of simple compounds under simulated early Earth conditions. One of the main products produced in these experiments were amino acids, the building blocks of proteins in all terrestrial organisms. Miller's studies transformed the study of the origin of life into a respectable field of inquiry and established the basis of prebiotic chemistry, a field of research that investigates of how the components of life as we know it can be formed in a variety of cosmogeochemical environments. In a recent review (*Chem. Soc. Revs.* 2013), I cover the continued advances in prebiotic syntheses that Miller's pioneering work inspired. The main focus is on recent state-of-the-art analyses carried out on achieved samples of Miller's original experiments, some of which had never before been analyzed, discovered in his laboratory material just before his death in May 2007. One experiment utilized a reducing gas mixture and an apparatus configuration (referred to here as the "volcanic" apparatus) that could represent a water-rich volcanic eruption accompanied by lightning. Another included H_2S as a component of the reducing gas mixture. Compared to the limited number of amino acids Miller Identified, these new analyses have found that over 40 different amino acids and amines were synthesized, demonstrating the potential robust formation of important biologic compounds under possible cosmogeochemical conditions. These experiments are suggested to simulate long-lived volcanic island arc systems (see Figure), an environment that could have provided a stable environment for some of the processes thought to be involved in chemical evolution and the origin of life.

The geochemically plausible synthesis of simple peptides on the early Earth:

The transition from simple molecules, such as amino acids, to more complex ones, such as peptides, has proven challenging under plausible primordial conditions. In 1958

Stanley Miller conducted a spark discharge experiment to study amino acid polymerization under simulated early Earth conditions. I have lead a study of archived samples from this experiment that have recently been analyzed for amino acids, dipeptides, and diketopiperazines using a combination of liquid chromatography, ion mobility spectrometry, and mass spectrometry techniques. The experiment involved sparking a gas mixture of CH_4, NH_3, and H_2O, while intermittently adding the plausible prebiotic condensing agent cyanamide. Over 12 amino acids, 10 glycine-containing dipeptides, and 3 glycine-containing diketopiperazines were detected. Miller's experiment was repeated and similar polymerization products were synthesized. Aqueous heating experiments indicate that intermediates in the Strecker synthesis of amino acids play a key role in facilitating polymerization. These results highlight the potential importance of condensing agents in generating complexity within the prebiotic chemical inventory.

Limits of living organisms in the deep sub-surface of the Earth:

Previous studies of the subsurface biosphere have deduced average cellular doubling times of hundreds to thousands of years based upon geochemical models. In collaboration with researchers at Princeton and elsewhere, we have been able to directly constrain the in situ average cellular protein turnover or doubling times for metabolically active micro-organisms based on cellular amino acid abundances, D/L values of cellular aspartic acid, and the in vivo aspartic acid racemization rate determined from studies I published in the 1970s and 80s. Application of this method to planktonic microbial communities collected from deep fractures in South Africa yielded maximum cellular amino acid turnover times of ~89 years for 1 km depth and 27 °C and 1–2 years for 3 km depth and 54 °C. The latter turnover times are much shorter than previously estimated cellular turnover times based upon complex geochemical arguments. The aspartic acid racemization rate at higher temperatures yields cellular protein doubling times that are consistent with the survival times of hyperthermophilic strains and predicts that at temperatures of 85 °C, cells must replace proteins every couple of days to maintain enzymatic activity. Such a high maintenance requirement may be the principal limit on the abundance of living microorganisms in the deep, hot subsurface biosphere, as well as a potential limit on their activity. The measurement of the D/L of aspartic acid in biological samples is a potentially powerful tool for deep, fractured continental and oceanic crustal settings where geochemical models of carbon turnover times are poorly constrained. Experimental observations on the racemization rates of aspartic acid in living thermophiles and hyperthermophiles are presently being developed to test this hypothesis. The development of corrections for cell wall peptides and spores will be required, however, to improve the accuracy of these estimates for environmental samples.

Recent Publications:

Parker, Eric T., et al. "A Plausible Simultaneous Synthesis of Amino Acids and Simple Peptides on the Primordial Earth." *Angewandte Chemie* 126.31 (2014): 8270-8274. doi: 10.1002/ange.201403683

Parker, E. T., et al. "Conducting Miller-Urey experiments." *Journal of Visualized Experiments: JoVE* 83 (2014). doi:10.3791/51039

Onstott, Tullis C, et al. "Does aspartic acid racemization constrain the depth limit of the subsurface biosphere?" *Geobiology* 12 (2014): 1-19. doi:10.1111/gbi.12069

Bada, J. L. "New insights into prebiotic chemistry from Stanley Miller's spark discharge experiments." *Chemical Society Reviews* 42.5 (2013): 2186-2196. doi**:** 10.1039/C3CS35433D

Katherine Barbeau

Professor, Marine Chemistry

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

Research in the Barbeau group focuses on the biogeochemical cycling of trace metals in marine systems. We study the ecological effects of trace elements as limiting or co-limiting micronutrients (or toxins); trace metal bioavailability to and cycling by marine microorganisms; and the chemistry of trace metals in seawater. This summary will focus on some of our most recent findings in the latter area of research.

We have made progress this year in in our work on the analysis of metal-binding ligands in seawater, some results of which were published in *Limnology and Oceanography* in 2014 (Bundy et al.). Recent PhD Randelle Bundy in my group has been the first to apply a Multiple Analytical Window approach to the analysis of dissolved iron-binding ligands in seawater via Competitive Ligand Exchange-Adsorptive Cathodic Stripping Voltammetry. MAW CLE-ACSV allows us to go beyond traditional electrochemical analyses of iron binding ligands in seawater, which generally define only one or two broad ligand classes. With MAW CLE-ACSV we can achieve significantly greater resolution of the ligand continuum, defining multiple ligand classes and revealing meaningful differences in the chemical nature of the iron binding ligand pool in different oceanic regimes.

We first applied MAW CLE-ACSV for dissolved iron speciation in a study conducted in collaboration with Ken Bruland's group (UC Santa Cruz), on spring and summer cruises in the coastal upwelling zones of central and northern California. In this work we focused on surface vs. benthic boundary layer waters as contrasting end members in terms of iron speciation, hypothesizing that surface waters would contain the strongest iron-binding ligands, while benthic boundary layers would be dominated by weaker ligands associated with organic degradation products and terrestrial humic substances. The weakest ligands were in fact detected in the benthic boundary layer at the lowest analytical window. Between 3% and 18% of the dissolved iron complexation in the benthic boundary layer was accounted for by humic substances (measured separately in samples by ACSV), indicating a potential source of iron-binding ligands from San Francisco Bay. The strongest ligands were found in nearshore spring surface waters at the highest analytical window and the concentrations of these ligands declined rapidly offshore (Figure 1). Overall, significantly different iron ligand pools were detected in surface versus benthic boundary layer waters, as anticipated. Principle component analysis revealed that variances in the ligand pool in surface waters were predominantly explained by water mass type, while variances in the benthic boundary layer pool were mostly explained by the shelf sediment type or the location on the continental shelf.

Additional publications which explore the use of MAW CLE-ACSV to study dissolved iron speciation along estuarine salinity gradients, in oceanic water column vertical profiles, and in mechanistic incubation experiments are in press or in preparation.

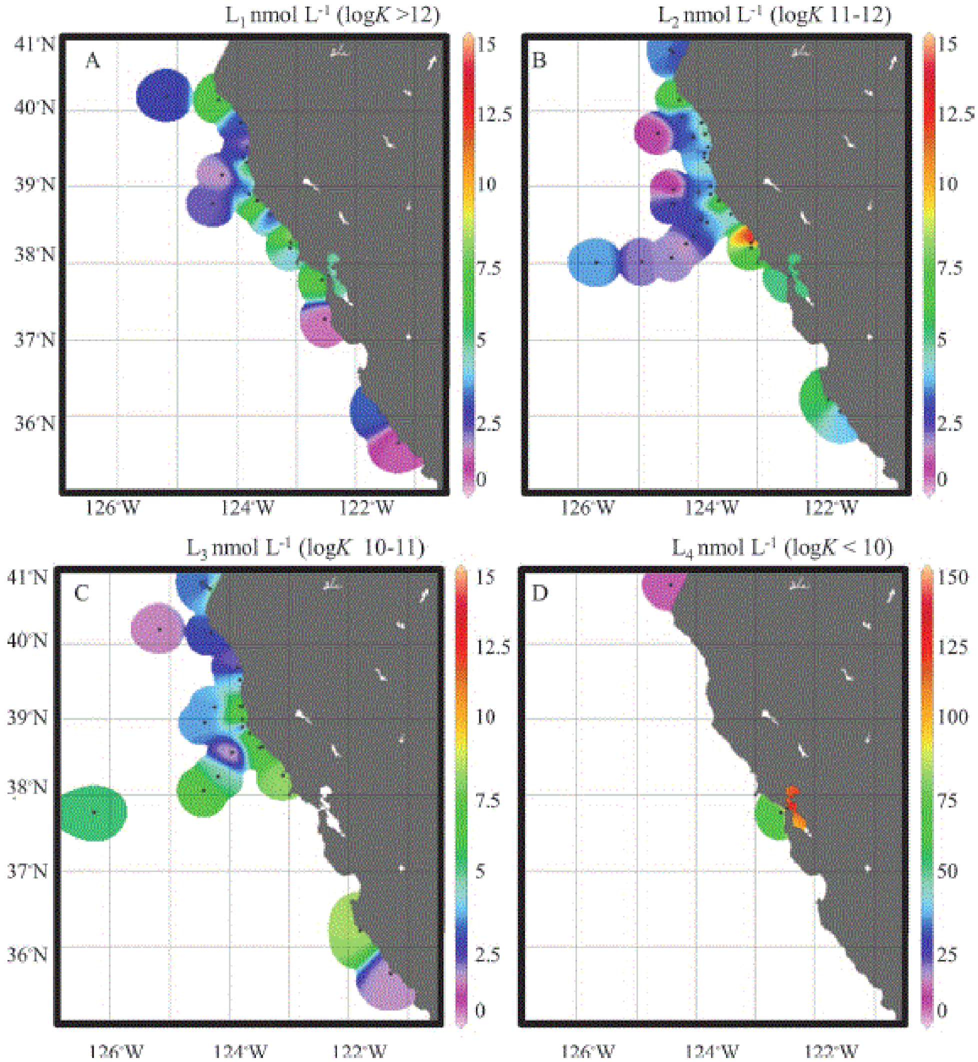

Figure 1. Concentrations (nmol L^{-1}) of four classes of dissolved iron-binding ligands as determined in California Current surface waters in spring and summer, using the MAW CLE-ACSV technique. Ligand classes are defined by conditional stability constants determined at optimal analytical windows, ranging from log K >12 for the strongest, L_1 (panel A), to log K < 10 for the weakest, L_4 (panel D). Figure from Bundy et al. 2014.

Most Recent Publications

Bundy, RM, Biller DV, Buck KN, Bruland KW, Barbeau KA. 2014. Distinct pools of dissolved iron-binding ligands in the surface and benthic boundary layer of the California Current. Limnology and Oceanography. 59:769-787.

Hogle, SL, Barbeau KA, Gledhill M. 2014. Heme in the marine environment: from cells to the iron cycle. Metallomics. 6:1107-1120.

Earley, PJ, Swope BL, Barbeau K, Bundy R, McDonald JA, Rivera-Duarte I. 2014. Life cycle contributions of copper from vessel painting and maintenance activities. Biofouling. 30:51-68.

Roe, K.L. and K.A. Barbeau. 2014. Uptake mechanisms for inorganic iron and ferric citrate in *Trichodesmium erythraeum* IMS101. Metallomics. 6: 2042-2051.

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

With my collaborators John Orcutt, Gabi Laske, and Jeff Babcock we continued our testing of the Autonomous Deployable Deep Ocean Seismic System. Late last year we deployed the system in 4000 m of water 120 nm west of Point Loma within a few km of the site of the DSDP Hole 469, drilled in 1978. The previous tests had ended prematurely due to a loss of communications between the wave glider and the towed acoustic modem. At the time it was thought that this failure was due to corrosion of the wave glider to tow cable connector. However, this turned out not to be the case. During the last test the tow cable parted completely and the towed acoustic modem was lost.

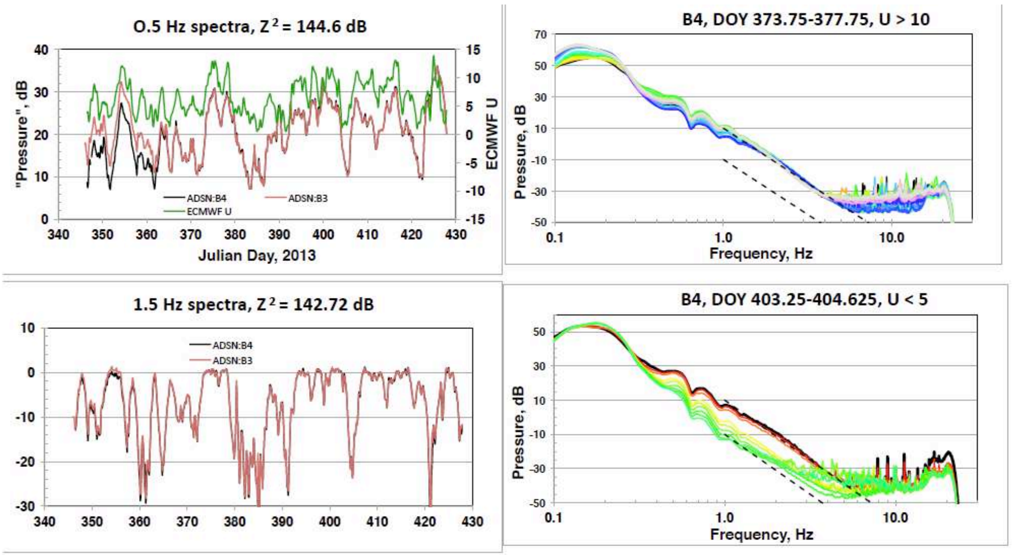
Analysis of the failed tow cables from these tests as well as failures experienced by others, led LRI to undertake a complete re-design and manufacture of both the tow cable and the connection points at the wave glider and the tow body. This process began in the spring of 2014 but the new cables were not tested and shipped until late September 2014. Re-deployment is scheduled for December, 2014.

Before the failure, however, the real-time telemetry of the data to shore worked well and we did capture several seismic events including a M5.4 event near Soccoro Island and a M6 near Kuril'sk. Additionally, we succeeded in obtaining 3-months of recorded data from two OBS units deployed close together.

Oceanographers are very interested in methods to infer the state of short ocean waves (10 m down to 10 cm) from deep-sea acoustic measurements. Longer waves are well studied by weather centers because of their economic importance (e.g. ship routing) and models for predicting the ocean swell are quite mature. However, it is the shorter waves that account for most of the energy transfer from the atmosphere to the ocean. These waves are too small to be accurately sensed by satellites, and are also difficult to measure from ships and buoys but can be inferred by pressure measurements on the seafloor.

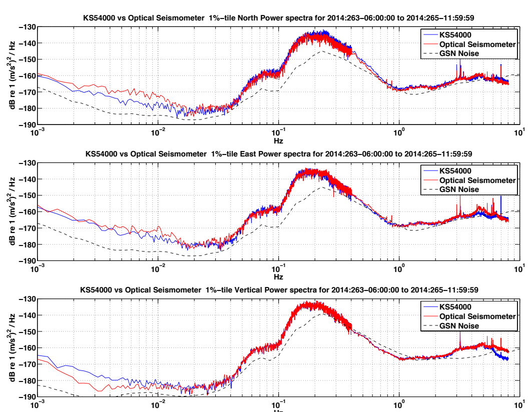
The right top panel in the figure below shows a typical spectrum of bottom pressure (4,000 m) when the overhead wind (U) is strong. There are slight variations in pressure with U at low frequencies and high, but virtually none in the middle range. The lower panel shows 20 dB variations in the spectrum when the wind is variable but low. The left panels compare the wind, for 90 days, (derived from modeling global satellite observations) to the history of bottom pressure and bottom velocity at two frequencies. The two sensors, after an appropriate scaling, differ by only 5 % (.2 dB), except at the start where the hydrophone suffered warping. The black and red traces are practically indistinguishable. The top left panel shows the bottom acoustics moving up and down with the wind. The bottom left panel shows that the spectra are clipped at the top whenever the wind is greater than about 5 m/s.

All these phenomena, we believe, are directly related to variations in the wave number spectrum of ocean waves overhead. There is a well-developed theory for how waves make sound, with the slanting dash line being a prediction of that theory. It may be possible to increase the SNR of the seismic data in this band by using the pressure record to reduce the noise.



In another area, my work with colleague Mark Zumberge continued on the development and testing of the 3-component borehole optical seismometer. One of these units was installed in a 200 m deep borehole at the USGS Albuquerque Seismological Laboratory for direct comparison with the KS54000 seismometer, the GSN standard, which is installed nearby at 500 m depth.

In the figure below, the deployment is shown in the left panel and a comparison between the two seismometers and the global averaged GSN noise spectra in the right. The noise levels of the optical seismometer over the seismic band are equal to or less than those of the KS54000 even though that unit is install some 300 m deeper.



Recent Publications

Jonathan Berger, John Orcutt, Gabi Laske, and Jeffrey Babcock (2014). ADDOSS Annual Report*, NSF, Sept 2014.*

Jonathan Berger, Peter Davis, Rudolf Widmer-Schnidrig, and Mark Zumberge (2014). Performance of an Optical Seismometer fro 1 μHz to 10 Hz. *BSSA. V. 104, N0. 5, pp. 2422-2429, Oct. 2014, doi:10.1785/0120140052*

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In 2014, recovering from hip operations, I focused on local natural history, with forays into local geology and botany. This resulted in a small book, entitled "Coast to Crest, and Beyond," with information on the natural history of the county along an east-west transect in the middle of it, and beyond the crest to the desert (rain shadow and general Southwest). The book was printed by Atlas Lithograph, San Diego, for the Francis Parker Program for Public Education at SIO. It has a foreword from Rand Newman, then the president of the board of the San Dieguito River Valley Conservancy. I sent the booklet to anyone at SIO requesting it.

Other research involved working on the history of the ocean, as seen in sediments. Nothing of this has been published, so far. I am corresponding with an interested publisher.

Recent Publications

Berger, W. H. (2014). *Coast to Crest and Beyond/Across San Diego County by Car Along the San Dieguito River*, 146 pp. (San Diego, Sunbelt Publications), can be purchased from Amazon.

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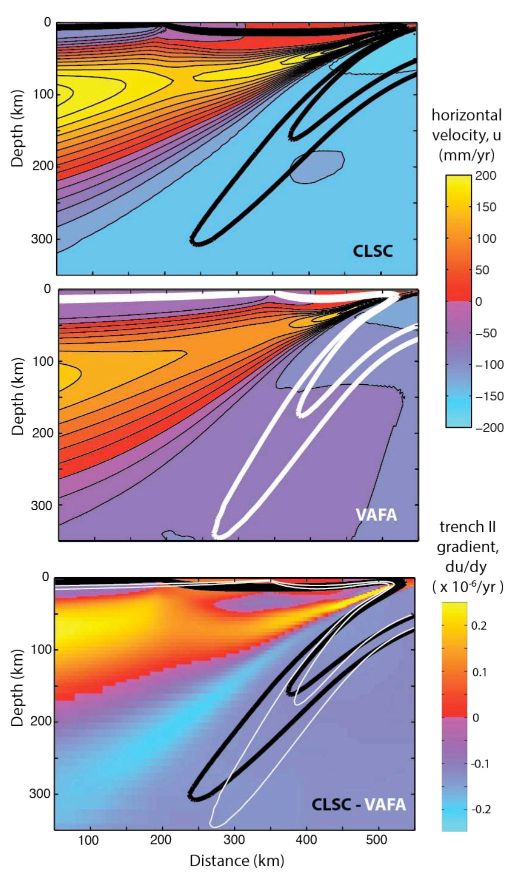
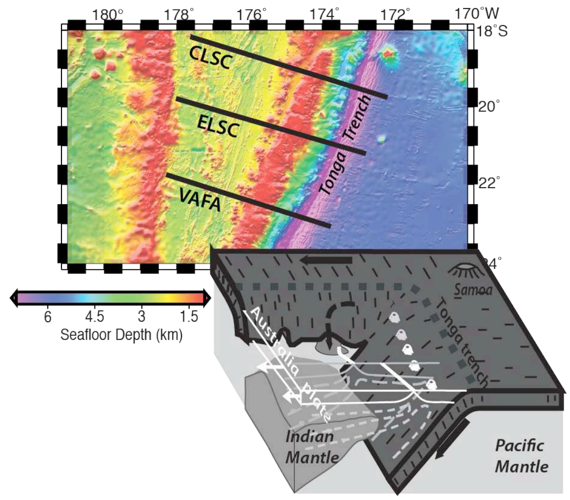
Research Interests*:* Understanding mantle flow, melting, and plate tectonic evolution along plate boundaries, using marine geophysics and numerical modeling.

My work this year was dominated by program management, for the Marine Geology & Geophysics program, as I complete a 3-yr rotation at the National Science Foundation. However, I was able to do some research in two areas- synthesizing ocean drilling results and numerical modeling of mantle flow and associated rheologic and seismic anisotropy.

One ocean drilling effort was to co-edit a book that synthesizes outcomes of the Integrated Ocean Drilling Program (IODP) 2003-2013. The authors of the chapter I edited nicely portrayed several aspects of Solid Earth science that uniquely benefited from data obtained by coring and logging. The second drilling related effort was to wrap up the main stage of postcruise analysis for 2012 borehole logging at Atlantis Massif oceanic core complex. With Alistair Harding and colleagues, we documented a relationship between physical properties and lithospheric hydration of a slow-spread intrusive crustal section. IODP Hole U1309D penetrates 1.4 km into the footwall to an exposed detachment fault on the 1.2Ma flank of the mid-Atlantic Ridge, 30°N. Downhole variations in seismic velocity and resistivity show a strong correspondence to degree of rock alteration, a recorder of past seawater circulation. Average velocity and resistivity are lower, and alteration is more pervasive above a fault ~750 m seafloor depth at this site. Deeper, these properties have higher values except in heavily altered ultramafic zones that are several tens of meters thick. Present circulation inferred from temperature mimics this pattern: advective cooling by seawater persists above 750 m, but below, conductive cooling dominates except for small excursions within the ultramafic zones. We infer that these alteration-related physical property signatures are probably a characteristic of gabbroic cores at oceanic core complexes.

Grad student Rachel Marcuson completed her Lau Basin mantle flow/anisotropy project, determining that measurable variations in shear wave splitting should be observed between the Valu Fa, Eastern Lau and Central Lau spreading centers. These anisotropy variations, directly linked to predicted mantle strain rate, indicate how flow could vary between the three transects. The differences are partly due to along-basin changes in subduction and backarc spreading rates, but they are also influenced by differences in the distance between the trench and the back-arc spreading center. Observed seismic anisotropy patterns (Zha et al, 2014; Menke et al. JGR in review; Wei et al., Nature in review) clearly require processes beyond 2-D flow of mantle peridotite, which would dominantly produce fast seismic directions that are spreading/convergent parallel. The difference in plate-driven flow rates between the Valu Fa and Central Lau Spreading Center transects would induce along-strike flow, but associated gradients are not strong enough to produce mineral alignment that would generate trench/arc parallel fast seismic direction such as have been documented east of the backarc spreading center. Flow gradients that are 1-2 orders of magnitude greater would be required if plastic deformation of mantle minerals is the dominant mechanism responsible for the anisotropy.





Lau Basin backarc spreading centers (above, map and 3D sketch) and mantle wedge flow in 3 transects (left). Comparison of predicted horizontal component of 2-D flow field at Central Lau Spreading Center (CLSC) and Valu Fa (VAFA). Top two panels have the same color scale for velocity, contour interval 25 mm/yr. Heavy lines show 500° and 700°C isotherms for CLSC (black) and VAFA (white). Lower panel shows difference in horizontal flow between these models, scaled by distance between them .

Modeling of anisotropic viscosity that develops as mantle flows beneath an oceanic spreading center is the main focus of my ongoing research. In collaboration with colleagues at Cornell and Paris, we are testing feedbacks between mineral alignment and flow pattern, tracking grain scale deformation by dislocation creep and linking that to regional scale flow.

Recent Publications

Marcuson, R., D.K. Blackman, N. Harmon, Seismic anisotropy predicted for 2-D plate-driven flow in the Lau back-arc basin, Phys. Earth Planet. Int., 233, 88-94, doi: 10.1016/j.pepi.2014.06.007, 2014.

Blackman, D. K., A. Slagle, G. Guerin, and A. Harding , Geophysical signatures of past and present hydration within a young oceanic core complex, Geophys. Res. Lett., 41, 1179–1186, doi 10.1002/ 2013GL058111, 2014.

Zha, Y., S.C. Webb, S.S. Wei, D.A. Wiens, D.K. Blackman, W. Menke, R.A. Dunn, J.A. Conder, Seismological imaging of ridge-arc interaction beneath the Eastern Lau Spreading Center from OBS ambient noise tomography, Earth Planet. Sci. Lett., in press 2014.

Earth and Life Processes discovered from subseafloor environment, R. Stein, D. Blackman, F. Inagaki, H-C. Larsen (eds.), Developments in Marine Geology, Elsevier, in press 2014.

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Research Interests: space geodesy, crustal deformation, early warning systems for natural hazards, seismogeodesy, GPS meteorology, data archiving and information technology, sensors

Our research group is application oriented with an emphasis on mitigating effects of natural hazards on people and critical infrastructure through early warning and rapid response to events such as earthquakes, tsunamis and severe weather. We approach this in a holistic manner from the design and deployment of geodetic and other sensors, real-time data collection and analysis, physical modeling, for example a kinematic earthquake source model followed by tsunami prediction (Figure 1), to communicating actionable information the "last mile" to emergency responders and decision makers during disasters. We maintain a global archive of GNSS[1] data and products with accompanying IT infrastructure and database management system and provide real-time data streams for precise positioning and navigation. In 2013-2014, the SOPAC (Scripps Orbit and Permanent Array Center) group included Peng Fang and Jennifer Haase, postdoctoral researchers Jianghui Geng and Yuval Reuveni, graduate students Diego Melgar, Dara Goldberg and Jessie Saunders, and Mindy Squibb, Anne Sullivan, Maria Turingan and Glen Offield.

Prediction of tsunami inundation triggered by 2011 Mw 9.0 Tohoku-oki, Japan earthquake

Integration of GNSS and accelerometer data at the observation level provides real-time estimates of seismic displacements, velocities, and point tilts that are more robust and informative than accelerometer or GPS data on their own (*Geng et al*., 2013). Seismogeodetic data can enhance earthquake early warning, rapid centroid moment tensor (CMT) solutions and finite fault slip models for near-source monitoring of large earthquakes such as the devastating 2011 Mw 9.0 Tohoku-oki earthquake in Japan (*Melgar et al*., 2013), which triggered a devastating tsunami. Using a kinematic source model to calculate deformation of the seafloor, incorporating seismogeodetic, ocean surface buoy displacements, and seafloor pressure sensor data, and using two-dimensional shallow water equations, *Melgar and Bock* (2013) demonstrated an accurate tsunami inundation model for the affected Japanese shoreline (Figure 1). This is a significant result for those in the region closest to the earthquake source where loss of life and damage to infrastructure is most severe. As was demonstrated during the actual response to the 2011 Tohoku-oki earthquake, traditional approaches are not accurate enough in the critical time period after the event and may severely underestimate the magnitude and regional extent of damage, to the detriment of rapid response.

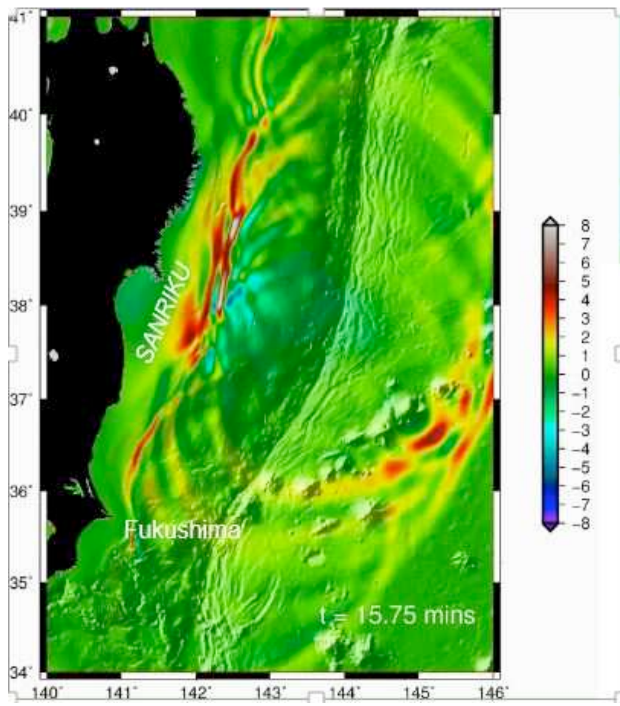

Figure 1. Tsunami wave propagation at 15.75 minutes after origin time of the 2011 Mw 9.0 Tohoku-oki, Japan earthquake based on a kinematic source model (D. Melgar, PhD thesis, 2014). The first waves inundated the shoreline at about 30 minutes, and waves continued to arrive for more than 30 more minutes. By replaying the available data *Melgar and Bock* (2013) demonstrated that an accurate tsunami prediction could have been made available well before arrival of the first waves.

[1] GNSS is an acronym for Global Navigation Satellite System, which encompasses all navigation satellite constellations, including GPS – U.S., GLONASS – Russia, Galileo – European Union, and Beidou – China.

Earthquake rapid response, flash flood forecasts and structural health monitoring

The SOPAC group has developed the SIO Geodetic Module (GM) that synchronizes data streams from GNSS receivers and small, inexpensive MEMS sensors, including accelerometers, meteorological (pressure and temperature), gyroscopes, and other sensors of opportunity to help in mitigating the effects of natural hazards on people and critical infrastructure. About 20 GNSS stations have been upgraded with these systems (Figure 2) across the southern segment of the southern San Andreas fault system in southern California, thought primed for a large earthquake. We estimate real-time displacement and velocity waveforms from these data as part of a prototype earthquake early warning and rapid response system. Another 10 systems are being installed along the Hayward fault in the San Francisco Bay region, and area of highest seismic risk in the Western U.S. Further upgrades are planned for the Cascadia region, where there is a risk of an earthquake and tsunami comparable in magnitude to the 2011 Mw9 Tohoku-oki events. With the collaboration with the Structural Engineering Department, Geodetic Modules and MEMS accelerometers were tested and validated atop a four-story building at UCSD's Large High Performance Outdoor Shake Table subjected to a series of replayed historical earthquakes (*Saunders, Goldberg et al*., 2014). The seismogeodetic data are also being used to evaluate the building's design – they provide static (permanent) as well as dynamic displacements of the building a critical factor in structural health monitoring and not typically available in current engineering practice. Finally, using a combination of GNSS and inexpensive pressure and temperature sensors, we estimate the variations of water vapor in the lower atmosphere (troposphere), a critical driver of extreme weather such as the southern California summer monsoons. NOAA's weather forecasting offices in San Diego and Los Angeles counties successfully used our data to forecast and track a monsoon in the summer of 2013 and issue an accurate flash flood warning for the region (*Moore et al*., 2014).

