EARTH SECTION

2016 ANNUAL REPORT SCRIPPS INSTITUTION OF OCEANOGRAPHY

EARTH SECTION

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.

Thanks to Jennifer Matthews for her efforts in compiling and producing this report.

Duncan Agnew, Head, Earth Section

Awards and Honors

Steve Constable *became a Fellow of the American Geophysical Union.*

Walter Munk *was appointed a Faculty Fellow of Revelle College.*

Lisa Tauxe *was elected to the American Academy of Arts and Sciences.*

Jane Willenbring *received an Antarctic Service Medal.*

2016

Duncan Carr Agnew, *Professor*
Lihini Aluwihare, *Professor**
Andreas Andersson, *Associate Professor**
Laurence Armi, *Professor**
Gustaf Arrhenius, *Professor Emeritus*
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, *Distinguished Research Scientist*
Adrian Borsa, *Assistant Professor*
Kevin Brown, *Professor**
James Brune, *Professor Emeritus**
Steven C. Cande, *Research Professor†**
Paterno Castillo, *Professor*
C. David Chadwell, *Research Scientist*
Christopher Charles, *Professor**
Emily Chin, *Assistant Professor*
Catherine Constable, *Professor**
Steven Constable, *Professor*
Geoffrey Cook, *Associate Teaching Professor**
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**
Deborah Lyman Kilb, *Project Scientist*
Kerry Key, *Associate Professor**
Gabi Laske, *Professor-in-Residence*
Peter Lonsdale, *Professor**
Gunter Lugmair, *Research Scientist*†*
Douglas J. Macdougall, *Professor Emeritus**
Todd Martz, *Associate Professor**
Guy Masters, *Distinguished Professor**
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**
Isabelle Rivera-Collazo, *Assistant Professor*
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*
Frank Vernon, *Research Scientist*
Martin Wahlen, *Professor Emeritus**
Jane Willenbring, *Associate Professor*
Peter Worcester, *Research Scientist*†*
Mark Zumberge, *Research Scientist*

*** no annual report available** **† RTAD = retired with active research program**

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

We have long 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 accumulated 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: 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.

We have recorded aseismic transients at CHL, DHL, and PFO, the last location giving the most interesting results (Figure 1), since here there seems to be evidence for relatively deep aseismic motion following moderate local or large regional earthquakes.

The high installation and operating costs of the LSM's has created a need for a cheaper, if lower-quality sensor. With Dr. Mark Zumberge, we continue to develop long-base laser strainmeters that use optical fiber, rather than a vacuum pipe, for the optical path, to provide a robust, widely deployable, inexpensive, and sensitive instrument. Since optical fibers have long-term drift and are temperature sensitive they cannot provide the same data quality over as wide a range of frequencies, but can still be useful for studying seismic waves, Earth tides, and slow slip events. At PFO we have installed a 250-m-long borehole optical fiber vertical strainmeter (BOFS, Figure 2), and two horizontal optical fiber strainmeters installed in trenches (TOFS): a 180 m instrument parallel to the NWSE vacuum laser strainmeter, and a 230 m two-fiber system (for temperature compensation) parallel to the EW vacuum strainmeter.

These instruments use optical fiber stretched between two points anchored to the Earth; length changes in this are measured using an interferometer, in which light from a laser is split by an optical fiber coupler into two fibers, one the Earth strain sensing fiber, the other a fixed reference length. Light travels the lengths of the two arms and recombines coherently: in a Michelson interferometer Faraday mirrors at the far end of each fiber reflect the light back, so the light recombines in the original coupler. By making the two arms of equal optical length the laser used can have relatively poor frequency stability. The reference arm is coiled around a quartz mandrel next to the laser and coupler, so that its temperature can be kept constant.

Comparisons at seismic frequencies show variations in even the long-base strains measured over parallel but different baselines, as is shown in Figure 3 for the two pairs of LSM/TOFS sensors. Along the NWSE strainmeter, the same seismic signal is recorded with about 7% larger amplitude on the TOFS: a result that initially suggested a systematic error. But along the EW baseline the two agree to within 1%. We believe that these differences are real, and occur because of slight elastic inhomogeneities on the scale of hundreds of meters, which cause the strains from even uniform stresses to be variable.

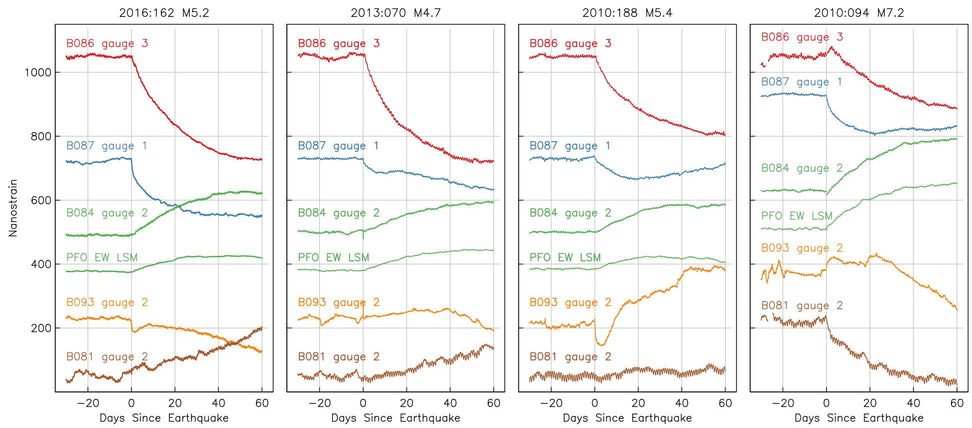

Figure 1: Aseismic strains seen following four earthquakes since 2010, showing one component of each of the laser strainmeters at PFO and five borehole strainmeters in the Anza area (B084 is at PFO).

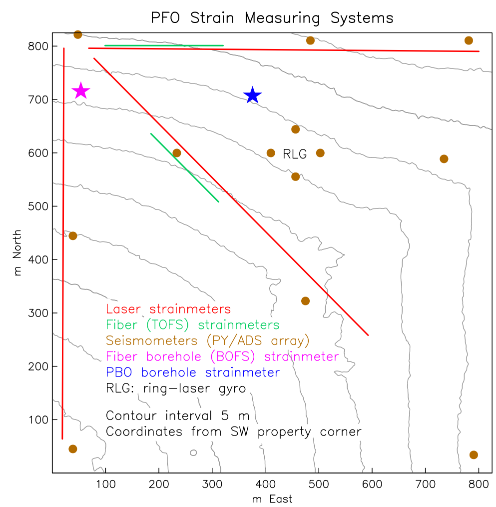

Figure 2: Map of PFO showing the location of various strainmeters and a Ring Laser Gyro.

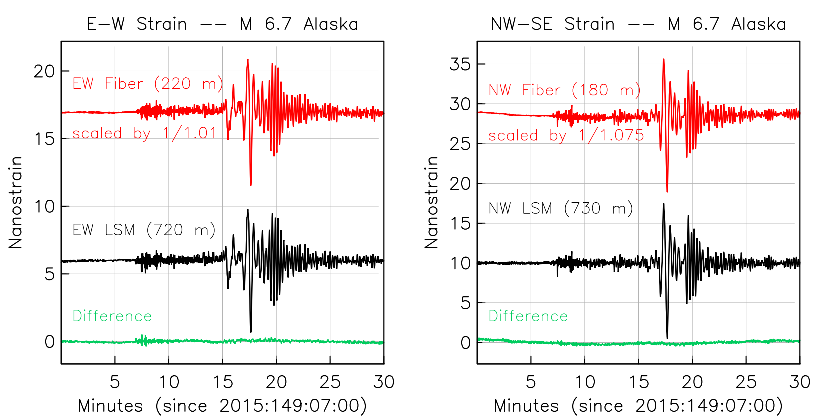

Figure 3: Comparison of the TOFS and long-base vacuum strainmeters.

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Research Interests: biogeochemistry. cosmochemistry, materials science

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In the oldest sedimentary rocks known on Earth, time, temperature, and pressure have led to the complete obliteration of any microfossil shapes by crystallization of the carbon to ordered graphite. However in slightly younger rocks at @ 3.4byr (Barberton Tract, S. Africa), electron micrography by Prof. Abha Misra in our group has revealed the carbon to be present as thin film fragments (Fig.1) and unbroken bulbs (Fig.2) and as spindle structures ending with thin spines (Fig.1), Like other biogenic kerogen this graphite is of disordered rhombohedral form while graphite formed inorganically by fluid deposition or carbonate disproproportionation crystallizes in hexagonal form – a biogenically distinctive feature.

While these graphitic objects are found for the first time, a large literature, not referable here for space reasons, has developed, describing other, generally larger, complex forms, several investigations strengthening the proposition of their biogenic origin by carbon isotope fractionation,

Contributors to the present report include importantly Saul Montano Perez and Mark van Zuilen. Support from The Agouron Research Foundation and from Robert W. Rex is gratefully acknowledged.

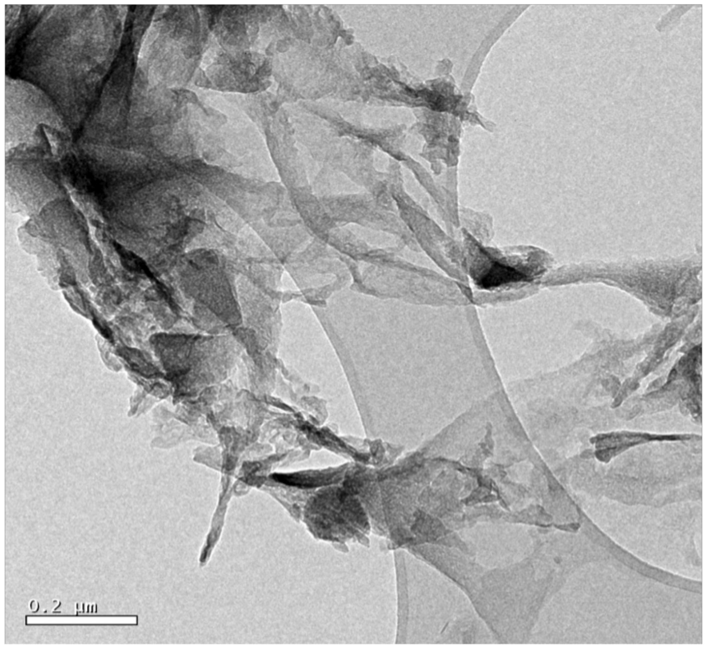

Fig.1 The carbon in the oldest section of the Barberton drill core consists entirely of this, mostly fragmented (by stress in the mineral separation process?) thin film and spiny spindles of disordered rhombohedral graphite.

The swath of film running through the image is a branch of the support membrane.

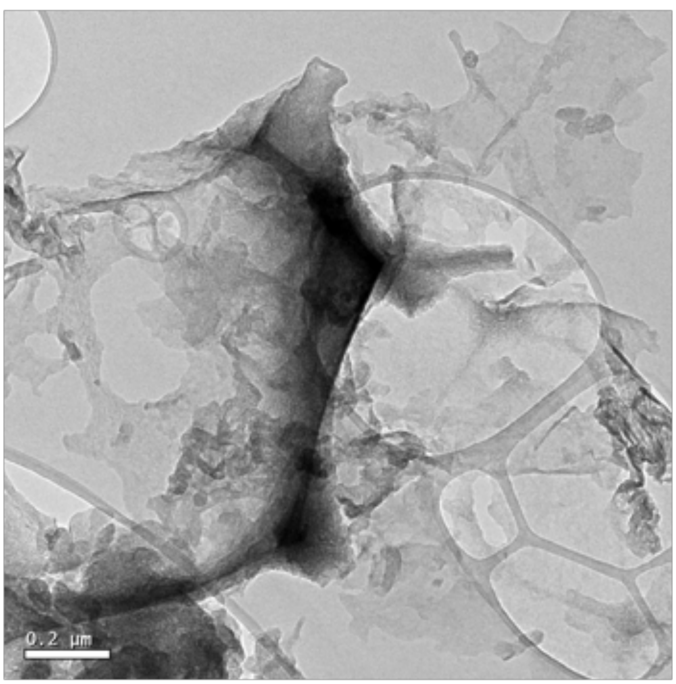

Fig.2. Unbroken carbon bulb with stubs of broken off spiny spindle protrusions

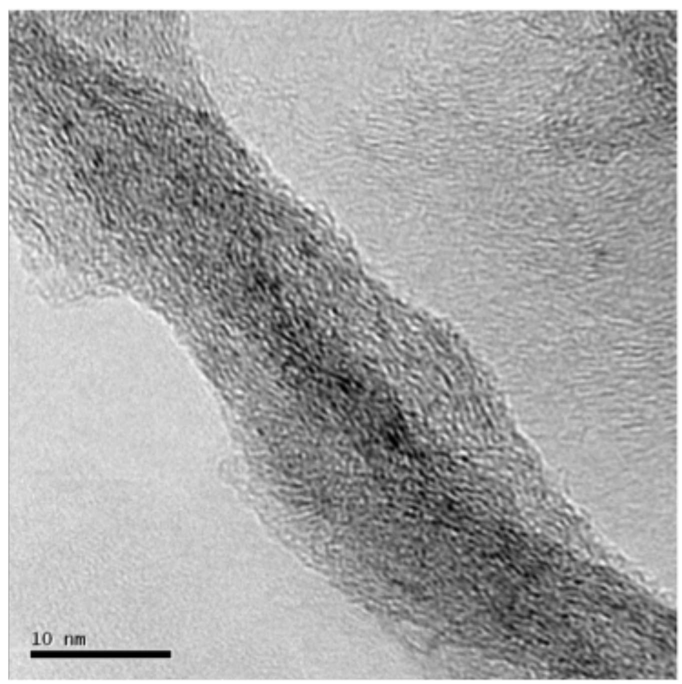

Fig.3. Spine at high image enlargement showing internal structure with incipient alignment of graphenes into rhombohedral graphite

Scale bar 10 nm

Research Summary Jeffrey L. Bada, Distinguished Research Professor, GRD

The fate of non-biological amino acids in the primitive oceans on Earth: Amino acids are biomolecules thought to have existed throughout the oceans of the early Earth, and likely played a vital role in the origin and evolution of life. However, the relative duration of amino acids in the early oceans remains unclear. Experiments were began in 1992 to evaluate this uncertainty. Beach sand and seawater were collected near the SIO pier. This mixture was paced in a small glass vessel (exposed to laboratory air via an open stop-cock) and then spiked with the protein amino acids glycine, racemic alanine, and racemic valine, as well as the non-protein amino acids α-aminoisobutyric acid and racemic isovaline. Aliquots were collected from this mixture over a 21-year period, and analyzed for the spiked amino acid abundances. The results showed that glycine, L-valine, and D, L- alanine degraded rapidly, yet surprisingly, D-valine was resistant to biological degradation. The non-protein amino acids studied here were also highly stable. In the early oceans, amino acid lifetimes were likely primarily dictated by circulation through hydrothermal systems. Considering such a scenario, our results indicate that select D-enantiomers of protein amino acids, and non-protein amino acids, could have persisted thousands to millions years longer than most protein amino acids.

Preliminary publication related to this research: Amino acid stability in the early oceans, E. T. Parker, K. L. Brinton, A. S. Burton, D. P. Glavin, J. P. Dworkin and J. L Bada, Astrobiology Science Conference; 15-19 Jun. 2015; Chicago, IL; United States

Geochemical conditions on the primitive Earth: Is formamide a plausible geochemical solvent? Prebiotic reactions required to convert simple monomers into simple polymers are generally very unfavorable in water. To overcome these issues, the use of pure formamide (H_2CNOH) as an alternative solvent has become increasingly popular. However, there are several concerns associated with whether pure formamide was geochemically plausible on the early Earth. The main problem is that formamide is very hydroscopic and rapidly absorbs water from the environment when exposed to air for only short periods of time. We have confirmed that pure formamide is very hydroscopic and rapidly picks up water that in turn acts to promote formamide hydrolysis to formic acid and ammonia, making formamide unstable and less suitable as an alternative reaction medium. Even if a plausible geochemical process that might have produced pure formamide existed, it would have still likely contained significant amounts of dissolved salts that could alter the solvent properties. How this affects prebiotic synthesis reactions in is basically unknown and need to be addressed. A peer-reviewed publication on this research was recently published.

Bada, Jeffrey L., John H. Chalmers, and H. James Cleaves. "Is formamide a geochemically plausible prebiotic solvent?." *Physical Chemistry Chemical Physics*2016, **18**, 20085-20090
DOI: 10.1039/C6CP03290G

Laboratory Simulated Volcanic Lightning and Prebiotic Synthesis

In 2014, a group at Ludwig Maximilian University in Munich, Germany published a paper titled “Experimental generation of volcanic lightning” **(**Cimarelli, Corrado, et al. 2014, *Geology* **42**, 79-82). This caught my attention because we had earlier published a paper on the potential importance on the synthesis of prebiotic compounds in lightning often associated with volcanic eruptions. I contacted the leader of the group, Donald Dingwell, about perhaps doing a collaborative project. He responded enthusiastically and we started some experiments using the volcanic lightning experimental setup he had in Munich. We selected what mixture of gases would be used in the apparatus and collected volcanic ash from various volcanic eruptions in Japan. After using a combination of gases and ash in the simulated volcanic lightning apparatus, we analyzed the ash for interesting prebiotic compounds. Initial analyses have indicated that ammonia as well as some amino acids were synthesized in the experiments with a mildly reducing gas phase. We are now carrying out a systematic series of analyses to determine whether some essential prebiotic reagents such as hydrogen cyanide, aldehydes/ketones, etc. were made during the experimental lightning. These reagents then combined to yield the amino acids we have detected.

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

Research in the Barbeau laboratory focuses on the chemistry and biology of trace element cycling in marine systems, in particular the elements iron (Fe) and copper (Cu). Both of these elements have significant biogeochemical impacts in the marine environment due to their role as necessary micronutrients (Fe and Cu) and/or toxins (Cu) for marine microbiota. In recent years we have expanded our research program in two areas in particular: (1) using electrochemical methods to characterize the organic chemical complexation of Fe and Cu in the marine environment; and (2) using molecular biology tools, -omics, and bioinformatics to study mechanisms of Fe acquisition in marine microorganisms. Examples of all these types of studies can be found in the list of recent publications from the lab (below). This year, for the first time, we published a paper which combines electrochemical analysis and metagenomic approaches to examine the connections between the production of strong Fe-binding ligands in the marine pelagic environment and the presence of specific microbial taxa (Hogle et al., *L&O Letters* 2016).

These published results come from a 2012 process cruise that the Barbeau group participated in as part of the California Current Ecosystem Long Term Ecological Research program aboard the R/V *Melville*. During the cruise we set up an incubation study using surface waters collected from an oligotrophic, warm anticyclonic eddy west of Point Conception. In a series of Fe- and macronutrient-amended 6-day grow-out incubations we compared total dissolved Fe and macronutrient drawdown, and phytoplankton pigments and community composition. The concentration and conditional binding strength of organic Fe-binding ligands were also measured using Multiple Analytical Window Competitive Ligand Exchange Adsorptive Cathodic Stripping Voltammetry methods (MAW CLE-ACSV). This methodology allows for the detection of a wider range of Fe-binding ligand classes than is determined in a single analytical window, and an improved definition of conditional stability constants based on the optimal analytical window for a given ligand strength. We coupled the MAW CLE-ACSV analysis with high-throughput 16S rRNA marker gene surveys in order to explore how bacterioplankton assemblage composition is connected to the production of different classes of Fe-binding ligands.

Incubations with low nitrate:Fe addition ratios had near complete macronutrient consumption and higher phytoplankton biomass compared with incubations with higher nitrate:Fe addition ratios, but both treatments were dominated by diatoms. However, we only detected the strongest Fe-binding ligand class (L_1) at the conclusion of the low nitrate:Fe treatments, and L_1 ligands were generally correlated with an increased abundance of copiotrophic bacteria, particularly *Alteromonas* strains (Figure 1). Ultimately, these robust correlations suggest a potential linkage between copiotrophic bacteria and strong Fe-binding ligand production during the early senescence phase of a phytoplankton bloom, perhaps as a means of increasing the efficiency with which bacteria recycle phytoplankton-associated forms of Fe. Although marine bacteria were identified nearly two decades ago as potential sources for strong Fe-binding organic ligands detected in seawater, specific linkages between ligands detected in natural water and the microbial community remain unclear. Our results suggest that copiotrophic bacteria deserve further attention as a source of strong Fe-binding ligands in marine environments, indicating that pulses of ligand production may be connected to the microbial turnover of organic matter in planktonic systems.

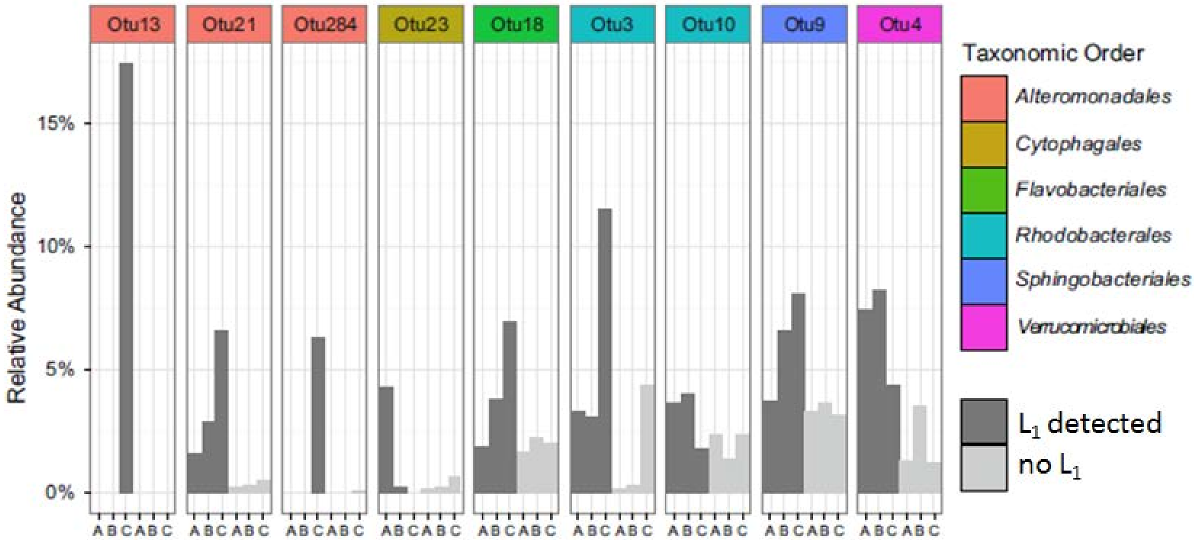

Figure 1. Bar plot of copiotroph OTUs most abundant in incubations where the strongest (L_1) class of Fe-binding organic ligands was detected. Copiotroph OTUs have a mean relative abundance greater than 1% of all reads in each replicate and the "L_1 detected" mean is at least 1.5 times greater than the "no L_1" mean. Samples where L_1 was detected are dark gray while no L_1 samples are light gray. Modified from Hogle et al. 2016, *L&O Letters*.

Recent Publications

Semeniuk, D. M., R.L. Taylor, R.M. Bundy, W.K. Johnson, J.T. Cullen, M. Robert, K.A. Barbeau, and M.T. Maldonado. 2016. Iron-copper interactions in iron-limited phytoplankton in the northeast subarctic Pacific Ocean. *Limnol. Oceanogr*. 61:279-297.

Hogle, S. L., J.C. Thrash, C.L. Dupont, and K.A. Barbeau. 2016. Trace metal acquisition by marine heterotrophic bacterioplankton with contrasting trophic strategies. *Appl. Env. Microbiol*. 82:1613-1624.

Hogle, S. L., R.M. Bundy, J.M. Blanton, E.E. Allen, and K.A. Barbeau. 2016. Copiotrophic marine bacteria are associated with strong iron-binding ligand production during phytoplankton blooms. *Limnol. Oceanogr. Letters.* doi: 10.1002/lol2.10026

Bundy, R.M., M. Jiang, M. Carter and K.A. Barbeau. 2016. Iron-Binding Ligands in the Southern California Current System: Mechanistic Studies. *Front. Mar. Sci.* 3:27. doi:10.3389/fmars.2016.00027

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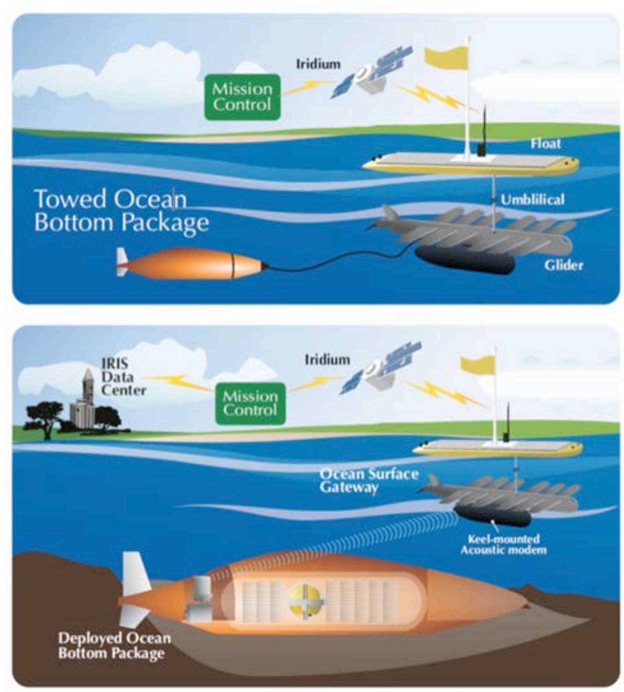
Research Interests: Global seismological observations, marine seismo-acoustics, geophysical instrumentation, deep ocean observing platforms, ocean robotics, global communications systems

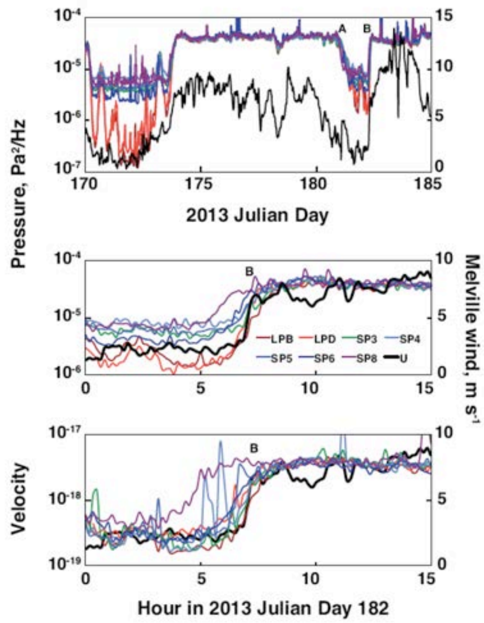
As a result of the MRI Autonomous Deployable Deep Ocean Seismic System, my collaborators John Orcutt, Gabi Laske, Martin Rapa, Jeff Babcock, and I have developed a concept for a robotically installed, online, ocean seismic observatory. Illustrated in the figure below, the top panel shows the system being autonomously deployed with the wave glider acting as the tug. The lower panel shows the ocean bottom package deployed and sitting on the seafloor. Sensor data are telemetered acoustically through the ocean column to a free-floating Ocean Surface Gateway (OSG) hovering above the OBP. The OSG re-transmits the data via satellite to the shore while it holds station over the OBP.

The principal design features of the system are:



1. Be deployable without the use of a ship. The hydrodynamic design of the bottom package is optimized for low drag when towed and to reduce current-induced noise on the bottom. When deployed it does not have the buoyancy to return to the surface – it can be left on the seafloor or be retrieved by a ROV at some convenient time when a ship is ready and available;
2. Provide continuous near-real time streaming of sensor data sampled at one sample per second or faster from the seafloor to land with a latency of less than a few minutes;
3. Provide higher rate data segments telemetered either upon request or automatically after signal detection; and
4. Operate for a two-years while streaming continuous data at one sample per second (sps) plus about 1200 hours of 40 sps data on-request.

I continued my analysis of the seismic and acoustic data collected during the OBSANP experiment in the deep ocean of the subtropical NE Pacific. A quick (~1 hr) and broad-band ($1 < f < 400$ Hz) increase in pressure and vertical velocity on the deep ocean floor was observed on seven ocean floor instruments comprising a 20 km array. We associate the jump with the passage of a cold front and focus on the 4 and 400 Hz spectra. At every station the time of the jump is consistent with the front coming from the northwest. The apparent rate of progress, 2.8 - 5.6 ms^{-1}, agrees with meteorological observations. The acoustic radiation below the front is modeled as arising from a moving half-plane of uncorrelated acoustic dipoles with a 10 km transition zone over which the radiator strength increases linearly from zero. With this model the time derivative of the jump at a station yields a second and independent estimate of the front's speed, 2.4 ms^{-1}. For the 4 Hz spectra, we take the source physics to be Longuet-Higgins radiation. The spectra at 400 Hz have a similar time constant but the jump occurs 25 minutes later. We are still working on the implications of this difference for the source physics.



The figure on the left shows that the 4 Hz spectral estimates of pressure (top) are nearly independent of wind in the middle week when the speed rarely dropped below 6 ms^{-1}. This span is bracketed by periods of low winds and spectral levels. The spectra have been equalized to obtain superposition during the intervals with high winds. For the hours surrounding time B, the spectra of pressure (middle) and vertical velocity (bottom, units $(ms^{-1})^2s$) show the acoustic jump varies with location and is more gradual than the jump in the wind. The legend in the middle panel shows the color coding for the 7 stations. The wind in top panel is smoothed over 1 hr, and in the others 10 minute smoothing was applied.

Recent Publications

Jonathan Berger, Gabi Laske, Jeffrey Babcock, and John Orcutt (2016). An ocean bottom seismic observatory with near real-time telemetry. Earth & Space Science, 2. doi:10.1002/2015EA000137.

W.E. Farrell, J. Berger, J.R. Bidlot, M. Dzieciuch, W. Munk, R.A. Stephen, and P.F. Worcester. (2016). Wind Sea behind a Cold Front and Deep Ocean Acoustics. J. Phys. Ocean. doi:10.1175/JPO-D-15-0221.1

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Sunbelt Publications has published my guide to local natural history, with forays into local geology and botany. *Coast to Crest, and Beyond* gives 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).

I am currently working on a revision (fourth edition) of my book *The Sea Floor: An Introduction to Marine Geology*, published by Springer. This was coauthored with Eugen Seibold (now deceased).

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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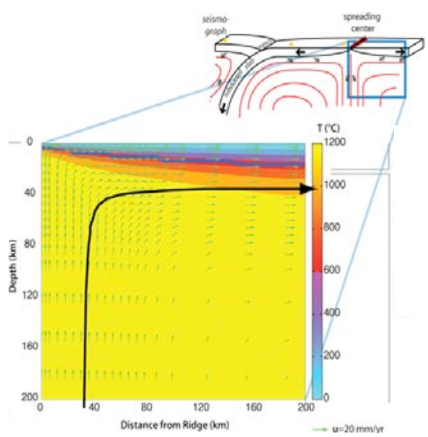
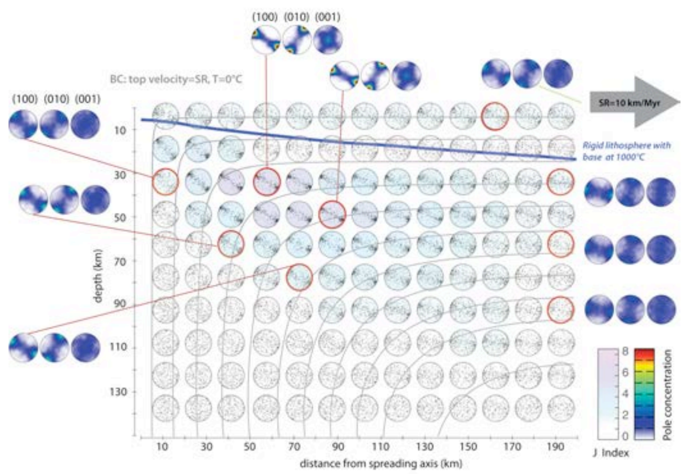
Research Interests*:* Mantle flow, mineral deformation, and tectonic evolution along plate boundaries using marine geophysics and numerical modeling.

This year my research focused in two areas– mantle flow with anisotropic rheology and oceanic core complex structure.

A collaborative project with colleagues at Cornell and Paris tested feedbacks between mineral alignment and upper mantle flow pattern, tracking grain-scale deformation by dislocation creep and linking that to regional scale flow. We employed a second-order visco-plastic self consistent method, linking the resulting viscosity solutions to a FEM calculation of regional flow. Local viscosity was calculated throughout the model, based on the response of a mineral aggregate with crystal preferred orientation (CPO) that developed along a flow path from the base of the model to the given finite element position.





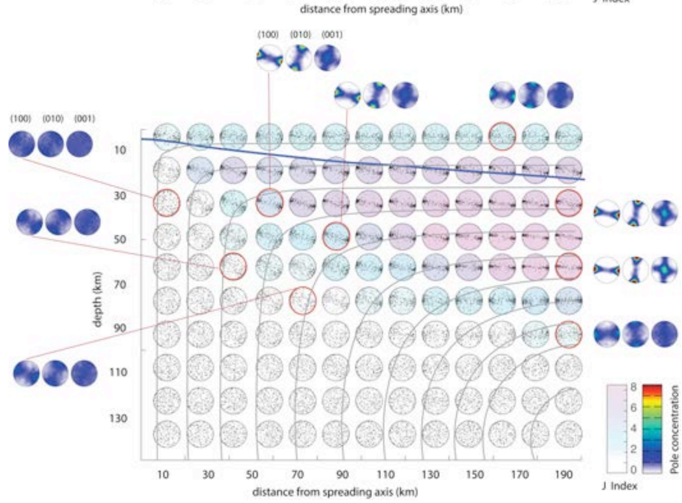


Figure. Model geometry (upper left) showing basic flow pattern (green vectors) and temperature (color). Reference model (upper right) and full-coupled, self-consistent model (lower right) show flowpaths (gray lines) and CPO (pole figures: olivine a-axes throughout model; a-, b-, and c-axis concentrations contoured in a few locations), shaded by J Index, which quantifies the strength of the local CPO.

Through a series of numerical experiments, we explored the rheologic effects of CPO and evaluated the magnitude of possible impacts on the pattern of flow and associated seismic signals. Stable flow and CPO distributions were obtained after several iterations. The textured olivine polycrystals were found to have anisotropic viscosity tensors in a significant portion of the model space. This directional dependence in strength impacted the pattern of upper mantle flow. For background asthenosphere viscosity of 10^{20} Pa s and a rigid lithosphere, the modification of the corner flow pattern was found to be modest, but the change could have geologic implications. Feedback in the development of CPO occurred, particularly near and below the base of the lithosphere. Stronger fabric was predicted below the flanks of a spreading center for fully coupled, power-law polycrystals than was previously determined for linear, intermediate coupling polycrystal models. The predicted SKS splitting was found to be modestly different (~0.5 s) between the intermediate and fully coupled cases for oceanic plates less than 20 Myr old. Surface waves, on the other hand, were predicted, in work with Gabi Laske, to have twice the magnitude of Rayleigh wave azimuthal anisotropy for fully coupled power law flow/polycrystals than for linear, intermediate coupled flow/polycrystal models.

The overall flow pattern is still essentially a corner flow, but upwelling rate in the subaxial zone is somewhat reduced. This could result in decreased partial melting. Material starting within 50 km of the spreading axis rises to a level that is a few km shallower when CPO-based anisotropic rheology is incorporated. Material starting at depth outside this zone rises as much as ~20 km shallower, and at higher rates near the inflection point where the flow turns the corner. This could broaden the low-percent partial melting zone compared to the isotropic (scalar) viscosity case. The distribution of CPO differs from past linked flow/anisotropy analyses in strength and alignment direction in key regions of the model space. As off-axis shearing becomes dominant, the sub-lithospheric region develops horizontal preferred direction rather than retaining a diffuse version of the inclined alignment that develops in the flow corner. The strength of the off axis CPO is greater than predicted for the intermediate coupling case. These asthenosphere anisotropy results indicate that proceeding with further modifications to optimize the linked numerical scheme is both warranted and would be necessary, for computational efficiency that would allow finer discretization so that lithosphere anisotropy could be more reliably estimated.

My oceanic core complex work this year started with 2 months at sea on the International Ocean Discovery Program drilling ship, where my role was to measure physical properties of core recovered from the footwall to detachment fault now exposed at the seafloor, and to analyze logs obtained in the borehole. These data indicate that physical properties (seismic velocity, resistivity, magnetic susceptibility) at the Atlantis Bank core complex, on the Southwest Indian Ridge, are generally similar to those I helped obtain previously at Atlantis Massif core complex, on the Mid-Atlantic Ridge. Current work focuses on more detailed investigation of the relation between velocity, anisotropy, and resistivity on geologic characteristics such as alteration and deformation.

Recent Publications

Harding, A.J., A.F. Arnulf, D.K. Blackman, Velocity structure near IODP Hole U1309D, Atlantis Massif, from waveform inversion of streamer data and borehole measurements, Geochem. Geophys. Geosys. 17, DOI: 10.1002/2016GC006312, 2016.

Blackman, D.K., D.E. Boyce, O. Castelnau, P. R. Dawson, and G. Laske, Effects of crystal preferred orientation on upper mantle flow near plate boundaries: Rheologic feedbacks and seismic anisotropy, Geophysical J. Intl., submitted July, moderate revision Nov 2016.

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Distinguished Researcher and Senior Lecturer
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Research Interests: GPS/GNSS, space geodesy, crustal deformation, early warning systems for natural hazards, seismogeodesy, GPS meteorology, data archiving and information technology, sensors

The SOPAC research group is application oriented with an emphasis on mitigating effects of natural hazards on people and critical infrastructure through improved forecasting, early warning and rapid response to events such as earthquakes, tsunamis, volcanoes 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, to communicating actionable information the "last mile" to emergency responders and decision makers during disasters. We maintain a global archive of GNSS data including a growing database of high-rate measurements of large earthquakes, with accompanying IT infrastructure and database management system. In 2015-2016, the SOPAC group included Peng Fang, Jennifer Haase, Jianghui Geng, graduate students Dara Goldberg, Jessie Saunders at SIO, Lina Su, Minghua Wang and Jing Qiao (visiting from China), and Mindy Squibb, Anne Sullivan, Maria Turingan, Glen Offield, Allen Nance and Alex Turner.