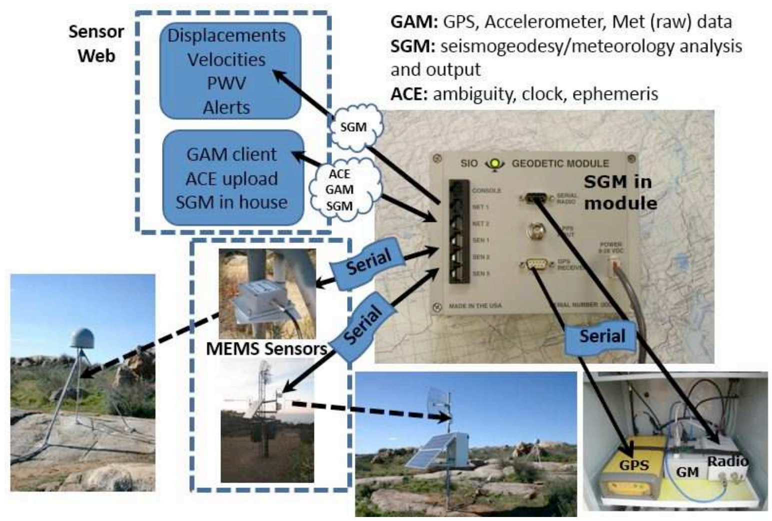

Figure 2. Components of an upgraded GNSS station.

Recent Publications

Geng, J., Y. Bock, D. Melgar, B. W. Crowell, and J. S. Haase (2013), A new seismogeodetic approach applied to GPS and accelerometer observations of the 2012 Brawley seismic swarm: Implications for earthquake early warning, *Geochem. Geophys. Geosyst*., *14*, doi:10.1002/ggge.20144.

Melgar, D. and Y. Bock (2013), Near-Field Tsunami Models with Rapid Earthquake Source Inversions from Land and Ocean Based Observations: The Potential for Forecast and Warning, *J. Geophys. Res.*, 118, doi:10.1102/2013JB010506.

Melgar, D., B. W. Crowell, Y. Bock, and J. S. Haase (2013), Rapid modeling of the 2011 Mw 9.0 Tohoku-oki earthquake with seismogeodesy, *Geophys. Res. Lett*., 40, 1-6, doi:10.1002/grl.50590.

Moore, A., I. Small, S. Gutman, Y. Bock, J. Dumas, P. Fang, J. Haase, M. Jackson, and J. Laber (2014), Densified GPS estimates of integrated water vapor improve forecaster situational awareness of variable moisture fields in the Southern California summer monsoon, *Bull. Amer. Meteorol. Soc*. (BAMS), in press.

Saunders, J., D. Goldberg, J. S. Haase, Y. Bock, D. Melgar, J. Restrepo, A. Nema, R. Fleischman, Z. Zhang, J. Geng, D. Offield, M. Squibb (2014), Seismogeodetic monitoring of engineered structures using MEMS Accelerometers, presented at SIO Student Symposium, La Jolla, Sept. 16.

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Research Interests: Remote hydrology from GPS and GRACE. Satellite altimeter calibration/ validation and measurements of topographic change. Differential lidar techniques applied to problems in geomorphology and tectonic geodesy. Kinematic GPS for positioning, mapping, and recording transient deformation due to earthquakes, fault creep and short-period crustal loading. GPS multipath and other noise sources. Dry lake geomorphology.

My most recent research involves the characterization of the hydrological cycle using crustal loading observations from GPS, in collaboration with SIO colleagues Duncan Agnew and Dan Cayan. Changes in water storage in lakes, aquifers, soil moisture, and vegetation results in elastic deformation of the crust that yields measureable vertical displacements of the surface. The seasonal signal from water loading has been extensively studied, but loading changes over longer periods are typically smaller and have not been broadly documented. Since 2013, however, drought in the western USA has caused rapid and widespread uplift of mountainous areas of California and the West. The vertical displacements from the drought are unprecedented in magnitude over the past decade of continuous GPS observations.

The drought uplift signal, which exceeds 15 mm at locations in the Sierra Nevada, is large enough to be obvious by inspection of GPS time series. We apply a seasonal filter derived from the econometrics literature (the Seasonal-Trend-Loess estimator) to completely remove the annual signal due to water loading and pumping, and we invert the filtered GPS position data to recover the spatiotemporal loading required to account for observed uplift. In the case of the current drought, our estimate of the accrued water deficit ranges up to 50 cm and totals 240 gigatons, equivalent to a 10 cm uniform layer of water over the land area east of the Rocky Mountains. Currently, we are extending our analysis to look at short-term changes in loading from individual storms, and we are investigating drought-induced Coulomb stress changes on all faults in the UCERF3 fault model.

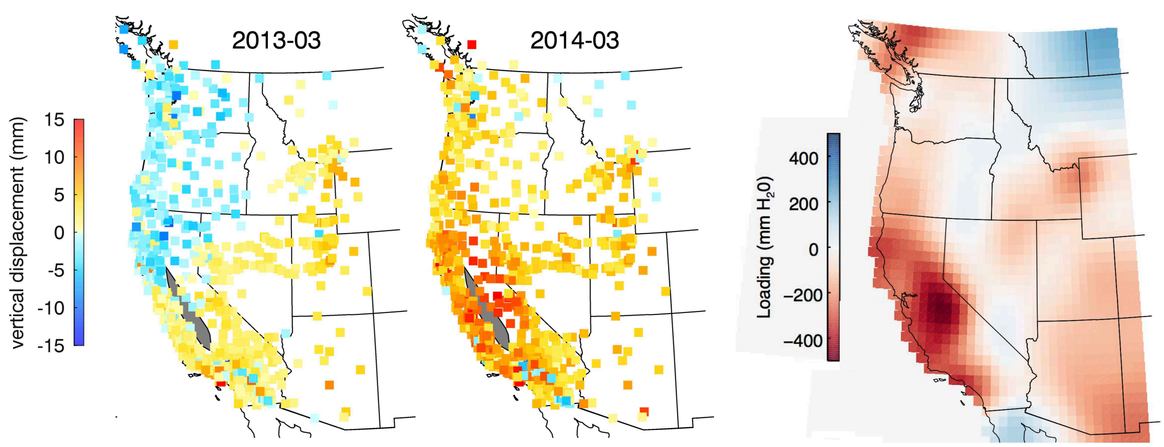

Figure 1: **Left**: Spatial distribution of vertical displacements from Plate Boundary Observatory continuous GPS stations in the western USA in March of 2013 and 2014. Color indicates deviations of seasonally-adjusted elevations from decadal mean, with blues related to subsidence and yellow-reds related to uplift. **Right**: Mass load in mm of water equivalent derived from inversion of March 2014 vertical displacements, assuming elastic strains on a spherical Earth.

My other primary area of research has been the calibration and validation of satellite altimeter measurements using a reference surface at the salar de Uyuni, Bolivia. In collaboration with SIO colleague Helen Fricker, I have led three expeditions to the salar de Uyuni (in 2002, 2009 and 2012) to survey the surface with kinematic GPS. We have established that the surface is both exceptionally flat (80 cm total relief over 50 km) and stable (< 3 cm RMS elevation change over a decade), while maintaining coherent geoid-referenced topography at wavelengths of tens of kilometers. In 2013, using our salar digital elevation model (DEM), I found and was able to identify the source of an inadvertent error in ICESat-1 processing that was the source of large shot-to-shot errors late in the mission period and that significantly changed ICESat-derived elevation change trends for the stable portions of the Greenland and Antarctic ice sheets.

Recently we have began to explore surface change at the salar using ALOS InSAR observations, with the goal of linking absolute GPS measurements with relative motions provided by InSAR to provide a continuous time series of surface displacement for calibration purposes. We have also expanded our cal/val activity to the Cryosat mission and are regularly providing our results to ESA.

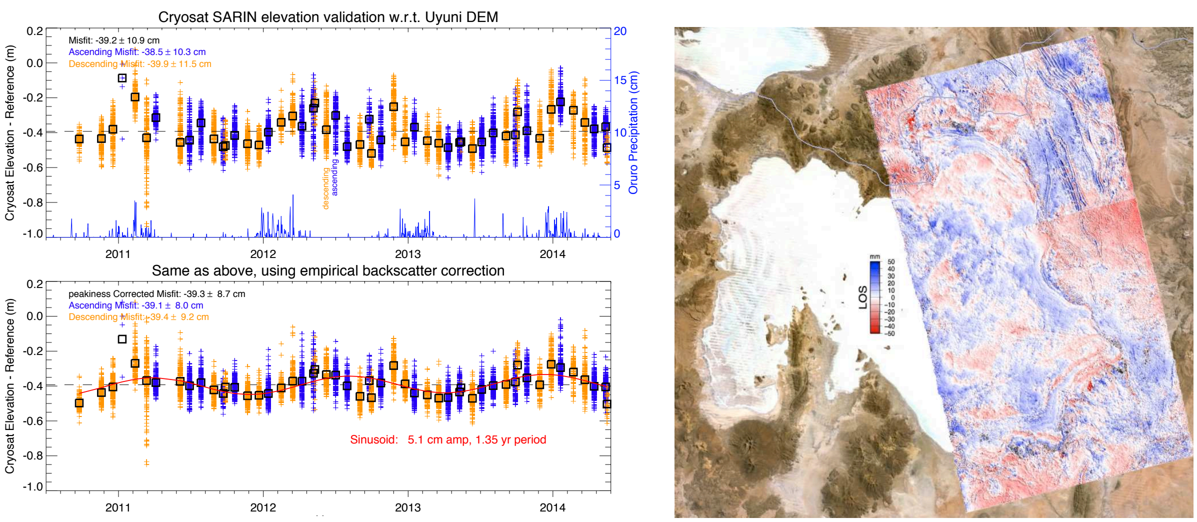

Figure 2: **Left**: Cryosat SARIN-mode elevation validation relative to the salar de Uyuni DEM, with residuals showing a.) a uniform range bias of -40 cm, b.) an apparent sinusoidal anomaly of 1.35 yr period that is still unexplained, and c.) higher range resolution than reported elsewhere, even with the sinusoidal anomaly. **Right:** ALOS InSAR results over the salar de Uyuni for the period 8/27/2010 ~ 1/12/2011, indicating that seasonal elevation change is <1 cm averaged over the salar surface.

Recent Publications

Borsa, Adrian Antal, Duncan Carr Agnew, and Daniel R. Cayan. (2014). "Ongoing drought-induced uplift in the western United States." *Science* 345.6204 (2014): 1587-1590.

Borsa, A. A., G. Moholdt, H. A. Fricker, and K. M. Brunt. (2014) "A range correction for ICESat and its potential impact on ice-sheet mass balance studies." *The Cryosphere* 8, no. 2: 345-357.

Hodgkinson, Kathleen, John Langbein, Brent Henderson, Dave Mencin, and Adrian Borsa. (2013). "Tidal calibration of plate boundary observatory borehole strainmeters." *Journal of Geophysical Research: Solid Earth* 118, no. 1: 447-458.

Glennie, Craig L., Alejandro Hinojosa-Corona, Edwin Nissen, Arpan Kusari, Michael E. Oskin, J. Ramon Arrowsmith, and Adrian Borsa. (2014) "Optimization of legacy lidar data sets for measuring near-field earthquake displacements." *Geophysical Research Letters*.

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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 main 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 ~near primitive and recycled crustal materials from the lower mantle; these stationary plumes generate and deposit OIB on the surface of moving oceanic plates. However, when, how and which recycled materials contribute to mantle plumes are still poorly understood.

Quite recently, I was involved in constraining the role of magmatism in the break-up of the eastern part of the African tectonic plate. It is now widely accepted that magmatism along the East African Rift System (EARS) is related to mantle plume activities, similar to those that form OIB in linear volcanic island chains, but the number and nature of mantle plumes are controversial. Recent geophysical data indicate a single megaplume, the African Superplume, as the main source of magmatism. On the other hand, the highly variable composition of EARS volcanic rocks appears to suggest a plume centered at or near the Afar region in the northern EARS and a number of plumes in the southern EARS such as those in e.g., Kenya Rift, Virunga volcanic province, Rungwe volcanic province, and the whole southern EARS. However, closer inspection of available data provides support for an alternative hypothesis that the compositions of EARS plumes converge to a single plume with a restricted range in composition. Thus, we (together with D. Hilton and S. Halldorsson) propose that the observed variation of EARS lavas is mainly due to mixing of material from the Superplume with the compositionally variable lithospheric mantle beneath the isotopically depleted, Late Proterozoic Pan-African mobile belt and isotopically enriched, Early Proterozoic Nubian plate (+/- Archaean Tanzanian craton). Additionally, the Superplume has been modifying the lithospheric mantle beneath the entire region to a ~common composition through carbonatite metasomatism for, at least, 500 my. This has created a fourth, lithospheric mantle pseudo-source, which is mainly characterized by extremely high incompatible trace element contents, but restricted, ~near bulk silicate Earth Sr and Nd isotopic ratios – similar to that of the Superplume. Although there are exceptions, mixing of Superplume/metasomatized lithosphere with Pan-African lithospheric mantle produces the bulk of lavas from the northern EARS as far south as the northern Kenya Rift. In contrast, mixing with lithospheric mantle beneath the Nubian plate/Tanzanian craton (+ variable upper crust) produces the bulk of lavas from the southernmost Kenya Rift and Western Rift. A depleted upper mantle contribution appears minimal and restricted to the northernmost EARS. EARS lavas have highly variable Pb isotopic ratios because of the variable Pb isotopes of the lithosphere and the Superplume is a young HIMU type, generated mainly from recycled marine carbonate with inherently high U/Pb ratio. The general model is illustrated in the figure below.

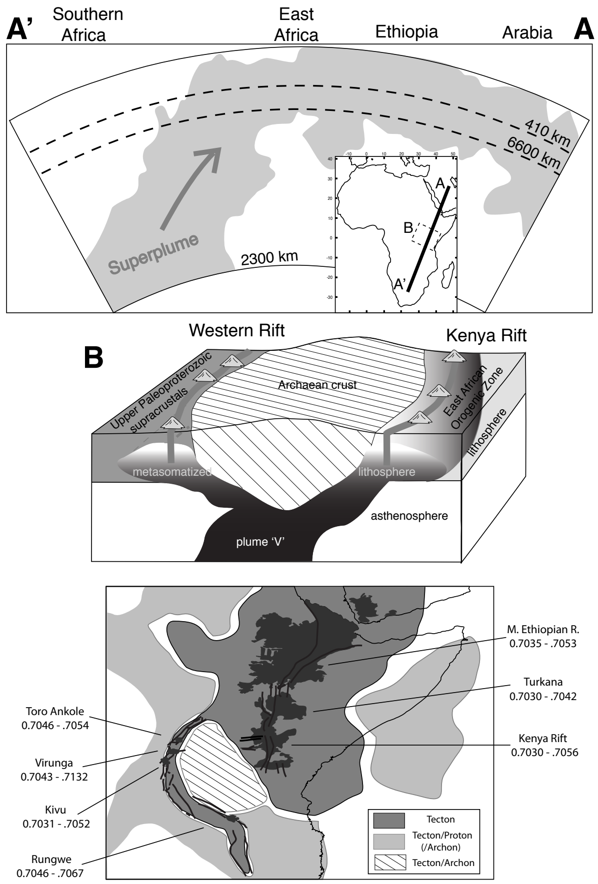

Figure from Castillo et al., 2014. Top panel - cross-section through the African and Arabian mantle (see inset for location of line A – A'). The gray area labeled Superplume is modified from a P-wave tomography model beneath East Africa. This cartoon shows that the superplume comes from the core-mantle boundary. Middle panel – schematic block diagram for the ~middle portion of the EARS (see inset for location of block B). The three major sources of the compositional spectrum of the EARS are (1) mantle plume V, (2) East African Orogenic Zone and (3) Upper Paleoproterozoic supracrustal (+ Archaean) lithosphere (mantle and crust). The metasomatized lithospheric mantle is the fourth, ~ubiquitous pseudo-source. The superplume apparently has been supplying carbonatitic or plume material to the lithosphere beneath east Africa for up to a b.y. It may be quite heterogeneous although in general, it still has a fairly limited range in composition especially compared to those of the lithospheric mantles. The combined effects of long-term metasomatism plus the heterogeneous composition and variable age and thickness of the lithosphere create an allusion of several compositionally distinct mantle plumes along the EARS. Bottom panel – a tectonothermal model for the 100- to 175-km depth slice of eastern Africa deduced from xenolith data. Archon = tectonothermal event that occurred at ≥2.5 Ga, Proton = 2.5 – 1 Ga, and Tecton = <1 Ga; boundaries are open/gradational. That the entire EARS belongs to the Tecton domain is highly consistent with our proposal that EARS lavas are coming from a common, metasomatized lithospheric mantle (e.g., see middle panel). However, the higher average (and absolute) $^{87}Sr/^{86}Sr$ isotopic ratios of western rift lavas represent the more variable composition of their relatively older lithospheric source compared to that of eastern rift lavas.

Recent Publications

Castillo, P.R., Hilton, D.R. and Halldórsson, S.A., "Trace element and Sr-NdPb isotope geochemistry of Rungwe Volcanic Province, Tanzania: implications for a Superplume source for East Africa Rift magmatism", Frontiers in Earth Science 2, doi: 10.3389/feart.2014.00021, 2014.

Liu, X., Xu, J., Castillo, P.R., Xia, W., Shi, Y., Feng, Z., and Guo, L., "The Dupal isotopic anomaly in the southern Paleo-Asian Ocean: Nd–Pb isotope evidence from ophiolites in Northwest China", Lithos 189, 185-200, http://dx.doi.org/10.1016/j.lithos.2013.08.020, 2014.

Yan, Q., Shi, X. and Castillo, P.R. "The late Mesozoic–Cenozoic tectonic evolution of the South China Sea: A petrologic perspective" Journal of Asian Earth Sciences 85, 178–201, http://dx.doi.org/10.1016/j.jseaes.2014.02.005, 2014.

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Research Interests: Seafloor tectonics of subduction, transform motion, and seafloor spreading. Volcanic collapse, slope stability and associated geo-hazards. Seafloor geodetic techniques with acoustics and GPS.

In 2014, I have developed a new, lower cost approach to collect GPS-Acoustic data for long-term measurements of seafloor deformation. The GPS-Acoustic method combines high-precision kinematic GPS positioning from an ocean surface platform with precision acoustic ranging from the platform to transponders on the seabed. The technique was developed by our group here at SIO. Wider adoption of GPS-A has been restricted by the high-cost of shiptime ~$50k/day) and the finite life of batteries in the seafloor transponders.

The first objective was to find some platform other than a costly ship from which to collect the GPS-Acoustic data. Moored buoys are one option, but are costly to maintain. A more general solution uses a platform that extracts the kinetic energy of the ocean wave motion to derive propulsion and solar energy for running the payload, i.e., a Wave Glider from Liquid Robotics. I re-engineered the GPS-Acoustic hardware into a smaller and lower power form factor that will fit into a Wave Glider. We have successfully tested the Wave Glider GPS-A approach and used the system in Sept. 2014 in the Cascadia Subduction zone offshore Newport, Oregon.

The next task was to design a methodology to extend the life of a seafloor survey past the span of the battery power in the seafloor transponders. The typical GPS-A site consists of three or four transponders deployed on the seabed to form a triangle or square with the nominal dimension of the water depth. GPS and acoustic data are typically collected for 4-5 days in each year and this continues for up to 5-7 years before the transponder batteries are depleted. The positional time series is attached to transponders so once the batteries fail the time series is lost. This was ok for the initial demonstration projects, but the potential for longer time series is desirable. An interim solution developed by our group was to place a new transponder within 1-2 m of the expired one and in a complicated manner transfer the 3-D position from one to the other. A better solution was needed, i.e., an inert benchmark that allowed the transponders to be placed and removed while maintaining millimeter resolution of the transponder position on the benchmark.

I designed a 3-Vee groove registration system that can be deployed free-fall from the sea surface. Once on the seafloor the transponders are used for the duration of the project and then acoustically recalled. An ROV can then be used to place a new transponder on the benchmark. In June 2014, I used the ROV Jason aboard R/V Thompson to successfully deploy four of the benchmark/Transponder packages and demonstrate the ease of their use with ROVs. This provides two significant advances: potential for long term time series and the transponders become re-useable. As a pool of transponders accumulates the cost of GPS-A experiments will continue to drop.

In September 2014 we established three GPS-Acoustic sites within the Cascadia subduction zone using the new approaches, and will measure the site position over the next three years.

Recent Publications

Burgmann, R. and Chadwell, C. D (2014). Seafloor Geodesy *Annu. Rev. Earth Planet. Sci.* **42** 509-534. 10.1146/annurev-earth-060313-054953

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Research Interests: Earth's Magnetic Field on all time scales; Paleomagnetic and geomagnetic secular variation; Linking paleomagnetic observations to numerical dynamo simulations; Paleo and rock magnetic databases; Electrical conductivity of Earth's mantle; Inverse problems; Statistical techniques.

Ongoing research projects over the past year have been concerned with (i) analysis of behavior of the geomagnetic field on centennial to 100 kyr timescales including development of new inversion strategies (with postdoc Sanja Panovska (IGPP) and Monika Korte of GeoForschungs Zentrum, Helmholtz Center, Potsdam); (ii) the magnetic field on million year time scales (with PhD student Geoff Cromwell, Catherine Johnson at University of British Columbia, Lisa Tauxe); (iii) continued 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. (iv) work with PhD student Margaret Avery, postdoctoral researcher Christopher Davies (Leeds University, U.K., currently an IGPP Green Scholar) and research associate David Gubbins on compatibility of numerical geodynamo simulations with paleomagnetic results. Some results from this work are highlighted below. New topics under exploration are using very long geomagnetic observatory records (back to the early part of last century) for deep mantle induction studies, and extension of interest to high frequency (> 1Hz) geomagnetic variations.

Linking Dynamo Simulations to Paleomagnetic Field Behavior:
Analysis of output from numerical geodynamo simulations, allows a comprehensive evaluation of magnetic and velocity fields associated with the synthetic experiments, and assessment of how energy is partitioned. Statistical properties of typical observables in the paleomagnetic record can be computed and used to assess whether the simulated fields are Earth-like in morphology and how they change with time. An analysis of this kind is described in Davies & Constable (2014), and shows that the time needed to obtain a converged estimate of the time-averaged field is comparable to the length of most of the simulations, even in non-reversing models, suggesting that periods of stable polarity spanning many magnetic diffusion times are needed to obtain robust estimates of the mean dipole field. Long term field variations were almost entirely attributable to the axial dipole while non-zonal (longitudinally varying) components converge to long-term average values on relatively short timescales (15 - 20 kyr). This suggests that the 100 kyr model under construction will be long enough to get a good grasp of any basic persistent geographic variations in the geomagnetic field and its secular variations.

Several years ago former graduate student Leah Ziegler and I co-authored a paper in which we analyzed PADM2M, our reconstruction of paleomagnetic axial dipole moment for the past 2 My. By filtering at successively longer periods we uncovered the result shown in Figure 1, that in a frequency band between about 7 and 50/Myr the dipole moment spends more time in decay mode than growing, and speculated that this could reflect dominance of diffusive processes on these time scales. New estimates of dipole diffusion times (based on revised estimates of conductivity for the core) are compatible with this interpretation. In ongoing studies we (Maggie Avery, Chris Davies, David Gubbins and I) have conducted further analyses of numerical simulations to assess whether this asymmetry in growth and decay times can be identified in numerical simulations and used as a further criterion for Earth-like behavior. Following tests on how long a record is needed

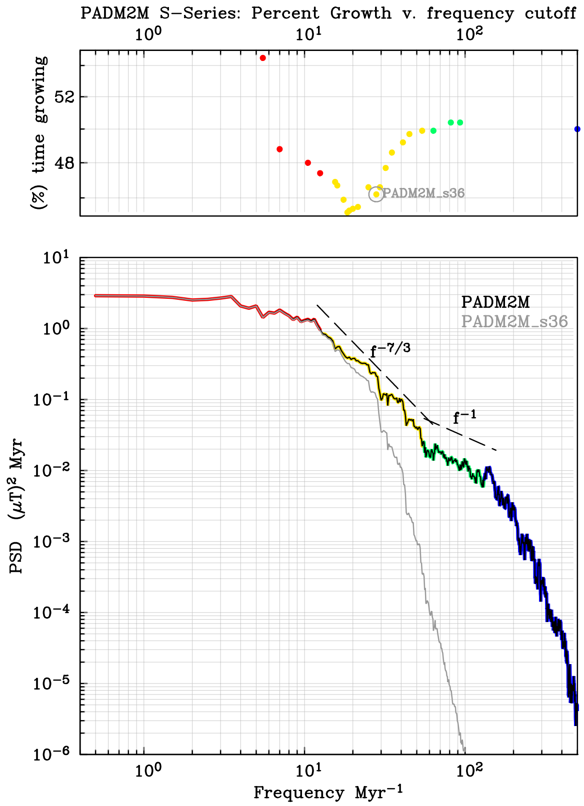
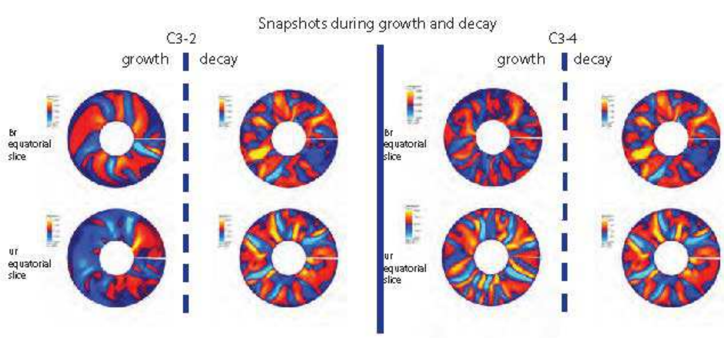


Figure 1: **Power spectrum for PADM2M and impact of smoothing on asymmetry in growth and decay:** (a) Percentage of time spent in periods of intensity growth versus frequency cutoff for the smoothing. (b) PADM2M power spectrum (black) highlighted with colors to show distinct behavioral regimes. Details are in Ziegler & Constable (2011, `10.1016/j.epsl.2011.10.019`).

we have identified asymmetry in some simulations (and the opposite form with more time growing than decaying in others). A major topic of interest is to determine what visual (see snap shots of magnetic field and flow velocity below) and physical behavior is exhibited in the simulations leads to these different scenarios, and then relate this back to real paleomagnetic field observations.

Recent Publications

Davies, C.J., & C.G. Constable (2014) Insights from geodynamo simulations regarding long-term geomagnetic field behaviour. *Earth Planet. Sci Lett.,* **404**, 238-249, `DOI:10.1016/j.epsl.2014.07.042`.



Steven Constable **Professor**
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Research Interests: Marine EM methods, electrical conductivity of rocks

Steven Constable runs the SIO Marine Electromagnetic (EM) Laboratory at IGPP, and along with Kerry Key oversees the Seafloor Electromagnetic Methods Consortium, an industry funding umbrella which helps support PhD students and postdocs working in the group. The two main field techniques we use 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. Both methods can be used to probe the geology of the seafloor, from the near surface to hundreds of kilometers deep, using electrical conductivity as a proxy for rock type.

Figure 1: Working near sea ice to map submarine permafrost off Alaska.

This year has seen our instrument fleet, consisting of 56 seafloor EM receivers and two deep-towed EM transmitters, in constant use. At around the time last year's annual report was released, we shipped all our gear to Uruguay for a study of sedimentary structure in a frontier (oil) exploration area. We carried out the experiment in January and early February on the R.V. Ocean Stalwart out of Montevideo. Our gear did not get back to La Jolla until mid-April, and was immediately put onto trucks to Newport, Oregon, for the MOCHA experiment headed up by Kerry Key to study the tectonics of subduction. The seafloor receivers stayed down until mid-June, and were trucked back just in time to load onto the R.V. New Horizon for a study of gas hydrates in the Santa Cruz Basin, offshore California. After demobilizing the New Horizon at the beginning of July we then shipped some gear to Prudhoe Bay, Alaska, for a study of offshore permafrost. After returning from Prudhoe Bay in late July we then started loading containers to ship our equipment to Japan for another gas hydrate study, which entailed almost three weeks constant use of our EM transmitter in August. The gear returned home from Japan in early October. Thanks to decades of instrument development, and the hard and careful work our our engineers and technicians, we lost only two seafloor receivers in over 200 deployments associated with these various projects, maintaining our excellent record of a long-term instrument loss rate of only 1% of deployments.

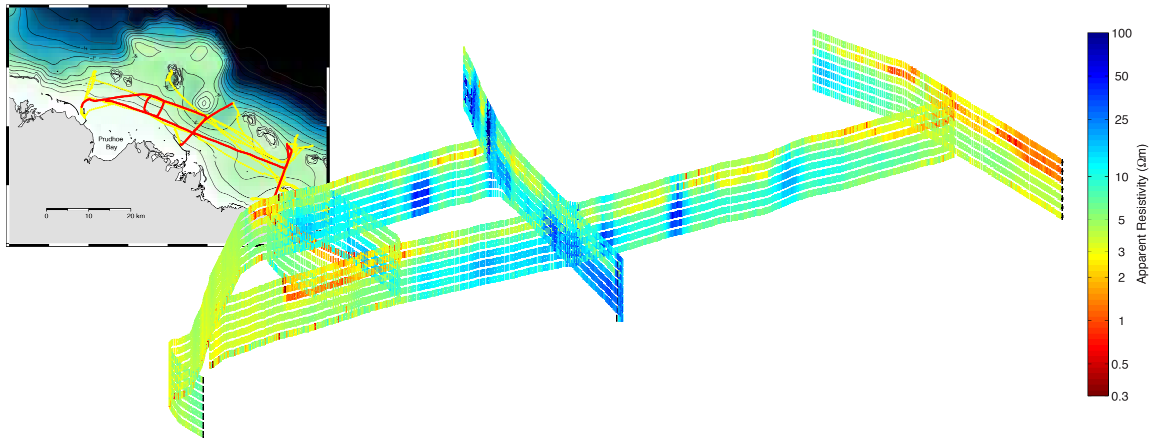
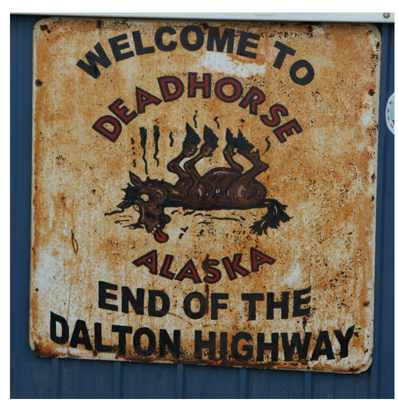


Figure 2: Preliminary results from our Prudhoe Bay permafrost study, showing apparent resistivities plotted along tow lines as a function of frequency on the vertical axis. Low frequencies are expected to propagate deeper into the seafloor. Blue is resistive, and probably an indication of frozen sediment. Red lines in the inset show our tow lines with respect to Prudhoe Bay.