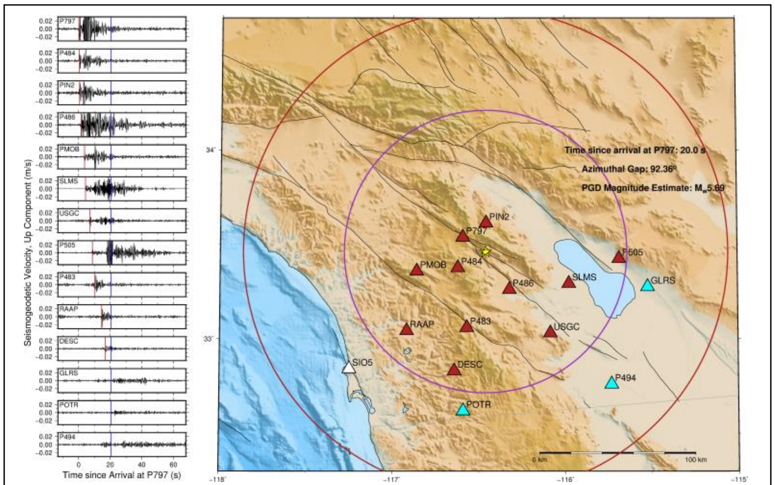

Figure 1. Example of SOPAC's seismogeodetic earthquake early warning system for the 2016 Mw5.2 Borrego Springs earthquake. Shown is the warning information available 20.0 s after the first detection at station P797 closest to the epicenter. Once 4 stations have triggered, an estimate of the hypocenter can be made, which is updated as more stations are triggered. The PGD scaling relationship indicates a magnitude of Mw5.66, 0.46 magnitude units larger than the final magnitude, which may be the lower limit because there was no permanent displacements at any of the stations. **Left:** Seismogeodetic velocity time series for local seismogeodetic stations (GNSS with SIO GAPs). Blue line denotes current epoch, red line denotes automated detection time at each station. **Right:** Automated hypocenter estimate (yellow star) from weighted least squares solution and seismogeodetic station coverage (triangles) for this event. Red triangles denote stations that recorded a trigger. Light blue stations did not trigger given their low signal-to-noise ratio. The white triangle shows the location of malfunctioning station SIO5, which was removed from the analysis. Concentric circles indicate theoretical P-wave (red) and trailing S-wave (magenta) fronts based on hypocenter location and calculated earthquake origin time. S-wave front is used as a proxy for shaking onset time. From Goldberg and Bock (2016).

Earthquake Early Warning and Seismogeodesy

Reducing warning time is the key goal in early warning for earthquakes of ~M5 or greater in the near-source where losses are most severe. Rapid earthquake characterization requires real-time near-field displacement data in addition to strong motion accelerometer data. Accurate broadband displacement and velocity waveforms can be estimated by *seismogeodesy,* the optimal combination of high-rate GNSS displacement observations with collocated very high-rate accelerometer data (Bock et al., 2011). Currently, few collocated GNSS/strong-motion stations exist along the western coast of the U.S. where large earthquakes, including tsunamigenic earthquakes, can occur. For the purposes of affordable monitoring, we developed the SIO Geodetic Module and low-cost MEMS accelerometer packages ("GAPs"), designed as a simple plug-in for existing GNSS stations. The Geodetic

Module is an instrument that receives, time tags, buffers, analyzes and transmits data from multiple sensors, including a GNSS receiver, MEMS accelerometer, and MEMS meteorological instruments (pressure, temperature and humidity). The MEMS meteorological data allows us to estimate the variations in water vapor content 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., 2015).

Testing of the GAPs against observatory-grade accelerometers was conducted in an experiment on the Large High-Performance Outdoor Shake Table (LHPOST) at UCSD in December 2013 through January 2014, which used large-magnitude earthquake simulations based off of the seismic hazard for Berkeley, CA and Seattle, WA. Direct comparison of SIO MEMS accelerometers with observatory-grade Kinemetrics EpiSensor ES-T accelerometers during these experiments indicated that the two types of accelerometers agree within frequency range of engineering and seismological interest (Saunders et al., 2016). Currently, there are 25 collocated GNSS stations equipped with SIO GAPs in the field, 10 in the San Francisco Bay Area and 15 in southern California. We were able to retrospectively analyze real-time data collected for several magnitude 4 earthquakes in southern and northern California equipped with the SIO GAPs (Saunders et al., 2016), as well as the real-time recording of displacements and seismic velocities for the 2016 M5.2 Borrego Springs earthquake whose epicenter was within our GAPs network.

In 2016 we implemented an automated detection algorithm that uses the seismogeodetic velocities to pick on the P-wave on an individual station basis (Figure 1). Once four detections have occurred the algorithm using a weighted least squares inversion for the earthquake's hypocenter. This is followed by a rapid magnitude estimation using P-wave amplitude (Pd) and peak ground displacement (PGD) based on earthquake scaling relationships (Melgar et al., 2015). The seismogeodetic dataset is uniquely able to rapidly estimate magnitude in the near-source region since it avoids saturation effects associated with seismic data alone. These initial products are used for a down-the-line CMT solution, finite fault slip model, and tsunami model to provide a more detailed description of rupture parameters and potential hazard. We are working under a NASA-funded project to transfer our seismogeodetic system to NOAA's Tsunami Warning Centers in Alaska (National TWC) and Hawai'i (Pacific TWC).

***Publications* (2015-2016)**

Bock, Y. and D. Melgar (2016), Physical Applications of GPS Geodesy: A Review, Rep. Prog. Phys. 79, 10, doi:10.1088/0034-4885/79/10/106801.

Bock, Y., D. Melgar, B. W. Crowell (2011), Real-Time Strong-Motion Broadband Displacements from Collocated GPS and Accelerometers, Bull. Seismol. Soc. Am., 101, 2904-2925, doi: 10.1785/0120110007.

Bock, Y., S. Kedar, A. W. Moore, P. Fang, J. Geng, Z. Liu, D. Melgar, S. E. Owen, M. B. Squibb, F. Webb (2016), Twenty-Two Years of Combined GPS Products for Geophysical Applications and a Decade of Seismogeodesy, International Association of Geodesy Symposia, Springer International Publishing, doi:10.1007/1345_2016_220.

Galetzka, J., et al. (2015), Slip pulse and resonance of Kathmandu basin during the 2015 Mw 7.8 Gorkha earthquake, Nepal imaged with space geodesy, Science, 349, 1091. doi: 10.1126/science.aac6383

Geng. J. and Y. Bock (2015), GLONASS fractional-cycle bias estimation across inhomogeneous receivers for PPP ambiguity resolution, J. Geod., doi 10.1007/s00190-015-0879-0

Goldberg, D., Y. Bock (2016), Self-contained local seismogeodetic early warning system: detection and location, submitted to J. Geophys. Res. Solid Earth.

Melgar, D., et al. (2015), Earthquake Magnitude Calculation without Saturation from the Scaling of Peak Ground Displacement, Geophys. Res. Lett. 42 (13), 5197-5205. doi: 10.1002/2015GL064278

Moore, A.W., I. J. Small, S. I. Gutman, Y. Bock, J. L. Dumas, P. Fang, J. S. Haase, M. E. Jackson, J. L. Laber (2015), National Weather Service Forecasters Use GPS Precipitable Water Vapor for Enhanced Situational Awareness during the Southern California Summer Monsoon, Bull. Amer. Meteorol. Soc. (BAMS) 96(11), 1867-1877. DOI:10.1175/BAMS-D-14-00095.1

Saunders, J. K., D. E. Goldberg, J. S. Haase, D. G. Offield, Y. Bock, D. Melgar, J. Restrepo, R. B. Fleischman, A. Nema, J. Geng, C. Walls, D. Mann, G. Mattioli (2016), Seismogeodesy using GNSS and low-cost MEMS accelerometers: perspectives for earthquake early warning and rapid response, Bull. Seismol. Soc. Am., 106, 6, pp. –, doi: 10.1785/0120160062.

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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 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.

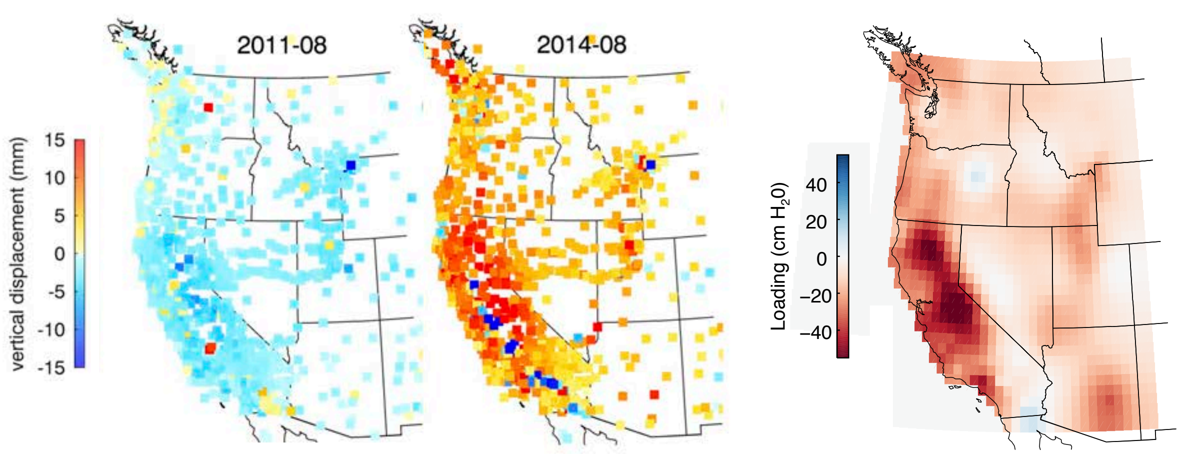

Figure 1: **Left**: Spatial distribution of vertical displacements from Plate Boundary Observatory continuous GPS stations in the western USA in March of 2013 and 2014. Color indicates deviations of seasonally-adjusted elevations from decadal mean, with blues related to subsidence and yellow-reds related 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 currently evaluating improvements between Baseline B and Baseline C datasets. Our ongoing interaction with the CryoSat mission team has led ESA to switch CryoSat from SARIN to LRM mode for all passes over the salar de Uyuni from 2015 onward, allowing us to provide a cross-calibration of elevations from these different operational modes.

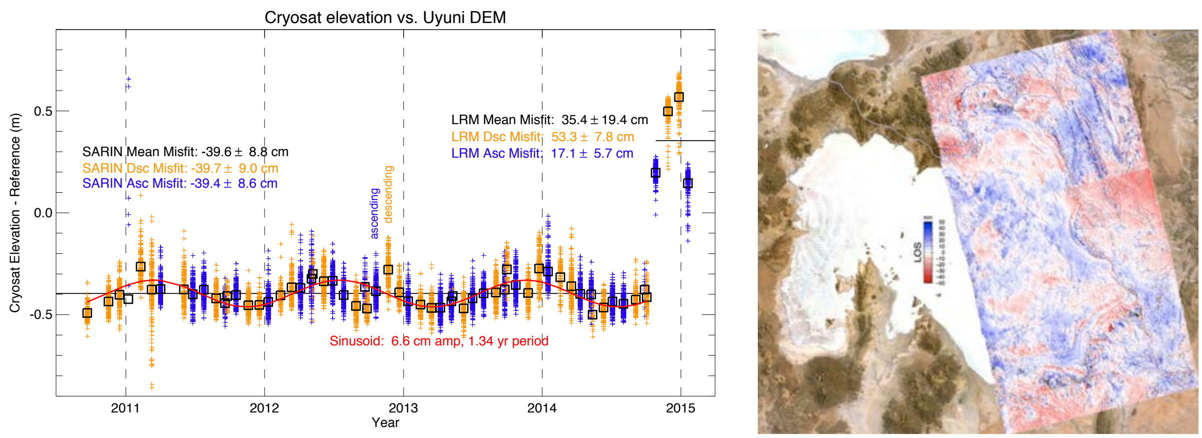

Figure 2: **Left**: Cryosat elevation validation relative to the salar de Uyuni DEM, with residuals showing a.) a uniform range bias of -40 cm for SARIN mode and +35 cm for LRM mode, b.) an 7 cm amplitude sinusoidal anomaly of 1.34 yr period that is still unexplained, and c.) higher range resolution 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.

Publications since October 2015

Kramer, M., W. Holt, A. Borsa, (in review). "Tectonic Seasonal Loading Inferred from cGPS Measurements as a Potential Trigger for the 6.0 Magnitude South Napa Earthquake." J. Geophysical Research: Solid Earth

Sun, X., Abshire, J., Borsa, A., Fricker, H., Yi, D., Dimarzio, J., Brunt, K., Harding, D., Neumann, G. (in review). "ICESat/Glas Altimetry Measurements: Signal Dynamic Range and Saturation Correction." IEEE Transactions on Geoscience and Remote Sensing

Trugman, D.T., P. Shearer, A. Borsa, Y. Fialko (2016). “A comparison of long-term changes in seismicity at the Geysers, Salton Sea, and Coso geothermal fields.” J. Geophysical Research: Solid Earth, **121**

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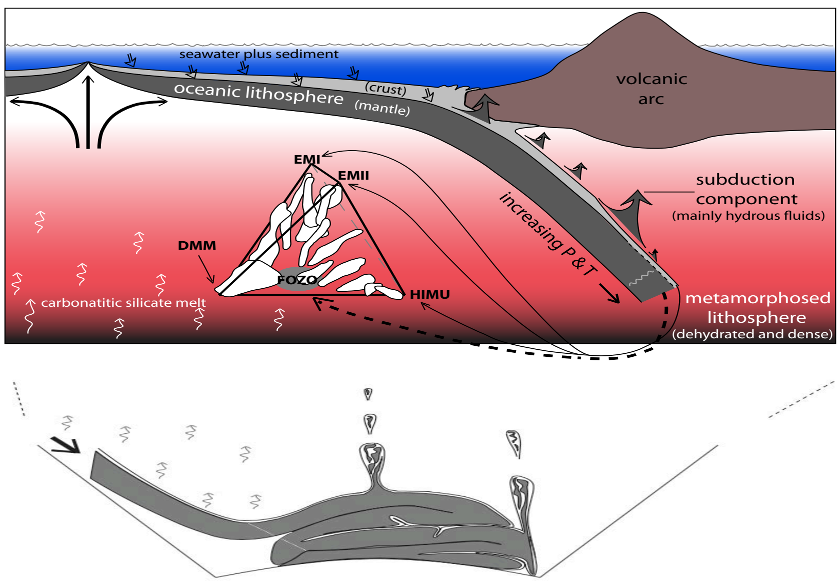
Research Interests: geochemistry and petrogenesis of magmas produced within and along divergent and convergent margins of tectonic plates; magmatic and tectonic evolution of continental margins; chemical geodynamics

The bulk of subduction zone or arc magmas are produced by partial melting of the mantle wedge metasomatized by the so-called 'slab component'. This component is enriched in volatiles and other fluid-mobile elements and mainly comes from subducted sediment and underlying altered oceanic crust (AOC). Many studies have shown a strong link between subduction component (input) and arc magmas (output), particularly in sedimented arc-trench systems. The Izu-Bonin system is basically sediment-poor and, thus, the observed latitudinal compositional variation of its arc magmas, particularly that of Pb isotopes, must be coming from AOC. Indeed, AOC is estimated to supply up to ~50% or more of the Pb in arc magmas. However, a part of the Izu-Bonin arc magma chemistry requires influx of Pb from a subducted Indian-type AOC, but the spot sample of incoming AOC at Ocean Drilling Program (ODP) Site 1149 in the Pacific Plate subducting beneath Izu-Bonin arc is Pacific-type. The apparent discrepancy of Pb input and output in the Izu-Bonin system thus puts into question the concept of AOC being an important source of Pb in arc magmas and our understanding of the slab component in general.

This past year, my student and I continued analyzing the AOC samples collected by dredging during the NSF-funded expedition aboard R/V Revelle in October-November 2014 (RR1412 Cruise) to sample the Pacific Plate subducting beneath the Izu-Bonin arc. The main objective of the entire investigation is to test whether AOC samples from the northern, younger (<125 Ma) segment of the Pacific Plate subducting beneath Izu-Bonin arc have an Indian-type signature, similar to the composition of arc magmas erupting in the northern section of the Izu-Bonin arc. Preliminary major element data for the AOC indicate that the older, southern side of ODP Site 1149 (127 Ma) is normal, Pacific-type tholeiitic basalt whereas the younger, northern side of the drill site is more alkalic. This compositional trend is supported by an increase in incompatible trace element concentrations and their ratios with less incompatible trace elements. Thus, preliminary data indicate that there is at least a compositional change in the subducting AOC at ~125 Ma. However, we need more analytical data, particularly Sr, Nd and Pb isotopes, in order to verify whether AOC indeed provides the subduction component responsible for the Indian-type isotopic composition of the northern Izu-Bonin arc magmas.

Oceanic basalts have high Pb isotopic ratios that indicate high U/Pb or high μ (HIMU) mantle components in their sources. This is inconsistent or paradoxical with the known geochemical behavior of U and Pb in the mantle. Previously, I proposed that recycled marine carbonates are the key ingredient in HIMU components. I hypothesized that a small amount (a few %) of recycled Archaean marine carbonates (primarily $CaCO_3$) inherently had high U/Pb and low $^{87}Sr/^{86}Sr$ and, thus, is the current main source of the distinctly high $^{206}Pb/^{204}Pb$, $^{207}Pb/^{204}Pb$ and low $^{87}Sr/^{86}Sr$ isotopic and some of the major-trace element compositions of classic HIMU whereas post-Archaean marine carbonates are the main source of younger HIMU or 'FOZO' mantle sources. I also proposed a conceptual model showing that FOZO mainly consists of the lithospheric mantle portion of ancient oceanic slabs that have accumulated deep in the mantle, perhaps all the way to the core-mantle boundary. Such an ultramafic source is geochemically depleted due to prior extraction of basaltic melt plus removal of the enriched subduction component from the slabs through dehydration and metamorphic processes. Combined with other proposed models in the literature, the conceptual model can provide reasonable solutions for the $^{208}Pb/^{204}Pb$, $^{143}Nd/^{144}Nd$, $^{176}Hf/^{177}Hf$, and $^{3}He/^{4}He$ isotopic characteristics of oceanic basalts.

Significantly, the HIMU signature of oceanic basalts additionally generated 2 other Pb paradoxes. These are the unexpectedly low Th/U of the mantle and constant Ce/Pb and Nb/U ratios of oceanic basalts. Many geochemists had been (and still are) trying to constrain the source(s) of the radiogenic Pb isotopes and solutions to the concomitant paradoxes for the last ~40 years. However, although available proposed solutions are highly satisfactory and potentially could indeed solve the paradoxes, in general they are highly individualized and most often contradict each other. In my follow up paper last year (Castillo, 2016), I proposed that the radiogenic Pb isotopes and concomitant paradoxes all pertain to the concentrations and isotopic compositions of inter-related elements in the (same) mantle and, thus, they comprise a 'system of equations' that must be solved altogether or simultaneously. That is, the radiogenic Pb isotopes and concomitant paradoxes pertain to the behavior of the same U, Th and Pb in the Earth's mantle and, thus, their concentrations and compositions must be conserved and/or their masses must be balanced in any solution or set of solutions to the paradoxes. The 3 Pb paradoxes can be solved simultaneously through marine carbonate-fluxed melting of the subducted slab, which is simply an extension of my proposed origin of the HIMU isotopic signature of oceanic basalts.



Cartoon illustrating that the Sr, Nd and Pb isotope-defined EMI, EMII and HIMU corners of the mantle tetrahedron represent recycled crustal material whereas FOZO represents the depleted, lithospheric mantle portion of subducted slab. Enriched carbonatitic silicate melt comes from the crustal material because of carbonate-fluxed melting and this mixes with depleted partial melts from DMM and FOZO. Binary mixing between enriched and depleted mantle components can explain the HIMU isotopic signature of oceanic basalts as well as the other Pb paradoxes.

Recent Publications

Castillo, P.R. "A proposed new approach and unified solution to old Pb paradoxes" Lithos 252-253, 32-40, 2016, doi:10.1016/j.lithos.2016.02.015.

Liu, X., Xu, J., Xiao, W., Castillo, P.R., Shi, Y., Wang, S., Huo, Q., and Feng, Z. " The boundary between the Central Asian Orogenic belt and Tethyan tectonic domain deduced from Pb isotopic data" Journal of Asian Earth Sciences, 2015 , doi:10.1016/j.jseaes.2015.04.039.

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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.

The first complete demonstration of the GPS-Acoustic method adapted to a Liquid Robotics Wave Glider (Fig. 1) was conducted in Cascadia. During July and August 2016, the GPS-A Wave Glider was on a 40-day mission and traveled ~300 hundred miles visiting two sites (one offshore Oregon (NNP1) and one offshore Washington (NGH1)) on the continental slope and a third (JNP1) on incoming Juan de Fuca plate (Fig. 2). The Wave Glider was deployed July 13th from a small boat ~10 miles out of Newport Oregon and travelled at ~1.5 kts to each site, collecting 4-6 days GPS-A data before proceeding to the next site. It returned to ~10 miles offshore Newport and was recovered on Aug. 22nd.

While collecting GPS-A measurements, subsampled data (one ping every two minutes) were sent back via Iridium and these data were processed while the Wave Glider was still on station to verify data quality. Positioning results are compatible with that achieved by GPS-A from ships.

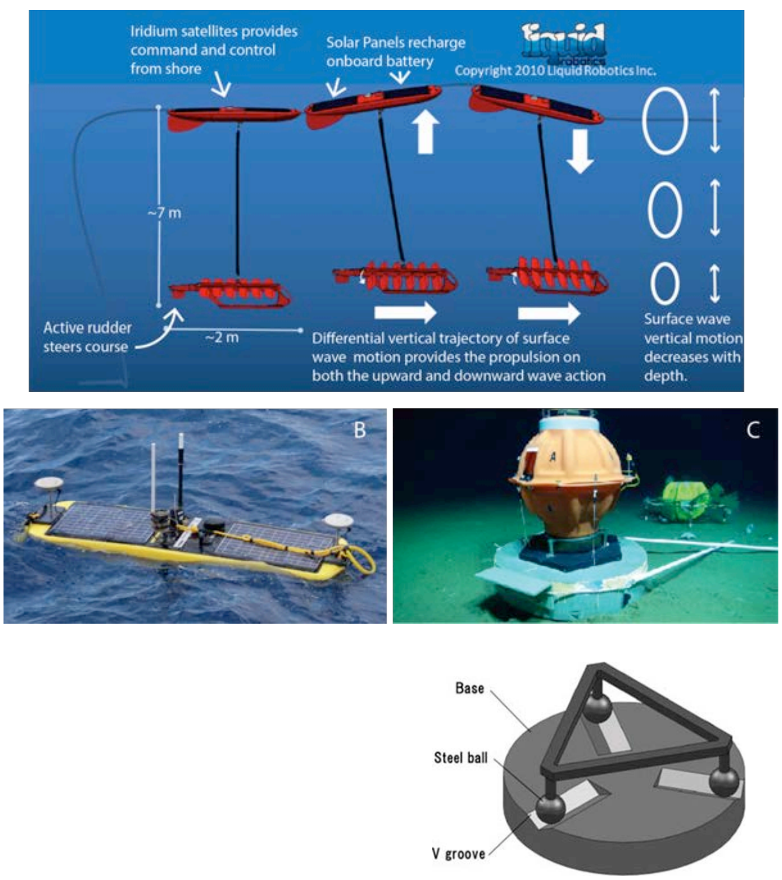

Fig. 1: (A) Wave Glider concept for harvesting wave motion for propulsion. (B) Wave Glider configured for GPS-Acoustic operations underway at sea. (C) Foreground shows new seafloor benchmark with commercial transponder placed approximately 2 m from old (circa 2000) transponder at site offshore Oregon. Insert (at bottom) shows the ball and groove concept that aligns transponder with benchmark. The transponder is held in place by a release that can be triggered acoustically such that it floats to the surface. A ROV can be used at a later date to place another transponder back onto the benchmark with precise registration. In June 2014, we successfully demonstrated ROV Jason removing and replacing the transponders with millimeter-level repeatability. The benchmark/transponder package can be free launched at the sea surface. At the end of the experiment the transponder can be recalled and reused (pool instruments) and the benchmark to be re-occupied to continue.

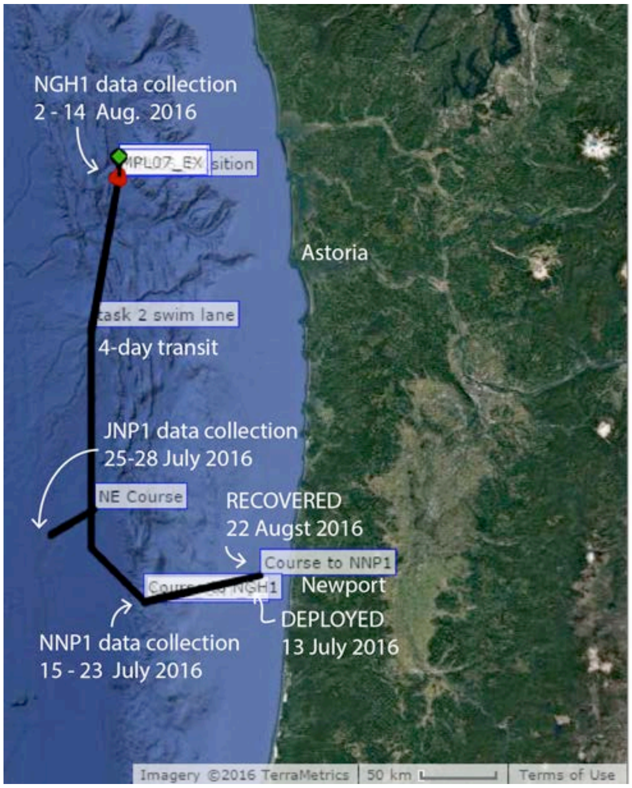

Fig. 2: During July/August 2016, the GPS-A Wave Glider (SFG1) conducted 40-day mission to collect GPS-A data at sites NNP1, JNP1 and NGH1. Nearly 100 hours of GPS-A were collected at NNP1 and ~100 hours at NGH1. RUDICS Iridium returned data parsed (and interpolated) at two minutes allowing a GPS-A solution for the array while still on mission. Results to date show GPS-A positioning with a few centimeter repeatability. The full data sampling is every 15 seconds without interpolation and should results in array repeatability of ~1 cm. While we did not exploiting the near-real time capability, it could be used in the future. Clearly, GPS-A from a Wave Glider provides both the measurement resolution and the operational capability to conduct experiments about 1/100 of the cost of using a UNOLS ship.

References:

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Research Interests*:* geology, igneous & metamorphic petrology, geochemistry, mantle petrology, continental crust, Western USA, tectonics

I am an igneous/metamorphic petrologist with a focus on mantle petrology, particularly, evolution of the lithosphere on Earth and other planets. I use a diverse set of analytical techniques to address fundamental questions such as:

1) **What is the origin and composition of the lithosphere?**
2) **How has the lithosphere evolved over time (Pressure-temperature-composition-deformation-time paths)?**
3) **How does the lithosphere participate in the overall geochemical and geodynamic evolution of a planet?**

I work extensively with mantle xenoliths, samples of the earth's deep interior erupted in volcanic eruptions. Xenolith studies form a fundamental basis of our understanding of earth's geochemical and rheological evolution and, along with indirect geophysical measurements, are the only probes into earth's deep interior. Utilizing recent advances in high resolution *in situ* analytical tools such as SIMS (secondary ion mass spectrometry), laser ablation ICP-MS, and field-emission electron microscopy, I conducted a detailed study of a suite of 30 xenoliths from the Sierra Nevada Batholith, California, USA. The Sierran peridotites are rare samples of deep lithosphere beneath a once active subduction zone, and therefore understanding these peridotites' P-T-t-deformation history will shed new insights into the inner workings of subduction zones. I plan to continue working on xenoliths and other field areas in the Western USA and offshore California here at Scripps Institution of Oceanography.

Recently, I have been interested in coupling geochemistry with microtexture to better understand the evolution of mantle rocks. I found that the LPO (lattice preferred orientation) of Sierran peridotites varied as a function of composition: melt-depleted peridotites had strong, orthorhombic olivine LPOs typical of deformation by dislocation creep, while re-fertilized peridotites had weak, axial-[010] olivine LPOs due to significant contribution from grain-size sensitive creep during melt infiltration (Chin et al., 2016).

Another important finding was that despite the Sierran peridotites' origin in a subduction zone mantle wedge and the observation that many of them had experienced significant (presumably hydrous) melt infiltration, the measured water contents in nominally anhydrous minerals in the peridotites were extremely low (5 – 10 ppm H2O; similar to MORB mantle, the driest reservoir). Such puzzling low water contents can be reconciled with the final cooling of the peridotites from >1000 C to ~700-750 C (Chin et al., 2012), because water solubility in NAMs decreases with decreasing temperature. Intriguingly, a detailed analysis of olivine subgrain boundary microstructures revealed a prevalence of boundaries that formed via the "wet" [100](001) slip system (Figure 1c), yet no evidence for E-type LPO in the xenoliths was found (Figure 1b). This suggests that earlier deformation under moderately hydrous conditions was actually preserved within individual intragranular microstructures, even though the bulk, nominally dry axial-[010] LPO (e.g., all the grains collectively) resulted predominantly from grain-boundary sliding (an inter-granular process) during the last deformation event, melt infiltration. The extremely fast diffusivity of water, combined with subsolidus cooling, is one explanation for apparent inconsistencies commonly observed between LPOs and measured water contents. Subgrains, because they are preserved in the largest grains, represent a "stranded" deformation feature that can help "see through" to earlier deformation events obscured by late-stage melt infiltration or metasomatism. Coupling microtextural information at various scales, from inside individual grains to the aggregate rock, together with mineral chemistry opens up new research directions into understanding mantle evolution.

Such an analysis of subgrain microstructure is only possible with the latest EBSD technology coupled to a FEG-SEM – an analytical capability that will be coming to SIO in Spring 2017. Combined with the basic information from LPO, high-resolution mapping maximizes the science return from a single sample and allows P-T-X-t-deformation paths to be more fully constrained.

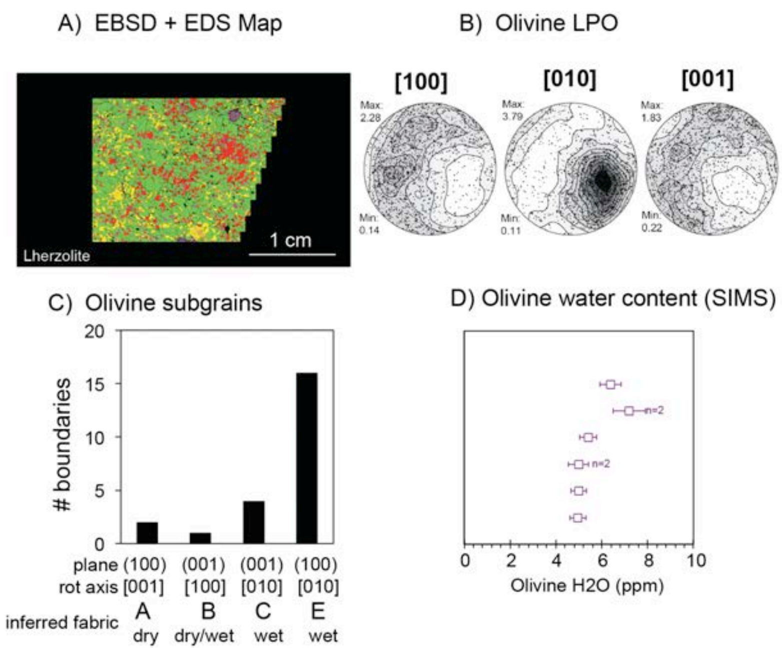

Figure 1. Combined textural and geochemical data of one peridotite xenolith. A) EBSD (crystallographic orientation) and EDS map acquired using automated stage scanning on a field-emission SEM. Green = olivine, red = clinopyroxene, yellow = orthopyroxene, purple = spinel B) Olivine LPO calculated from all the indexed olivine grains in the map and plotted on lower-hemisphere pole figures C) Subgrain microstructures in olivine D) Water content in olivine measured by SIMS

Recent Publications

Chin, E. J., Lee, C. T. A., Luffi, P., & Tice, M. (2012). Deep lithospheric thickening and refertilization beneath continental arcs: case study of the P, T and compositional evolution of peridotite xenoliths from the Sierra Nevada, California. Journal of Petrology, 53(3), 477-511.

Chin, E. J., V. Soustelle, G. Hirth, A. E. Saal, S. C. Kruckenberg, and J. M. Eiler (2016), Microstructural and geochemical constraints on the evolution of deep arc lithosphere, Geochem. Geophys. Geosyst., 17, 2497–2521, doi:10.1002/2015GC006156.

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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. 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: The research vessel Alpha Helix tied up at Santa Rosalia, Baja California, Mexico, prior to the second leg of our 2016 offshore geothermal study.

There are many applications for EM methods in geophysics, and some of our recent efforts have been directed towards offshore geothermal energy, in collaboration with Centro de Investigación Cientifici y de Educación Superior de Ensenada (CICESE). Last year we carried out MT and CSEM surveys in the northern Gulf of California, off San Felipe, and this year we made measurements in the central Gulf out of Santa Rosalia. We used the research vessel Alpha Helix, originally operated by Scripps from 1965–1980 and recently purchased and refurbished by CICESE (Figure 1). The 2015 data were used in the masters theses of Thalia Anaid Aviles Esquivel and Valeria Reyes-Ortega. Thalia used MT data to estimate the location of the spreading center which extends from the East Pacific Rise to the northern Gulf of California, where its location becomes obscured by a thick sequence of sediments. Valeria (now at IGPP as a PhD student) used surface-towed CSEM measurements, collected with the system developed for permafrost studies and described in the 2014 annual report, to look for areas of increased conductivity due to hot fluids in the sediments. Her results (Figure 2) are in good agreement with heat flow measurements, but extend the area studied significantly.

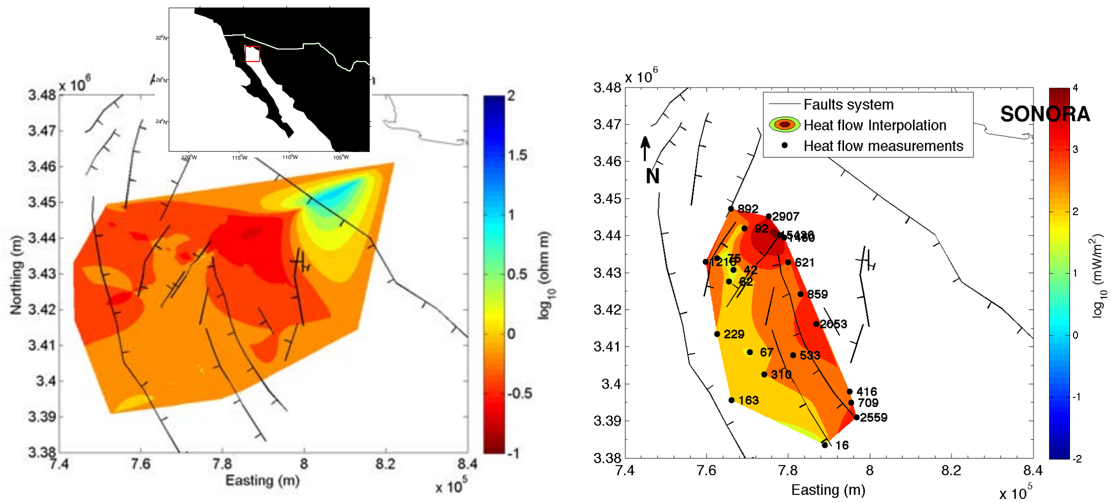

Figure 2: Left: Electrical resistivity at a depth of 500 m in the northern Gulf of California, interpolated from inversions of surface-towed EM data. Red indicates high conductivity/high temperature. Right: Heatflow, interpolated from seafloor measurements. *From the MSc thesis of Valeria Reyes-Ortega, 2016.*

Peter Kannberg continues to work on CSEM data sets we collected in the Santa Cruz and San Nicolas Basins of the California borderlands, and has identified features that are likely to be gas hydrates and cold seeps. Peter helped write a Department of Energy proposal which has been recommended for funding and will support Peter as a postdoc at IGPP and fund a data collection cruise in the Gulf of Mexico in 2017. This proposal will also fund continued laboratory studies of hydrate conductivity of the type described in the 2012 Annual Report. Dallas Sherman is still working on the Prudhoe Bay permafrost project, and has discovered that permafrost has a high degree of electrical anisotropy. We think that the permafrost ice is layered, perhaps associated with layering of the sediments, and the exciting result is that the electrical anisotropy provides a more distinctive image of permafrost than the absolute magnitude of the resistivity.

We are working on a multi-institution, multi-disciplinary study of the lithosphere-asthenosphere boundary in the mid Atlantic. In March 2016 postdoc Dan Bassett deployed 40 MT instruments at the same locations as an ocean-bottom seismic array being deployed by Southampton University, UK. The instruments will be out for a full year until the OBS instruments are recovered. As part of this work, WesternGeco (a seismic contractor) collected seismic reflection data for this project all the way across the Atlantic using its latest streamer technology.

Recent Publications

Constable, S., P.K. Kannberg, and K. Weitemeyer (2016) Vulcan: A deeptowed CSEM receiver, *Geochemistry, Geophysics, Geosystems,* **17,**1042–1064, `10.1002/2015GC006174`

Naif, S., K. Key, S. Constable, and R.L. Evans (2015) Water-rich bending faults at the Middle America Trench, *Geochemistry, Geophysics, Geosystems,* **16,** 2582–2597, `10.1002/2015GC005927`

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

J. Peter Davis

Specialist

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Phone: 4-2839

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 IRIS/USGS Global Seismographic Network (GSN), a collection of 41 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.

IDA recently added a new station, SIMI (Simiganch, Tajikistan) to the network. (*See Figure 1*). SIMI is IDA's second station in that country – GAR, one of the original IDA GSN stations, was closed in 1992 as the result of the Tajik civil war. Conditions have improved since then, and we are very glad to be recording data in that region again. SIMI is well positioned to pick up many deep-focus regional events from the Pamir region (*Figure 2*).

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.