Our years work highlights the broad scope of applications for marine electromagnetic methods, from hydrocarbon exploration, the mechanics of plate tectonics, to the impacts of climate change. The figures show our work off Prudhoe Bay, headed up by student Peter Kannberg. This is the first time we have been to the arctic, and involved not only some new equipment but a lot of new experiences associated the logistics working so far north and out of what is essenitally a company town (Deadhorse, Alaska). The study used equipment that is a miniature version of our deepwater systems and small enough to be air-freighted around the world, fit into the back of one pickup truck for mobilization at the destination, and deployable from a small vessel (Figure 1).

We built a 60 amp transmitter that is only as big as a large briefcase, and a 1,000 m array of surface-towed electric field receivers. The new equipment worked very well, and although the sea ice prevented us working more than 15 km offshore, the preliminary results look very good, showing high electrical resistivities in the seafloor most likely associated with permafrost, and much more lateral variability that we expected from looking at the seismic data during our cruise planning (Figure 2).



Recent Publications

Ray, A., K. Key, T. Bodin, D. Myer, and S. Constable (2014) Bayesian inversion of marine CSEM data from the Scarborough gas field using a transdimensional 2-D parameterization, *Geophysical Journal International*, **199,** 1847–1860, `10.1093/gji/ggu370`

Weitemeyer, K., and S. Constable (2014) Navigating marine electromagnetic transmitters using dipole field geometry, *Geophysical Prospecting*, **62,** 573–593, `10.1111/1365-2478.12092`

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

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Specialist

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

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 recently concluded upgrading the core data acquisition and power system equipment at all stations using funding provided by NSF via the IRIS Consortium. A map of the network showing upgraded systems denoted by orange triangles is shown in Figure 1. The remaining stations, ABKT and NRIL, are effectively closed.

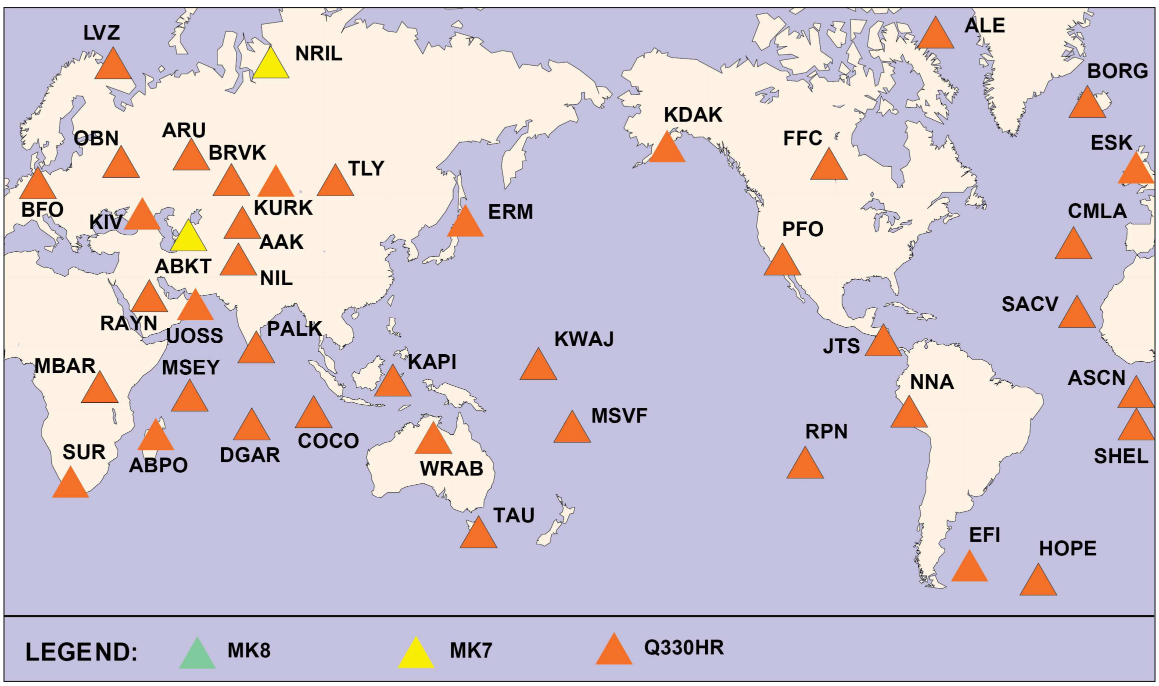

Figure 1. Current global seismic stations operated by Project IDA.

During the next phase of network operation, IDA's staff will fine-tune each station's instruments to enable scientists to extract the most accurate information possible from the data collected. One method for accomplishing this task is by examining key phenomena such as Earth tides and normal modes that should register the same on these important geophysical sensors. To the extent that measurements made with multiple instruments that 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.

In coordination with our counterparts at the US Geological Survey, we are also engaged in a program to verify instrument responses using portable instruments. Figure 2 shows three-component seismograms recorded by two instruments at the IDA station NNA in Peru. The extent to which the recordings from these independent instruments match gives us confidence that our methods for verifying the accuracy of our published instrument responses are effective.

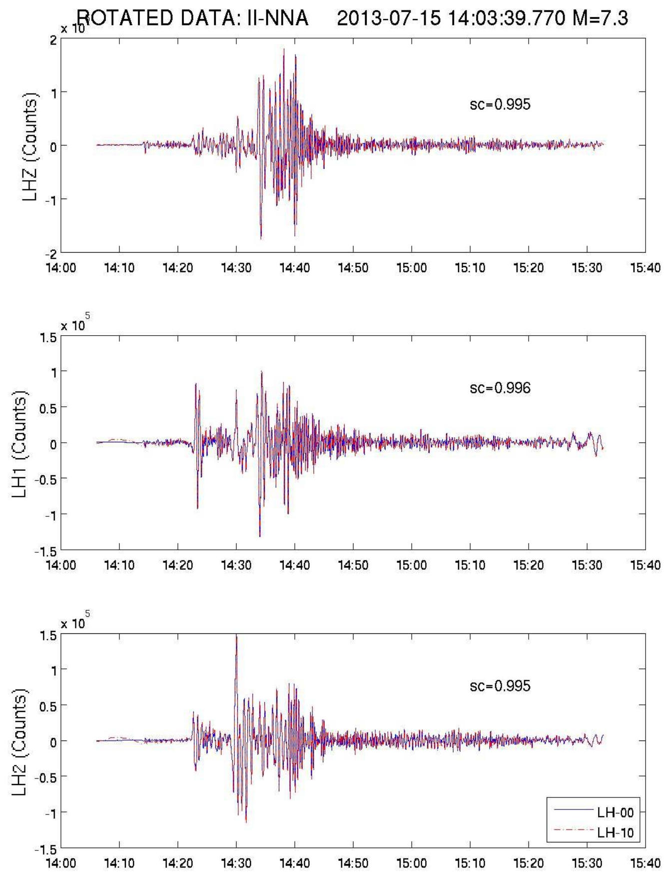

Figure 2. Seismograms from a large earthquake recorded on two instruments in Peru. The data from the three orthogonal components (vertical, north and east) nearly match, indicating the instrument responses are known precisely. The response's accuracy is verified with similar tests using Earth tides and normal modes of oscillation.

Relevant Publications

Berger, J., P. Davis, R. Widmer-Schnidrig and M. Zumberge, Performance of an Optical Seismometer from 1 μHz to 10 Hz, *Bull. Seis. Soc. Am.*, **104**, 2422-2429, 2014 doi: 10.1785/0120140052

Davis, P., and J. Berger, Initial impact of the Global Seismographic Network quality initiative on metadata accuracy, *Seis. Res. Lett.,* **83(4)**, 697-703, 2012.

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Scripps Isotope Geochemistry Laboratory (SIGL)

Research Interests: Planetary accretion and differentiation processes; cosmochemistry; mantle geochemistry; igneous and metamorphic petrology; volcanology; ore genesis

Mantle petrology and geochemistry – The mantles of terrestrial bodies are largely inaccessible due to thin layers of crust that obscure them from view. The Earth is no exception, with mantle materials only becoming readily accessible through relatively rare tectonic exhumation, or by incorporation of mantle fragments (xenoliths), in some volcanic rocks. Because of the importance of the mantle in Earth processes, it is important to use and develop other means for probing its composition. Using mantle-derived basaltic rocks from oceanic islands, we are continuing to refine methods for understanding the composition of the upper mantle. Recent work has included studies of mantle composition beneath the Cook Islands, and the source of the archetypal HIMU end-member (Herzberg et al., 2014), as well as to investigate the oxygen isotope composition of continental-derived alkali basalts for comparison with oceanic island basalt lavas (Day et al., 2014). PhD student Brad Peters recently led an investigation of the robustness of trace-elements, such as Ti, Ta and Nb (so-called ‘TITAN’ elements), for understanding mantle heterogeneity (Peters & Day, in press). What we found is that these trace-elements are less useful for probing mantle composition than previously thought, but provide valuable information on petrogenetic processes. Current terrestrial work in the SIGL includes petrological, geochemical and isotopic studies of oceanic island basalts, continental flood basalts and mantle peridotites.

Planetary accretion and differentiation processes – Our NASA-supported endeavours currently include studies of the Moon, Mars and asteroidal bodies. A continuing theme of our work is the study of volatile elements in planets. The latest developments include refining models for understanding post-core formation accretion and interpreting and understanding how volatile inventories in planets were obtained and/or lost. Recent analysis of moderately volatile elements like S, Cl, K and Zn in the Moon suggest that this body is volatile-poor and may have lost its volatiles immediately after its formation, through evaporative processes (Day & Moynier, 2014). We have also recognized an intriguing relationship between the velocity required to escape a planets gravity (‘escape speed’) and characteristic volatile/refractory element ratios, or Zn isotopic composition (**Figure 1**). To a first-order, this relationship may suggest that volatile loss or retention is intimately related to mass, on fully differentiated planets. Other work by our group has included S-isotopic studies of martian meteorites (Franz et al., 2014), examination of weathering in meteorites (Hyde et al., 2014), and the first report of isotopically ‘light’ iron in Solar System material, from the oligoclase-rich achondrite meteorites, GRA 06128 and GRA 06129 (Wang et al., 2014). Current planetary work in the SIGL includes petrological, geochemical, isotopic and modelling studies of chondrites, partially-melted achondrites and martian and lunar samples to study planetary accretion, differentiation, late-accretion and volatile elements.

Recent Publications

Peters, B.J., Day, J.M.D., Assessment of relative Ti, Ta, and Nb (TITAN) enrichments in ocean island basalts. *Geochemistry, Geophysics, Geosystems*, in press.

Day J.M.D., Moynier F. (2014) Evaporative fractionation of volatile stable isotopes and their bearing on the origin of the Moon. *Philosophical Transactions of the Royal Society A* 20130259. http://dx.doi.org/10.1098/rsta.2013.0259

Hyde B.C., Day J.M.D., Tait K.T., Ash R.D., Holdsworth D.W., Moser D.E. (2014) A study of weathering and heterogeneous mineral phase distribution in brachinite Northwest Africa 4872. *Meteoritics and Planetary Science*, 49, 1141-1156.

Day J.M.D., Peters B.J., Janney P.E. (2014) Oxygen isotope systematics of South African olivine melilitites and implications for HIMU mantle reservoirs. *Lithos*, 202-203, 76-84.

Herzberg, C., Cabral, R.A., Jackson, M.G., Vidito, C., Day, J.M.D., Hauri, E.H. (2014) Phantom Archean crust in Polynesian hotspot lavas and the meaning of heterogeneous mantle. *Earth and Planetary Science Letters*, 396, 97-106.

Franz, H.B., Kim, S.-T., Farquhar, J., Day, J.M.D., Economos, R.C., McKeegan, K.D., Schmitt, A.K., Irving, A.J., Hoek, J., Dottin, J. (2014) Sulphur isotopic signature links atmospheric chemistry to sulfur assimilation by martian magmas. *Nature*, 508, 364-368.

Wang K., Day J.M.D., Korotev R.L., Zeigler R.A., Moynier F. (2014) Iron isotope fractionation during sulfide-rich felsic partial melting in early planetesimals. *Earth and Planetary Science Letters*, 392, 124-132.

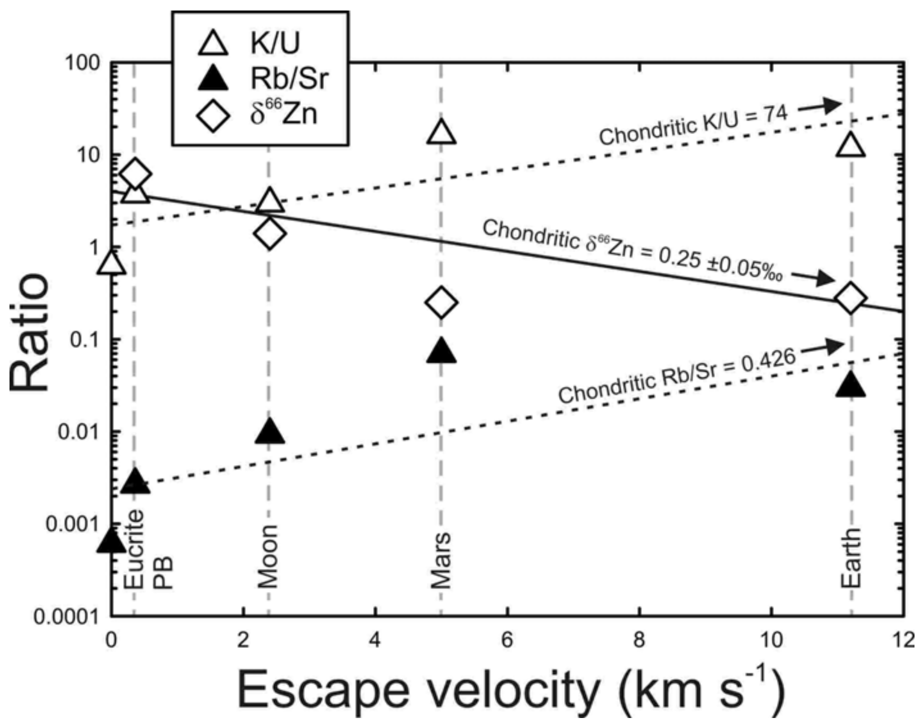

Figure 1: Escape velocity versus abundance ratios of K/U and Rb/Sr and $^{66}Zn/^{64}Zn$ ratios (as $\delta^{66}Zn$ in per mille) for Earth, Mars, Moon, the eucrite parent body (Eucrite PB) and the angrite parent body (on Y-axis). Exponential regressions are shown for $\delta^{66}Zn$ (R^2 = 0.66; solid line), Rb/Sr (R^2 = 0.55; long dashed line) and K/U (R^2 = 0.54; short dashed line). Ratios of Rb/Sr and K/U decrease, and $\delta^{66}Zn$ shows heavy isotope enrichment, with lower escape speeds. This implies more extreme volatile loss in smaller-mass bodies. Chondritic values for Rb/Sr, K/U and $^{66}Zn/^{64}Zn$ are reported along the exponential regression lines. Figure adapted from Day & Moynier (2014).

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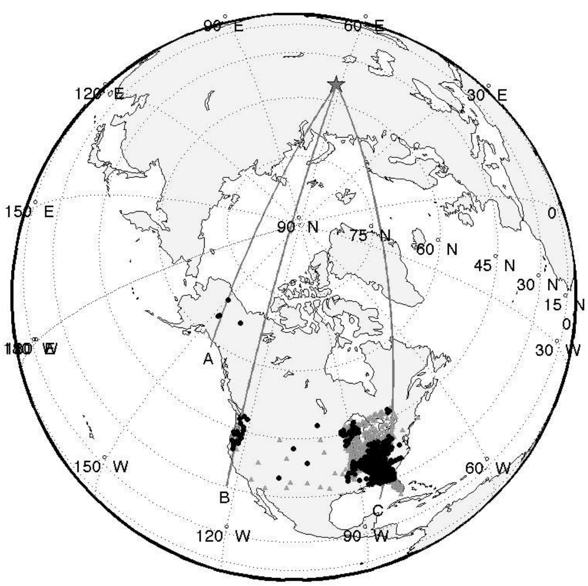
Research Interests*:* Acoustic propagation modeling with application to infrasound and hydroacoustics; application of hydroacoustics and infrasound to nuclear test-ban verification and hazard monitoring; use of dense seismic and infrasound networks to analyze infrasound signals.

My main research area is in the basic physics of infrasound – sound at frequencies lower than human hearing - as well as its practical applications to investigating explosive processes such as bolides and large explosions.

Meteor detection: In the past year, I analyzed infrasound signals from two bolides. The first event examined was the explosive fragmentation of a small asteroid over Chelyabinsk, Russia in February 2013 that generated a large airburst with an equivalent yield of 500 kT TNT. Events of this type are extremely rare, having a recurrence rate of one every several decades. It was recorded at infrasound sensors deployed at sites in the 400-station USArray in the continental United States and Alaska, at distances from 6000 to 10000 km. The findings highlight the importance of accurate atmospheric specifications in predicting infrasound signal characteristics.



The global map at right shows the site of the Chelyabinsk meteor burst (dark grey star) and the USArray barometers. Stations with signal detections are shown by black circles; grey triangles indicate USArray stations that did not record a detectable signal.

The second event analyzed, in association with Dr. Michael Hedlin and a Canadian colleague, Dr. Wayne Edwards, was a much smaller one that occurred near Montreal in late November, 2013. The sky was overcast, making it impossible to confirm this event with photographs or video. Fortunately, the airburst was recorded at several dozen USArray infrasound sensors in eastern North America. These data were used to confirm that this was probably a meteor event, find the location of its terminal burst, and estimate its approximate size and equivalent source yield (6 T TNT). This study highlights the importance of using infrasound data to monitor the flux of bodies impacting the Earth.

Gravity waves: With funding from NSF, I have worked with the L2A (Laboratory for Atmospheric Acoustics) group to examine very low frequency pressure data recorded at USArray sensors. The entire USArray spans a region of approximately 2,000,000 square km. At this vast scale, even very large-scale arrivals are not coherent over the entire scale of the array, but do show coherence over the scale of at least the 70 km inter-station spacing. I developed a technique that splits the USarray up into a large number of small sub-arrays to detect large-scale coherent wave motions and track their progression across large regions. This work is continuing with a German colleague, Lars Hoffmann, to investigate gravity wave activity over a 5 year period and delve more deeply into the meteorological mechanisms for generating the observed waves.

Numerical modeling: A basic research goal in infrasound is to understand the transmission of infrasound through variable atmospheric conditions. To this end I have developed a computationally efficient numerical method to synthesize 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, volcanic eruptions, or nuclear and chemical explosions. With support from the Air Force Research Laboratory (AFRL), work on this code is continuing so that, in future, it will allow for the incorporation of more realistic atmospheric effects, such as topography, atmospheric absorption, and both spatially and temporally varying sound speeds and wind speeds. The current goal is to determine to what extent nonlinearity affects the estimated source yields for anthropogenic explosions.

Recent Publications

Edwards, W.E., C. de Groot-Hedlin & M. Hedlin, 2014 Forensic investigation of a probable meteor sighting using USArray acoustic data, Seis. Res. Lett.,

de Groot-Hedlin, C.D., Hedlin, M.A.H. 2014, Infrasound detection of the Chelyabinsk meteor at the USArray., *Earth Planet. Sci Lett*, http:/dx.doi.org/10.1016/j.epsl.2014.01.031

Walker, K.T., A. Le Pichon, T. S. Kim, C. de Groot-Hedlin, I.-Y. Che, M. Garces, 2013, An analysis of ground shaking and transmission loss from infrasound generated by the 2011 Tohoku earthquake, J. Geophys. Res., doi:10.1029/2013JD020187

Brown, P.G., J. D. Assink, L. Astiz, R. Blaauw, M. B. Boslough, J. Borovicka, N. Brachet, D. Brown, M. Campbell-Brown, L. Ceranna, W. Cooke, C. de Groot-Hedlin, & 21 others, 2013, A 500-kiloton airburst over Chelyabinsk and an enhanced hazard from small impactors, Nature Letter, doi:10.1038/nature12741

de Groot-Hedlin, C, Hedlin, M. & Walker, K., 2013, Detection of gravity waves across the USArray: A case study, *Earth Planet. Sci Lett*, http://dx.doi.org/10.1016/j.epsl.2013.06.042

de Groot-Hedlin, C., 2012, Nonlinear synthesis of infrasound propagation through an inhomogeneous, absorbing atmosphere", *J. Acoust. Soc. Am*., v132, p646-656.

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Research Interests: Seismology, especially seismic structure of the seafloor; Scholte waves; seafloor instrument development, especially of Ocean-Bottom seismometers, (OBS's) and seismic sources; seismic noise and fluid flow associated with tremor and slip

Historically, seismograms were seen to contain discrete events (earthquakes) and noise (everything but earthquakes). Now a third phenomenon has been recognized, non-volcanic tremor (NVT). NVT looks a lot like noise, in that discrete events are absent, but it is statistically different. I am looking at ways of distinguishing NVT from noise, based on coherence between different frequencies, which is absent for stationary processes. These statistics may contain information about the sources of NVT, which are obscure.

Recent Publications

Yildiz, S, Sabra K, Dorman LM, Kuperman WA. (2013). Using hydroacoustic stations as water column seismometers. *Geophys. Res. Let.*, **40**, 2573-2578. 10.1002/grl.50371; see also this supplement.

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

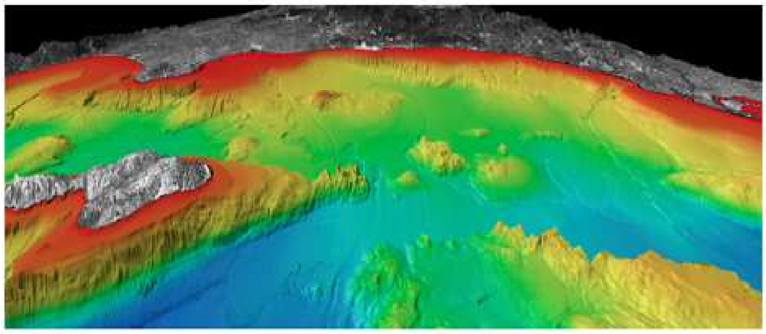

Figure 1: Perspective image of the Inner California Borderlands bathymetry. Catalina Island is in the foreground. The newly acquired data extend from San Diego to Santa Monica.

Recent observations of compressional deformation in the Inner California Borderlands (ICB) offshore southern California have sparked debate over tectonic processes in the region. Two end-member models have been proposed to explain the young apparent compressional deformation observed in the ICB. One model invokes reactivation of detachment faults such as the Oceanside blind thrust (OBT) to explain the deformation and margin architecture (e.g., San Mateo/Carlsbad trends). In contrast, the other model explains this deformation by step-overs along several northwest-oriented strike-slip fault systems. Reprocessed, industry multichannel seismic (MCS) reflection data were examined to characterize the geometry of faulting in the ICB. New observations gained from these data, provide evidence that deformation in the ICB is more consistent with the step-over geometry than a regional blind thrust model. For example, regions in the ICB exhibit both compressional and extensional structures across the margin, which are more readily explained by the strike-slip model. Localized transpression and transtension occurs as predicted at fault bends and step-overs. In addition, onlapping turbidite layers reveal that the deformation becomes stratigraphically younger towards the east, an observation not consistent with a westward verging blind thrust fault system (Figure 2). Finally, rotational deformation previously attributed to a splay off the OBT instead appears to be a southward transported slide deposit (Figure 3). In summary, ICB tectonic deformation and margin architecture are best explained by step-overs along strike-slip fault systems. The lack of an OBT reduces the hazard for coastal regions in southern California because there would be no hanging-wall effects and nearby slip rates would be reduced.

Recent Publications

Coyan, M.M., Arrowsmith, J.R., Umhoefer, P., Coyan, J., Kent, G., Driscoll, N., Gutierrez G. M. (2013). Geometry and Quaternary slip behavior of the San Juan de los Planes and Saltito fault zones, Baja California Sur, Mexico: Characterization of rift-margin normal faults, *Geosphere* **9** 426-443 10.1130/ges00806.1

Denny, J.F., Schwab, W.C., Baldwin, W.E., Barnhardt, W.A., Gayes, P.T., Morton, R.A., Warner, J.C., Driscoll, N.W., Voulgaris, G. (2013). Holocene sediment distribution on the inner continental shelf of north-

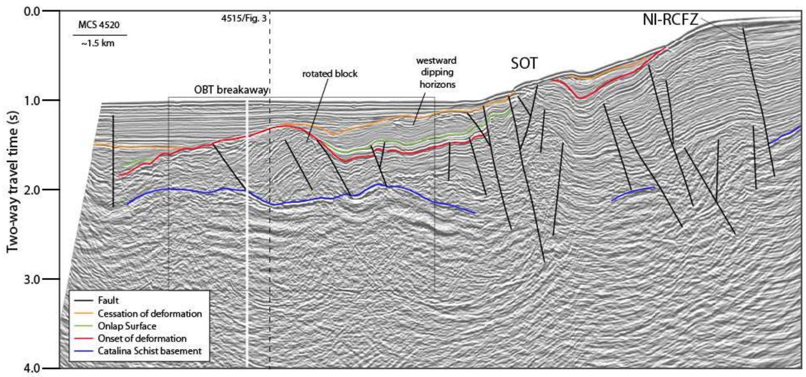

Figure 2: MCS line 4520 showing that horizons west of the San Onofre trend above the orange horizon are regionally flat lying and show that deformation is younger eastward. The vertical white line marks the geographic location of the purported Oceanside blind thrust breakaway zone. Abbreviations: SOT San Onofre trend; NI-RCFZ Newport Inglewood-Rose Canyon fault zone; OBT Oceanside blind thrust.

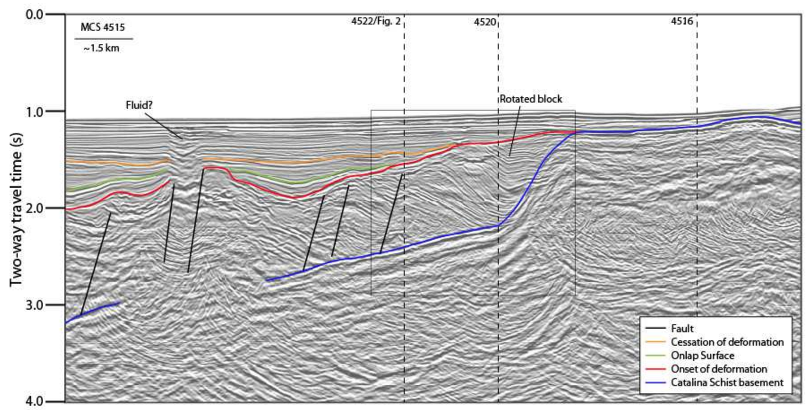

Figure 3: MCS line 4515 imaging acoustic basement relief and the rotated and deformed reflectors. The basement dips to the south, away from the high in the north and deformation is parallel the margin not perpendicular as predicted by the OBT. Vertical dashed lines show intersection with labeled profiles (Figure 2).

eastern South Carolina: Implications for the regional sediment budget and long-term shoreline response, *Continen. Shelf Res.* **56** 56-70. `10.1016/j.csr.2013.02.004`

Dong, S.P., Ucarkus, G., Wesnousky, S.G., Maloney, J., Kent, G., Driscoll, N., Baskin, R. (2014). Strike-slip faulting along the Wassuk Range of the northern Walker Lane, Nevada, *Geosphere* **10** 40-48. `10.1130/ges00912.1`

Umhoefer, P.J., Maloney, S.J., Buchanan, B., Arrowsmith, J.R., Martinez-Gutierrez, G., Kent, G., Driscoll, N., Harding, A., Kaufman, D., Rittenour, T., (2014). Late Quaternary faulting history of the Carrizal and related faults, La Paz region, Baja California Sur, Mexico, *Geosphere* **10** 476-504. `10.1130/ges00924.1`

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Research Interests: Acoustical oceanography, ocean acoustic tomography, signal processing

My research is on the use of sound in the ocean to understand some of the dynamic processes that are present. Sound is an effective tool to study the ocean interior because it is trapped in a natural occurring waveguide (due to vertical gradients of pressure and temperature) present in all the worlds oceans. Some of the processes that can be studied include climate change, ocean circulation, internal waves, and tides. I am part of a group that has conducted several large experiments in regions as diverse as the Philippine Sea in the tropical Pacific, to the Fram Strait in the Arctic.

To highlight one small part of this effort, a new tracking algorithm developed for ocean acoustic arrivals will be described here. The usual experimental situation is that a single pulse is transmitted and multiple pulses are received. The travel-time of the pulse contains information about the ocean sound-speed and current. To use that information, it must be compared to an expected time-of-arrival from a model. The subtle difficulty is in associating one of the measured sound pulses with one of the model pulses. This problem is very similar to radar tracking of multiple aircraft in the midst of clutter

The Viterbi algorithm is an effective automated method for tracking peaks and associating them with model arrivals. There may be multiple detected peaks per expected peak or no measured peak at all due to scattering. A likelihood ratio can be defined that expresses the probability that any particular measured peak can be associated with any particular expected peak. This likelihood ratio is the transition probability that the new measurement is the correct association given the previous expectation. The Viterbi algorithm itself is easily described, but the transition probabilities themselves are somewhat complicated expressions.

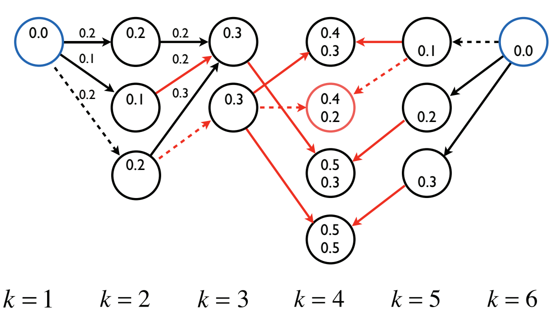

Figure 1: The nodes represent detected peaks at different transmission times k. The arrows represent transition costs between nodes. The total cost of a path from the left/right is the sum of the costs along the path and is shown in the top/bottom number at a node. The most likely node at a particular time is the one with lowest total costs.

We can represent the situation with a trellis diagram as shown in Fig. 1. The branches in the trellis are weighted by the transition cost, the best path must be chosen from the various possibilities, and is represented by the dotted line in the example diagram.

An example of this algorithm applied to actual experimental data taken in the Philippine Sea is shown in Fig. 2. In the figure, the measured peaks are represented by dots. The plot shows numerous arrival sidelobes, grating lobes from other arrivals, against a noisy background. The Viterbi tracking algorithm was run on this data set, and the tracked peaks are shown in the figure as black dots. Close examination does not reveal any differences from what might have been picked from hand-guided peak picking.