IDA is playing a leading role in the GSN program by evaluating new models of seismometers that may be deployed within the GSN in the future. IDA makes use of IGPP's Seismic Test Facility at Pinyon Flat Observatory to test the behavior of instrument prototypes under conditions likely probe the limits of a sensor's capabilities. Pinyon Flat is quiet enough to permit the recording of faint signals from distant earthquakes but also experiences violent shaking from local events on nearby faults.

Publications:

http://dx.doi.org/doi:10.7914/SN/II

Figure 1. Representatives of the Geophysical Service and Institute of Geology, Earthquake Engineering and Seismology, the hosts of our new station in Tajikistan, taken at the tunnel entrance. The seismometers are placed deep in the tunnel to provide the best possible recording conditions.

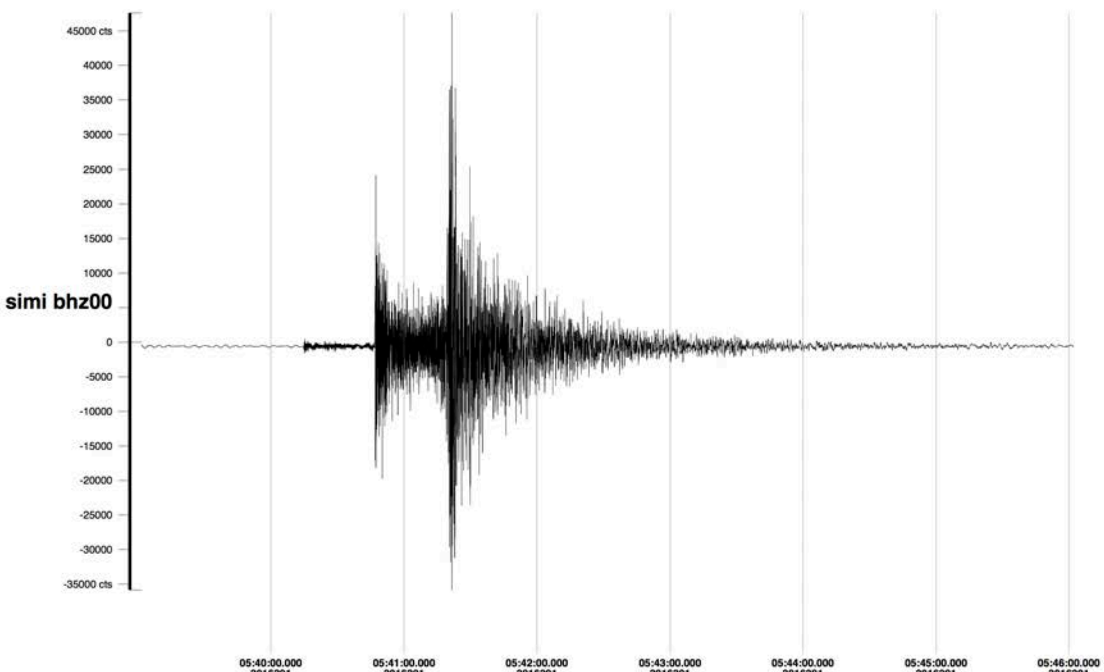

Figure 2. Recording of a magnitude Mw=4.6 earthquake 150 km deep beneath the Pamir Mountains at a distance of 284 km, the first of many such events we expect to capture.

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Research Interests
Isotope geochemistry; cosmochemistry; petrology; planetary dynamics; geodynamics; volatile inventories of planets; ore genesis; analytical methods

Research Focus – Ancient bits of Earth's mantle dragged to the surface
By investigating lavas and associated cumulate rocks - formed by crystals growing and settling out of magmas - it is possible to examine the composition of Earth's mantle. We utilized a suite of cumulate xenoliths from Piton de la Fournaise, La Réunion (Indian Ocean), to examine the mantle source composition of the Réunion hotspot (*Peters et al., EPSL, 2016*). We wanted to know if the Réunion hotspot was sourced from mantle like other hotspots (e.g., Hawaii), or if it was unusual in composition. This is important information, since the Réunion hotspot is the present-day manifestation of volcanism that occurred in the Cretaceous-Tertiary Deccan Traps of India. What we discovered is that the isotopic composition of the source of Réunion is quite homogeneous, but that the island has relative enrichments in ruthenium and palladium relative to what we think the composition of the Earth's mantle was before plate tectonics and crust formation. These relative enrichments are not seen in possible materials that formed the Earth, such as chondrites, either. The existence of these signatures demonstrates that the Réunion hotspot samples a new type of mantle source. We suggest that the origin of this source may arise from mantle that experienced limited addition of impactor material after the Earth's core had formed (late accretion), or limited interaction between Earth's mantle and core. The unique isotope characteristics of Réunion also suggest it's mantle source formed very early, and has been isolated until quite recently.

Left hand image – olivine-rich cumulate xenoliths in lava from the Canary Islands, found on fieldwork by PhD student, Brian Oller in September 2016. Similar types of cumulate xenolith were studied in Peters et al. (2016). Right hand image – PhD student, Brian Oller, at an outcrop of the exposed Pliocene seamount of La Palma, Canary Island. Pillow lavas are cut by sheeted dikes, with the whole sequence having experienced greenschist faciest metamorphism.

The work formed part of Dr. Brad Peters' recent PhD thesis, '*Secular and recent trends in the geochemistry of the Reunion hotspot and other global hotspots*', and was supported by NSF grants 1116089 and 1447130, the Devendra Lal fellowship, a generous donation from R. Rex, and by the *National Geographic Society*. Dr. Peters is now a post-doctoral fellow at Carnegie Institution of Science, Washington DC.

Other lab goings-on – Cosmochemistry, Geochemistry and Ore Geology

Work in the *Scripps Isotope Geochemistry Laboratory* currently involves a range of research problems. There are currently five PhD, three Masters and one undergrad student working in the lab, studying: volatile inventories of the Moon and asteroids; effects of early core formation; mantle geodynamics; mantle geochemistry and heterogeneity; California borderlands volcanism and tectonics; gold ore genesis, and magma-sediment interactions.

Recent Publications:

Day, JMD, O'Driscoll B, Strachan RA, Daly JS, Walker RJ. 2017. Identification of mantle peridotite as a possible Iapetan ophiolite sliver in south Shetland, Scottish Caledonides. Journal of the Geological Society. 174(1):1-5. http://dx.doi.org/10.1144/jgs2016-074

Day, JMD. 2016. Evidence against an ancient non-chondritic mantle source for North Atlantic Igneous Province lavas. Chemical Geology. 440:91-100. 10.1016/j.chemgeo.2016.07.002

Day, JMD. 2016. Extraordinary World. Nature. 537:310-311. 10.1038/537310a

Pringle, EA, Moynier F, Savage PS, Jackson MG, Moriera M, Day JMD. 2016. Silicon isotopes reveal recycled altered oceanic crust in the mantle sources of Ocean Island Basalts. Geochimica et Cosmochimica Acta. 189:282-295. 10.1016/j.gca.2016.06.008

Peters, BJ, Day JMD, Taylor LA. 2016. Early mantle heterogeneities in the Réunion hotspot source inferred from highly siderophile elements in cumulate xenoliths. Earth and Planetary Science Letters. 448:150-160. 10.1016/j.epsl.2016.05.015

Day, JMD. 2016. Siderophile Elements. Encyclopedia of Geochemistry. (White WM, Ed.).: Springer 10.1007/978-3-319-39193-9_234-1

Day, JMD, Qiu L, Ash RD, McDonough WF, Teng F-Z, Rudnick RL, Taylor LA. 2016. Evidence for high-temperature fractionation of lithium isotopes during differentiation of the Moon. Meteoritics and Planetary Science. 51:1046-1062. 10.1111/maps.12643

Day, JMD, Waters CL, Schaefer BF, Walker RJ, Turner S. 2016. Use of Hydrofluoric Acid Desilicification in the Determination of Highly Siderophile Element Abundances and Re-Pt-Os Isotope Systematics in Mafic-Ultramafic Rocks. Geostandards and Geoanalytical Research. 40:49-65. 10.1111/j.1751-908X.2015.00367.x

Harvey, J, Day JMD. 2016. Highly siderophile and strongly chalcophile elements in high temperature geochemistry and cosmochemistry. (81):774pp.: Mineralogical Society of America. 10.2138/rmg.2015.81.00

Gannoun, A, Burton KW, Day JMD, Harvey J, Schiano P, Parkinson I. 2016. Highly Siderophile Element and Os Isotope Systematics of Volcanic Rocks at Divergent and Convergent Plate Boundaries and in Intraplate Settings. Reviews in Mineralogy and Geochemistry. 81:651-724. 10.2138/rmg.2016.81.11

Day, JMD, Brandon AD, Walker RJ. 2016. Highly Siderophile Elements in Earth, Mars, the Moon, and Asteroids. Reviews in Mineralogy and Geochemistry. 81:161-238. 10.2138/rmg.2016.81.04

Harvey, J, Day JMD. 2016. Introduction to highly siderophile and strongly chalcophile elements in high temperature geochemistry and cosmochemistry. Reviews in Mineralogy and Geochemistry. 81:iii-xiv. 10.2138/rmg.2016.81.0

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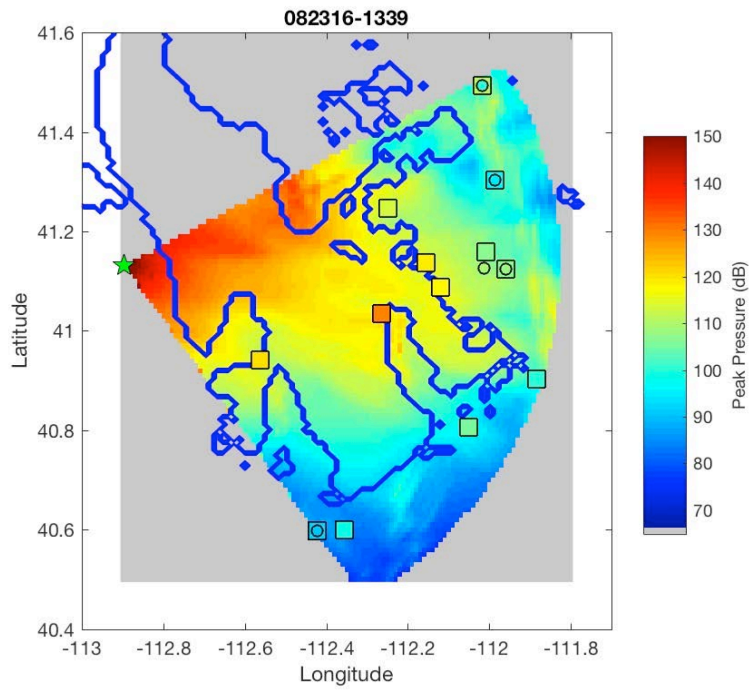
Research Interests*:* Acoustic propagation modeling with application to infrasound; application of infrasound to nuclear test-ban verification and hazard monitoring; use of dense seismic and infrasound networks to analyze very long wavelength gravity waves, as well as infrasound and seismic signals.

My main research area is in the physics of infrasound – sound at frequencies lower than human hearing – its applications to investigating both large scale atmospheric processes and explosions, either natural (bolides) or anthropogenic. Here, I outline two projects that I have worked on in the past several years.

An automated event detector and locator*:* I have developed an automated, method to detect and locate events in two-dimensional space and time using large volumes of data. The method is used to create a catalog of infrasound sources in the eastern United States and southeastern Canada using infrasonic and seismic data recorded by the USArray Transportable Array (TA). The purpose of developing this catalog is twofold. First, the catalog provides a list of sources that can be used for basic infrasound research, either for remote study of the events themselves or to study of properties of the atmosphere. Second, we need to understand and document the noise field or other sources that may hamper the performance of International Monitoring System infrasound arrays in monitoring the Comprehensive Nuclear Test Ban Treaty. The method has been successfully applied to TA data – over 1000 events were found in the Midwest and on the east coast in 2013. The method is currently being tested on seismic data to improve current methods of finding small seismic events.

Numerical modeling: A basic research goal in infrasound is to understand the transmission of infrasound through variable atmospheric conditions. To this end, I developed a computationally efficient numerical method to synthesize the propagation of nonlinear acoustic waves through the atmosphere. Nonlinearity, or shock wave propagation, arises when pressure perturbations associated with acoustic waves are a significant fraction of the ambient atmospheric pressure. Shock waves are associated with meteoroid explosions in the upper atmosphere, volcanic eruptions, or nuclear and chemical explosions. Work on this code has progressed to allow for the incorporation of realistic atmospheric effects, such as spatially varying sound speeds and wind speeds, topography, and atmospheric attenuation.

In a recent project, this code has been used to compute the penetration of sound into areas typically thought of as being in a "shadow zone", where sound refracts upwards, away from the Earth's surface due to the decrease in sound speed with altitude, much as light bends as it travels between air and water. In the summer of 2016, rocket motor were detonated at the Utah Test and Training Range (UTTR), and sound sensors were placed at up to 14 sites eastward of the blasts. Numerical codes were used to create a map to predict the peak sound levels in areas to the east of the detonations. Predicted peak sound levels are compared to observed levels in the figure below.



Caption: A map of predicted peak sound pressures for a 17,700 kg detonation at UTTR, which is marked by a green star. Winds carry the peak sound off to the northwest. Sound sensor sites, marked by squares and circles, are color-coded by the recorded peak sound pressure levels. Results show agreement within about 6 dB.

Recent Publications

de Groot-Hedlin, C.D., 2016, Long-range propagation of nonlinear infrasound waves through an absorbing atmosphere, *J. Acoust. Soc. Am.,* 139, 1565-1577, doi: 10.1121/1.4944759.

de Groot-Hedlin, C.D., Hedlin, M.A.H. 2015, A method for detecting and locations geophysical events using groups of arrays, *Geop. J. Int.,* doi: 10.1093/gji/ggv345

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

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

Stephan, C.C., M. J. Alexander, M. Hedlin, C. de Groot-Hedlin, L. Hoffmann, 2016, A Case study on the far-field properties of propagating tropospheric gravity waves, *Monthly Weather Review,* **144**, 2947-2961, doi: 10.1175/MWR-D-16-0054.1

Tytell, J., F. Vernon, M. Hedlin, C. de Groot Hedlin, J. Reyes, B. Busby, K. Hafner, J. Eakins, 2016, The USArray transportable array as a platform for weather observation and research, *Bull. Of the Am. Met. Soc.,* **97**, 603-619, doi:10.1175/BAMS-D-14-00204.1

LeRoy Dorman **Professor Emeritus,RTAD**

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Research Interests*:* Seismology, especially of the seafloor

Whenever possible while I was operating Ocean-Bottom Seismographs, I tried to use any available seafloor source to generate interface waves trapped at the water-sediment boundary. These Scholte waves are strongly dispersed and contain information about the shear-velocity waveguide in which seafloor noise travels.
The only models which seismologists understand at an analytical level are those comprised of layers of uniform velocity. Where strong gradients in the vertical direction are present, they may be approximated accurately using many thin layers. This complicates analysis by making the problem severely underdetermined.
Recently Godin and Chapman showed that power-law shear velocity models provide a simple starting point for modeling. The group velocity dispersion from these models manifests itself as a straight line in slowness-frequency space. I am now exploiting this simplicity in the analysis of seafloor data from the Cascadia Basin. And I am reporting on this work at the Fall AGU meeting.

Recent Publications

Yildiz, S, Sabra K, Dorman LM, Kuperman WA. 2013. Using hydroacoustic stations as water column seismometers. Geophysical Research Letters. 40:2573-2578. 10.1002/grl.50371

Neal Driscoll
Professor of Geology & Geophysics
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***Research Interests**:* Landscape and seascape evolution in response to tectonic deformation, sea-level fluctuations, and climate; neotectonics and geohazards

Dextral shear is unevenly distributed along the western margin of North America with ~75-80% of the Pacific and North American plate motion being accommodated by the San Andreas Fault and other fault systems to the west. The remaining deformation occurs east toward the Basin and Range province. The structurally complex transition between the Sierra Nevada microplate and the Basin and Range (Fig. 1), known as the Walker Lane Deformation Belt, is identified by seismic, geodetic, and geologic data.

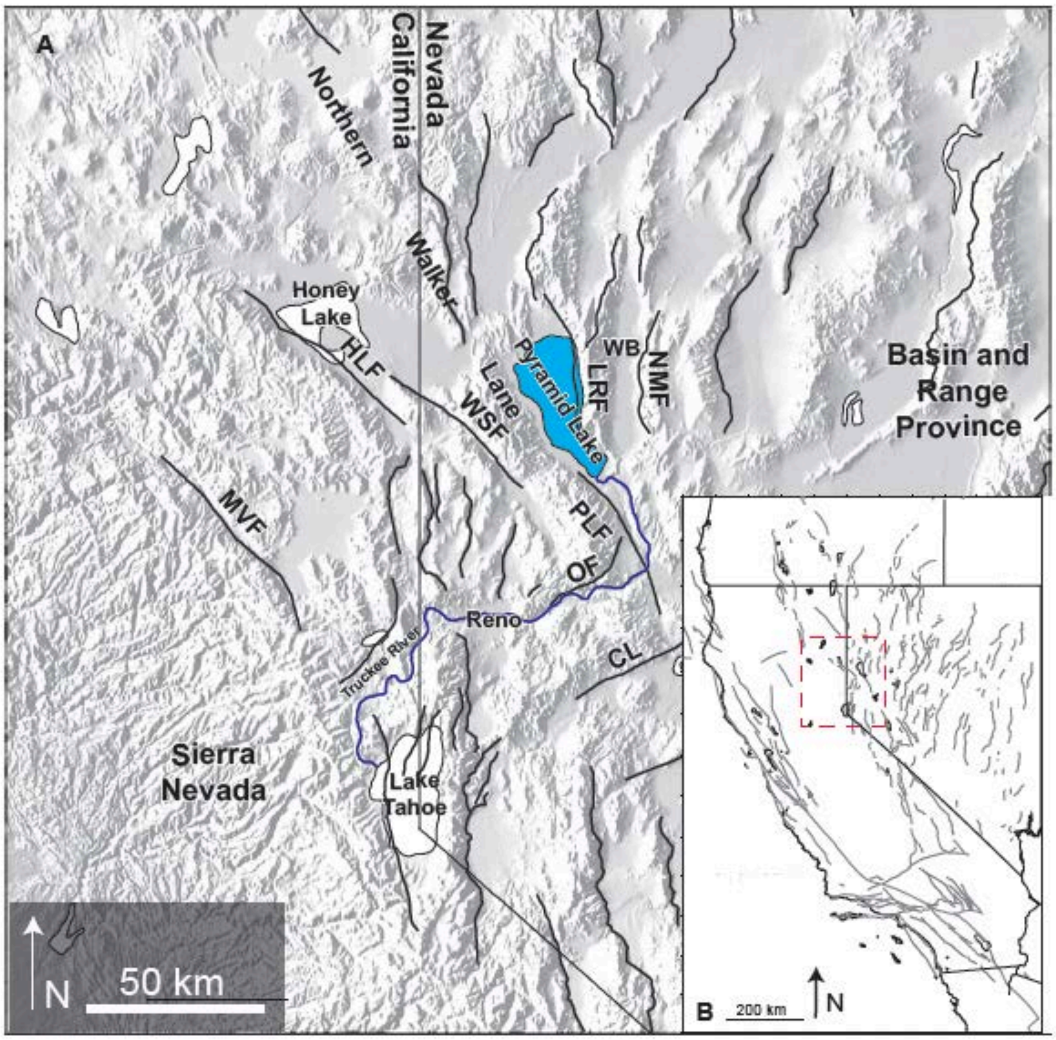

Figure 1. Regional map of the western United States, red box shows the enlarged map of the northern Walker Lane Deformation Belt. (A) Map of the northern Walker Lane Deformation Belt, northwest Basin and Range province, and northern Sierra Nevada microplate. River and state boundary lines are dark gray and faults are thin black lines. Pyramid Lake is shaded in

light blue and the Truckee River is dark blue. CL – Carson Lineament; HLF – Honey Lake fault; LRF – Lake Range fault; MVF – Mohawk Valley fault; NMF – Nightingale Mountains fault; OF – Olinghouse fault; WB – Winnemucca Basin; WSF – Warm Springs Valley fault

This approximately 100-km-wide belt of seismicity and active faulting accommodates up to 20-25% or 8-13 mm/yr of relative motion between the Sierra Nevada microplate and stable North America plate. Studies show that most of the deformation in the Walker Lane occurs along the eastern and western margins of the belt. Furthermore, seismicity is concentrated at the eastern and western boundaries of the Basin and Range, with higher rates of strain localized on the western side within the central Nevada seismic belt and the Walker Lane.