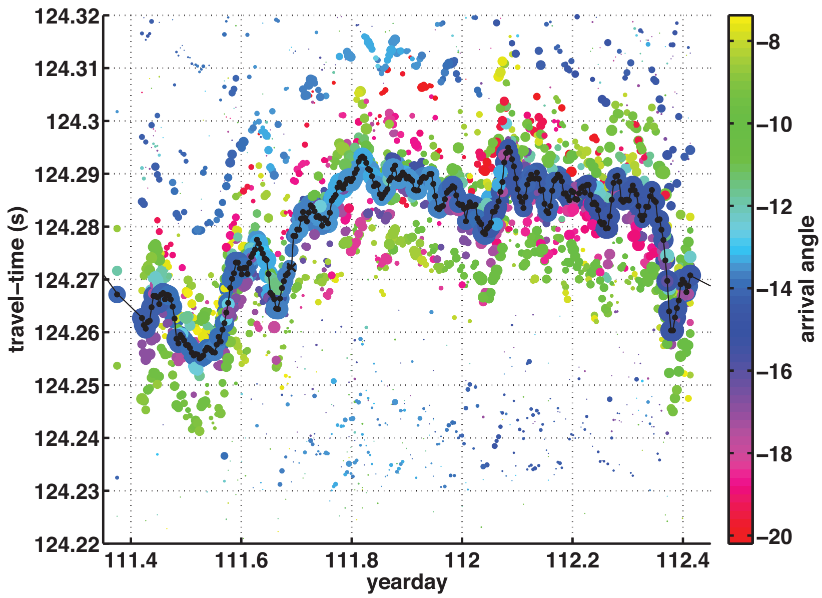

Figure 2: Philippine Sea 2009 arrival-time vs. transmission time. Arrival-angle is represented by the dot color, and arrival strength is represented by dot size.

Peak tracking has been a limiting factor in tomographic experiments because of the time and energy required by manual analysis. Since the number of paths to be tracked scales as the product of the number of sources and receivers, even a moderate sized experiment with six transceivers represents a large amount of labor. The Viterbi algorithm solves this problem, while also providing a rational and repeatable method of analysis. While the definition of the transition probabilities is complicated, the process is direct and programmable.

Recent Publications

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

Skarsoulis, E.K., Cornuelle, B.D., Dzieciuch, M.A., (2009) Travel-time sensitivity kernels in long-range propagation, J. Acoust. Soc. Am., **126**, 2223–2233.

Dzieciuch, M.A., (in print) Signal processing and tracking of arrivals in ocean acoustic tomography, J. Acoust. Soc. Am..

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

Professor 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 and the Global Positioning System (GPS) to investigate the response of the Earth's crust to seismic and magmatic loading.

Among recent projects are studies of the mechanisms of post-seismic deformation due to large earthquakes. Prof. Fialko and graduate student Kang Wang used data from the L-band Advanced Land Observing Satellite (ALOS) and C-band Envisat satellites to investigate the aftermath of the 2005 magnitude 7.6 Kashmir (Pakistan) earthquake that occurred in the northwestern Himalaya. The line-of-sight (LOS) postseismic velocities in the epicentral area of the Kashmir earthquake indicate an uplift (decrease in radar range), primarily in the hanging wall of the earthquake rupture over the period of synthetic aperture radar observations (2005-2010). These data were compared to models of post-seismic relaxation. Models assuming poroelastic response of the fluid-saturated upper crust predict uplift of both the footwall and the hanging wall, while models of viscoelastic relaxation below the brittle-ductile transition predict subsidence (increase in radar range) in both the footwall and the hanging wall. Therefore, the observed pattern of surface velocities is good evidence that the early several years of postseismic deformation were dominated by afterslip on the fault plane, possibly with a minor contribution from poroelastic rebound. Kinematic inversions of interferometric synthetic aperture radar and GPS data confirm that the observed deformation is consistent with afterslip, primarily downdip of the seismic asperity.

Similar results were also obtained for the El Mayor-Cucapah earthquake that occurred on 4 April 2010 in northeastern Baja California just south of the U.S.-Mexico border. The earthquake ruptured several previously mapped faults, as well as some unidentified ones, including the Pescadores, Borrego, Paso Inferior and Paso Superior faults in the Sierra Cucapah, and the Indiviso fault in the Mexicali Valley and Colorado River Delta. Prof. Fialko and his students and colleagues conducted several GPS campaign surveys of preexisting and newly established benchmarks within 30 km of the earthquake rupture. Most of the benchmarks were occupied within days after the earthquake, allowing measurements of the very early postseismic transient motions. The GPS data show postseismic displacements in the same direction as the coseismic displacements; time series indicate a gradual decay in postseismic velocities with characteristic time scales of a few months. Interferometric synthetic aperture radar (InSAR) data from the Envisat and ALOS satellites indicate subsidence concentrated in the southern and northern parts of the main rupture, in particular at the Indiviso fault, at the Laguna Salada basin, and at the Paso Superior fault. The near-field GPS and InSAR observations over a time period of 5 months after the earthquake can be explained by a combination of afterslip, fault zone contraction, and a possible minor contribution of poroelastic rebound. Far-field data require an additional mechanism, most likely viscoelastic relaxation in the ductile substrate.

Other areas of prof. Fialko interests include interseismic deformation and mechanics of damage zones associated with major crustal faults. In a series of recent studies prof. Fialko and graduate student Eric Lindsey investigated the spatial pattern and rates of deformation due to active faults in southern California such as the San Andreas and San Jacinto faults. Radar observations using data from the Envisat satellite were used to con-

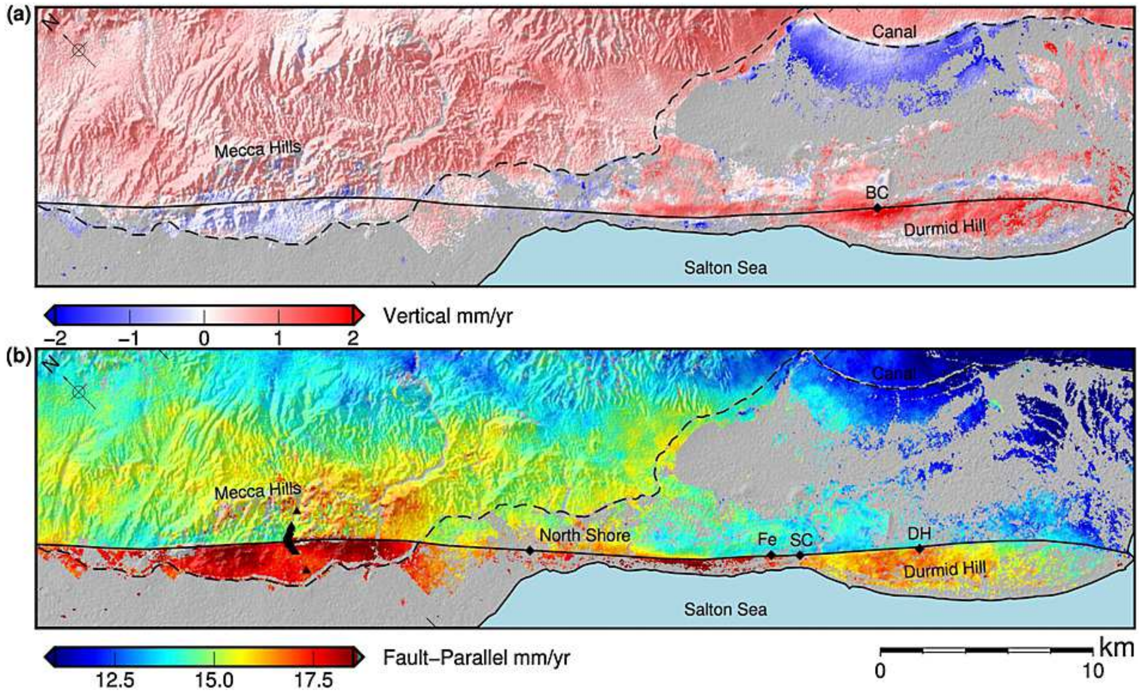

Figure 1: (a) Vertical and (b) horizontal (fault-parallel) velocities of the Earth's surface along the Southern San Andreas fault inferred from Envisat InSAR observations. BC denotes location of Bat Caves Buttes leveling line. Black line denotes trace of the SAF. Diamonds indicate locations of creepmeters at: North Shore, Ferrum (Fe), Salt Creek (SC), and Durmid Hill (DH). Triangles indicate locations of GPS monuments at Painted Canyon. Dashed line indicates location of the Coachella Canal. From Lindsey et al. [2014b].

struct a high-resolution map of surface motion near the fault traces. In case of San Andreas, the data reveal pervasive shallow creep along the southernmost 50 km of the fault. Creep is localized on a well-defined fault trace only in the Mecca Hills and Durmid Hill areas, while elsewhere creep appears to be distributed over a 1-2 km wide zone surrounding the fault. The degree of strain localization is correlated with variations in the local fault strike. The occurrence of shallow, localized interseismic fault creep within mature fault zones may thus be partly controlled by the local fault geometry and normal stress, with implications for models of fault zone evolution, shallow coseismic slip deficit, and geologic estimates of long-term slip rates.

Recent publications:

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Gonzalez-Ortega, A., Y. Fialko, D. Sandwell, A. Nava, J. Fletcher, J. Gonzalez-Garcia, B. Lipovsky, M. Floyd, and G. Funning, El Mayor-Cucapah (Mw 7.2) earthquake: Early postseismic deformation from InSAR and GPS observations, *J. Geophys. Res., 119*, 1482-1497, 2014.

Wang, K. and Y. Fialko, Space geodetic observations and models of postseismic deformation due to the 2005 M7.6 Kashmir (Pakistan) earthquake, *J. Geophys. Res., 119*, 7306-7318, 2014.

Lindsey, E., Y. Fialko, Y. Bock, D. Sandwell, and R. Bilham, Localized and distributed creep along the southern San Andreas Fault, *J. Geophys. Res.*, DOI:10.1002/2014JB011275, 2014b.

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Research Topics: cryosphere, Antarctic ice sheet, subglacial lakes, ice shelves, satellite remote sensing

My research focuses on the Earth's **cryosphere**, in particular the **Antarctic ice sheet.** I lead the **Scripps Glaciology Group**, which currently has two postdocs (Sasha Carter and Oliver Marsh) and three graduate students (Fernando Paolo, Matthew Siegfried and Julia Ruth). One of the primary research questions concerning Antarctic Ice Sheet is whether its mass is changing. The mass loss processes are iceberg calving and basal melting, and the primary driver of changes seems to be the ocean.

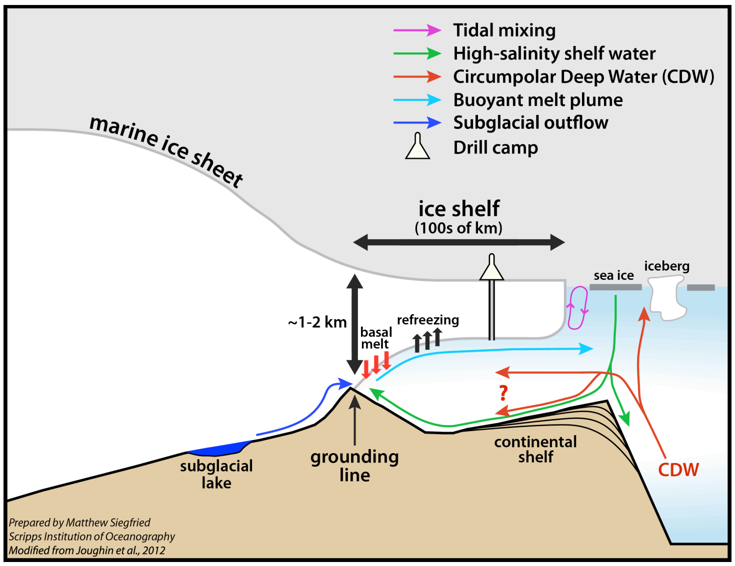

***Figure 1:** Antarctic ice sheet mass loss processes*

Satellite data are crucial for routine monitoring of Antarctica (due to its vast size, and the long time periods over which it can change), in particular data from radar and laser altimetry, and imagery. One useful dataset is laser altimetry from NASA's Ice, Cloud & land Elevation Satellite (ICESat. 2003-2009). I was a member of the ICESat Science Team and I am a member of ICESat-2 Science Definition Team. My group works on validating ICESat elevation data, using "ground-truth" from our repeated GPS surveys of the salar de Uyuni in Bolivia (in 2002, 2009 and 2012), led by IGPP Researcher Adrian Borsa. My group studies Antarctic ice sheet processes, as follows:

i) Antarctic subglacial water In 2006 I discovered active subglacial water systems under the fast-flowing ice streams of Antarctica using ICESat data. This was inferred from observations of large height change signals in repeat-track ICESat data (up to 10 m in some places), which corresponded to draining and filling of subglacial lakes beneath 1-2 km of ice; in total, we found 124 "active" lakes throughout Antarctica. We studied a large active subglacial lake system under Recovery Ice Stream (3). My graduate student Matt used ICESat, WISSARD's GPS and CryoSat-2 data to generate a 10-year time series of lake activity for Whillans Ice Stream (9).

Changing the basal conditions of an ice sheet, particularly beneath fast flowing ice streams and outlet glaciers, is one possible mechanism to increase its contribution to sea level rise, through increased ice flow speeds in the ice streams. With the current interest in Antarctic ice sheet mass balance and its potential impact on sea-level rise, it is important to understand the subglacial water process so that it can become incorporated into models; Sasha Carter works with me on this aspect of the problem. I am a PI on the Whillans Ice Stream Subglacial Access Research Drilling (WISSARD) project, a large, interdisciplinary NSF project to drill into one of the subglacial lakes that I discovered – Subglacial Lake Whillans (SLW) on Whillans Ice Stream, lead PI is Slawek Tulaczyk at UCSC. IGPP student Matt Siegfried took part in the surface geophysics fieldwork 2011-2012/2012-2013/2013-2014 (team leader), and installed GPS on the lakes to monitor their activity. SLW was drilled during the 2012-2013 field season (5). Matt will return to Whillans Ice Stream in 2014-2015, along with IGPP postdoc Oliver Marsh. UCSC graduate student Lucas

Beem published a paper on the slowing of Whillans Ice Stream (10). A paper describing the biological discoveries from WISSARD was published in Nature (2).

ii) Ice shelf grounding zones: We use ICESat data to map the grounding zones (GZs) of the ice shelves - the transition zones between grounded and floating ice. ICESat can detect the tide-forced flexure zone in the GZ because repeated tracks are sampled at different phases of the ocean tide; this has provided accurate GZ location and width information for each track. As part of WISSARD, we acquired GPS data across the GZ in two different geometries, which is helping us understand how the local topography influences the ice shelf flexure and properties. IGPP student Matt Siegfried is currently working on this.

iii) Ice shelf stability and change: We analyze elevation changes on Antarctic ice shelves observed by satellite radar and laser altimetry. IGPP student Fernando Paolo is improving on our initial work that was over the Antarctic Peninsula only, and extending to all Antarctic ice shelves. Former IGPP postdoc Geir Moholdt worked on an innovative method to derive basal melt rates from ICESat data 2003-2008 (1). My work on this also extends to the floating parts of the outlet glaciers Greenland (7).

iv) Glacio-seismology: I recently completed an NSF project with Jeremy Bassis, Shad O'Neel, Fabian Walter and David Heeszel (all former IGPP postdocs) investigating the source processes for seismic signals recorded in three different glaciological environments: Amery Ice Shelf; Ross Ice Shelf; and Columbia Glacier, Alaska. IGPP postdoc David Heeszel, who also received supplemental Greens funding, worked on this project until August 2013 (9).

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1. MOHOLDT, G., **H.A. FRICKER**, L. PADMAN (2014) Basal mass budget of Ross and Filchner-Ronne ice shelves, Antarctica, derived from Lagrangian analysis of ICESat altimetry, *Journal of Geophysical Research: Earth Surface,* doi: 10.1002/2014JF003171.
2. B.C. Christner, J.C. Priscu, A.M. Achberger, C. Barbante, S.P. Carter, K. Christianson, A.B. Michaud, J.A. Mikucki, A.C. Mitchell, M.L. Skidmore, T.J. Vick-Majors & the **WISSARD Science Team (2014)**. A microbial ecosystem beneath the West Antarctic ice sheet. *Nature ,* doi:10.1038/nature13667.
3. **FRICKER, H.A.**, S. P. CARTER, R.E. BELL, T.A. SCAMBOS (2014) Active lakes of Recovery Glacier, East Antarctica: a bedrock-controlled subglacial hydrological system, *Journal of Glaciology*, 60 (223), doi: 10.3189/2014JoG14J063..
4. HOLT, T.O., N.F. GLASSER, **H.A. FRICKER**, L. PADMAN, A. LUCKMAN, O. KING, D.J. QUINCEY, M.R. SIEGFRIED, The structural and dynamic responses of Stange Ice Shelf to recent environmental change, *Antarctic Science*, doi:10.1017/S095410201400039X, 15pp.
5. TULACZYK, S., J.A. MIKUCKI, M.R. SIEGFRIED, J.C. PRISCU, C.G. BARCHECK, L.H. BEEM, A. BEHAR, J. BURNETT, B.C. CHRISTNER, A. T. FISHER, **H.A. FRICKER**, K. D. MANKOFF, R.D. POWELL, F. RACK, D. SAMPSON, R.P. SCHERER, S.Y. SCHWARTZ and THE WISSARD SCIENCE TEAM (2014), WISSARD at Subglacial Lake Whillans, West Antarctica: scientific operations and initial observations, *Annals of Glaciology,* 55(65) 2014 doi: 10.3189/2014AoG65A009.
6. CHRISTOFFERSEN**,** P., M. BOUGAMONT, S.P. CARTER**, H.A. FRICKER**, S. TULACZYK, 2014. Significant groundwater contribution to Antarctic ice streams hydrologic budget, *Geophysical Research Letters*, 2014GL059250 doi:10.1002/2014GL059250.
7. MÜNCHOW, A., L. PADMAN AND **H. A. FRICKER** (2014) Interannual Changes of the Floating Ice Shelf of Petermann Gletscher, North Greenland from 2000 to 2012, *Journal of Glaciology*, 60, (221), 498-499, doi: 10.3189/2014JoG13J135.
8. HEESZEL, D. S., **H. A. FRICKER**, J. N. BASSIS, S. O'NEEL, AND F. WALTER (2014), Seismicity within a propagating ice shelf rift: The relationship between icequake locations and ice shelf structure, *J. Geophys. Res. - Earth Surf.*, 119, 731–744, doi:10.1002/2013JF002849.
9. SIEGFRIED, M.R. **H.A. FRICKER**, M. ROBERTS, T.A. SCAMBOS, S. TULACZYK (2014) A decade of West Antarctic subglacial lake interactions from combined ICESat and CryoSat-2 altimetry, *Geophysical Research Letters*, http://dx.doi.org/10.1002/2013GL058616.
10. BEEM, L.H., S.M. TULACZYK, M.A. KING, M. BOUGAMONT, **H.A. FRICKER,** P. CHRISTOFFERSEN (2014) Variable Deceleration of Whillans Ice Stream, West Antarctica, *J. Geophys. Res. - Earth Surf.,* 119 (2), 212-224, doi: 10.1002/2013JF002958.

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Research Interests: New methods of atmospheric remote sensing using GPS signals, applied to targeted observations of tropical storms and improving numerical weather prediction in undersampled areas such as Antarctica. Precise GPS positioning applied to measurements of near field earthquake ground motions for earthquake early warning. Seismic wave propagation and amplification applied to seismic hazard analysis.

GPS receivers were deployed on stratospheric balloons to measure properties of the atmosphere and provide a comprehensive assessment of the accuracy of atmospheric models in the Antarctic, in support of continued International Polar Year climate science. The project provides balloon position for Lagrangian measurements of in-situ winds and vertical radio occultation profiles of atmospheric refractivity and derived temperature products. The data from 2 instrumented balloons, each making on the order of 6 to 20 profile measurements per day, will be assimilated into weather models to demonstrate the potential impact of the new observation system and its contribution to the currently data sparse Antarctic upper air observing network. This effort adds resolution and provides additional constraints for understanding the interaction between the atmosphere and sea surface, which affects changes in Antarctic sea ice extent and volume. This exceptionally dense data set provides a unique opportunity to test specific hypotheses about whether improved atmospheric observations and higher resolution can lead to better wind information that drives dynamic motion and accumulation of sea ice. Gravity wave observations will provide important estimates of the momentum flux which is ultimately deposited in the upper stratosphere and mesosphere, and makes significant contributions to driving the global-scale Brewer-Dobson circulation and therefore to the transport of ozone in the middle atmosphere.

The new GPS system was developed by Dr. Jennifer Haase at Scripps Institution of Oceanography and flown on the stratospheric balloons developed by the French Space Agency (CNES). Unlike meteorological satellite images, the signals from GPS satellites travel through heavy precipitation and clouds. By making precise measurements of the time delays in GPS signals received onboard a high altitude balloon or aircraft as the GPS satellite sets, it is possible to determine the properties of the atmosphere, information that is very useful in weather forecasting. The signals pass nearly horizontally through the atmosphere and are strongly affected by the pressure, temperature and moisture so it is possible to derive high-resolution vertical profiles of atmospheric properties as the balloon is transported around the Antarctic continent by stratospheric westerly winds. Haase and her colleagues have shown that the new measurements are accurate and the group is now testing the ability to diagnose deficiencies in the weather forecast models in the sparsely sampled Antarctic atmosphere.

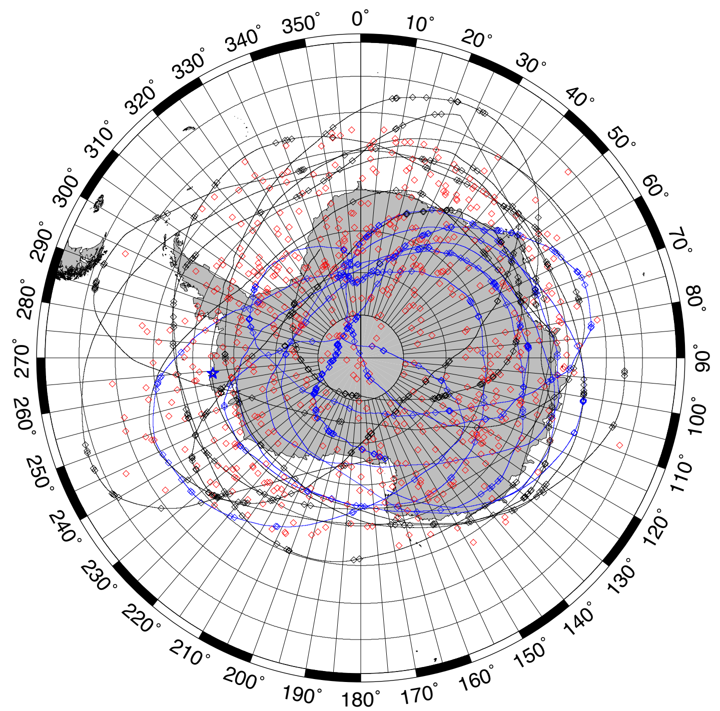

Figure 1 Paths of the two stratospheric balloons carrying GPS radio occultation sensors showing profile locations (black and blue diamonds), and profile locations from 13 balloons carrying dropsondes (red diamonds).

Recent Publications

Sussman, J., and J. Haase (2014). Using Radio Occultation and Dropsondes for Assessing Antarctic NWP model Accuracy, in *Eighth FORMOSAT-3/COSMIC Data Users' Workshop*, 30 Sep. - 2 Oct., 2014, Boulder, Colorado U.S.A.

Villamil-Otero, G., R. Meiszberg, J. S. Haase, K.-H. Min, M. Jury, and J. J. Braun (2014). Topographic - thermal circulations and associated GPS-measured moisture variability at Mayaguez, Puerto Rico, Earth Interactions **Accepted**.

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Melgar, D., B. W. Crowell, Y. Bock, and J. S. Haase (2013), Rapid modeling of the 2011 Mw 9.0 Tohoku-oki earthquake with seismogeodesy, *Geophys. Res. Lett.*, *40*(12), 2963-2968.

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Haase, J. S., J. Maldonado-Vargas, F. Rabier, P. Cocquerez, M. Minois, V. Guidard, P. Wyss, and A. V. Johnson (2012). A Proof-of-Concept Balloon-borne GPS Radio Occultation Profiling System for Polar Studies, Geophysical Research Letters **39** doi:10.1029/2011GL049982.

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

A long standing objective of ocean drilling has been to gain a better understanding of the relationship between the seismic and geologic structure of the oceanic crust, and thus better extrapolate insights gained from coring and logging beyond the confines of an individual borehole. Conversely borehole seismic data provide a valuable way to ground truth the accuracy of processing and inversion methods applied to surface seismic data. Although well-log ties are a routine part of oil and gas exploration in sedimentary environments they are less common for the igneous oceanic crust because of the small number of deep penetration holes and because the tie generally needs to be made primarily through velocity rather than reflectivity. One borehole suitable for such analysis is IODP Hole U1309D at Atlantis Massif, which was sited based on modern high-quality multichannel seismic (MCS) data and was drilled to a depth of 1.4 km, recovering primarily gabbroic rocks.

Atlantis Massif is an oceanic core complex situated at 30° N at the intersection of the Mid-Atlantic ridge with the Atlantis transform. The surface of the massif is the footwall of a detachment fault that initially formed at the spreading axis and over the last 2 Ma has exhumed lower crustal and upper mantle material through uplift and rotation, accounting for the presence of gabbroic rocks in Hole U1309D. The recovered rocks record an integrated history of hydrothermal alteration as well as detachment and uplift related deformation. Although Hole U1309D was initially drilled in 2004/5 on the central dome of the massif, we extended the geophysical logging in early 2012, collecting a complete sonic log and vertical seismic profile (VSP) [*Blackman et al.*, 2012].

The borehole velocity profiles derived from the sonic log and from inverting the first arrival travel times of the VSP are used to benchmark the accuracy of different velocity inversions of the nearby surface MCS data, Figure 1. The initial inversion applied travel time tomography to shot gathers downward continued to a horizon just above the seafloor simulating an extended on-bottom experiment [*Henig et al.*, 2012]. The more recent inversion extends this analysis and applies waveform inversion to the same downward continued dataset [e.g. *Arnulf et al.*, 2014]. Although the travel time tomography result matches the general trend of the velocity profiles recorded in the borehole, it is unable to resolve the changes in vertical velocity gradient that are captured by the waveform inversion result. The vertical velocity structure can be split into three zones with dividing horizons at 250-300 m and 750-800 m, which correlate to drops in the degree of deformation and alteration. The top horizon corresponds to the base of intense detachment related deformation of the footwall, while the second horizon, based on other analysis marks the overall limit of such deformation. The second horizon also corresponds to the current base of advective fluid flow with the borehole temperature gradient being conductive below this level [*Blackman et al.*, 2014]. It these horizons that can be extrapolated beyond the borehole in the waveform inversion results to help map deformation and alteration.

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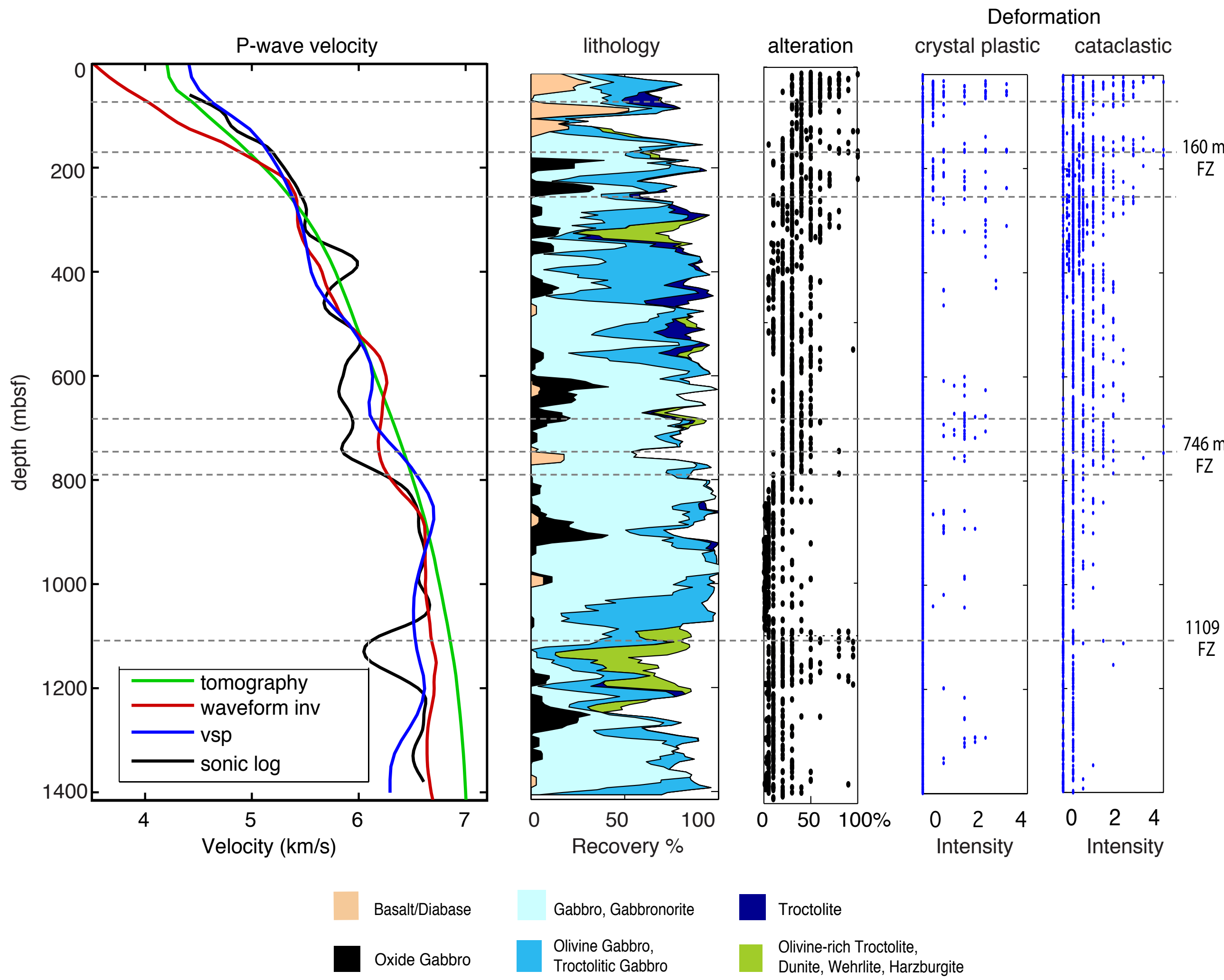

Figure 1 Vertical velocity profiles for Hole U1309D compared with logs of lithology, alteration and deformation. The changes in velocity due to lithology are expected to be minor except for the intervals of olivine-rich rocks. Instead velocity changes are closely correlated with changes in alteration and deformation, which in turn can be ascribed to damage in the footwall produced by motion of the detachment fault

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Research Interests: Study of large atmospheric phenomena, study of long-range propagation of subaudible sound in the atmosphere, seismo-acoustics

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 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. This network has been supplemented with deployments, such as the 400-station seismo-acoustic USArray Transportable Array (TA), for basic research and enhanced monitoring of regions of great interest.

Research at L2A: The 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. More information about this lab can be found at l2a.ucsd.edu. Presently we study a broad suite of problems related to both natural and man-made sources.

Dense network studies: The global infrasound network is unprecedented in scale however it is still very sparse, with ~ 100 stations operating worldwide. To increase the density of sampling of the infrasonic wavefield we have used acoustic–to-seismic coupled signals recorded by dense networks, such as the 400-station USArray Transportable Array (TA) and various PASSCAL deployments. We have used the original (seismic-only) TA network to create a catalog of atmospheric events in the western 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 use the recorded signals to study long-range infrasound propagation. Recorded signals from instantaneous sources are commonly dispersed in time to several 10's of seconds. Modeling indicates that this is due to interaction of the sound waves with fine-scale structure in the atmosphere due to gravity waves. We are currently using infrasound to constrain the statistics of this time-varying structure.

The National Science Foundation funded our group to upgrade the entire TA with infrasound microphones and barometers. Our sensor package is sensitive to air pressure variations from D.C. to 20 Hz, at the lower end of the audible range. The upgrade converted the TA into the first-ever semi-continental-scale seismo-acoustic network. The network has moved east across the US as stations are redeployed. Figure 1 (left panel) shows station locations from January 1, 2010 through the end of September, 2014. We have divided this collection of stations into 3,600 elemental arrays (triads) to study atmospheric gravity waves. An early result is shown in the right panel of figure 1. This map shows a histogram of gravity waves in the 2-6 hour pass-band weighted by the amplitude of each detected wave. As expected, large gravity waves are common to the west of the Great Lakes due largely to convective activity. Other structure apparent in the image, such as the low along the Appalachian mountain trend, with the string of hotspots to the east, is actively being studied.

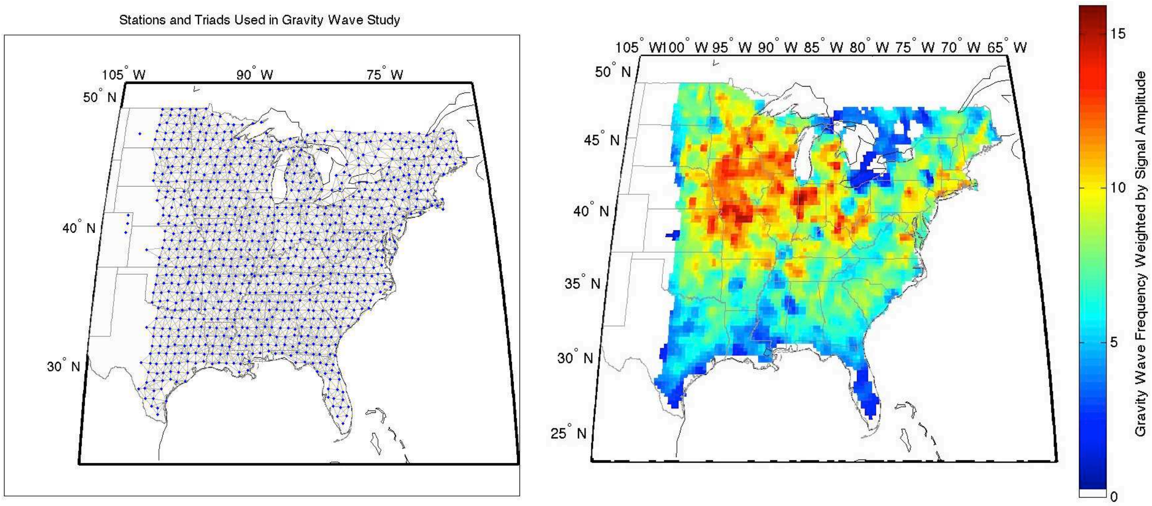

Figure 1. left) sites occupied by stations in the TA from January 1, 2010 through Sept 30, 2014. These stations have been grouped into 3-element arrays (triads) for the study of long-period atmospheric gravity waves. The panel on the right shows the frequency of gravity waves in this time period with the count weighted by the amplitude of each detected wave. The most vigorous activity occurs to the west of the Great Lakes, as expected from satellite studies.

Field operations: Our group has built infrasound arrays for nuclear monitoring in the US and Africa. We operate research arrays located near San Diego.

Recent Publications

Brown, P., Assink, J., Astiz, L.,Blaauw, R., Boslough, M., Borovicka, J., Brachet, N., Brown, D., Campbell-Brown, M., Ceranna, L., Cooke, W., de Groot-Hedlin, C., Drob, D., Edwards, W. Evers, L., Garces, M., Gill, J., Hedlin, M.A.H., Kingery, A., Laske, G., Le Pichon, A., Mialle, P., Moser, D., Saffer, A., Silber, E., Smets, P., Spalding, R., Spurny, P., Tagliaferri, E., Uren, D., Weryk, R., Whitaker, R., Krzeminski, Z., 2013, The Chelyabinsk airburst: Implications for the Impact Hazard, *Nature*, DOI: 10.1038/nature12741.

Chunchuzov, I., Kulichkov, S., Popov, O. and Hedlin, M.A.H., 2014, Modeling propagation of infrasound signals observed by a dense seismic network, *Journal of the Acoustic Society of America,* 135, 38 (2014), DOI: 10.1121/1.4845355.

de Groot-Hedlin, C.D., Hedlin, M.A.H. and Walker, K.T., 2013, Detection of gravity waves across the USArray: A case study, in press with *Earth and Planetary Sciences Letters*, DOI: 10.1016/j.epsl.2013.06.042

de Groot-Hedlin, C.D. and Hedlin, M.A.H., 2014, Infrasound detection of the Chelyabinsk Meteor at the USArray, *Earth and Planetary Sciences Letters* http://dx.doi.org/10.1016/j.epsl.2014.01.031

Edwards, W.N., de Groot-Hedlin, C.D. and Hedlin, M.A.H., 2014, Transportable Array Acoustic capabilities confirm apparent meteor sighting, in press with Seismological Research Letters.

Hedlin, M.A.H. and Drob, D.P., 2014, Statistical characterization of atmospheric gravity waves by seismoacoustic observations, *J. Geophys. Res. Atmos.*, doi: 10.1002/2013JD021304

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

We continue to engage in a variety of studies involving volatiles – noble gases and major volatiles (such as CO_2 and N_2) – from different tectonic environments. New publications this year include two papers on the East Africa Rift System - the Rungwe Volcanic Province (RVP) in southern Tanzania (Castillo et al., 2014) and a rift-wide study of the neon isotope systematics of xenoliths and lavas (Halldorsson et al., 2014). Both studies make the case that the African Superplume, a large seismically anomalous feature originating in the lower mantle beneath southern Africa, influences magmatism throughout eastern Africa with magmatism at RVP and the Main Ethiopian Rift representing two different heads of a single mantle plume source.

Continuing research on volatiles in hotspot regions suggests that the carbon dioxide (CO_2) content of the Icelandic mantle overlaps with previous estimates from the upper mantle, even though Iceland bears the ubiquitous high $^3He/^4He$ fingerprint of the lower mantle (Barry et al., 2014). In addition, CO_2 fluxes along the Icelandic neovolcanic zones may be larger than expected, due to higher crustal production rates in Iceland compared to submarine spreading centers. We report new CO_2 abundance and isotope data for 71 geothermal gases and fluids from both high- and low-temperature geothermal systems located throughout Iceland and 47 subglacial basaltic glasses from the rift zones (Fig. 1). This extensive carbon compilation reveals important information about carbon sources and fluxes as well as the overall extent of degassing. Using an equilibrium-degassing model, we estimate that pre-eruptive basaltic melts beneath Iceland have CO_2 source contents in good agreement with olivine-hosted melt inclusions and estimates of depleted MORB mantle (DMM). Further, the CO_2 flux from Iceland was estimated to be 0.1–10% of the estimated global ridge flux. These findings suggest that the upper and lower mantle may be homogenized with respect to carbon. This work represents an important calibration point for future carbon studies in plume-influenced regions.

Finally, we have published a number of review chapters on various aspects of volatile geochemistry. Hilton and Porcelli (2014) present an overview of the current state of research in using noble gases as tracers of processes occurring in Earth’s mantle. The relationships between gas geochemistry and active tectonics and volcanism in Turkey is covered by Gulec et al (2014) whereas Mutlu et al (2014) consider the origin of thermal waters in Turkey using both mineral equilibria and isotope constraints.

New Publications

Hilton, D. R. and Porcelli, D. (2014) Noble gases as tracers of mantle processes. In: The Mantle and Core (ed. Carlson, R.W.) Vol. 3, Treatise on Geochemistry, 2nd edition (eds. Turekian, K.K and Holland, H.D.), Elsevier-Pergamon, Oxford, UK pp 327-353.

Mutlu, H., Güleç, N., **Hilton, D.R.** (2014) Chemical and isotopic constraints on the origin of thermal

waters in Anatolia, Turkey: Fluid-mineral equilibria approach**.** In: Geothermal Systems and Energy Resources: Turkey and Greece. (eds. Baba, A., Bundschuh, J. and Chandrasekharam, D.), Taylor and Francis, Leiden, The Netherlands, pp 1-11.

Güleç, N., Mutlu, H., **Hilton, D.R** (2014) Gas geochemistry of Turkish geothermal fluids: He-CO_2 systematics in relation to active tectonics and volcanism. In: Geothermal Systems & Energy Resources: Turkey and Greece. (eds. Baba, A., Bundschuh, J. and Chandrasekharam, D.), Taylor and Francis, Leiden, The Netherlands, pp 13-23.

Barry, P.H., **Hilton, D.R.**, Furi, E., Halldórsson, S. A. and Gronvold, K. (2014) Carbon isotope and abundance systematics of Icelandic geothermal gases, fluids and subglacial basalts with implications for mantle plume-related CO_2 fluxes. Geochim. Cosmochim. Acta 134, pp 74-99.

Halldórsson, S.A., **Hilton, D.R.**, Scarsi, P., Abebe, T. and Hopp, J. (2014) A common mantle plume source beneath the entire East African Rift System revealed by coupled helium-neon systematics. Geophys. Res. Lett. 41, 2304-2311, doi:10.1002/2014GL059424.

Castillo, P.R., **Hilton, D. R.** and Halldorsson, S.A. (2014) Trace element and Sr-Nd-Pb isotope geochemistry of Rungwe Volcanic Province, Tanzania: Implications for a superplume source for East Africa Rift magmatism. Frontiers Earth Science 2:21, doi: 10.3389/feart.2014.00021.

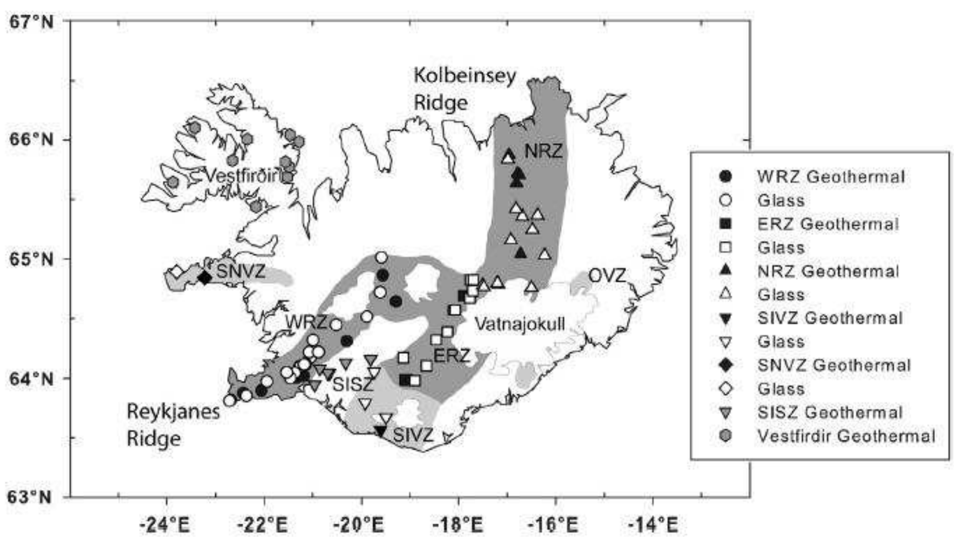

Fig. 1. Map of Iceland showing neovolcanic rift zones, sample locations, and the location of current glacial cover. The Western (WRZ), Eastern (ERZ), and Northern rift zones (NRZ) are shaded with dark grey, whereas transitional-alkalic to alkalic off-axis volcanic zones, i.e., the South Iceland Volcanic Zone (SIVZ), Snæfellsnes Volcanic Zone (SNVZ), and Öræfajökull Volcanic Zone (OVZ), are shown in light grey. Also shown are the South Iceland Seismic Zone (SISZ), Vestfirðir (the northwest peninsula of Iceland), and the adjacent submarine Reykjanes and Kolbeinsey ridge segments. Sample locations for geothermal fluids are denoted with closed symbols and open symbols are used for basalts.

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Research Interests: The role and fluxes of fluids and solutes in subduction zones and ridge-crests; Marine gas hydrates and implications for the C cycle and global change; Chemical paleoceanography; The geochemistry and diagenesis of marine sediments and the implications for paleoceanographic interpretations.

Fluid Origins, Thermal Regimes, and Fluid and Solute Fluxes in the Forearc of Subduction Zones

Evidence of large-scale fluid flow is manifested by widespread seafloor venting, associated biological communities, extensive authigenic carbonate formation, chemical and isotopic anomalies in pore-fluid depth-profiles, and thermal anomalies. An in-depth analysis and synthesis of newly acquired and published data on the chemical and isotopic compositions of forearc fluids, fluid fluxes, and the associated thermal regimes in five well-studied, representative erosional and accretionary subduction zone (SZ) forearcs indicate that the nature of fluid venting seems to differ at the two types of SZ's. At both, fluid and gas venting sites are primarily associated with faults. The décollement and underthrust coarser-grained stratigraphic horizons are the main fluid conduits at accretionary SZ's, whereas at non-accreting and erosive margins, the fluids from compaction and dehydration reactions are to a great extent partitioned between the décollement and focused conduits through the prism, respectively.

The measured fluid output fluxes at seeps are high, ~15-40 times the amount that can be produced through local steady-state compaction, suggesting that in addition, other fluid sources or non-steady-state fluid flow must be involved. Recirculation of seawater must be an important component of the overall forearc output fluid flux in SZ's.

The most significant chemical and isotopic characteristics of the expelled fluids relative to seawater are: Cl dilution, sulfate, Ca and Mg depletions and enrichments in Li, B, Si, Sr, alkalinity, and hydrocarbon concentrations; they often have distinctive δ^{18}O, δD, δ^{7}Li, δ^{11}B, and δ^{37}Cl values, and variable Sr isotope ratios. These characteristics provide key insights on the source of the fluid and the temperature at the source. Based on the fluid chemistry, the most often reported source temperatures reported are 120 – 150°C.

Considering an ocean volume of 1340×10^{6} km^{3} and the average composition of end-member fluids across the five representative SZ's, the return fluxes of the solutes and isotope ratios from subduction zone forearcs to the ocean were recently estimated (Kastner et al., 2014). The results show that a residence time of the global ocean in SZ's of ~100 million years, is about 5 times faster than the previous estimate, is similar to the residence time of ~90 million years for fluids in the global ridge crest estimate by Elderfield and Schultz (1996), and ~3 times longer than the 20-36 million years estimate by German and von Damm (2004). Based on this extrapolated fluid reflux to the global ocean, SZ's are an important, mostly overlooked, source and sink for several elements and isotopic ratios, in particular an important sink for seawater Mg and SO_4, and an important source of Li and B. For example, the SZ's estimated Mg output flux is up to 27% of the output flux estimated for hydrothermal circulation at mid-ocean ridges and accounts for 8% of the input flux from rivers; at SZ's the sink of seawater SO4 accounts for 10% of the river flux and up to 44% of the hydrothermal flux. The results also show that the output flux of Ca at SZ's is high enough to completely consume the input of Ca from hydrothermal circulation. The flux of B from SZ's is ~13-100% of the flux from hydrothermal circulation, and the Li input flux is ~10-30% of the input flux from hydrothermal circulation. As yet the data-base for Li and B isotopic compositions of SZ fluids is too sparse for flux estimates, thus for impact on seawater chemistry calculations.

Recent Publications

Rose, K.K., Johnson, J.E., Torres, M.E., Hong, W., Giosan, L., Solomon, E.A., Kastner, M., Cawthern, T., Long, P.E., and Schaef, T.H., (2014). Anomalous porosity preservation and preferential accumulation of gas hydrate in the Andaman Accretionary Wedge, NGHP-01 Site 17A. Marine Petrol. Geol. Spec. Publication. 10.1016/j.marpetgeo.2014.04.009

Solomon, E.A,, Spivack, A.J., Kastner, M., Torres, M.E., and Robertson, G., (2014). Gas hydrate and carbon sequestration through coupled microbial methanogenesis and silicate weathering in the Krishna-Godavari basin, offshore India. In Marine and Petrol. Geol. Special Publ. In Press.

Kastner, M., Solomon, E.A., Harris, R.N., and Torres, M.E. (2014). Fluid origins, thermal regimes, and fluid and solute fluxes in the forearc of subduction zones. In Developments in Marine Geology, V. 7, on "Earth and Life Processes Discovered from Subseasurface Environment", Stein, R., Blackman, D., Inagaki, F. and Hans-Christian Larsen, H.-C., Eds. ,Elsevier Publ. In Press.

Martinez-Ruiz, F., Kastner, M., Gallego-Torres, D., Rodrigo-Gámiz, M., Nieto-Moreno, V., Ortega-Huertas, M., (2014). Paleoclimate and Paleoceanography Over the Past 20,000 yr in the Mediterranean Sea Basins as Indicated by Sediment Elemental Proxies. Quaternary Science Reviews. In Press.

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Research Interests*:* Marine electromagnetic exploration, subduction zones, mid-ocean ridges, continental margins, hydrocarbon exploration, finite element methods, parallel computing, geophysical inversion.

My research uses electromagnetic geophysical methods to study the geologic structure and fluids of the oceanic crust and upper mantle. Along with Steven Constable, I manage the Seafloor Electromagnetic Methods Consortium at Scripps, an industry funded program that brings in support for the PhD students and postdocs working in our group. This past year we continued our efforts to develop practical Bayesian inversion for characterizing the resolution and uncertainty of electrical conductivity models derived from marine controlled-source electromagnetic (CSEM) data. Graduate student Anandaroop Ray extended his reversible-jump Markov chain Monte Carlo algorithm to two dimensions through the use of an adaptive Voronoi cell parameterization that had been previously shown to work well for teleseismic studies. Application of this approach to the CSEM data we had previously collected at the Scarborough gas field shows that the known reservoir region has a higher probability for increased resistivity due to the presence of hydrocarbons (Figure 1). After graduating in May, Dr. Ray began a position as a researcher with Chevron in Houston.

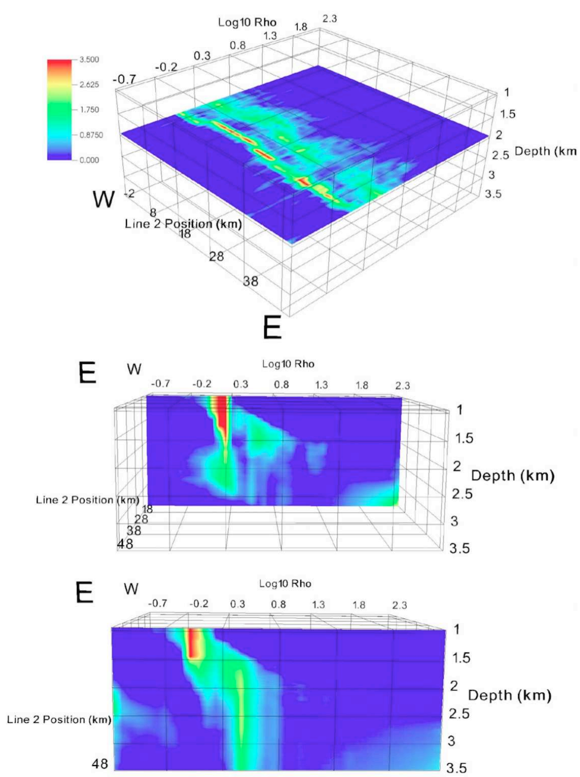

Figure 1. Bayesian inversion of data from the Scripps marine CSEM survey of the Scarborough gas field. All three panels show slices through a probability cube of resistivity as a function of depth and position along the survey profile. Brighter colors correspond to more probable resistivity values. Top panel: A horizontal slice at the reservoir depth of 1950 m. Most of the survey profile has a high probability of about 1 ohm-m resistivity (log10(rho) = 0), indicating porous sediments, but higher resistivity is probable at positions of 6-24 km where the reservoir is located. Middle panel: a vertical slice through the middle of the gas reservoir, which is indicated by a peak in resistivity near 2000 m depth. Bottom panel: a vertical slice at a position 48, which is located outside the reservoir; here the peak in resistivity at the reservoir depth has disappeared.

This past year we received National Science Foundation funding to carry out the data collection for the Magnetotelluric Observations of Cascadia using a Huge Array (MOCHA) project. This collaborative project uses magnetotelluric (MT) data to the image details of convergent margin segmentation and the distribution of fluids associated with the subducting slab using combined onshore and offshore MT in Oregon and Washington. This data will allow us to image the electrical conductivity of the crust and upper mantle of the subduction system in 3D to map the distribution of fluids, constraining both the fluid input to the system from offshore and the distribution of fluids released from the down-going slab, including along the transitional zone where episodic tremor and slip occurs. We collected the offshore data during a 7-day deployment cruise in May 2014 and a 10-day recovery cruise in June 2014. We were fortunate to mostly have good weather during both cruises, and we are thankful for the assistance of several graduate students and scientists who volunteered to participate in the cruises. Onshore MT data was collected in 2012-2014 by our collaborators at Oregon State University, University of Oregon and the USGS. The data analysis is ongoing and we are excited by what we will learn from this first 3D amphibious survey of a subduction zone.

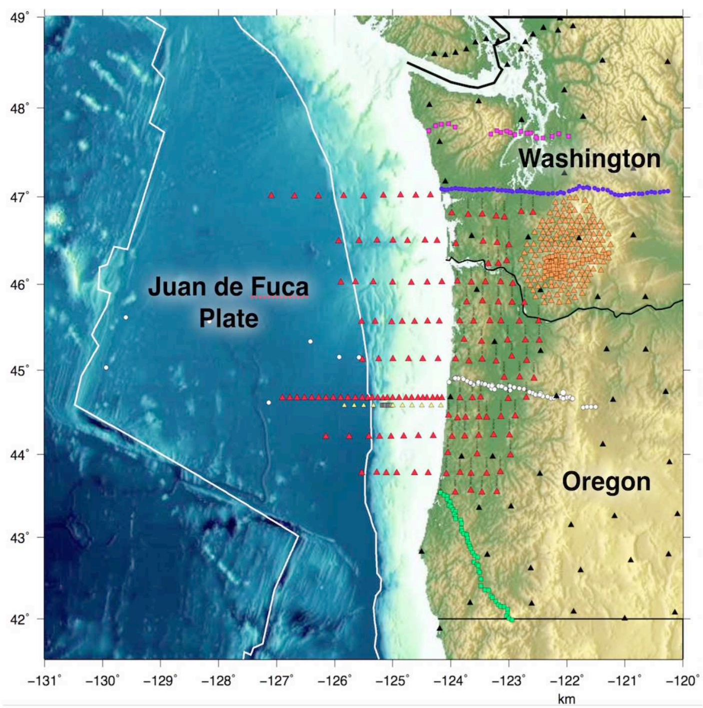

Figure 2. The amphibious magnetotelluric stations collected for the MOCHA project (red triangles) include 71 offshore and 75 onshore stations. This large scale 3D data set fits into a broader context of MT stations collected by other researchers in the Pacific northwest, including the US Array MT (black triangles), the ongoing iMUSH volcano survey (orange triangles) and regional 2D profiles (magenta, blue, white and green symbols).

Photos and videos from the MOCHA deployment and recovery cruises can be viewed on our website:

http://marineemlab.ucsd.edu/Projects/MOCHA

Recent Publications

Ray, A., K. Key, T. Bodin, D. Myer and S. Constable, Bayesian inversion of marine CSEM data from the Scarborough gas field using a trans-dimensional 2D parameterization (2014), *Geophysical Journal International*, 199, 1847–1860, 10.1093/gji/ggu370.

Trainor-Guitton, W., G.M. Hoversten, A. Ramirez, J. Roberts, E. Juliusson, K. Key, and R. Mellors, (2014), The value of spatial information for determining well placement: A geothermal example, *Geophysics*, 79, W27-W41, 10.1190/GEO2013-0337.1

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

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

Humming Icequakes (Heeszel et al., 2014): Mountain glaciers represent one of the largest repositories of fresh water in alpine regions globally. However, little is known about the processes by which water moves through these systems. Gornersee is a lake that forms each spring at the confluence of two glaciers in the Swiss Alps. This lake drains during most summers, sometimes suddenly. Because glacial lake drainage events can occur with little or no warning, there is the potential for damaging floods in valleys below the glacier. We use seismic recordings collected near the lake to look for signs of water moving through fractures near the glacier bed. We see tremor, signals that are stronger at specific frequencies, in both single icequakes and over long periods. These observations suggest there is a complex network of fluid induced fracture processes at the glacier base. Modeling changes in the observed harmonic frequencies indicates that seismic data's spectral characteristics can provide important information about hydraulic fracture geometry and fluid pressure at depth. Similar to industrial fracking (Figure 1), this hydraulic fracturing at the base of a glacier can provide a mechanism to track fluid flow within glaciers in near real-time.

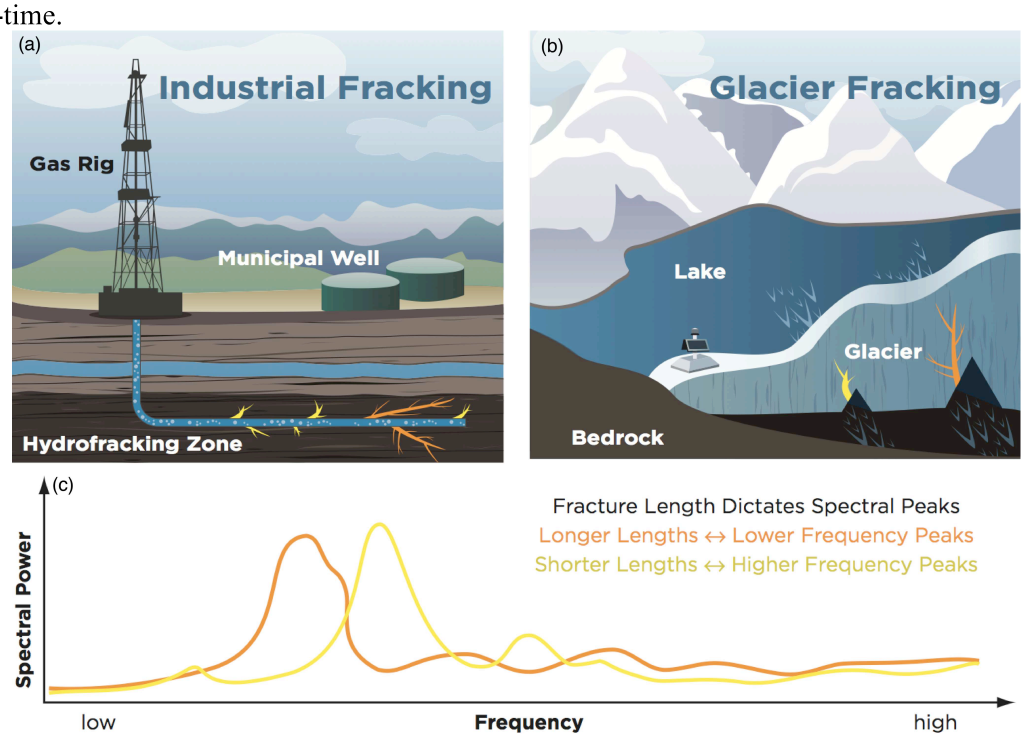

Figure 1: Cartoon depicting the relationship between hydrofracture length and spectral resonance peaks. (A) Industrial fracking within a geothermal reservoir showing both short (yellow) and long (orange) fracture lengths. (B) Fracking within a glacier near a draining lake (dark blue), again both short (yellow) and long (orange) fracture lengths are shown. Tremor-generating water resonances may form in fracture networks near major englacial and subglacial conduits. (C) The orange and yellow line colors correspond to the different crack lengths shown in cartoons (A) and (B). The shorter (longer) fracture lengths correspond to higher (lower) peak resonance frequencies.

Exploring Remote Earthquake Triggering Potential Across using Frequency Domain Array Visualization (Linville et al., 2014). To better understand earthquake source processes involved in dynamically triggering remote aftershocks, we use data from the EarthScope Transportable Array (TA) that provide uniform station sampling, similar recording capabilities, large spatial coverage, and in many cases, repeat sampling at each site. To avoid spurious detections, which are an inevitable part of automated time-domain amplitude threshold detection methods, we develop a frequency domain earthquake detection algorithm that identifies coherent signal patterns through array visualization. This method is tractable for large datasets, ensures robust catalogs, and delivers higher resolution observations than what are available in current catalogs. We explore seismicity rate changes local to the TA stations following 18 global mainshocks (M≥7) that generate median peak dynamic stress amplitudes of 0.001-0.028 MPa across the array. For these mainshocks, we find no evidence of prolific or widespread remote dynamic triggering in the continental U.S. within the mainshock's wavetrain or following mainshock stress transients within 2 days. However, limited evidence for rate increases exist in localized source regions. These results suggest that for these data, prolific, remote earthquake triggering is a rare phenomenon. We further conclude that within the lower range of previously reported triggering thresholds, surface wave amplitude does not correlate well with observed cases of dynamic triggering. Therefore, other characteristics of the triggering wavefield, in addition to specific site conditions, must contribute to triggering at these amplitudes.

Selecting Empirical Green's Functions in Regions of Fault Complexity: A Study of Data From the San Jacinto Fault Zone, Southern California (Kane et al., 2013). To constrain the source properties of an earthquake, path- and site-effect contributions to the seismic waveform can be approximated using another earthquake as an empirical Green's function (EGF). An ideal EGF earthquake is smaller in magnitude than the mainshock and shares a similar focal mechanism and hypocenter. We quantify how to optimally select EGF events using data from the spatially complex San Jacinto Fault Zone (SJFZ) in southern California. The SJFZ's high seismicity rate allows us to test the EGF method for 51 target M>3 mainshock events over a range of potential EGFs (>200 for each mainshock). We purposely select a large population of inappropriate EGFs so we can identify thresholds and restrictions to define optimal EGF selection criteria. We assume a suitable EGF event will produce similar corner frequency estimates at every station. Surprisingly, we find separation distances of 2-14 km produce negligible changes in corner frequency variability, suggesting that EGF events at 2 km distance may be as poor a choice as EGF events at much greater distances.