Pyramid Lake is located toward the eastern margin of the northern Walker Lane in a transitional zone between two distinct geological regions, the Walker Lane Deformation Belt and the Basin and Range province (Fig. 1). Within the Pyramid Lake region, transtension is accommodated through a series of mainly dextral oblique strike-slip faults (e.g., Lake Range Fault, Fig. 2). A change in structural architecture occurs near Pyramid Lake; to the north the dextral faults strike northwest (e.g., Honey Lake fault zone), whereas toward the south north-striking normal faults dominate (e.g., Lake Tahoe basin).

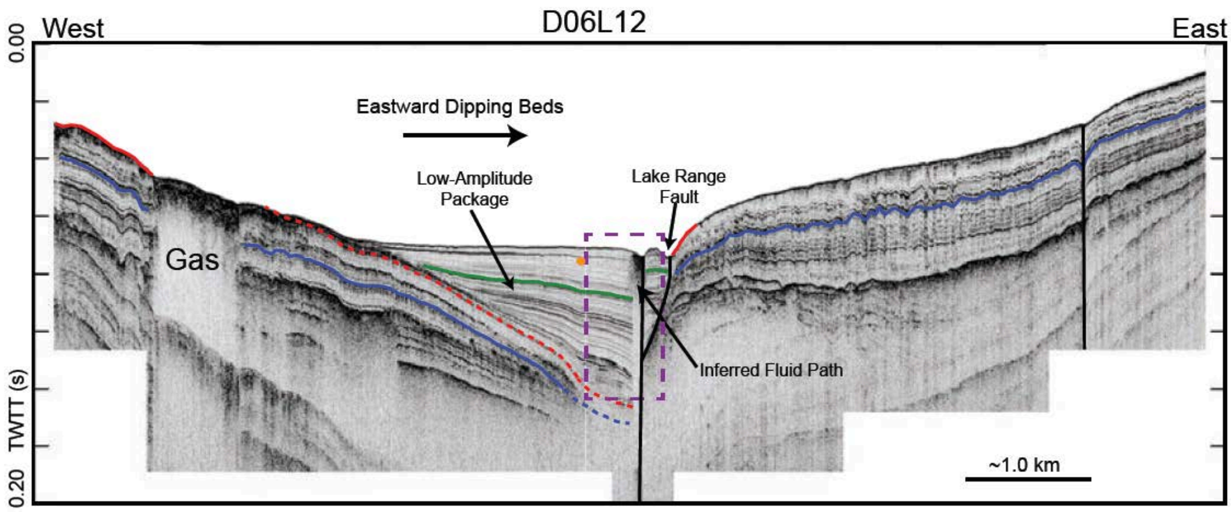

Figure 2. CHIRP seismic data images the Lake Range fault and the low amplitude sediment package infill to the west. The increasing dip with depth in the divergent package indicates that sedimentation was occurring during deformation. High-resolution seismic data together with geologic sampling allows us to define the timing and magnitude for the most recent event (MRE) along fault systems as well as the earthquake recurrence interval.

Selected Publications:

Eisses, AK, Kell A, Kent GM, Driscoll NW, Baskin RL, Smith KD, Karlin RE, Louie JN, Pullammanappallil SK. 2015. New constraints on fault architecture, slip rates, and strain partitioning beneath Pyramid Lake, Nevada. Geosphere. 11:683-704. 10.1130/ges00821.1

Dong, SP, Ucarkus G, Wesnousky SG, 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

See http://scrippsscholars.ucsd.edu/ndriscoll for a complete list of publications as well as teaching and research interests.

Matthew Dzieciuch   **Project Scientist**
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Research Interests: Acoustical oceanography, ocean acoustic tomography, signal processing

Acoustical oceanography seeks to use sound propagation 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 Beaufort Sea in the Arctic.

As an example, recently we deployed a 60 element vertical line array in the Arctic to learn about the propagation of sound under the ice, Fig. 1. As the sound propagates under the ice, its attenuation is affected by the under-ice roughness. The under-ice roughness is a measure of the age of the ice, old ice is rougher than new ice. So the sound attenuation is a proxy for the sea-ice age. Information about the sea-ice age is very important in understanding the dynamics of the yearly ice melting cycle as it is under increasing stress from a warming planet. Furthermore this direct measurement is an complementary alternative to satellite measurements.

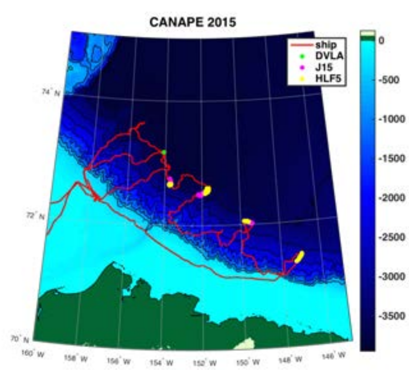

Figure 1: A vertical line array of hydrophones (DVLA) was deployed at afixed location and then two sound sources, at 125Hz (J-15) and at 250 Hz (HLF-5) were deployed at various ranges to learn about the relationship between attenuation and range. Ship tracks reflect the tortuous route taken to avoid thick sea-ice.

The results revealed that the ice attenuates the sound in a complicated manner shown in Fig. 2. The deep hydrophone shows an attenuation that is steeper than the expected spherical spreading. That deep hydrophone measures sound that has traveled at steep angles and interacts with the sea-ice at every bounce and thus is strongly attenuated. The shallow hydrophone shows less attenuation particularly at shorter ranges. This is a bit of a mystery but perhaps there is enough of a duct present that some sound can become trapped and not strongly interact with the ice, at least over the part of the path. On-going modeling work using environmental data collected simultaneously will enable us to understand these results.

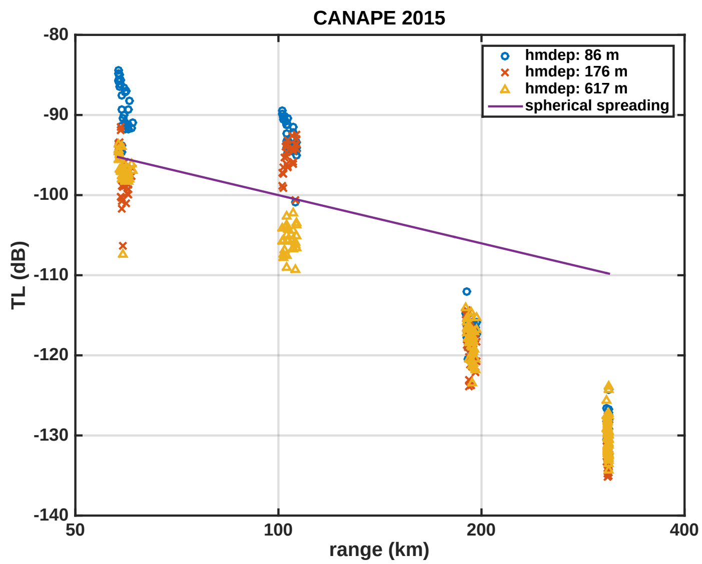

Figure 2: CANAPE2015 sound attenuation or transmission loss (TL) vs. range. Deep hydrophones show a loss greater than spherical spreading (purple). Shallow hydrophones show a more

This experiment was conducted with funding from the Office of Naval Research and they have supported a larger experiment, which is deployed now, to further our ability to monitor and understand the changing Arctic.

Recent Publications

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., Signal processing and tracking of arrivals in ocean acoustic tomography, (2014) J. Acoust. Soc. Am., **136**, 2512–2522.

Sagen, H., Geyer, F., Sandven, S., Babiker, M., Dushaw, B., Worcester, P., Dzieciuch, M., and Cornuelle, B., (under review) Resolution, identification, and stability of broadband acoustic arrivals in Fram Strait, J. Acoust. Soc. Am.

Your Name Peng Fang

Your Title Specialist

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Phone: 534-2445

Research Interests*:* High precision GNSS positioning and its applications for geodynamics and meteorology

Developed and maintained automatic GNSS data processing and analysis systems. Provided related scientific and technical consultation for a wide range of user community, including educational institutions, government agencies, and public or industrial entities, both domestically and internationally. In recent years, involved in researches focusing on reference frame definition and realization, high rate realtime GNSS positioning for early warning, as well as high sampling tropospheric delay estimation.

Recent Publications

Melgar D., R. M. Allen, S. Riquelme, J. Geng, F. Bravo, J. C. Baez, H. Parra, S. Barrientos, P. Fang, Y. Bock, M. Bevis, D. J. Caccamise II, C. Vigny, M. Moreno and R. Smalley Jr. Local Tsunami Warnings: Perspectives from Recent Large Events, Geophys. Res. Lett (2015) doi: 10.1002/2015GL067100

Moore, A.W, I. J. Sma ll, S. I. Gutma, Y. Bock, J. L. Dumas ,P. Fang, J. S. Haas e, M. E. Jackson, and J. L. Laber, National Weather Service Forecasters Use GPS Precipitable Water Vapor for Enhanced Situational Awareness during the Southern California Summer Monsoon, Bull. Amer. Meteor. Soc. (2015), 96 DOI:10.1175/BAMS-D-14-00095.1

Dong, D, W. Qu, P. Fang, D. Peng, Non-linearity of geocenter motion and its impact on the origin of the terrestrial reference frame, Geophys. J. Int. (2014) 198, 1071–1080

Sadeh, M., Y. Hamiel, A. Ziv, Y. Bock, P. Fang, and S. Wdowinski (2012), Crustal deformation along the Dead Sea Transform and the Carmel Fault inferred from 12 years of GPS measurements, J. Geophys. Res., 117, B08410, doi:10.1029/2012JB009241

A. Ozgun Konca, Jean-Philippe Avouac, Anthony Sladen, Aron J. Meltzner, Kerry Sieh, Peng Fang, Zhenhong Li, John Galetzka, Jeff Genrich, Mohamed Chlieh, Danny H. Natawidjaja, Yehuda Bock, Eric J. Fielding, Chen Ji, Don V. Helmberger., Partial rupture of a locked patch of the Sumatra megathrust during the 2007 earthquake sequence, Nature 456, 631 - 635 (04 Dec 2008), doi: 10.1038/nature07572, Letter

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

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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 interseismic deformation and earthquake cycle. Prof. Fialko and former graduate student Eric Lindsey (now a joint postdoc at the Earth Observatory in Singapore and UC Berkeley) investigated the spatial pattern and rates of deformation due to the Imperial Fault in southern California. In this study more than 100 survey-mode GPS velocities were combined with InSAR data from the ascending and descending tracks of the ENVISAT datellite processed using a persistent scatterers method. The result is a dense map of interseismic velocities across the Imperial Fault and surrounding areas that allows one to evaluate the rate of interseismic loading and along-strike variations in surface creep (Figure 1). Available geodetic data (incuding data from the most recent 1979 M_w6.6 Imperial Valley earthquake) were compared to models of the earthquake cycle with rate- and state-dependent friction. It was found that a complete record of the earthquake cycle is required to constrain key fault properties including the rate-dependence parameter $(a - b)$ as a function of depth, the extent of shallow creep, and the recurrence interval of large events. The study demonstrated that the data are inconsistent with a high (>30 mm/yr) slip rate on the Imperial Fault. An alternative possibility is that an extension of the San Jacinto-Superstition Hills Fault system through the town of El Centro may accommodate a significant portion of the slip previously attributed to the Imperial Fault. Models including this additional fault are in better agreement with the available observations (Figure 1). These results indicate that the long-term slip rate of the Imperial Fault is lower than previously suggested, and that the Imperial Fault is not the only active plate boundary structure at the latitude of the U.S.-Mexico border. Geodetic evidence suggests that significant strain is accommodated by a subparallel fault located 10-20 km west of the Imperial Fault, which slips at a long-term rate comparable to that of the San Jacinto Fault to the north. If so, this fault represents a significant unmapped hazard to the U.S. and Mexican communities of El Centro, Calexico, Heber, and Mexicali.

Other areas of Prof. Fialko interests include rock mechanics and physics of earthquakes. In a series of recent studies Prof. Fialko in collaboration with Prof. Brown and graduate student Erica Mitchell investigated the effect of temperature on slip stability of typical crystalline rocks such as granite and gabbro. The study included laboratory experiments on both solid samples and simulated gouge over a wide range of temperatures and loading conditions. Previous experimental data on granite suggest a transition from unstable slip to creep at about 350 °C. Assuming a reasonable geotherm, this corresponds to depth of ~15 km, close to the deep limit to seismicity in the Western US. This is consistent with a view that the thickness of the seismogenic layer is controlled by a transition from velocity-weakening to velocity-strengthening friction. However, the new results from direct shear experiments on Westerly granite at both dry and hydrated conditions show increasingly unstable slip (velocity-weakening behavior) at temperature up to 600 °C. A comparison of previously published experimental results with the new data suggests that

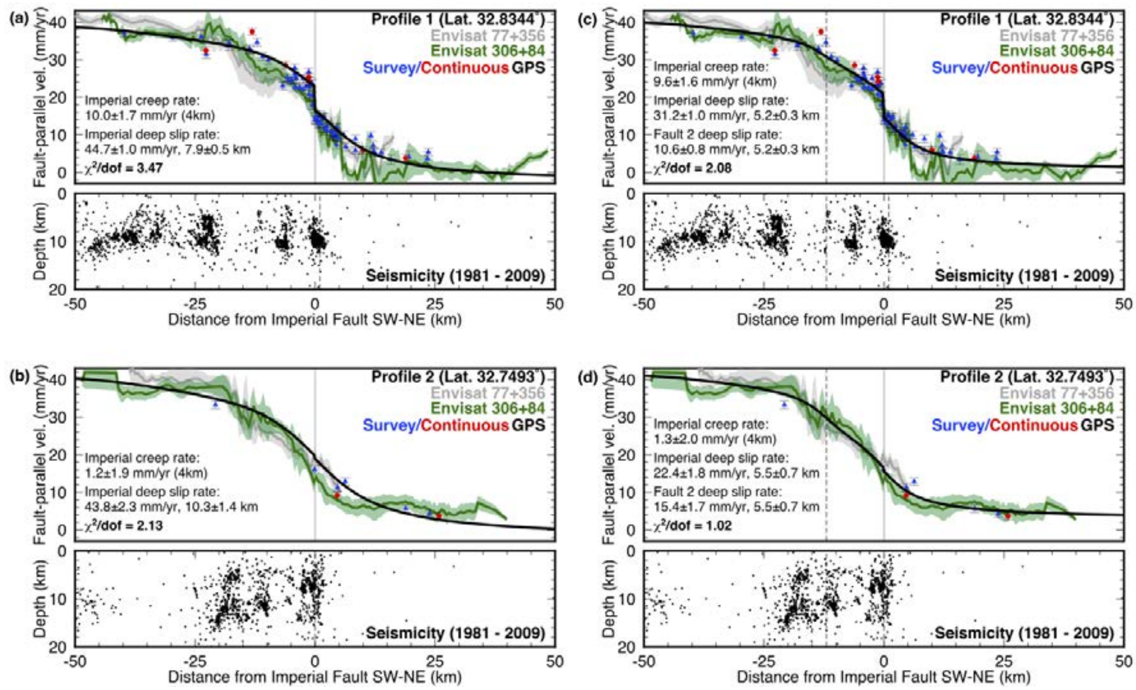

Figure 1: Profiles across the Imperial Fault showing InSAR-derived fault-parallel velocities (gray and green curves), and GPS velocities from campaign (blue) and continuous stations (red). Black curves denote best-fitting models assuming one fault (a, b), and two faults (c, d). Fault locations are denoted by dashed lines. Model uncertainties are 2σ confidence intervals. From Lindsey and Fialko [2016].

the rate and state friction parameters strongly depend on normal stress and pore pressure at high (>400 °C) temperature. The new study suggests that the depth extent of the seismogenic zone in continental crust may not be fully controlled by the onset of plasticity in either quartz or plagioclase, and that frictional properties of common crustal rocks can be velocity-weakening over a wider depth range than previously believed, in particular under dry conditions or low pore pressure. This may help explain the observed regional variations in the depth distribution of earthquakes in continental crust. The measured temperature dependence of the rate and state friction parameters may also contribute to strong dynamic weakening observed in high-speed friction experiments, with important implications for the dynamics of earthquake ruptures.

Recent publications:

Lindsey, E. and Y. Fialko, Geodetic constraints on frictional properties and earthquake hazard in the Imperial Valley, southern California, *J. Geophys. Res., 121*, 1097-1113, 2016.

Basset, D., D. Sandwell, Y. Fialko, and A. Watts, Upper-plate structural controls on co-seismic slip in the 2011 Mw 9.0 Tohoku-oki earthquake, *Nature, 531*, 92-96, 2016.

Trugman, D., P. Shearer, A. Borsa, and Y. Fialko, A comparison of long-term changes in seismicity at The Geysers, Salton Sea, and Coso geothermal fields, *J. Geophys. Res., 121*, 225-247, 2016.

Mitchell, E., Y. Fialko, and K. Brown, Velocity-weakening behavior of Westerly granite at temperature up to 600 °C, *J. Geophys. Res., 121*, 6932-6946, 2016.

Mitchell, E., Y. Fialko, and K. Brown, Frictional properties of gabbro at conditions corresponding to slow slip events in subduction zones, *G-cubed, 16*, 4006-4020, 2015.

Helen Amanda Fricker, Professor, John Dove Isaacs Chair

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

My research focuses on glaciology and polar science, and specifically on understanding the processes driving changes on the Antarctic ice sheet. One of the main unknowns in Antarctica is its current contribution to global sea level, and predicting how that will increase in the future. Because Antarctica is so large, and it changes on long time scales (years to decades), satellite data are crucial for routine monitoring. Our main techniques for doing this are satellite altimetry, either satellite radar altimetry from ERS-1/ERS-2 and Envisat which provides a long record (1994-2012) or NASA's Ice, Cloud & land Elevation Satellite (ICESat), which provides accurate elevation data for ice sheet change detection for the period 2003-2009. Using these long, continuous records we can learn about the processes that are leading to accelerated mass loss. My group focuses mainly on two key dynamic components of the ice-sheet system: (1) the floating ice shelves and (2) active subglacial lakes.