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

Recent Publications

Kilb, D, D Rohrlick, A Yang, Y Choo, L Ma, and R Ruzic (2014). The Game of Curiosity: Using Videogames to Cultivate Future Scientists. *Seis. Res. Lett.,* 85, 923-929, 2014.

Heeszel, D., F. Walter and **D.L. Kilb** (2014). Humming Glaciers, *Geology,* in press.

Lawrence, JF, ES Cochran, A Chung, A Kaiser, CM Christensen, R Allen, JW Baker, B Fry, T Heaton, **D Kilb,** MD Kohler and M Taufer (2014). Rapid earthquake characterization using MEMS accelerometers and volunteer hosts following the M 7.2 Darfield, New Zealand, Earthquake. *Bull. Seism. Soc. Am.*, 104:184-192. 10.1785/0120120196.

Linville L., K. Pankow, **D. Kilb** and A. Velasco (2014). 'Exploring Remote Earthquake Triggering Potential Across Earthscopes' Transportable Array through Frequency Domain Array Visualization', *J. of Geoph. Res.*, in press, 2014. Dynamic Content: interactive visualization of a high-resolution array image http://siogames.ucsd.edu/Zoom/linville_etal_2014

Kane, D.L., **D. Kilb,** F.L. Vernon (2013). Selecting Empirical Green's Functions in Regions of Fault Complexity: A Study of Data from the San Jacinto Fault Zone, Southern California, *Bull. Seism. Soc. Am.*, 103, doi: 10.1785/0120120189.

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Research interests: regional and global seismology; surface waves and free oscillations; 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. She has gone to sea to collect seismic data on the ocean floor. 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.

Global reference models: Laske has collaborated with Guy Masters, graduate student Zhitu Ma and Michael Pasyanos at LLNL to compile a new lithosphere model, LITHO1.0. A 1-degree crustal model, CRUST1.0 was released in 2013 for initial testing. This year, Laske has been compiling community feedback for a planned update of the model. Applications relying on CRUST1.0 are found across multiple disciplines in academia and industry, and sometimes reach into quite unexpected fields such as the search for Geoneutrinos.

The PLUME project: Laske has been the lead-PI of the Hawaiian PLUME project (Plume–Lithosphere–Undersea–Mantle Experiment) to study the plumbing system of the Hawaiian hotspot. Two ocean bottom seismometer (OBS) field campaigns collected continuous broadband data. Initial results from both body wave and surface wave tomography were published. During the previous year, Laske collaborated with Kate Rychert who identified two upper-mantle boundaries that align with anomalies found in the surface wave study. The published images suggest a restite root beneath the Island of Hawaii around which ascending plume material has to flow, providing a possible cause for the low-velocity anomaly to the west of Hawaii.

This year, IRIS intern Rachel Marzen continued the analysis of frequency-dependent Rayleigh-wave **azimuthal anisotropy** around Hawaii. While shear-wave splitting results appear to be sensitive only to the fossil spreading direction "frozen" into the lithosphere, Marzen found a clear signal in the long-period data that suggests a plume-related flow in the asthenosphere beneath Hawaii.

Laske has been collaborating with Christine Thomas at Münster University, Germany to search for new and **previously unmapped D" precursors** in the PLUME database. The good quality of vertical-component records allowed the team to detect PdP waves for some areas and found convincing null-results for other areas. This is the first study of its kind using OBS data.

Graduate student Adrian Doran began the analysis of PLUME **seafloor compliance as well as ambient-noise** Green's functions. The combined analysis will help constrain elastic parameters in the shallow sediments and crustal layers that were not resolved by the surface wave study.

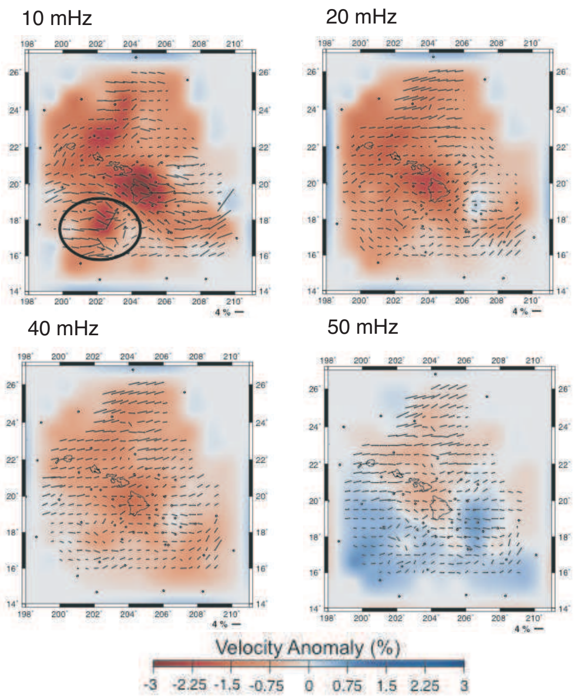

Figure 1: Frequency-dependent Rayleigh-wave azimuthal anisotropy as observed during the PLUME deployments. Data were binned into 1 x 1° cells. Higher frequencies are sensitive to upper-lithosphere structure, while lower frequencies reach into the asthenosphere. The signal for lower frequencies suggest that mantle flow in the asthenosphere is "disturbed" by plume-related upwelling.

The ADDOSS project: For the ADDOSS (Autonomously Deployed Deep-ocean Seismic System) Laske collaborates with Jon Berger, John Orcutt and Jeff Babcock and Liquid Robotics Inc. to develop an untethered OBS system capable of providing near-real time data collected on the ocean floor. A wave glider facilitates an acoustic-modem link to the ocean bottom instrument, where the data are then sent to shore via satellite. The group performed two week-long tests in shallow water (1000 m) and a 3-month test in the deep ocean (4500 m) off-shore La Jolla. Initial data recovery rates were excellent, and several local and teleseismic earthquakes were recorded in near-real time. A flawed tow-cable on the wave glider corroded prematurely and disrupted data transfer. A redesigned cable is being shipped and a new test is planned for this year.

Recent publications:

Rychert, C.A., Laske, G., Harmon, N. and Shearer, P.M., Seismic imaging of melt in a displaced Hawaiian plume, *Nature Geoscience*, 6, 657-660, 2013.

Marzen, R. and Laske, G., Rayleigh Wave Azimuthal Anisotropy Beneath Hawaii Using PLUME Ocean-Bottom Seismometers, *AGU Fall Meeting 2013*, Abstract DI21A-2247, 2013.

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Research Interests: Volcano seismology, volcano acoustics, active volcanism and eruption dynamics, seismology, infrasound, seismo-acoustics.

I am an observational seismologist studying active volcanic and tectonic processes. My research involves the collection and systematic analyses of large seismic and acoustic datasets, as well as data-driven modeling. I use seismic waves to study magmatic, hydrothermal, and faulting processes occurring within and around volcanoes. I use acoustic waves to study the mechanisms and dynamics of explosive eruptions and shallow degassing. This work is central to our understanding of how volcanoes grow, transport and store fluid, and erupt. My research has applications in monitoring volcanic hazards, local and regional seismicity, geothermal resources, and nuclear test-ban treaty monitoring.

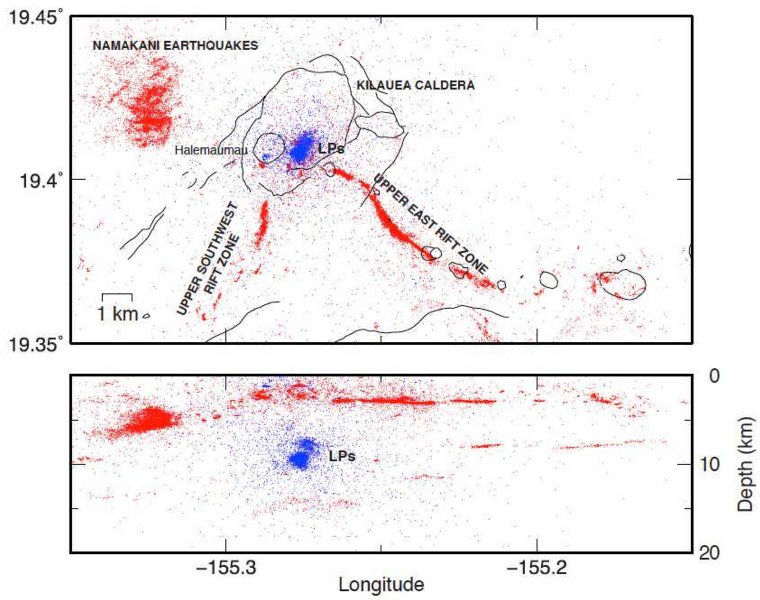

Figure 1: High-precision relocations of seismicity in the summit region of Kilauea Volcano, Hawaii from 1986 to 2009 [*Matoza et al.*, 2013, 2014a]. Blue dots are events we automatically classify as LP and red dots are non-LP. We produce a dramatic sharpening of earthquake locations along faults and magmatic features compared to standard earthquake catalog locations.

The analysis and interpretation of seismicity from mantle depths to the surface plays a key role in understanding how volcanoes work. Together with Peter Shearer, IGPP and Paul Okubo of the USGS Hawaiian Volcano Observatory (HVO), I am developing and applying methods for the systematic re-analysis of growing volumes of waveform data from volcano-seismic networks, including high-precision earthquake relocation, spectral event classification, and stress drop estimates. Two volcano-seismic signal types, known as the long-period (LP, 0.5-5 Hz) event and volcanic tremor, are of particular interest. These signals are used routinely by volcano monitoring scientists to forecast volcanic eruptions despite an incomplete understanding of their origin. LP seismicity has been recorded for decades in the summit region of Kilauea Volcano, Hawaii and is postulated as linked with the magma transport and shallow hydrothermal systems. Systematic identification and relocation of LPs near the summit region of Kilauea Volcano shows that most intermediate depth (5-15 km) LP events occur within a compact volume that has remained at a fixed location for over 23 years [*Matoza et al.*, 2014a] (Figure 1).

Atmospheric infrasound is acoustic waves with frequencies from ~0.01-20 Hz, which are inaudible to the human ear. Infrasound is useful for studying volcanic eruptions for two main reasons: (1) Shallow and subaerial volcanic processes radiate sound directly into the atmosphere; sampling this sound complements seismic data, which record subsurface processes, and (2) Infrasound propagates long distances in the atmosphere and is routinely detected on sparse ground-based infrasound networks. There are numerous types of volcano infrasound resulting from a broad spectrum of volcanic eruption styles, but I am currently focused on powerful blast-waves and roaring jet-noise sounds from volcanic explosions. In the past year, I have worked on characterizing volcanic explosion complexity using campaign infrasound datasets from volcanoes Sakurajima, Japan; Karymsky, Russian Federation; and Tungurahua, Ecuador [*Matoza et al.*, 2014b]. I have also worked on air-ground coupling of strong acoustic signals from volcanic eruptions to understand how this complicates seismic tremor recordings during eruptions [*Matoza and Fee*, 2014]. I am beginning a new project, funded by a research award from the Comprehensive Test-Ban Treaty Organization, to catalog the global detection of explosive volcanic infrasound on the International Monitoring System (IMS). The IMS infrasound network is designed to detect atmospheric nuclear tests anywhere on the planet, and this project will assess its utility for global volcano monitoring.

Recent Publications

Matoza, R.S., D. Fee, and T.M. Lopez (2014b), Acoustic characterization of explosion complexity at Sakurajima, Karymsky, and Tungurahua Volcanoes *Seismol. Res. Lett.*, **86**, 6, `10.1785/0220140110`, *in press*.

Rowell, C., D. Fee, C.A.L. Szuberla, K. Arnoult, R.S. Matoza, P. Firstov, K. Kim, and E. Makhmudov (2014), Three-dimensional volcano-acoustic source localization at Karymsky Volcano, Kamchatka, Russia *J. Volcanol. Geotherm. Res.*, **283**, 101-115, `10.1016/j.jvolgeores.2014.06.015`.

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Lin, G., P.M. Shearer, R.S. Matoza, P.G. Okubo, and F. Amelung (2014) Three-dimensional seismic velocity structure of Mauna Loa and Kilauea volcanoes in Hawaii from local seismic tomography *J. Geophys. Res.*, **119**, 4377-4392, `10.1002/2013JB010820`.

Matoza, R.S., and D. Fee (2014) Infrasonic component of volcano-seismic eruption tremor *Geophys. Res. Lett.*, **41**, 1964-1970, `10.1002/2014GL059301`.

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The ICSU World Data System (ICSU-WDS) (http://www.icsu-wds.org/) was established in 2008 to replace the former World Data Centers (WDC) and the Federation of Astronomy and Geophysics Data Analysis Services (FAGS). Since 2008, I have chaired the WDS Scientific Committee (WDS-SC). WDS is administered through an International Program Office (WDS-IPO) generously supported by the Japanese Government and hosted by Japan's National Institute of Information and Communications Technology (NICT). The WDS slogan is *"Trusted Data Services for Global Science."* This report is extracted from the ICSU-WDS 2014 report to ICSU.

In recent years, WDS has attracted an ever-growing membership. As of 2014, the fully processed WDS membership comprises:

53 Regular Members: Organizations that deal directly with data curation and data analysis services.

9 Network Members: Umbrella organizations representing groups of data centers and/or data services, some of which may or may not be WDS Regular Members. Usually serve as coordinating agents for nodes that have common characteristics and mostly common disciplines.

3 Partner Members: Organizations that do not deal directly with the practical details of data collection, curation, and distribution, but that contribute funding or other support to ICSU-WDS.

15 Associate Members: Organizations that are interested in the WDS endeavor and participating in our discussions, but that do not contribute direct funding or other material support.

Of special note is the increasing number of *WDS Network Members*, a concept that is perfectly consonant with the initial concept of ICSU-WDS as a 'system of data systems.' The implications are profound: whereas WDS Regular Members are primarily well-established organizations, often with headquarters in countries within the Organization for Economic Cooperation and Development (OECD), Network Members typically have a much larger global geographical footprint—including in Less Economically Developed Countries (LEDC)—so that their participation affords ICSU-WDS an immediate, strong position in all continents. Some of the largest networks (e.g., the International Global Navigation Satellite System Service [IGS]) boast elaborate structures comprising numerous nodes: instrument management and operations centres, analysis centres, and regional and global data centres. These can number in the hundreds, and are already well organized around the network's mission. Thus, a simple headcount does not measure the overall scientific reach and impact of WDS correctly, and more appropriate metrics will need to be devised, even more so because increased participation of WDS Network Members is facilitating, and even fueling, the continued broadening of ICSU-WDS into Socioeconomic disciplines, the Humanities, and the Health Sciences.

Predictably, ICSU-WDS is emerging as a scale-free complex system, accommodating giant repositories with holdings measured in petabytes (e.g. NASA DAACs, NOAA data centers), that we seek to link harmoniously with small, yet equally important facilities requiring only a few gigabytes of storage (e.g. World Data Center for Earth Tides). Nowhere was that more evident than at the 2013 International Forum on '*Polar Data Activities in Global Data Systems*' co-convened by ICSU-WDS in Tokyo, Japan, and the resulting declaration.

With the strong encouragement of ICSU, WDS D has continued forging closer collaboration with the ICSU Committee on Data for Science and Technology (CODATA), resulting in SciDataCon 2014, a global conference held November 3-5, 2014 in New Delhi, India, which is the first of what we hope will be a sustained series of biennial scientific data conferences that cater to a constantly widening scope of countries and disciplines. To pursue its strategic targets, the WDS Scientific Committee (WDS-SC) has created several Working Groups to address major issues such as data publication and member certification, and to advance concepts such as a WDS Knowledge Network. In keeping with our mandate, these activities are coordinated with other organizations including the Research Data Alliance (RDA link), the Data Seal of Approval (DSA, link), and national efforts such as NSF's EarthCube. The reader is also urged to learn more by visiting the WDS website and to tune into its new Webinar series.

WDS has adopted five strategic targets for 2014-18. These are:

1) Make *trusted* data services an integral part of international collaborative scientific research

2) Nurture active disciplinary and multidisciplinary scientific data services *communities*

3) Improve the *funding* environment

4) Improve the trust in and quality of *open* Scientific Data Services

5) Position WDS as the *premium* global multidisciplinary network for quality-assessed scientific research data

These targets were presented to the ICSU General Assembly in Auckland, NZ, in September, 2014, and were approved by the Assembly. Over the years, WDS has presented posters and talks at numerous scientific venues, the next one will be at the 2014 Fall meeting.

Looking forward, ICSU-WDS is visible and active in the development of an effective data policy for Future Earth the new ICSU global scientific initiative that builds on the work of IGBP and the Nobel prize winning IPCC, and is making its voice heard in essential supporting organizations such as the Belmont Forum which coordinates funding activities across numerous countries. After considerable effort— notably by Professor Takashi Watanabe, Senior Advisor to the WDS-IPO— WDS is now able to manage contributions from external sources through a newly established nonprofit WDS Scientific Association, thereby satisfying a long-standing wish of the Scientific Committee.

My second term as Chair of the WDS-SC will end in June, 2015. However, after investing so much work in helping WDS become reality since 2008, and having worked more than a decade with ICSU before that, I fully intend to continue contributing to the ultimate success of WDS and its expansion into other fields. For instance, I will chair an international panel discussion on November 6, 2014, on the role of *Open Access to Data* in the response to future potential pandemics epidemics such as the 2014 *Ebola* breakout. I continue to work on fostering a fundamental change of attitude in academia about recognizing data publication as equal to publication of scholarly papers.

References

ICSU-WDS 2014 Report to ICSU http://www.icsu-wds.org/news/news-archive/wds-at-the-31st-general-assembly-of-icsu ; http://www.icsu-wds.org/publications/annual-reports
ICSU-WDS Strategic Plan 2014-2018: http://www.icsu-wds.org/organization/strategic-plan
Polar forum declaration, Kyoto, 2013: http://www.icsu-wds.org/publications/press-releases

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1. I have returned to the classical problem on WIND DRAG. This is due to viscous shear forces and normal pressures on ocean roughness. There are some new results. At winds of less than U10 =3D 2 m/s it is entirely viscous. At winds of 7 m/s it is 2/3 normal pressures. This has implications on a number of problems.
2. Acoustic noise at depth (deeper than 1 km, say) is highly correlated with surface winds, but the physics of the noise generation is not clear. There is some excellent new observational material [see report by J. Berger] and we are looking into a variety of possible physical processes.

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Research Interests: Paleobiology, paleoceanography, human impacts on ocean ecosystems, marine biodiversity, extinctions, evolution of pelagic ecosystems, tipping points in reef communities

Racetrack Playa – Mystery of the "moving rocks" solved.

An enduring mystery in geology is why and how rocks move of their own accord over a nearly flat, mud-cracked lake bed in Death Valley National Park–the Racetrack Playa. Jim Norris and I set up the "Slithering Stones Research Initiative" in 2011 to find out. With NPS permits in hand, we set up a weather station and outfitted 15 rocks with GPS loggers to record when they moved, how fast they went, and where they went. Our observations show that rock movement involves a rare combination of events. First, the playa fills with water, which must be deep enough to allow formation of floating ice during cold winter nights but shallow enough to expose the rocks. As nighttime temperatures plummet, the pond freezes to form sheets of floating "windowpane" ice, which must be thin enough (several mm) to move freely but thick enough to maintain strength. On sunny days, the ice begins to melt and break up into large floating panels, which light winds drive across the playa pool. The ice sheets shove rocks in front of them and the moving stones leave trails in the soft mud bed below the pool surface.

We observed rocks in motion numerous times in December 2014 and January 2014 and out GPS stones recorded the velocities and timing of movement. Rocks move at 2-6 m/minute, near midday when sunny conditions and light breezes cause ice breakup. We have begun studies of the frictional forces involved in rock motion using a load cell and an artificially flooded playa surface for our experiments. We have also examined satellite images of other playas in the Western US to look for characteristic geomorphic features associated with ice dynamics. These observations suggest that ice-related processes are common on playa lakes. Our PLOS ONE paper on the Racetrack phenomenon has been viewed over 197,000 times – a reflection of public interest in the topic.

Recovery of Open Ocean fish populations after the Cretaceous-Paleogene Mass Extinction

With Ph.D student Elizabeth Sibert, I have been using the fossil record of fish teeth in the open ocean to reconstruct fish populations through recent geologic history. Pelagic fish teeth and shark scales (ichthyoliths) are durable, highly resistant to dissolution or breakage, readily identifiable, easily separated from sediments, and ubiquitous in the deep sea. Hence, both their abundance (as a productivity proxy) and their identification (as a measure of ecosystem structure by analogy with living fish distributions and ecologies) makes them useful as direct recorders of environmental information. We have been using this remarkable record to reconstruct the impact of major ecosystem disruptions – the Cretaceous-Paleogene mass extinction, the Paleocene-Eocene thermal Maximum, and the Eocene-Oligocene glaciation—on fish productivity and biodiversity. A recent result of this work is the finding (Sibert *et al.* 2014) that fish production was almost unchanged by the Cretaceous-Paleogene mass extinction in the Pacific while fish production plummeted in the Atlantic during this same event. This finding supports previous work showing that other parts of ocean ecosystems recovered much faster in the Pacific than in the Atlantic. I think this unexpected pattern reflects differences in the sensitivity of the two oceans to disturbance owing to their different basin size and oceanography.

Recent Publications

Norris, R. D., Norris, J. M., Lorenz, R. D., Ray, J., Jackson, B. (2014) Sliding rocks on Racetrack Playa, Death Valley National Park: First observation of rocks in motion, *PLoS ONE*, 9:e105948., 10.1371/journal.pone.0105948

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Yamaguchi, T, Norris R. D., Dockery D. (2014). Shallow-marine ostracode turnover during the Eocene-Oligocene transition in Mississippi, the Gulf Coast Plain, USA *Marine Micropaleont.* **106** 10-21, 10.1016/j.marmicro.2013.11.003

Kirtland Turner, S., P. F. Sexton, C. D. Charles and R. D. Norris (2014). Persistence of carbon release events through the peak of early Eocene global warmth, *Nature Geosci.* **7** 748-751.

Sibert, E. C., P. M. Hull and R. D. Norris (2014). Resilience of Pacific pelagic fish across the Cretaceous/Palaeogene mass extinction. *Nature Geosci.* **7**, 667-670.

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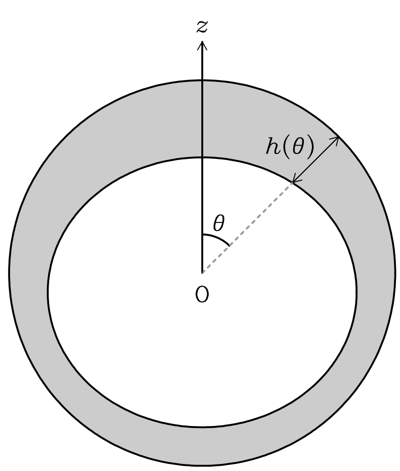
Research Interests: Inverse theory, geomagnetism, spectral analysis, electromagnetic induction.

In the past year Parker has returned to an old question, the lack of uniqueness in solutions to the inverse problem for density based on gravity data. Despite the existence of counterexamples drawn from systems discovered by Newton, papers continue to appear giving models of interior density derived solely from gravitational or geoid data, the authors claiming to have overcome the difficulties with regularization and an analysis of resolution. The simplest inverse problem of this kind is linear: observations (geoid heights, spherical harmonic coefficients, field values, etc) written as integrals over the source region. Even exact data known everywhere outside the gravitating body are compatible with an enormous variety of alternative interior densities. Consider a spherical body S and a potential function U that vanishes exactly on ∂S the boundary, and is twice differentiable inside, but is otherwise arbitrary. This potential can be generated by the density distribution within S given by

$$\rho = -\frac{\nabla^2 U}{4\pi G}\,. \tag{1}$$

But such a distribution has no external effect, because $U = 0$ on the surface and therefore it vanishes exactly everywhere outside. Because of the linearity of the problem, the function ρ can be added to any solution (scaled if necessary to maintain positivity), without affecting the match of the original model to the data. Recall U is an arbitrary function, subject only to its being smooth and vanishing on ∂S. This represents an huge family of alternative densities whose gravitational fields are identical with the observed one.



Sometimes a condition is imposed that the unknown density be piecewise constant, with known value, for example as a uniform layer of variable thickness. There is a uniqueness theorem then, which requires that every vertical line either intersects the gravitating body once, or not at all (Smith, 1961). The additional condition is too restrictive for many plausible situations. To illustrate this Parker considered the following problem. Inside a sphere, radius a, there is surface layer of uniform density ρ and thickness $h(\theta)$, where θ is the angle from an axis passing through the center of the body. If one expands the potential U and $h(\theta)$ in axisymmetric spherical harmonics thus:

$$U(r,\theta) = \sum_{l=0}^{\infty} u_l \left(\frac{a}{r}\right)^{l+1} P_l(\cos\theta), \;\; r \ge a; \qquad h(\theta) = \sum_{l=0}^{\infty} h_l P_l(\cos\theta) \tag{2}$$

then

$$u_l = -2\pi G\rho \int_0^\pi \frac{a^{l+3} - (a - h(\theta))^{l+3}}{(l+3)a^{l+1}} P_l(\cos\theta) \sin\theta \, d\theta \tag{3}$$

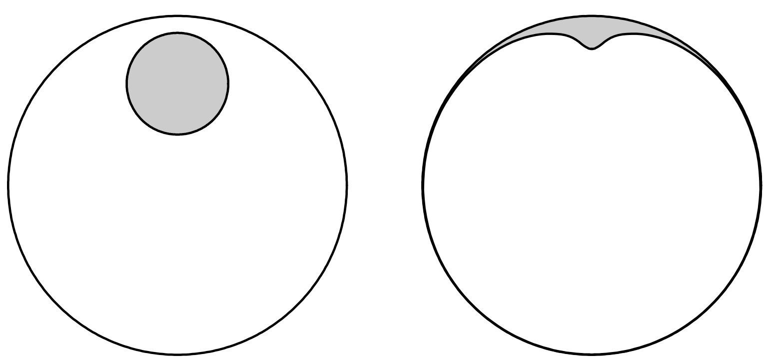
$$= -\frac{4\pi G\rho a}{2l+1} h_l + \Delta_l[h] \tag{4}$$

where Δ_l depends on $h(\theta)^2$ and higher powers. Equation (4) can be trivially rearranged thus:

$$h_l = -\frac{2l+1}{4\pi G\rho a} u_l + \frac{2l+1}{4\pi G\rho a} \Delta_l[h]\,. \tag{5}$$

When the layer is very thin, Δ_l can be neglected and (5) gives an approximate solution for the inverse problem in that case; when it is not thin, (5) can be employed as the basis for a fixed point iteration in which successive approximations from the right side are substituted into Δ_l on the left. While a rigorous convergence theory has not be discovered (except for a very simple case), in practice the scheme converges in a satisfactory manner, allowing matching of given potentials to a few parts in 10^7 by layer models.

As an example consider the gravitational field of a buried uniform mass anomaly, that might be associated in the moon with a mascon. Using the machinery developed above it is possible over a large range of parameters to match that potential exactly with a uniform layer of the same density. There is no way on the basis of the gravity data to distinguish between the two perfectly plausible geological models, a surface layer or an isolated, buried mass.



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Smith, R. A., A uniqueness theorem concerning gravity fields, *Proceedings of the Cambridge Philosophical Society*, **57**, 865-70, 1961.

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Research Interests: Physics and chemistry of silicate melts; electrical properties of mantle materials; role of magma in planetary interiors, from the scale of volcanic magma reservoirs to planetary-scale magma oceans; evolution of planetary interiors from "deep time" (e.g., planet formation and evolution) to the present (e.g., kinetics of magmatic processes).

Ongoing research projects over the past year have been mainly concerned with (A) the experimental investigation of the electrical properties of Earth's upper mantle rocks under pressure, and (B) the correlation between electrical and seismic properties of partially molten materials, with application to mid-ocean ridges, hot-spots, and subduction zones.

(A). The motion of lithospheric plates produces deformation of mantle rocks near the lithosphere-asthenosphere boundary. The transition from a rheologically strong lithosphere to a comparatively weak asthenosphere may involve a small amount of melt and/or water in the asthenosphere, reducing viscosity and explaining possibly detected electrical anomalies that extend to ˜200 km depth. Under funding from NSF Cooperative Studies Of The Earth's Deep Interior, my collaborators David Kohlstedt, Kurt Leinenweber, Stephen Mackwell, James Tyburczy and I have investigated at ASU the effect of melt on the electrical conductivity of deformed materials at upper mantle conditions (Pommier et al., under review). Based on electrical anisotropy measurements at ˜3 GPa on mantle analogues (i.e., deformed olivine aggregates and on sheared partially molten rocks), we observed that electrical conductivity is highest parallel to deformation direction and quantified the effect of shear on conductivity with increasing temperature. We also developed an electrical model alternating layers of sheared olivine with layers of melt to model high anisotropies. Our experimental results and model show that field data are best reproduced by an electrically anisotropic asthenosphere overlain by an isotropic, high-conductivity deep lithosphere (Figure 1 A). The high conductivity could arise from partial melting associated with localized deformation resulting from differential plate velocities relative to the mantle, with upward melt percolation from the asthenosphere.

(B). Fluids influence electrical conductivity and seismic velocity in different ways. These physical properties are measured using electromagnetic and seismic methods, respectively, and offer a unique way to map *in situ* fluid distribution in real time in the Earth's crust and mantle. When interpreted together with petrological results, geophysical data can be used to constrain fluid chemistry, temperature, fraction, and connectivity. Seismic and magnetotelluric (MT) studies do not necessarily agree on melt fraction estimates, a possible explanation being the assumptions made about melt chemistry as part of MT data interpretation. Melt fraction estimates from electrical anomalies usually assume a basaltic melt phase, whereas petrological knowledge suggests that the first liquids produced have a different chemistry, and thus a different conductivity. Together with Ed Garnero, I explored melt properties by interpreting geophysical data sets sensitive to the presence of melt (electromagnetic and seismic) with considerations of petrology and, in particular, peridotite partial melting (Pommier and Garnero, 2014). We developed a petrology-based model of the electrical conductivity of fertile and depleted peridotites during partial melting. Our results showed that melts produced by low-degree peridotite melting (¡15 vol%) are up to 5 times more conductive than basaltic liquids. Such conductive melts significantly affect bulk rock conductivity. Application of our electrical model to magnetotelluric results suggested melt fractions that are in good agreement with seismic estimates (Figure 1.B). With the aim of a simultaneous interpretation of electrical and seismic data, we combined our electrical results with seismic velocity considerations in a joint model of partial melting. We observed that field electrical and seismic anomalies can be explained by ˜1 vol% melt beneath Hawaii and ˜1–8 vol% melt beneath the Afar Ridge. As part of another study compiling electromagnetic and seismic results from various subduction zones, I observed a possible correlation between electrical conductivity and seismic wave attenuation anomalies in the mantle wedge is observed, consistent with fluid accumulation (Pommier, 2014). A possible relationship between geophysical properties and the slab age is also suggested, whereas no significant trend is observed between electrical conductivity or seismic wave attenuation and estimates of water flux in the mantle wedge. These field-based relationships require further constrains, emphasizing the need for new measurements in the laboratory.

Recent Publications

Pommier A., K. Leinenweber, D. Kohlstedt, C. Qi, E. J. Garnero, S. Mackwell, J. Tyburczy (2014) Experimental Constraints on the Electrical Anisotropy of the Lithosphere-Asthenosphere System, under review.

Pommier A. (2014) Geophysical assessment of fluid storage conditions and migration in subduction zones, *Earth Planets Space* **66** 38.

Pommier A., and E. J. Garnero (2014). Petrology-based modeling of mantle melt electrical conductivity and joint-interpretation of electromagnetic and seismic results, *J. Geophys. Res.* 10.1002/2013JB010449

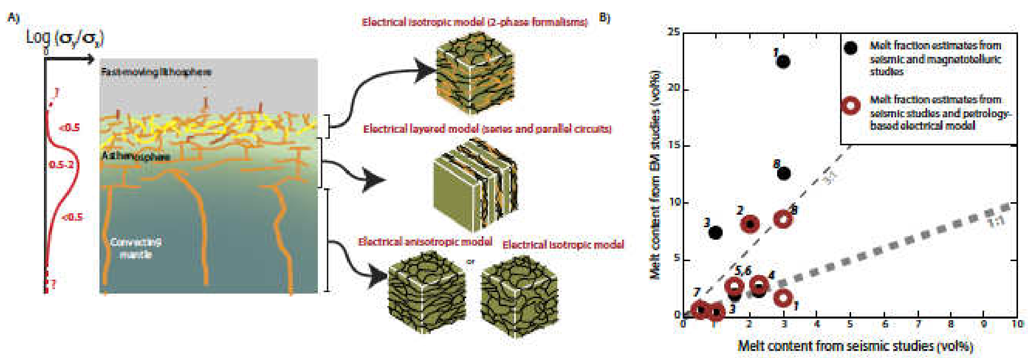

Figure 1: (A) Cross-section portrayal of the electrical conductivity (σ) of the uppermost mantle in melt-bearing context (fast-moving plates), with corresponding conductivity ratio for the lowest conductivity direction (σ_y) to the highest conductivity direction (σ_x). Melt reaches the asthenosphere from the deeper mantle, where melt pathways do not significantly cause electrical anisotropy. In the asthenosphere, electrical anisotropy is enhanced due to plate motion, causing horizontal alignment (melt sheets, tubules). Melt accumulates at the bottom of the lithosphere due to a less permeable lithosphere, and becomes well interconnected in all directions despite a deformed solid matrix. This melt is isolated from mantle flow, cooling and crystallizing. (1B) Comparison between average melt content estimates from electromagnetic and seismic studies (black circles) and between the model by Pommier and Garnero and seismic studies (red circles) for several locations. Estimates using the model by Pommier and Garnero are in better agreement than the ones from field electrical studies. The high difference in melt content estimates that persists for two locations (labeled 2 and 8) may be due to the abundance of volatiles, that are not accounted for in the Pommier and Garnero model. Locations are: 1: Mid-Atlantic rodge; 2: East Pacific Rise (8-11N segment); 3: Hawaiian hotspot; 4: Taupo Volcanic Zone; 5: East Pacific Rise (17S segment); 6: Yellowstone; 7: Philippine Sea; 8: Afar ridge.

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Research Interests: Geodynamics, global bathymetry, crustal motion modeling

Students and Funding - Research for the 2013-14 academic year was focused on understanding the dynamics of the crust and lithosphere. Our group comprises three graduate students Soli Garcia, Eric Xu, and John Desanto, two postdocs Xiaopeng Tong and Alejandro Gonzalez-Ortega and two lab assistants Chris Olson and Rachael Munda. Our research on improvement in the marine gravity field is co-funded by the National Science Foundation (NSF) the Office of Naval Research, and the National Geospatial Agency. In addition we are funded by NSF and Google to improve the accuracy and coverage of the global bathymetry. The NSF EarthScope Program funds our investigation of the strain rate and moment accumulation rate along the San Andreas Fault System from InSAR and GPS.

Global Gravity and Bathymetry – We are improving the accuracy and spatial resolution of the marine gravity field using data from three new satellite radar altimeters (CryoSat-2, Jason-1, and Envisat). This is resulting in a factor of 2-4 improvement in the global marine gravity field. Most of the improvement is in the 12 to 40 km wavelength band, which is of interest for investigation of seafloor structures as small as 6 km. The current version of the altimeter-derived gravity field has an accuracy of 1.7 mGal in the Gulf of Mexico (*Garcia et al.,* 2013; *Sandwell et al*., 2014). The improved marine gravity is important for exploring unknown tectonics in the deep oceans as well as revealing thousands of uncharted seamounts (Figure 1).

Integration of Radar Interferometry and GPS - We are developing methods to combine the high accuracy of point GPS measurements with the high spatial resolution from radar interferometry to measure interseismic velocity along the San Andreas Fault system (*Tong et al.,* 2013). We analyzed InSAR observations, initially from ALOS ascending data, spanning from the middle of 2006 to the end of 2010, and totaling more than 1100 interferograms. The final InSAR line-of-sight data match the point GPS observations with a mean absolute deviation of 1.3 mm/yr. These combined GPS/InSAR data are critical for understanding the along-strike variations in stress accumulation rate and associated earthquake hazard. The InSAR processing was performed with new software called GMTSAR developed at SIO (http://topex.ucsd.edu/gmtsar).

Crustal Motion Modeling – Xiaopeng Tong and Bridget Konter-Smith (at the University of Texas, El Paso) are refining a semi-analytic earthquake cycle model for the deformation of western North America using crustal velocity measurements from the growing array of continuous GPS stations and InSAR acquisitions (*Tong et al.,* 2014). This model is used to estimate the seismic moment accumulation rates along the fault system.

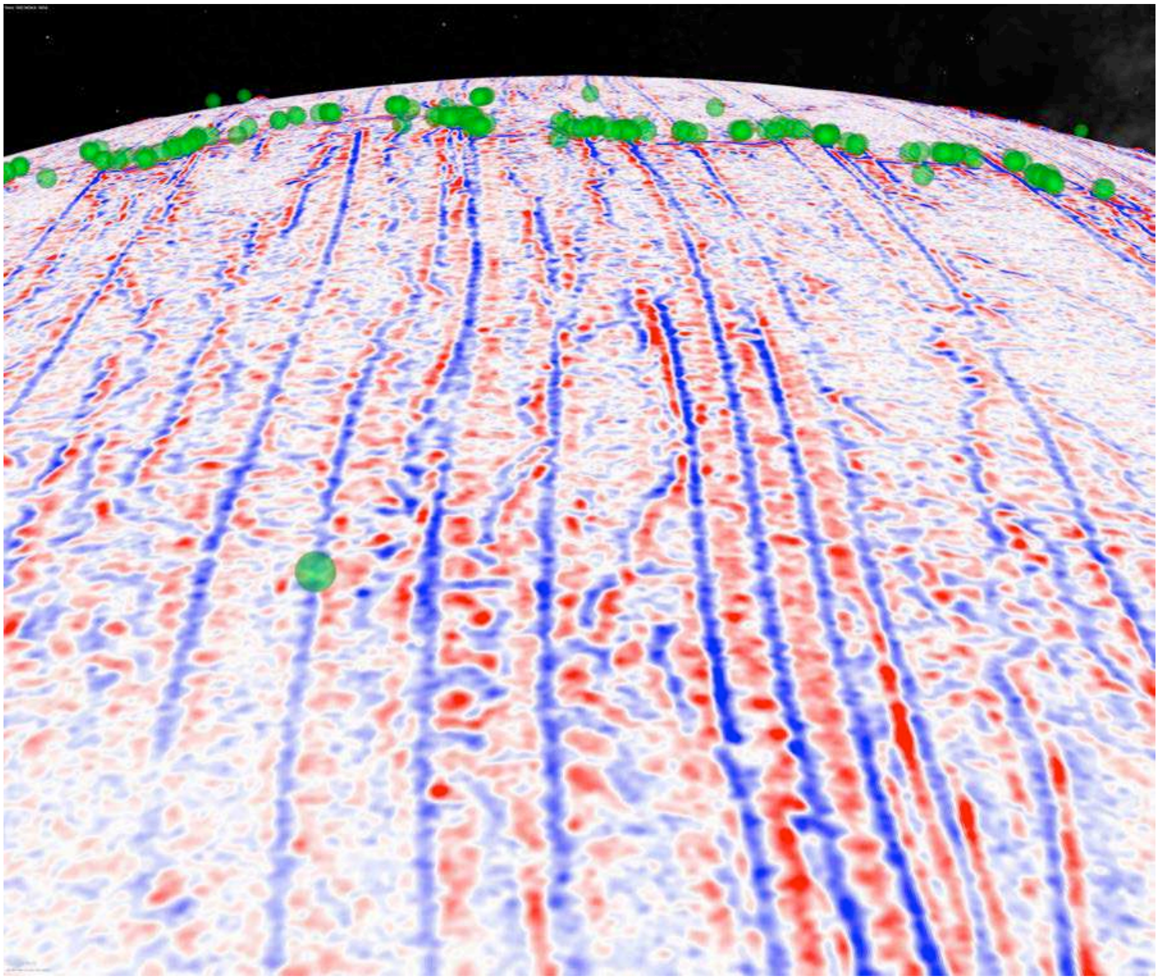

Figure 1. Vertical gravity gradient (VGG) model of the southern mid-Atlantic Ridge. Earthquakes with magnitude > 5.5 are shown as green dots and highlight the current location of the spreading ridges and transform faults. The linear fracture zone signatures record the rifting and spreading between South America and Africa.

Relevant Publications

Garcia, E., D. T. Sandwell, W. H. F. Smith. Retracking CryoSat-2, Envisat, and Jason-1 Radar Altimetry Waveforms for Improved Gravity Field Recovery, Geophysical Journal International, doi: 10.1093/gji/ggt469, 2014.

Kaneko, Y., Y. Fialko, D. T. Sandwell, X. Tong, and M. Furuya, Interseismic deformation and creep along the central section of the North Anatolian Fault (Turkey): InSAR observations and implications for rate-and-state friction properties, *J. Geophys. Res. Solid Earth, 118*, doi:10.1029/2012JB009661, 2013.

Sandwell, D. T., R. D. Müller, W. H. F. Smith, E. Garcia, R. Francis, New global marine gravity model from CryoSat-2 and Jason-1 reveals buried tectonic structure, Science, Vol. 346, no. 6205, pp. 65-67, doi: 10.1126/science.1258213, 2014.

Tong, X., D. T. Sandwell, and B. Smith-Konter, High-resolution interseismic velocity data along the San Andreas Fault from GPS and InSAR, *J. Geophys. Res.; Solid Earth, 118,* doi:10.1029/2012JB009442, 2013.

Tong, X., B. Smith-Konter, and D. T. Sandwell, Is there a discrepancy between geological and geodetic slip rates along the San Andreas Fault System?, J. Geophys. Res. Solid Earth, 119, doi:10.1002/2013JB010765, 2014.

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

Together with a team of radiolarian colleagues I continue the work stimulated by the World Registry of Marine Species (WoRMS) and the Encyclopedia of Life (EOL) in an ambitious effort to produce an illustrated catalog of all Cenozoic radiolarian genera including type species, revision of genera, discussions of descriptions and synonymies.

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. 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.

Radiolarian microfossil slides containing type and figured specimens described in publications throughout my career are currently being inventoried, and will be deposited in the U.S. National Museum, Washington, D.C.

A rewarding effort that I especially enjoy is doing outreach to K-12 schools in San Diego. While talking to the students about geology and paleontology, and what geologists do, I encourage the students to study math and science. The students especially enjoy the hands-on experience of using microscopes, sieves and other equipment that I bring to the classroom. Handling rocks and fossils is an unforgettable learning experience that the young students truly enjoy.

Recent Publications

Lazarus, D., Suzuki, N, Caulet, J.-P., Nigrini, C., Goll, I., Goll, R., Dolven, J.K., Diver, P. and Sanfilippo, S., *In preparation*. An evaluated list of Cenozoic-Recent radiolarian species names, based on those used in the DSDP, ODP and IODP deep-sea drilling programs.

The abstract of the above paper is being presented at the GSA meeting in Vancouver, BC, Oct. 20-24, 2014. (see below for summary)

A First Comprehensive Evaluated List of Cenozoic Radiolarian Species

D. Lazarus1, N. Suzuki2, J.-P. Caulet3, C. Nigrini4, R. Goll5, J. K. Dolven6, A. Sanfilippo7, P. Diver8, I. Goll5
1-Museum für Naturkunde, Berlin, Germany; 2-Tohoku Univ., Sendai, Japan, 3-Charavines, France, 4-(deceased), 5-Blinn College, Bryan, TX, USA; 6-Univ. Oslo, Norway; 7-Scripps Inst. Oceanography, La Jolla, CA, USA; Divdat Consulting, Wesley, AK, USA
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Summary
Despite their extensive use in biostratigraphy and paleoceanography, no reasonably complete catalogs or even check lists exist for Cenozoic radiolarian species names, although there are several partial catalogs/databases in development. We present here a first step towards creating such a catalog in the form of a list of all species names, with family membership, author, year, and most importantly taxonomic status (with link, if synonym, to the valid name), for all polycystine species names published by the DSDP or ODP phases of the deep-sea drilling program, or cataloged online by the community www.radiolaria.org website (Dolven). Information for each species is supplemented by additional data drawn from two unpublished taxonomic databases: Radworld (Caulet, Nigrini, Sanfilippo) and an unnamed database compiled by Suzuki. Our primary goal has been name equivalence, not formal revision, with emphasis on objective synonyms, though some subjective synonyms are given as well. Given the highly unclear nomenclatural state of Cenozoic taxonomy, no attempt has been made to determine the 'true' correct generic or species name for most species, leaving this work to future revisions, based on newly available reillustrations of older type collections, e.g. Tanimura et al. (2009). Nor have we attempted to capture other Cenozoic names found only in the non-deep-sea drilling external literature. Nonetheless we feel this list represents the large majority of valid Cenozoic radiolarian species. Currently there are ca 1,200 valid names, plus more than 700 synonyms (including many published misspellings). Most valid species or subspecies are Nassellaria (nearly 900), while there are fewer than 400 valid species in Spumellaria. Five families (Theoperidae, Actinommidae, Trissocyclidae, Plagiacanthidae and Spongodiscidae) contain a clear majority of all valid names. There are 29 genera with >10 valid species or subspecies. *Eucyrtidium* has the most, with 34 species/subspecies. The list is currently maintained by Lazarus in Berlin, and is integrated into the NSB microfossil occurrences database (www.nsb-mfn-berlin.de, for access please contact senior author). A formal publication is in preparation.
Compilation of this list was in part supported with funding from the IODP.

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Research Interests: The implications of global marine heat flow measurements for the thermal history of the Earth and the heat flow anomaly across continental margins and the measurement of this anomaly across the passive margins of the Guaymas Basin (Gulf of California).

I submitted an extended abstract for a talk in a 2013 symposium celebrating the work of P.M.S. Blackett and Teddy Bullard. (Dan McKenzie gave the talk because I could not attend). Bullard, single handedly, developed the field of marine heat flow. He was responsible for the design of the first heat flow instrument that SIO colleagues (Revelle and Maxwell) used to take the first measurements. He interpreted the higher than expected first measurements as evidence for thermal convection in the upper mantle. The discovery by the same group of very high values near the crest of the East Pacific Rise was one of the major pieces of evidence used by Hess justifying sea floor spreading.

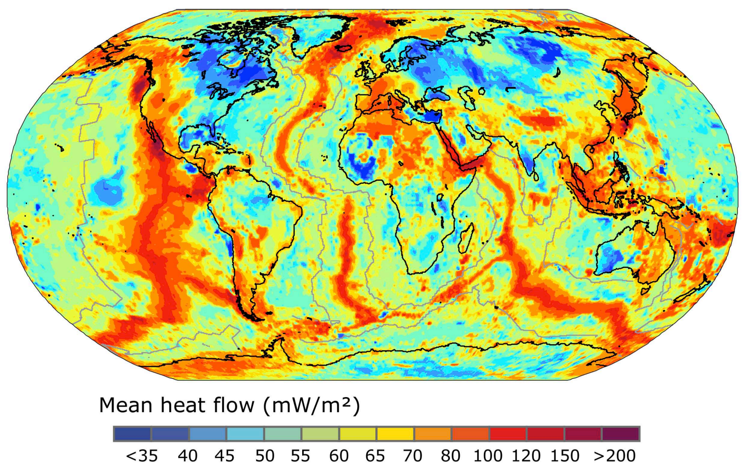

Figure 1: Map of global heat flow, using a "similarity method" to fill in gaps in coverage. This figure shows how much the creation of oceanic plate dominates the oceanic heat loss.

I followed this paper with a review, with a number of colleagues, of Marine Heat Flow (Sclater *et al*. 2014). We showed that, in addition to the early discoveries of Bullard and his colleagues mentioned above, the measurements have led to many additional fundamental advances in our understanding of the Earth:

1. The high scatter in heat flow measurements near the crest of the mid-ocean ridges led to the proposal widespread hydrothermal circulation at the crest of mid-ocean ridges;

2. Examination of heat flow measurements unperturbed by water circulation led to a simple thermal model that can explain the general dependence of both oceanic heat flow and bathymetry on age.

3. Removing the effect of dynamic topography in determining the relation between depth and age allows the construction of two self-consistent models that match both the heat flow and subsidence on old ocean floor without requiring significant radioactivity in the oceanic crust;

4. This shows that the oceanic lithosphere is a thermal boundary layer on top of major convection systems in the upper-mantle;
5. Creation of oceanic plate represents more than 60% 0f the global heat loss (Figure 1). The global loss is 45-47 TW with three-quarters coming from the oceans with ~one-fifth of this occurring by the advection of seawater at the crest of the mid-ocean ridges;
6. A combination of oceanic plate creation, convection in the upper mantle and radioactive decay on the continents is the source of almost all of the Earth's surface heat flow. To a first approximation, the continental cratons and platforms act as insulators on top of convections in the upper mantle.

In my second area of research I have been examining the change in the heat flow difference across the ocean continent boundary with age. The effect of the relation between heat flow and age for ocean crust and the increased radioactivity on the continents tend to counteract each other creating a decrease in heat flow across the ocean-continent transition at a young and an increase in heat flow across an older margin. I, and colleagues, have shown that, where disturbance due to salt movement or water circulation are absent, the expected heat flow anomaly is as observed. The 15 Ma margin of the Gulf of Aden shows a negative change and the 180 Ma Northeastern margin of the Gulf of Mexico shows a positive change in heat flow .Currently, I am proposing to participate in a major program of joint research between CICESE , UNAM, SIO, UCSC, and OSU to measure the heat flow from shelf to shelf across the axis of three of three-major-deepwater basins (Guaymas, Farallon, Alarcon) of the Gulf of California Rift System. As a pilot project, we propose to carry out a seismically controlled detailed heat flow measurements across the northern basins of the Gulf and a finer resolution survey over a recently imaged "saucer shaped sill" above stretched continental crust. These profiles will specifically investigate the effect of the intrusion of dykes and sills into the sediments within the recently forming basin.

Recent Publications

Sclater, J. G., Hasterok, D., Goutorbe, B., Hillier, J., and R. Negrete (2014). Marine Heat Flow, *Encyclopedia of Marine Geosciences* (Springer) accepted for publication.

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

My research uses seismology to learn about Earth structure and earthquakes, using data from the global seismic networks and local networks in California, Hawaii, and Japan. My work in crustal seismology has focused on improving earthquake locations using waveform cross-correlation and systematically estimating small-earthquake stress drops from *P*-wave spectra. Recently I collaborated with former IGPP Green Scholar Yoshihiro Kaneko (now at GNS New Zealand) to model simple yet dynamically self-consistent circular ruptures and test methods for estimating corner frequency and stress drop from far-field seismic records (*Kaneko and Shearer,* 2014). Our results show that the most widely used approach overestimates stress drops by about a factor of 1.7 and that large variations in stress drop estimates are expected in real observations from inadequate sampling of the focal sphere.

In Hawaii, recent work with Robin Matoza used spectral analysis to produce a much more complete catalog of long-period (LP) events below Kilauea Volcano on Hawaii Island (*Matoza et al*., 2014). Waveform cross-correlation and cluster analysis show that the vast majority of intermediate depth LP events are located within a single compact volume only about 2 km across. The stability of these locations over the last 23 years suggests a source process controlled by geological or conduit structure.

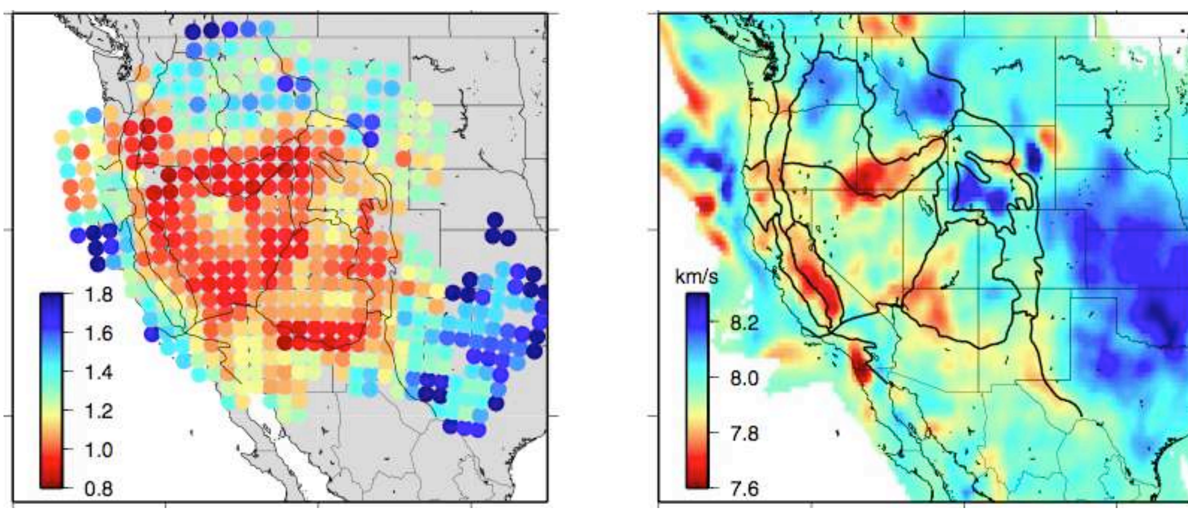

Figure 1. (left) *Sn* signal strength at 3.5 degrees from envelope function stacks of USArray data. Note that the weak *Sn* signals in the central Great Basin. (right) Uppermost mantle *P* velocity from *Pn* tomography. Figure from *Buehler and Shearer* (2013).

Work with IGPP postdoc Janine Buehler has focused on regional *Pn* and *Sn* phases in the USArray dataset. *Buehler and Shearer* (2013) used seismogram stacks to map *Sn* propagation efficiency in the western United States and identify highly attenuating regions in the uppermost mantle. We found evidence for some *Sn* propagation at short ranges in the central Great Basin and strong *Sn* propagation around its perimeter, a pattern that shows some agreement with *Pn* velocities over the same region (see Fig. 1). *Buehler and Shearer* (2014) performed joint *Pn/Sn* tomography in the western United States to create unified models of crustal thickness and *Pn* and *Sn* velocity and azimuthal anisotropy. Our results indicate partially molten mantle beneath the Snake River Plain and the Colorado Plateau and changes in the orientation of azimuthal anisotropy with depth.

I am also interested in new approaches to imaging large earthquake ruptures, including waveform back-projection and other approaches. Work with graduate student Wenyuan Fan and Peter Gerstoft tested a regularized frequency-domain approach to the finite-slip inversion problem, obtaining good results for the synthetic test data of the Source Inversion Validation Exercise 1 (*Fan et al*., 2014). IGPP postdoc Zhongwen Zhan has been studying deep earthquake ruptures and recently identified supershear rupture in a M 6.7 aftershock of the 2013 Sea of Okhotsk earthquake (*Zhan et al., 2014*). This earthquake had a very short duration compared to most earthquakes of similar size (see Fig. 2). Comparisons to the Okhotsk mainshock and the 1994 Bolivian earthquake suggest there is more than one rupture mechanism for deep earthquakes.

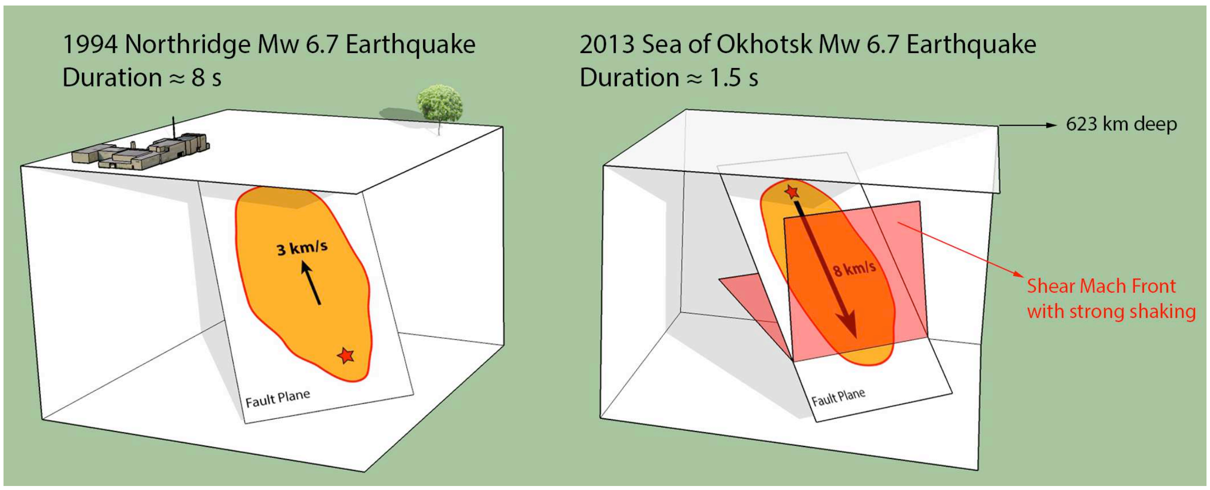

Figure 2. A comparison between the 1994 Northridge earthquake in southern California and the 2013 M 6.7 deep earthquake in the Sea of Okhotsk. Although both earthquakes had similar dimensions and moment (Mw 6.7), the Okhotsk event had a much shorter duration and a very high rupture velocity, exceeding the local shear wave speed and creating a Mach front with very strong shaking.

Selected Recent Publications

Buehler, J. S., and P. M. Shearer, Sn propagation in the Western United States from common midpoint stacks of USArray data, *Geophys. Res. Lett.*, **40**, 1–6, doi: 10.1002/2013GL057680, 2013.

Kaneko, Y., and P. M. Shearer, Seismic source spectra and estimated stress drop from cohesive-zone models of circular subshear rupture, *Geophys. J. Int.*, **197**, 1002–1015, doi: 10.1093/gji/ggu030, 2014.

Buehler, J. S., and P. M. Shearer, Anisotropy and Vp/Vs in the uppermost mantle beneath the western United States from joint analysis of Pn and Sn phases, *J. Geophys. Res.*, **119**, doi: 0.1002/2013JB010559, 2014.

Matoza, R. S., P. M. Shearer, and P. G. Okubo, High-precision relocation of long-period events beneath the summit region of Kilauea Volcano, Hawaii, from 1986 to 2009, *Geophys. Res. Lett.*, **41**, doi:10.1002/2014GL059819, 2014.

Zhan, Z., D. V. Helmberger, H. Kanamori, and P. M. Shearer, Supershear rupture in a Mw 6.7 aftershock following the 2013 Sea of Okhotsk earthquake, *Science*, **345**, 204–207, doi: 10.1126/science.1252717, 2014.

Fan, W., P. M. Shearer, and P. Gerstoft, Kinematic earthquake rupture inversion in the frequency domain, *Geophys. J. Int*., **199**, 1138–1160, doi: 10.1093/gji/ggu319, 2014.

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Research Interests*:* Land and marine electromagnetic (EM) methods; integrated geophysical data analysis and interpretation; inverse theory; energy outlooks and global change

In the first year of my SIO appointment, I orchestrated the contribution of three ExxonMobil seafloor multicomponent EM receivers, plus spares, to Professor Steven Constable's marine EM lab to further strengthen the capabilities of that world-leading fleet of instruments. These three instruments were the last of a group of thirty developed for ExxonMobil in cooperation with Scripps to validate controlled-source electromagnetic methods (CSEM) for offshore resource identification and development. This technology also has important applications to global change research, such as identifying marine hydrates that hold significant amounts of carbon below the seafloor.

In the professional society arena, I co-organized and led a European Geoscientists and Engineers (EAGE) workshop on integrated EM, seismic, acoustic multi-beam, and geochemical data interpretation, held in Singapore on March 31 - April 2, 2014. The outcome is summarized in *First Break (*http://fb.eage.org/publication/content?id=76649). This workshop demonstrated again the considerable power of joint interpretation of complementary data sets, and called for more acquisition of that kind both offshore and onshore.

Recent Publications

Chavez, L., Altobelli, S., Fukushima, E., Zhang, T., Nedwed, T., Palandro, D., Srnka, L., and Thomann, H., 2015, Using NMR to detect Arctic oil spills. *Near Surface Geophysics,* **13** (in press).

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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, the lithosphere and biosphere. My most recent focus aims at the biogeosciences of volcanic systems in particular seamounts and in the extreme environments of McMurdo/Antarctica. I am teaching field methods and I have worked with graduate students developing lesson plans for middle and high schools. References to my broader research interests and other prior work can be found in the bibliography at my website: earthref.org/whoswho/ER/hstaudigel/index.html.

Microbes in Volcanoes: In collaboration with colleagues in Oregon and Maine, 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 and explore specific morphological features of these trace fossils might give us some leads on the physiological traits of the microbes that cause them. This work demonstrated that microbes are active in any ocean crust section studied to date 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. While we are still in the dark about the actual microbes involved, I am working with microbiologists to explore microbe – rock interaction inside volcanoes and their hydrothermal systems. We studied Vailulu'u seamounts in the Samoan archipelago and Loihi Seamount off the Big Island on Hawaii. There we characterized and isolated microbes from natural rock surfaces and exposure experiments for future experiments. My current field 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. Most of our 2012/13 field season was spent in ice caves on Erebus and sub-ice diving. Details are on our expedition website: (earthref.org/ERESE/projects/GOLF439/2012/), in an on-line lecture I gave at Birch Aquarium (www.uctv.tv/search-details.aspx?showID=16074 and we put together a movie on our diving on Youtube: www.youtube.com/watch?v=CSlHYlbVh1c (footage by Henry Kaiser, famed Antarctic diver and movie director).