1. Antarctica's floating ice shelves

Antarctica's floating ice shelves surrounded the entire continent and this is where most of the mass loss takes place. Since ice shelves displace their own weight in water, their melting does not contribute directly to sea level. However, ice shelves provide mechanical support to 'buttress' seaward flow of grounded ice, so that ice-shelf thinning and retreat result in enhanced ice discharge to the ocean. Our group specializes in monitoring Antarctic ice shelves from satellite altimetry (radar and laser), and we also work on understanding the mass loss processes from ice shelves; we are funded by NASA to do this work. I am also a PI on a large NSF project ROSETTA to investigate the Ross Ice Shelf using airborne geophysical techniques (gravity, laser and radar). Matthew Siegfried took part in the 2015/2016 season of ROSETTA and was part of the airborne field team, and 2nd year student Maya Becker is taking part in the 2016/2017 season.

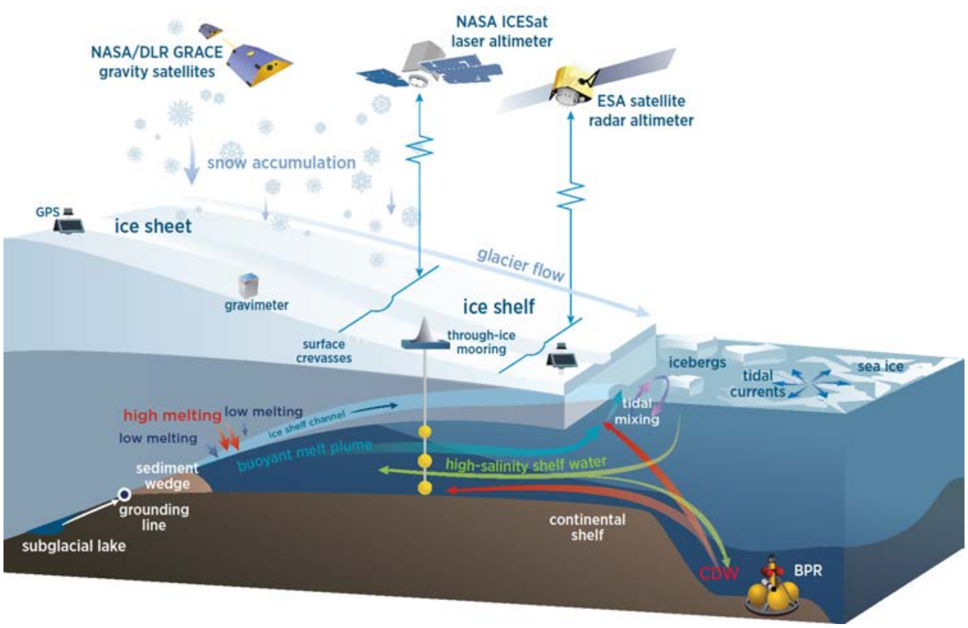

Figure 1: *Schematic of the marine margin of an ice sheet where there is a floating ice shelf. The ice shelf's mass budget is the sum of inputs from glacier flow across the grounding line and snow accumulation, and losses by net basal melting and iceberg production. Basal melting depends on ocean heat flow under the ice shelf, and the turbulence in the upper ocean near the ice base which comes from the general ocean circulation, generation of buoyant freshwater plumes by melting ice and by outflow from the subglacial hydrology system, and tides. Sedimentation near the grounding line depends on strength of currents and tidal migration of the grounding line. Figure by Jennifer Matthews.*

We used satellite radar altimeter data from a series of three ESA satellites to obtain estimates of ice-shelf surface height since the early 1990s. These data revealed accelerated losses in total Antarctic ice-shelf volume from 1994 to 2012 (*Paolo et al., 2015, 2016*). Changes in mass for East and West Antarctic ice shelves were not synchronous. In East Antarctica the first half of the record showed a mass increase, believe to be a result of increased accumulation. In West Antarctica, and in particular its Bellingshausen and Amundsen Sea regions, ice shelves lost mass throughout the record although with changes in rates on multi-year time scales. Ice-shelf thinning in these regions was substantial: some ice shelves thinned by up to 18% in 18 years. This thinning raises concerns about future loss of grounded ice and resulting sea level. Susheel Adusumilli (IGPP graduate student) is currently updating all of these time series to 2016 using CryoSat-2 radar altimeter data.

2. Subglacial lakes. The Antarctic Ice Sheet is on average 2.2 km thick and rests on top of bedrock; the insulation, high pressures, and geothermal heat flux at the ice-bed interface leads to melting of the basal ice layers on the order of mm/year. When averaged over the entire ice sheet, this produces high volumes of subglacial water (estimated volume is 65 Gt/yr), much of which is stored in subglacial lakes and subglacial aquifers. 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 changes (up to 10m in some places) in repeat-track ICESat data, which corresponded to draining and filling of subglacial lakes beneath 1-2 km of ice. We continue to monitor active lakes, and we have found 124 in total throughout Antarctica. In the decade since the discovery of active Antarctic subglacial water systems, much progress has been made in our understanding of these dynamic systems. Matt Siegfried extended the record of volume change for all lakes under the CryoSat-2 mask up to 2016.

I was a PI on a large, interdisciplinary 6-year NSF project (Whillans Ice Stream Subglacial Access Research Drilling (WISSARD)) to drill into one of the subglacial lakes that I discovered – Subglacial Lake Whillans (SLW) on Whillans Ice Stream (WIS) – and the region of the grounding line across which the subglacial water flows and enters the ocean. The final field season was 2015-2016 and my graduate student Matthew Siegfried led the GPS survey, which was centred on the lakes themselves, and the grounding line downstream. A new NSF-funded 4-year project Subglacial Antarctic Lakes Scientific Access (SALSA) began in the 2016-17 field season, and Matt Siegfried is leading the geophysics team.

The **Scripps Glaciology Group** has 3 postdocs and 2 graduate students.

Publications 2016

1. CARTER, S. P., **FRICKER, H. A.**, SIEGFRIED, M. R. (2016) Antarctic subglacial lakes drain through sediment-floored canals: Theory and model testing on real and idealized domains, *The Cryosphere*, doi:10.5194/tc-2016-74.
2. PAOLO, F.S., **FRICKER H.A.**, PADMAN L. 2016. Constructing improved decadal records of Antarctic ice shelf height change from multiple satellite radar altimeter. *Remote Sensing of Environment*. 177:192-205.
3. SIEGFRIED, M.R, **FRICKER H.A**, CARTER SP, TULACZYK S. 2016. Episodic ice velocity fluctuations triggered by a subglacial flood in West Antarctica. *Geophysical Research Letters*. 43:2640-2648.
4. ALLEY, K. E., T. A. SCAMBOS, M. R. SIEGFRIED, **H.A FRICKER** (2016) Impacts of warm water on Antarctic ice shelf stability through basal channel formation, *Nature Geoscience* 9, (4), 290-293.
5. **FRICKER, H.A.**, SIEGFRIED M.R., CARTER S.P., SCAMBOS T.A. 2016. A decade of progress in observing and modelling Antarctic subglacial water systems. *Philosophical Transactions of the Royal Society* a-Mathematical Physical and Engineering Sciences. 374.
6. MARSH, O.J., **FRICKER H.A.**, SIEGFRIED M.R., CHRISTIANSON K., NICHOLLS K.W., CORR H.F.J., CATANIA G. 2016. High basal melting forming a channel at the grounding line of Ross Ice Shelf, Antarctica. *Geophysical Research Letters*. 43:250-255.
7. MIKUCKI, J.A., LEE P.A., GHOSH D., PURCELL A.M., MITCHELL A.C., MANKOFF K.D., FISHER A.T., TULACZYK S., CARTER S., SIEGFRIED M.R., **FRICKER H.A.**, et al. 2016. Subglacial Lake Whillans microbial biogeochemistry: a synthesis of current knowledge. Philosophical Transactions of the Royal Society a-Mathematical Physical and Engineering Sciences. 374.

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

One of the challenges in documenting past variations in the intensity of the geomagnetic field is identifying geological materials with sufficiently fine magnetite particles to accurately record the field and that are stable during the multiple laboratory heatings required to estimate the paleofield intensity. With collaborators Julie Bowles (Univ. Wisconsin, Milwaukee) and Mike Jackson (University of Minnesota) and graduate student Maggie Avery, we have been investigating two historical ash flows – the 1980 ash flows at Mt. St. Helens, Washington (Figure 1), and the 1912 flows from Novarupta in the Valley of Ten Thousand Smokes, Alaska – to determine whether they might be suitable for determining the intensity of the geomagnetic field. We find that many samples from the small-volume ash flows at Mt. St. Helens yield high quality results that accurately record the field intensity but that caution is needed in larger flows such as the 1912 Novarupta where post-emplacement alteration is prevalent (Bowles et al., 2015).

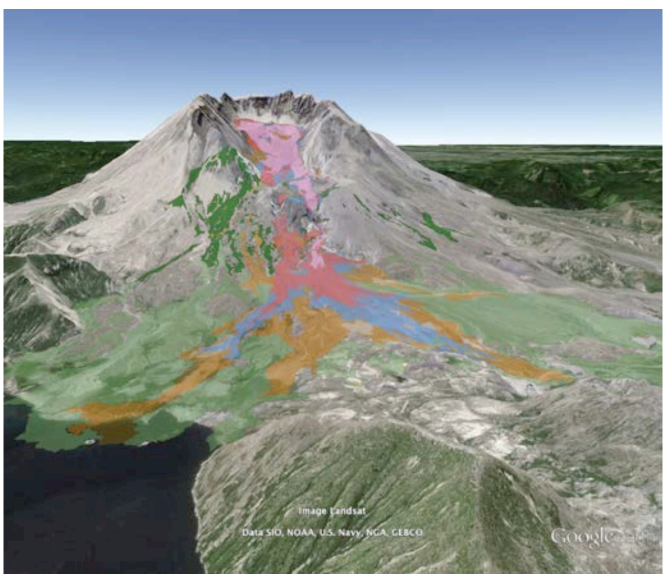

Figure 1: Google Earth image of pyroclastic flows on Mt. St. Helens (view is to the south). Titanomagnetite compositions of most 1980 flows exhibit temperature-dependent Curie temperatures. The May 18, 1980 deposits are shown in green. June 12, 1980 deposits are shown in shades of brown. Smaller pyroclastic flows from July 22, August 7 and October 16 are shown in blue, red, pink, respectively.

Two ongoing research projects illustrate different applications of magnetic data from oceanic crust. Recently completed research (Avery et al., in review) used near-bottom magnetic anomaly data to evaluate possible asymmetry in the growth and decay of the geomagnetic field. Sedimentary records of axial dipole variations over the past 2 million years have revealed that the field spends more time decaying than growing. Although the main signal in the magnetization of the ocean crust is the pattern of reversals, geomagnetic intensity fluctuations should also be recorded in the thermal remanence of seafloor lavas. We find that crustal magnetization variations display asymmetry in the same sense as the sedimentary records, corroborating this asymmetry in a very different recording medium.

An upcoming cruise in early 2017 will use the magnetic anomaly signature above a tectonically-exposed section of fast-spread oceanic crust to examine how the lower oceanic crust is constructed. Pito Deep is a ~6000m deep depression near the tip of the northward-propagating East Rift of the Easter Microplate (Fig. 2). The nearly ridge-perpendicular exposures span multiple geomagnetic polarity intervals within Chron C2An, providing a unique opportunity to document the shape of the fossil 580°C isotherm in the lower crust and thus to differentiate between the thermal predictions of models for lower crustal accretion. While no single crustal exposure is likely to definitively resolve the processes by which the gabbroic lower crust is accreted, the exposures at Pito Deep offer the possibility to address outstanding questions regarding the depth of hydrothermal heat extraction, the width and temporal evolution of the axial magma chamber and the processes of melt transport and crystallization.

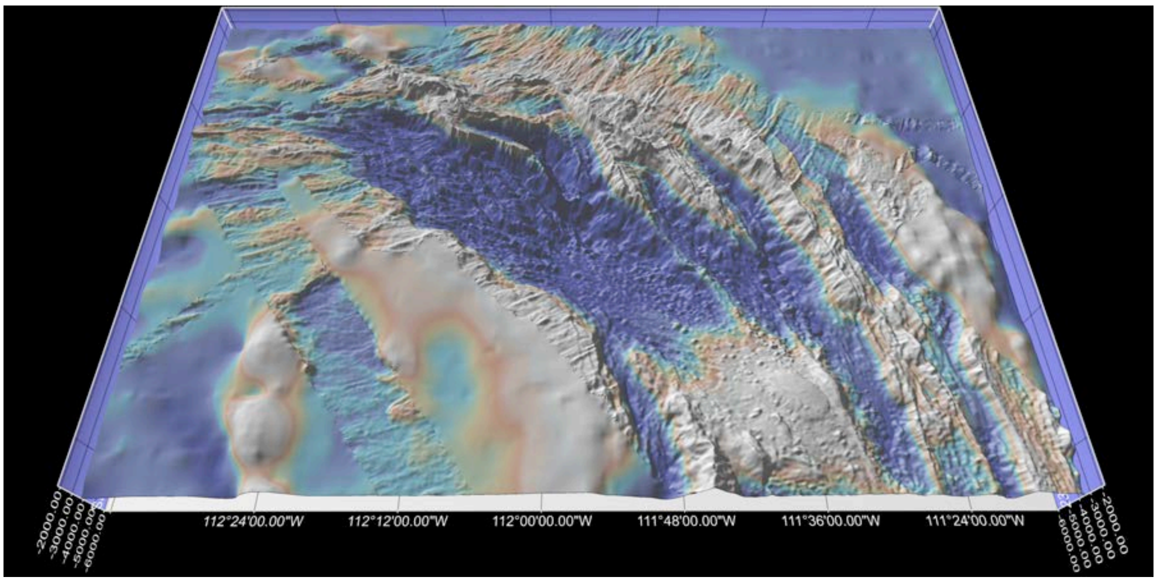

Figure 2: Perspective view of the bathymetry of Pito Deep. Relatively complete exposures of lavas, dikes and lower crustal gabbros to the north of the deepest basin will be the subject of a cruise in early 2017.

Recent Publications

Avery, M.S., Gee, J.S. and C.G. Constable, Asymmetry in growth and decay of the geomagnetic dipole revealed in seafloor magnetization, *Earth and Planetary Science Letters*, in review.

Bowles, J.A., Gee, J.S., Jackson, M.J. and M.S. Avery, 2015, Geomagnetic paleointensity in historical pyroclastic density currents: Testing the effects of emplacement temperature and postemplacement alteration, *Geochemistry Geophysics Geosystems*, 16:3607-3625, doi: 10.1002/2015gc005910.

Kent, D.V., Kjarsgaard, B.A., Gee, J.S., Muttoni, G. and L.M. Heaman, 2015, Tracking the Late Jurassic apparent (or true) polar shift in U-Pb-dated kimberlites from cratonic North America (Superior Province of Canada), *Geochemistry Geophysics Geosystems*, 16:983-994, doi: 10.1002/2015gc005734.

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Research Interests

- Real-time seismogeodesy and earthquake early warning
- Seismotectonics and seismic hazard
- Seismology and wave propagation
- Seismic tomography
- Airborne atmospheric remote sensing with GPS
- Hurricane development
- Polar climate
- Ionospheric observations with GPS

Recent Research Results: Airborne Radio Occultation & Hurricane Forecasting

The airborne radio occultation (ARO) technique uses anomalous delays in GPS signals to measure moisture profiles in focused field campaigns where the evolution of moisture is critical to the development of convection and storms. The GNSS Instrument System for Multistatic and Occultation Sensing (GISMOS) [*Garrison et al.*, 2007; *Healy et al.*, 2002; *Xie et al.*, 2008] was deployed in the joint NASA/NSF/NOAA Genesis and Rapid Intensification Project/PREDICT/IFEX in 2010 to study the development of tropical storms from African easterly waves [*Evans et al.*, 2012; *Haase et al.*, 2014; *Montgomery et al.*, 2012]. The highest variability of moisture in developing tropical storms was shown to be at mid-levels in the atmosphere where dry air intrusions can significantly inhibit development [*Murphy et al.*, 2015].

a) b)

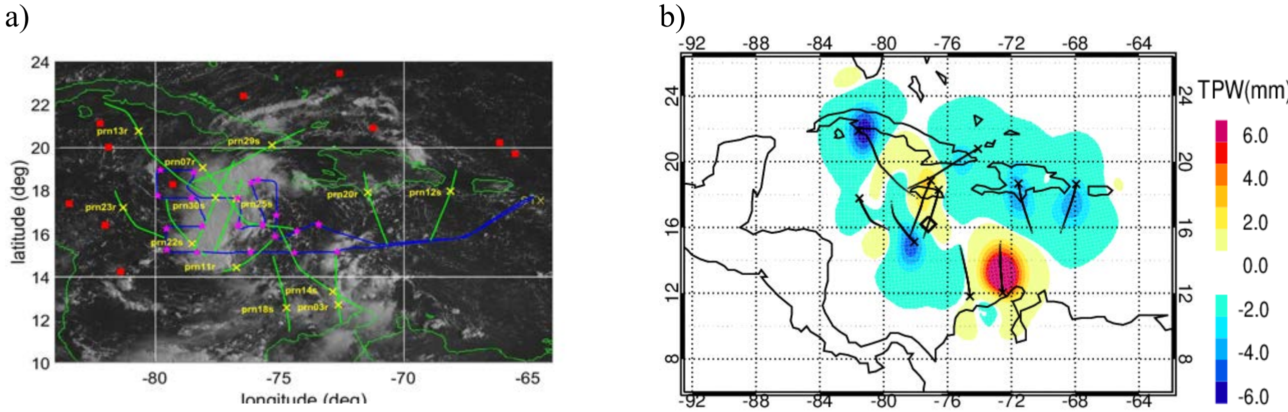
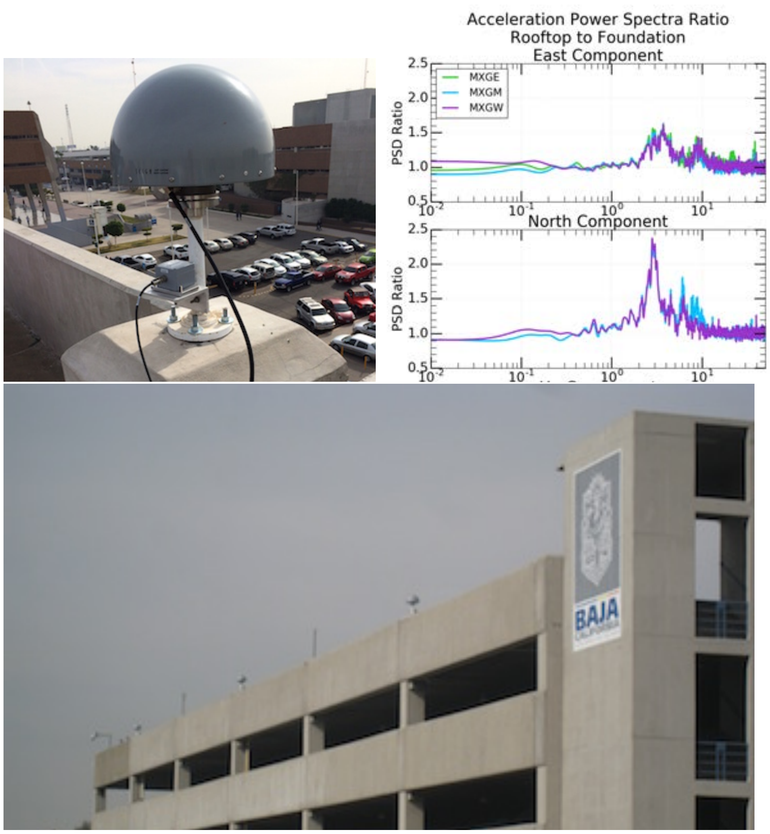


Figure 1 a) Aircraft flight track (blue) and visible GOES image on 13 Sep 2016 12Z, the day prior to development of 2010 hurricane Karl. Occultation tangent point sampling points (green), dropsondes (pink stars) and COSMIC RO profiles (red squares) show the complementary nature of the ARO observations that sample the deepest convection to the sides of the flight track. COSMIC RO profiles from 13 Sep were not found near the storm center, but captured the larger scale environment. b) Analysis increment of precipitable water from assimilation of ARO observations showing the increase in moisture southeast of the center (diamond) in the inflow region.