Seamounts: Most recent field work focused on Loihi Seamount and seamounts in the Samoan Chain including Vailulu'u seamount. 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 articles in this volume are freely available from the website of The Oceanographic Society (www.tos.org/oceanography/archive/23-1.html). My papers include in particular contributions regarding the geological history and structure of seamounts their role in subduction systems and the associated deep-sea metal deposits. Other recent papers on seamounts include the description of microbial consortia in their hydrothermal systems and the discovery that fungi are common in these submarine systems, not unlike in terrestrial soils.

Teaching: I am teaching SIO 239, an introduction to geological field methods for Geophysicists and, 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" (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 one-third 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

Connell, L., Staudigel, H. (2013). Fungal diversity in a dark oligotrophic volcanic ecosystem (DOVE) on Mount Erebus, Antarctica. *Biology*, **2**, 798-809.

Knowles, E., Staudigel, H., Templeton, A. (2013). Geochemical characterization of tubular alteration features in subseafloor basalt glass, *Earth Planet. Sci. Lett.* **374**, 239-250 10.1016/j.epsl.2013.05.012

Staudigel, H, Furnes, H, and Smits, M. (2014). Deep biosphere record of in-situ oceanic lithosphere and ophiolites, *Elements* **10**, 121-126.

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Research Interests: Global tectonics, mantle dynamics, planetary geophysics, high-performance computing

Dr. Stegman researches dynamic processes within planetary interiors that shape their geologic, tectonic, magnetic and magmatic evolutions. My research group employs some of the nations fastest supercomputers to simulate these processes with the ultimate goal of developing a dynamical theory that explains how Earth and other planets evolve.

One of the main questions I've been investigating in the past year is why *does* Earth have plate tectonics?

Plate tectonics is a special case of a more general class of tectonic style referred to as mobile lid convection, in which the cold, high-viscosity thermal boundary layer (i.e. lithosphere) is recycled into the mantle. Other planetary bodies, such as Mars and Earth's Moon, have a single, stationary plate covering their entire surface which is referred to as the stagnant lid mode of convection. Stagnant lid convection occurs because the strong temperature-dependence of viscosity, however the finite strength of rocks represented by their yield stress limits the lithosphere from reaching the extremely high viscosities predicted. While this yield stress allows modeled stagnant lid planets to become mobile lid planets, however they still do not exhibit plate tectonic behavior. In models of mobile lid planets, convergent plate boundaries can range from broad and diffuse to concentrated and narrow, but always result in 2-sided symmetric downwellings. A distinguishing characteristic of plate tectonics on Earth is subduction, whereby two tectonic plates converge in a 1-sided, asymmetric manner along a discrete subduction zone. So in order to answer the question of why Earth has plate tectonics, one must first understand why models of mobile lid planets do not exhibit Earth-like subduction.

Plate motion on Earth is driven by slab pull, with subducted slabs pulling the trailing plates to which they are attached. In typical mobile lid convection models, the yield stress is exceeded throughout much of the subduction hinge, thereby precluding any stress guide that would allow the slab to pull the surface plate. In the recent models I've developed with PhD student Robert Petersen, we show that this lack of a stress-guide is why previous models of mobile lid convection are always 2-sided and symmetric. In our models which allow for a continuous stress guide, we find that asymmetric 2-sided downwellings commonly arise due to varying plate ages, as older plates don't bend as easily as younger plates. Such dynamics are made possible through our treatment of how we model plates, which is based on the theory of bending and stretching of thin viscous sheets. Plates in our models tend to be weaker with respect to bending than previous studies, but somewhat counter-intuitively, are relatively stronger towards being pulled and stretched. By varying the strength of the plates and buoyancy forcing, our models exhibit an entire spectrum of mobile lid to stagnant lid behavior. Figure 1 shows a mobile lid model that evolves from a system that is asymmetric and 2-sided into one that is symmetric and 2-sided system but with short-lived episodes of 1-sided subduction. In a recently submitted manuscript (Petersen et al, 2014), we describe an entire suite of models and present a regime diagram that can be explained by understanding the balance of stresses within the system.

Recent Publications

Petersen, R.I., **D.R. Stegman**, and P.J. Tackley (2014) A Regime Diagram of Mobile lid Convection with Plate-like Behaviour, *Physics of the Earth and Planetary Interiors* (in revision).

Druken, K.A., C. Kincaid, R.W. Griffiths, **D.R. Stegman**, S.R. Hart (2014). Plume-slab interaction: The Samoa-Tonga system, *Physics of the Earth and Planetary Interiors* **232** 1-14.

Davies, C., **D.R. Stegman**, and M. Dumberry (2014). The strength of gravitational core-mantle coupling, *Geophys. Res. Lett.* **41**, 37863792 10.1002/2014GL059836

Jackson, C., Ziegler, L. B., Zhang, H., Jackson, M., and **D.R. Stegman** (2014). A geochemical evaluation of potential magma ocean dynamics using a parameterized model for perovskite crystallization *Earth Planet. Sci. Lett.,* **392** 154-165

Ziegler, L.B. and **D.R. Stegman** (2013). Implications of a long-lived basal magma ocean in generating Earth's ancient magnetic field, *Geochem. Geophysics Geosystems* **14** (11), 4735-4742.

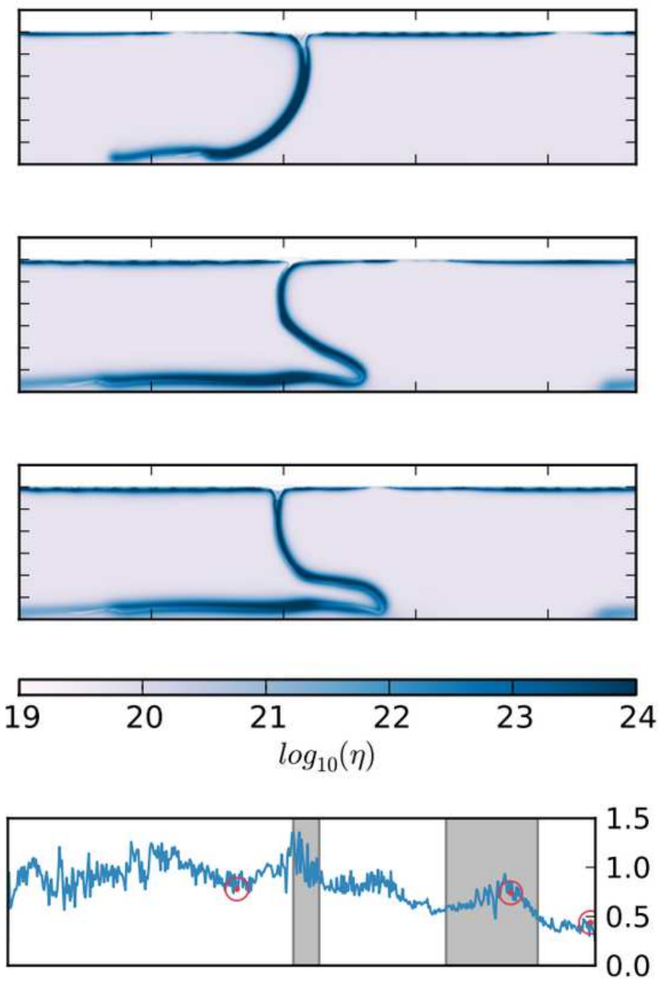

Figure 1: Time evolution of a mantle convection model that is predominantly 2-sided but includes 1-sided episodes (shaded regions on bottom panel) that occur when the overriding plate becomes thin. The top three panels show viscosity as the model evolves from young to old, top to bottom, corresponding to the red circles in the bottom panel which indicates the (dimensionless) Mobility number of the model.

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.

In 2014, my research has largely focused on improving the methods by which paleointensity data are evaluated (Paterson et al., 2014). We also acquired new results from lavas (di Chiara et al., 2014) and archeological artifacts (Cai et al., 2014).

Cai et al., (2014), published the first new archaeointensity results from China since the the 80s. We discovered a new period of quite low virtual axial dipole moments (VADMs) of ~25% of the present day field at around 2250 BCE followed by a sharp six-fold increase to a high field intensity (160% of present day field) at around 1300 BCE. The rate of change of geomagnetic intensity during this period is ~6 µT/century or 47% per century which is faster than the rate of change anywhere on Earth today.

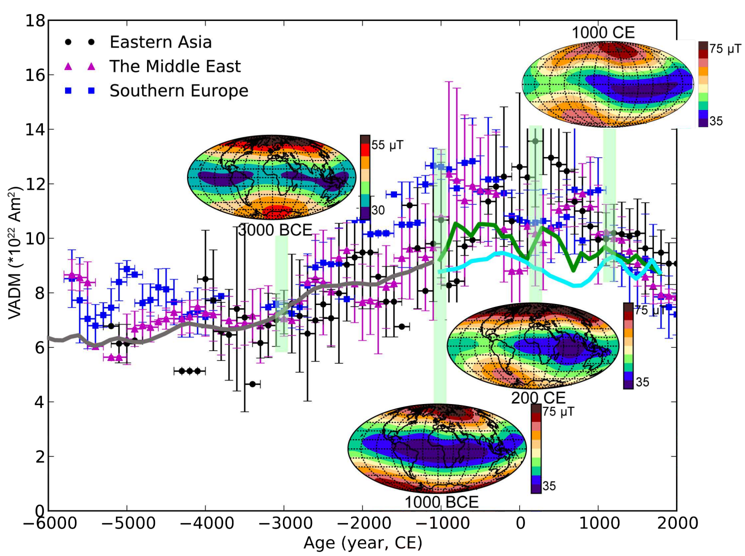

Figure 1: Variations of average VADMs in the areas of Eastern Asia (black solid circles), the Middle East (magenta triangles) and Southern Europe (blue squares) from data in the MagIC database and in Cai et al., 2014. The averages are calculated every 200 years with a 100-years sliding window. Balloons are predictions of the geomagnetic field intensities at the earth surface from CALS10k.1b (older than 1000 BCE) or ARCH3k.1 (younger than 1000 BCE) models (Korte et al., 2011 and Korte et al., 2009 respectively). Grey/ cyan/ green heavy line represents the VADMs predicted by the models. [Figure from Cai et al., 2014.]

Our new data allow a comparison with data along a latitudinal transect from Eastern Asia to Europe and with the geomagnetic field models published by Korte et al., 2009, 2011, Korte and Constable, 2011 and Korte et al., 2011) which are mutually incompatible in their predictions of field intensity in China. Our data are in better agreement with the ARCH3k.1 model of Korte et al., (2009). We also found that the high field values observed in the Middle East around ~1000 BCE is unlikely to be a global feature (see Figure 1). The three areas of Eastern Asia, the Middle East and Southern Europe appear to evolve quite indepentently from one another with non-dipole field features growing and decaying in place as opposed to being caused by migrating flux patches.

In the study of di Chiara et al., (2014) we presented the first dataset of reliable paleointensity estimates for the central-northern Atlantic Ocean. The new data are internally consistent and radiocarbon dated, so they can be included in global geomagnetic datasets, and used to help improve the next generation of global geomagnetic field models.

The paleomagnetic literature on paleointensity is rife with competing methods of selecting "good" data and rejecting "bad" data, with many different statistics for estimating the degree of alteration and other common proplems with the method. Paterson et al., (2014) assembled a definitive list of published paleointensity selection criteria. These statistics have been incorporated into the program Thellier_gui.py of Shaar and Tauxe (2013) and allow great flexibility in choice of selection criteria. In an examination of data obtained from material produced in known fields, we concluded that certain sets of selection criteria in common use are quite inefficient at choosing accurate results while excluding inaccurate ones.

Selected publications:

Paterson, G.A., Tauxe, L., Biggin, A.J., Shaar, R., Jonestrask, L., On improving the selection of paleointensity data, Geochem., Geophys., 15, Geosyst., doi:10.1002/2013GC005135, 2014.

Cai, S., Tauxe, L., Deng, C., Pan, Y., Zheng, J., Xie, F., Qin, H., Zhu, R., Geomagnetic intensity variations for the past 8 kyr: New archaeointensity results from Eastern China, Earth Planet. Sci. Lett., 392, 217-229, doi: 10.1016/j.epsl.2014.02.030, 2014.

Di Chiara, A., Tauxe, L., Speranza, F., Paleointenstiy determination from S\~ao Miguel (Azores Archipelago) over the last 3 ka, Phys. Earth Planet. Int., 234, 1-13, doi:10.1016/j.pepi.2014.06.008, 2014.

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Korte, M. and C. Constable (2011). "Improving geomagnetic field reconstructions for 0-3 ka." Phys. Earth Planet. Int. 188: 247-259.

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

I am a Research Seismologist at the Institute of Geophysics and Planetary Physics, Scripps Institution of Oceanography, University of California at San Diego. My current research interests are focused on developing distributed networked real-time sensor networks in terrestrial and marine environments. Currently I am the Director for the USArray Array Network Facility for the NSF EarthScope program (http://anf.ucsd.edu). This network currently has over 500 stations using seismic, acoustic, and atmospheric pressure sensors delivering real-time data to UCSD, which are redistributed to multiple sites. The ANF is responsible for real-time state-of-health monitoring for the network in addition to the real time data processing, archiving, and distribution. Data are acquired over multiple types of communication links including wireless, satellite, and wired networks. We are currently winding down the TA deployment in the lower 48 states while starting the next phase of the project of deploying across Alaska and the Yukon.

I am the PI on the ANZA broadband and strong motion seismic network that has operated since 1982 providing real-time seismic monitoring capability for southernmost California (http://eqinfo.ucsd.edu). I am a co-PI on very dense seismic deployment around the San Jacinto fault zone, focusing on earthquake source physics, fault structure, and providing real-time seismic monitoring capability for southernmost California. In addition I am co-PI on the HPWREN program creating a large-scale wireless high-performance data network that is being used for interdisciplinary research and education applications, as well as a research test bed for wireless technology systems in general. HPWREN provides wide area wireless internet access throughout southernmost California including San Diego, Riverside, and Riverside counties and the offshore regions. Under UCSD's HPWREN program, research being conducted on building "last kilometer" wireless links and developing networking infrastructure to capture real-time data from multiple types of sensors from seismic networks, hydrological sensors, oceanographic sensors, video sensors as well as data from coastal radar and GPS.

Recent Publications

Kane, D. L., D. L. Kilb, F. L. Vernon (2013). Selecting Empirical Green's Functions in Regions of Fault Complexity: A Study of Data from the San Jacinto Fault Zone, Southern California. *Bulletin of the Seismological Society of America*, **103**, p. 641-650, doi:10.1785/0120120189

Kane, D. L., P. M. Shearer, B. P. Goertz-Allmann, and F. L. Vernon (2013), Rupture directivity of small earthquakes at Parkfield, *J. Geophys. Res. Solid Earth*, **118**, 212–221, doi:10.1029/2012JB009675.

Jacobeit, E., C. Thomas, F. Vernon (2103). Influence of station topography and Moho depth on the mislocation vectors for the Kyrgyz Broadband Seismic Network (KNET) *Geophys. J. Int.* **193** (2): 949-959 doi:10.1093/gji/ggt014

Kurzon, I., F.L. Vernon, A. Rosenberger and Y. Ben-Zion (2014). Real-time Automatic Detectors of P and S Waves Using Singular Value Decomposition, *Bull. Seism, Soc. Am.*, **104**, 1696–1708, doi: 10.1785/0120130295.

Allam, A. A., Y. Ben-Zion, I. Kurzon and F. L. Vernon (2014). Seismic velocity structure in the Hot Springs and Trifurcation Areas of the San Jacinto Fault Zone, California, from double-difference tomography, *Geophys. J. Int.*, **198,** 978–999, doi: 10.1093/gji/ggu176.

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Astiz, L., J. A. Eakins, V. G. Martynov, T. A. Cox, J. Tytell, J. C. Reyes, R. L. Newman, G. H. Karasu, T. Mulder, M. White, G. A. Davis, R. W. Busby, K. Hafner, J. C. Meyer, F. L. Vernon (2014). The Array Network Facility Seismic Bulletin: Products and an Unbiased View of United States Seismicity. *Seismological Research Letters*, v. **85**, p. 576-593, doi:10.1785/0220130141

Burdick, S., R. D. van der Hilst, F. L. Vernon, V. Martynov, T. Cox, J. Eakins, G. H. Karasu, J. Tylell, L. Astiz, G. L. Pavlis (2014). Model Update January 2013: Upper Mantle Heterogeneity beneath North America from Travel-Time Tomography with Global and USArray Transportable Array Data. *Seismological Research Letters*, v. **85**, p. 77-81, doi:10.1785/0220130098

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Research Interests: Acoustical oceanography, ocean acoustic tomography, underwater acoustics.

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

Acoustic Propagation in the Philippine Sea.

During 2009-2011 the Acoustical Oceanography Group at Scripps Institution of Oceanography worked with investigators from other oceanographic institutions to conduct a series of experiments to investigate deep-water acoustic propagation and ambient noise in the oceanographically and geologically complex Philippine Sea: (i) 2009 NPAL Pilot Study/Engineering Test (PhilSea09), (ii) 2010-2011 NPAL Philippine Sea Experiment (PhilSea10), and (iii) Ocean Bottom Seismometer Augmentation of the 2010-2011 NPAL Philippine Sea Experiment (OBSAPS). Worcester et al. (2013) provides an overview of the three experiments. Initial results are given in Colosi et al. (2013), Freeman et al. (2013), Van Uffelen et al. (2013), and White et al. (2013).

The goals of the Philippine Sea experiments included (i) understanding the impacts of fronts, eddies, and internal tides on acoustic propagation, (ii) determining whether acoustic methods, together with other measurements and 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) improving our understanding of the physics of scattering by internal waves and spice (density-compensated temperature and salinity variations), (iv) characterizing the depth dependence and temporal variability of the ambient noise field, and (v) understanding the relationship between the acoustic field in the water column and the seismic field in the seafloor for both ambient noise and signals.

The measured low-frequency travel-time series compare remarkably well with time series computed from an ocean state estimate made using a high-resolution regional implementation of the MIT Ocean General Circulation Model (MITgcm) that was constrained by satellite altimetric and Argo (but not acoustic) data (Fig. 1). Significant (~30 ms) differences remain, however.

Thin-ice Arctic Acoustic Window (THAAW).

The Arctic Ocean is currently undergoing dramatic changes, including reductions in the extent and thickness of the ice cover and extensive warming of the intermediate layers. The multiyear ice is melting. Ice keels are getting smaller. With more open water, the internal wave energy level is likely increasing, at least during summer. The long-term objectives of this research program are to understand the effects of changing Arctic conditions on low-frequency, deep-water propagation and on the low-frequency ambient noise field. The hope is that these first few steps will lead to a larger, permanent acoustic monitoring, communications, and navigation network in the Arctic Ocean (Mikhalevsky et al., 2014).

A mooring with a vertical receiver array was deployed through the ice near the North Pole at Russian ice camp Barneo during 12–15 April 2013. On 3 May 2013 ALARM messages from the Iridium-GPS beacon located on top of the subsurface float indicated that the mooring had surfaced prematurely. The mooring drifted slowly south toward Fram Strait after surfacing. The mooring was recovered on 20 September 2013 north of Fram Strait using a Norwegian Coast Guard icebreaker. Preliminary analysis of the ambient noise data show median noise levels roughly comparable to those observed during April 1982 at the Fram IV ice camp.

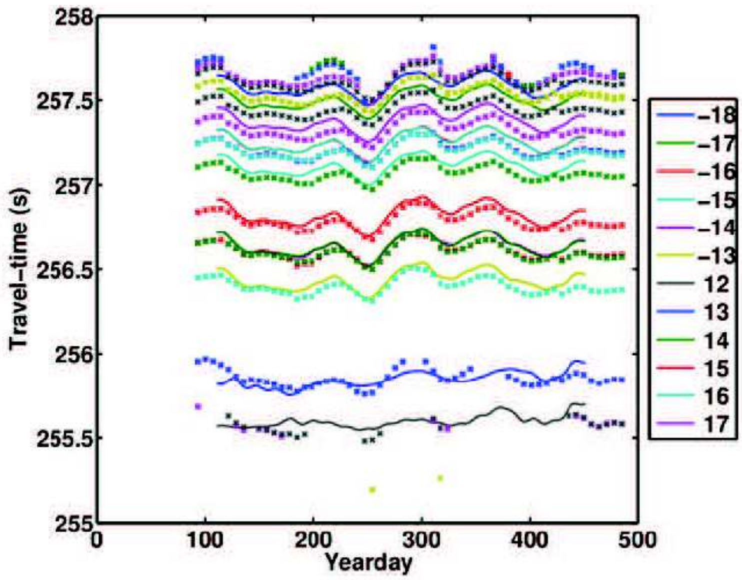

Figure 1: Measured low-frequency travel-time series (solid lines) for transmissions from T2 to T3 compared with travel times (symbols) computed from an ocean state estimate. The colors correspond to different ray identifiers.

Recent Publications

Colosi, J. A., L. J. Van Uffelen, B. D. Cornuelle, M. A. Dzieciuch, P. F. Worcester, B. D. Dushaw and S. R. Ramp (2013) Observations of sound-speed fluctuations in the western Philippine Sea in the spring of 2009. *J. Acoustical Soc. America* **134** 3185-3200.

Freeman, S. E., G. L. D'Spain, S. D. Lynch, R. A. Stephen, K. D. Heaney, J. J. Murray, A. B. Baggeroer, P. F. Worcester, M. A. Dzieciuch and J. A. Mercer (2013) Estimating the horizontal and vertical direction-of-arrival of water-borne seismic signals in the northern Philippine Sea. *J. Acoustical Soc. America* **134** 3282-3298.

Mikhalevsky, P. N., H. Sagen, P. F. Worcester, A. B. Baggeroer, J. A. Orcutt, S. E. Moore, C. M. Lee, K. J. Vigness-Raposa, L. Freitag, M. Arrott, K. Atakan, A. Beszczynska-Moeller, T. F. Duda, B. D. Dushaw, J.-C. Gascard, A. N. Gavrilov, H. Keers, A. K. Morozov, W. H. Munk, M. Rixen, S. Sandven, E. Skarsoulis, K. M. Stafford, F. Vernon and M. Y. Yuen (2014) Multipurpose acoustic networks in the Integrated Arctic Ocean Observing System *Arctic*, in press.

Van Uffelen, L. J., E.-M. Nosal, B. M. Howe, G. S. Carter, P. F. Worcester, M. A. Dzieciuch, K. D. Heaney, R. L. Campbell and P. S. Cross (2013) Estimating uncertainty in subsurface glider position using transmissions from fixed acoustic tomography sources *J. Acoustical Soc. America* **134** 3260-3271.

White, A. W., R. K. Andrew, J. A. Mercer, P. F. Worcester, M. A. Dzieciuch and J. A. Colosi (2013) Wavefront intensity statistics for 284-Hz broadband transmissions to 107-km range in the Philippine Sea: Observations and modeling *J. Acoustical Soc. America* **134** 3347-3358.

Worcester, P. F., M. A. Dzieciuch, J. A. Mercer, R. K. Andrew, B. D. Dushaw, A. B. Baggeroer, K. D. Heaney, G. L. D'Spain, J. A. Colosi, R. A. Stephen, J. N. Kemp, B. M. Howe, L. J. Van Uffelen and K. E. Wage (2013) The North Pacific Acoustic Laboratory deep-water acoustic propagation experiments in the Philippine Sea *J. Acoustical Soc. America* **134** 3359-3375.

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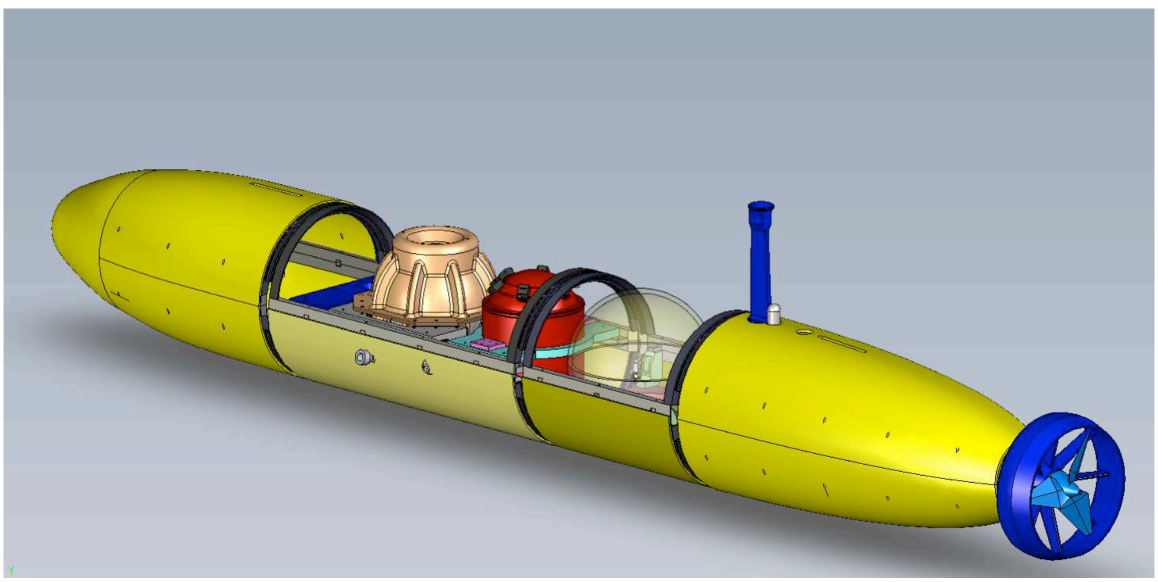
Research Interests: Measurement of gravity and pressure in the marine and subaerial environments, development of new seismic instrumentation, optical fiber measurements of strain and pressure

Gravity measurements from an Autonomous Underwater Vehicle (with Gerald D'Spain, Glenn Sasagawa, and Jeff Ridgway)

Our group has been attempting gravity measurements from an AUV (Autonomous Underwater Vehicle) for several years, funded by industrial sponsors interested in using near-seafloor gravity data in exploration for oil and gas. Success in operating a gravity meter on an AUV has been elusive until just recently when we finally gained the experience needed to configure both the gravity sensor and the AUV to perform in a mutually compatible manner, allowing us to obtain high quality gravity data for the first time.

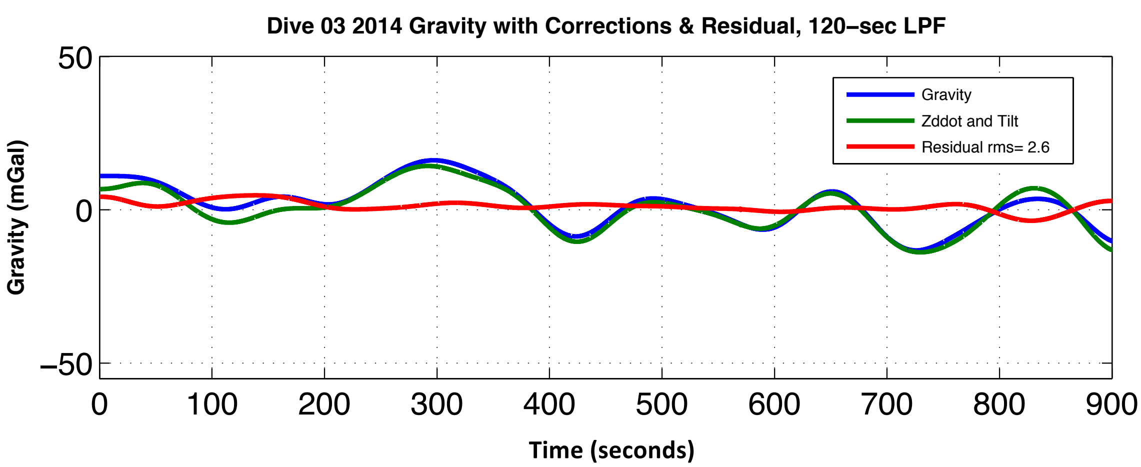


A BlueFin 21 AUV carries an inertial guidance system and a land gravity meter modified for submerged, underway use. (For scale the "21" in the model refers to its 21 inch diameter.)

Because the signal size falls off rapidly with distance between source and observer, gravity is best measured as near to the seafloor as possible when using it to explore for subsurface density variations. As many interesting targets for research (e.g., subsea volcanoes and mid-ocean ridges) are in fairly deep water, and the oil and gas industry's focus on offshore reservoirs is in ever deeper locations, moving gravity meters off of surface vessels and onto submerged vehicles has been desirable for some time. However measuring gravity from a moving vehicle is difficult because the apparent gravity change that results from rotations and vertical accelerations of the vehicle must be removed from the record at the part-per-million level.

The normal approach on ships is to stabilize the gravity sensor from rotations with a gyro-stabilized platform, but these are too large and power demanding to be of much use on an autonomous submarine that must operate from batteries. Ours has been a "strapdown" approach in which the gravity meter is fixed to the vehicle (with its average orientation aligned with local vertical) while vertical accelerations are determined from seawater pressure records and rotations, which momentarily misalign the sensor with respect to vertical, are measured with a tiltmeter. From these signals a correction is calculated and subtracted from the gravity time series.

Attempts to do this in the lab, with a vertical actuation platform and a dynamic tilt table, were largely successful, indicating the feasibility of this approach working in the ocean onboard a real AUV. However we failed for many years in our attempts because of two difficulties: 1) vibrations interfered with the gravity meter's extremely sensitive spring, and 2) the control loop on the AUV failed to maintain the trajectory of the vehicle within required limits. These two problems have finally been solved, and a test in shallow water showed for the first time that we could collect gravity data and subtract the two main noise sources (vertical acceleration – Zdotdot in the graph below – and tilt, which causes a cosine error in the record). As can be seen in the plot, the observed gravity record in blue clearly detects the signals caused by tilt and up-down vehicle motion (the combined effect in green). Subtraction of the correction signal yields the red line, which, for the first time in our experimentation, shows noise of only a few mGal. Plans for tests in deep water are currently being developed.



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Wielandt, E. and Zumberge, M. A., "Measuring Seismometer Nonlinearity on a Shake Table." *Bul. Seis. Soc. Am.*, **103**, No. 4, 2247-2256 (2013).

DeWolf, S., Walker, K., Zumberge, M. A., and Denis, S., "Efficacy of Special Averaging of Infrasonic Pressure in Varying Wind Speeds." *J. Acoustical Soc. Am.*, **133**, No. 6, 3739-3750 (2013).

Berger, J., Davis, P., Widmer-Schnidrig, R., and Zumberge, M., (2014). Performance of an Optical Seismometer from 1 μHz to 10 Hz, *Bul. Seis. Soc. Am.*, **104**, No. 5, 2422-2429 (2014). doi: 10.1785/0120140052