Recent advances in the technique, especially in the lowest layers of the atmosphere, have been developed to mitigate the effects of atmospheric multipath propagation when sharp moisture gradients are present as is often the case in the tropics [*Adhikari et al.*, 2016; *Murphy et al.*, 2015; *Wang*, 2015; *Wang et al.*, 2016a; *Wang et al.*, 2016b]. These recent advances extend the sampling down to within 2 km of the ocean surface. In our most recent work, we show that ARO provides useful complementary data to dropsondes and other remote sensing techniques for improving the description of the convective environment that can lead to improvements in hurricane forecasting [*Chen et al.*, 2016; *Haase et al.*, 2012]. The particular benefits it brings is the ability to sample in the regions of deepest convection without compromising safety and the ability to make observations in the presence of clouds and precipitation. The high-vertical resolution sampling of regional variations in the mid-level moisture made it possible to resolve dry air intrusion that affect storm intensification. For the case of Hurricane Karl 2010, the geographical sampling of moisture fields north of Venezuela provided new information to the model about moisture in the inflow region to the storm that significantly impacted the development into a tropical storm on the following day, and the later evolution of the storm as it made landfall in eastern Mexico. This work was carried out with graduate students Xue Meng Chen, Brian Murphy, Eric Wang, and Paytsar Muradyan.

Recent Research Results: High Rate GPS-seismic Structural Monitoring



High rate GPS sensors with co-located accelerometers were installed in December 2015 on a 4-story structure in Mexicali, Mexico, as a test of a structural monitoring system. The site is near the aftershock zone of the 2010 M7.2 El Mayor Cucapah earthquake.

On 10 June 2016 a Mw 5.2 earthquakes struck on the San Jacinto fault 100 km to the northwest of the structure. The seismogeodetic monitoring system [*Saunders et al.*, 2016] captured motions on the roof that were amplified ~60% relative to the foundation. The new technique was able to verify that no permanent deformation resulted from the shaking. This work was carried out with graduate students Jessie Saunders and Dara Goldberg.

Recent Publications

1) Wang, K.-N., J. L. Garrison, U. Acikoz, J. S. Haase, B. J. Murphy, P. Muradyan, and T. Lulich (2016), Open-loop tracking of rising and setting GNSS radio-occultation signals from an airborne platform: signal model and error analysis, *IEEE Transactions on Geosciences and Remote Sensing*, *54*, 3967-3984.
2) Zhang, W., J. S. Haase, A. Hertzog, Y. Lou, and R. Vincent (2016), Improvement of stratospheric balloon positioning and the impact on gravity wave parameter estimation for the Concordiasi campaign in Antarctica, *Journal of Geophysical Research Atmospheres*, *121*, 9977-9997.
3) Adhikari, L., F. Xie, and J. S. Haase (2016), Application of the Full Spectrum Inversion Algorithm for Airborne GPS Radio Occultation Measurements, *Atmospheric Measurement Technology*, *9*, 5077-5087.
4) Aiken, C., K. Chao, H. Gonzalez-Huizar, R. Douilly, Z. Peng, A. Deschamps, E. Calais, and J. S. Haase (2016), Exploration of remote triggering: A survey of multiple fault structures in Haiti, *Earth and Planetary Science Letters*, *455*, 14-24.
5) Saunders, J. K., D. E. Goldberg, J. S. Haase, Y. Bock, D. G. Offield, D. Melgar, J. Restrepo, R. B. Fleischman, A. Nema, J. Geng, C. Walls, D. Mann, and G. Mattioli (2016), Seismogeodesy using GPS and low-cost MEMS accelerometers: Perspectives for earthquake early warning and rapid response, *Bull. Seis. Soc. Am*, *106*.
6) Zhang, W., Y. Lou, J. S. Haase, R. Zhang, G. Zheng, J. Huang, C. Shi, and J. Liu (2016), The use of ground-based GPS precipitable water measurements over China to assess radiosonde and ERA-Interim moisture trends and errors from 1999-2015 *J. Geoph. Res.*, *submitted*.
7) Wang, K.-N., J. L. Garrison, J. S. Haase, and B. J. Murphy (2016), Implementation of the phase matching (PM) method for the GPS airborne radio occultation (ARO) system, *Journal of Geophysical Research*, *submitted*.
8) Chen, X.-M., S.-H. Chen, J. S. Haase, B. J. Murphy, K.-N. Wang, J. L. Garrison, S.-Y. Chen, C. Y. Huang, L. Adhikari, and F. Xie (2016), Assimilation of Airborne Radio Occultation Measurements and Their Impact on the Prediction of Hurricane Karl in 2010, *Journal of Advances in Modeling Earth Systems*, *submitted*.

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

The relationship between the velocity of the uppermost layer of the oceanic crust, layer 2A, and hydrothermal circulation has been studied for four decades since *Houtz & Ewing* (1976) showed that seismic velocities of layer 2A almost doubled over ~30 Ma from a compilation of sonobuoy results. The increase in velocity occurs because precipitation of minerals during low temperature circulation seals cracks and reduces porosity, the primary control on velocity. More recent compilations, with better constrained velocities, reveal that, on average, the increase velocity is more rapid, occurring over ~10 Ma, but their usefulness is limited by the fact that they are comprised of individual spot measurements from different data types with differing analysis methods, resulting in a large scatter. While the average velocities are robust, it is hard to know whether the scatter is consequence of, for example, different patterns of hydrothermal alteration, variation inherited from crustal accretion, or simply a consequence of analysis errors.

One means of addressing these deficiencies is to create continuous high-resolution models of velocity from multichannel seismic (MCS) profiles using modern analysis methods along representative transects. We have analyzed a flow-line profile from the eastern flank of the Juan de Fuca ridge using a combination of downward continuation and travel time tomography that have been successful in bare-rock ridge settings (*Henig et al.*, 2012; *Arnulf et al.*, 2014; *Harding et al.*, 2016). This profile is a useful test bed for new methods as there are earlier systematic seismic analyses of layer 2A and it is the location of the Flank Flux experiment and a drilling transect that studied the thermal and geochemical consequences for hydrothermal circulation of the rapid burial of young oceanic crust by turbidite sediments (*Davis et al.*, 1992; *Davis et al.*, 1997). *Nedimovic et al.*, (2008) analyzed the current dataset by interactive travel time fitting producing a set of one-dimensional models of the upper crust, while *Rohr et al.* (2004) analyzed an earlier MCS dataset using stacking velocities to estimate average layer 2A velocities.

Downward continuation, which is used to simulate a near-bottom experiment from surface MCS data, collapses most of the reflection energy from the sediments, allowing efficient picking of the refraction arrivals from the upper crust and the creation of a seismic tomography model, Figure 1a. There is relatively little change in upper crustal velocity structure in the unsedimented region near the ridge, but velocities increase rapidly between 19 & 50 km from the ridge, starting immediately the crust is fully sediment covered. This increase in layer 2A velocity coincides with a rapid increase in basement temperature, Figure 1b, and related changes in geochemical signals indicative of hydrologic sealing and enhanced precipitation of alteration minerals. The shape of the layer 2A velocity curve is closer to that found by *Rohr et al.* (2004) than the approximately linear gradient found by *Nedimovic et al.* (2008). Velocities are consistently lower than the upwardly biased interval velocities of *Rohr et al.* (2004) and show considerably smaller scatter. Upper crustal velocities of ~4 km/s are unusually fast for young, ~1.9 Ma, crust but are still somewhat below the layer 2A velocities expected of fully mature crust ~4.5-5 km/s.

Arnulf, A. F., A. J. Harding, G. M. Kent, S. C. Singh, and W. C. Crawford (2014), Constraints on the shallow velocity structure of the Lucky Strike Volcano, Mid-Atlantic Ridge, from downward continued multichannel streamer data, *J. Geophys. Res.*, 119, 1119–1144, doi:10.1002/2013JB010500.

Harding, A. J., A. F. Arnulf, and D. K. Blackman (2016), Velocity structure near IODP Hole U1309D, Atlantis Massif, from waveform inversion of streamer data and borehole measurements, *Geochem. Geophys. Geosys.*, 17, doi:10.1002/2016GC006312.

Henig, A., D. K. Blackman, A. J. Harding, J.-P. Canales, and G. M. Kent (2012), Downward continued multichannel seismic refraction analysis of Atlantis Massif oceanic core complex, 30° N, Mid-Atlantic Ridge, *Geochem. Geophys. Geosys.*, 13, Q0AG07, doi:10.1029/2012GC004059.

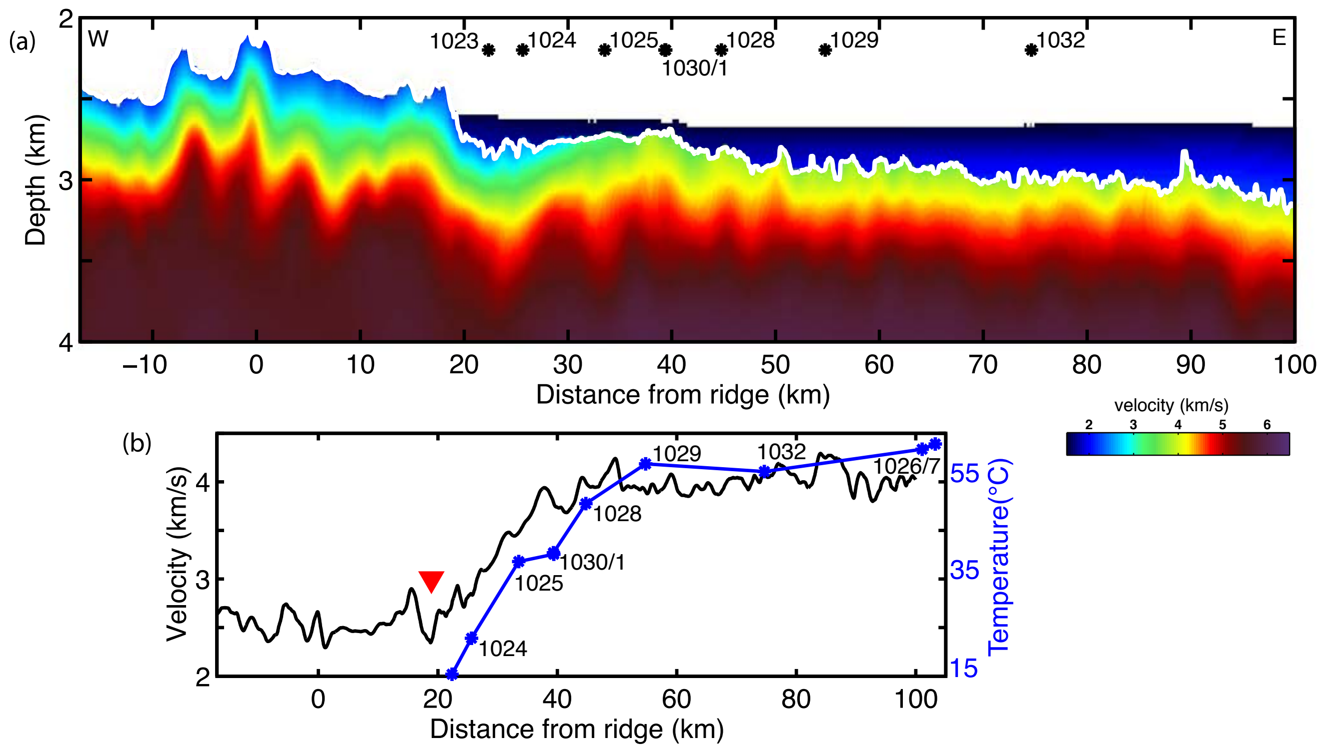

Figure 1 (a) Seismic tomography model of the Endeavour transect. White line is top of igneous basement. Numbered black dots are locations of ODP Leg 168 holes on or near the seismic profile. (b) Average velocity of the top 200 m of basement, upper layer 2A, left axis. Basement temperatures of the ODP boreholes, right axis. Red triangle indicates the onset of sediment burial.

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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 the variance of atmospheric pressure in the 2-6 hour pass-band at local night. Elevated variance of atmospheric pressure is due to the presence of atmospheric gravity waves. As expected, large gravity waves are common to the west of the Great Lakes and are from convective activity.

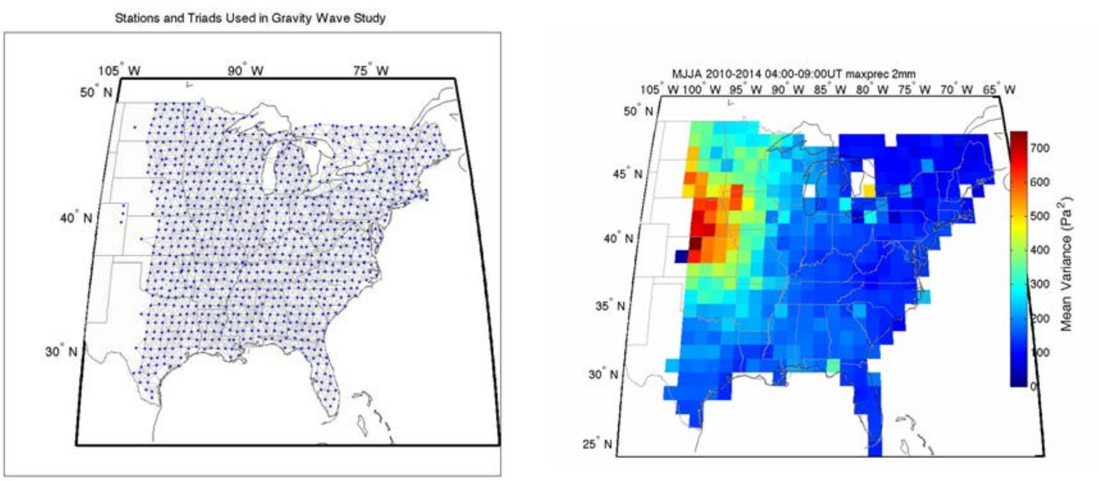

Figure 1. left) sites occupied by stations in the TA from January 1, 2010 through Sept 30, 2014. These stations have been grouped into 3-element arrays (triads) for the study of long-period atmospheric gravity waves. The panel on the right shows the variance of atmospheric pressure in the 2-6 hr passband during the thunderstorm seasons from 2010 through 2014. The highest variance to the west of the Great Lakes is due to gravity waves excited by convective storms.

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.

de Groot-Hedlin, C.D. and Hedlin, M.A.H., 2015, A method for detecting and locating geophysical events using groups of arrays, *Geophys. J. Int.*, v203, 960-971, doi: 10.1093/gji/ggv345

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

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.

Stephan, C., Alexander, M.J., Hedlin, M.A.H., de Groot-Hedlin, C.D. and Hoffmann, L., 2016, A case study on the far-field properties of propagating tropospheric gravity waves, *Monthly Weather Review*, v144, p2947-2961, DOI: 10.1175/MWR-D-16-0054.1.

David R. Hilton

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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, halogens, and major volatiles (such as CO_2 and N_2) – from different tectonic environments. New publications this year include two papers on the Icelandic hotspot – involving N and Cl isotopes – where we assess and discuss the extent of volatile heterogeneity in the plume source and conclude that recycling of material once at Earth's surface mixes with pristine volatiles in Earth's deep mantle to yield the observed distributions in Iceland's neovolcanic zones. Other studies describe (a) the coupling of a mantle volatile input observed in hot springs in the mid-US to distinctive microbial communities, and (b) establishing criteria to study how CO_2 is sequestered in geothermal systems in Turkey with the general aim of evaluating if geothermal systems represent viable storage sites for CO_2.

We also present a new reference model to explain how surface volatiles began cycling into the deep Earth via subduction and out again at volcanoes, gradually changing both the atmosphere and the planet's interior. We used oceanic basalts and phenocrysts collected along the Central Indian Ridge, its off-axis ridges and at Réunion Island to report new nitrogen and noble gas data showing evidence for both plume-derived and recycled volatiles in the underlying mantle (see Figure). The reference model reveals how N and potentially other volatile elements (e.g., C, O) behave during subduction. We concluded that the deep Earth nitrogen cycle favors regassing of Earth's lower mantle, which in turn has slowly changed atmospheric N concentrations as well. This conclusion has far-reaching consequences for our understanding of deep Earth volatile cycles. For example, the new reference model is consistent with a higher nitrogen content in Earth's early atmosphere. Such elevated nitrogen concentrations potentially instigated nitrogen-enhanced greenhouse warming, thus explaining the lack of global glaciations on the young Earth as a consequence of a faint young Sun.

<ins>New Publications</ins>

Crossey, L.J., Karlstrom, K.E., Schmandt, B., Crow, R.R., Colman, D., Cron, B., Vesbacj, C., Dahm, C., Northup, D.E., **Hilton, D.R.,** Ricketts, J. and Lowry, A.R. (2016) Continental smokers couple mantle degassing and distinctive microbiology within continents. Earth Planet. Sci. Lett. <ins>435</ins>, pp 22-30. 10.1016/j.epsl.2015.11.039

Halldórsson, S.A., **Hilton, D.R.**, Barry, P.H., Furi, E. and Gronvold, K. (2016) Recycling of crustal material by the Iceland mantle plume: new evidence from nitrogen elemental and isotope systematics of subglacial basalts. Geochim. Cosmochim. Acta <ins>176</ins>, pp 206-226. 10.1016/j.gca.2015.12.021

Gulec, N. and **Hilton, D.R.** (2016) Turkish geothermal fields as natural analogues of CO_2 storage sites: Gas geochemistry and implications for CO_2 trapping mechanisms. Geothermics <ins>64</ins>, pp 96-110. 10.1016/j.geothermics.2016.04.008

Barry, P.H. and **Hilton, D.R.** (2016) Release of subducted sedimentary nitrogen throughout Earth's mantle. Geochemical Perspectives Letters <ins>2</ins>, pp 148-159. 10.7185/geochemlet.1615

Halldórsson, S.A., Barnes, J.D., Stefansson, A., **Hilton, D.R.**, Hauri, E.H. and Marshall, E.W. (2016) Subducted lithosphere controls halogen enrichments in the Iceland mantle plume source. Geology 44, pp 679-682. 10.1130/g37924.1

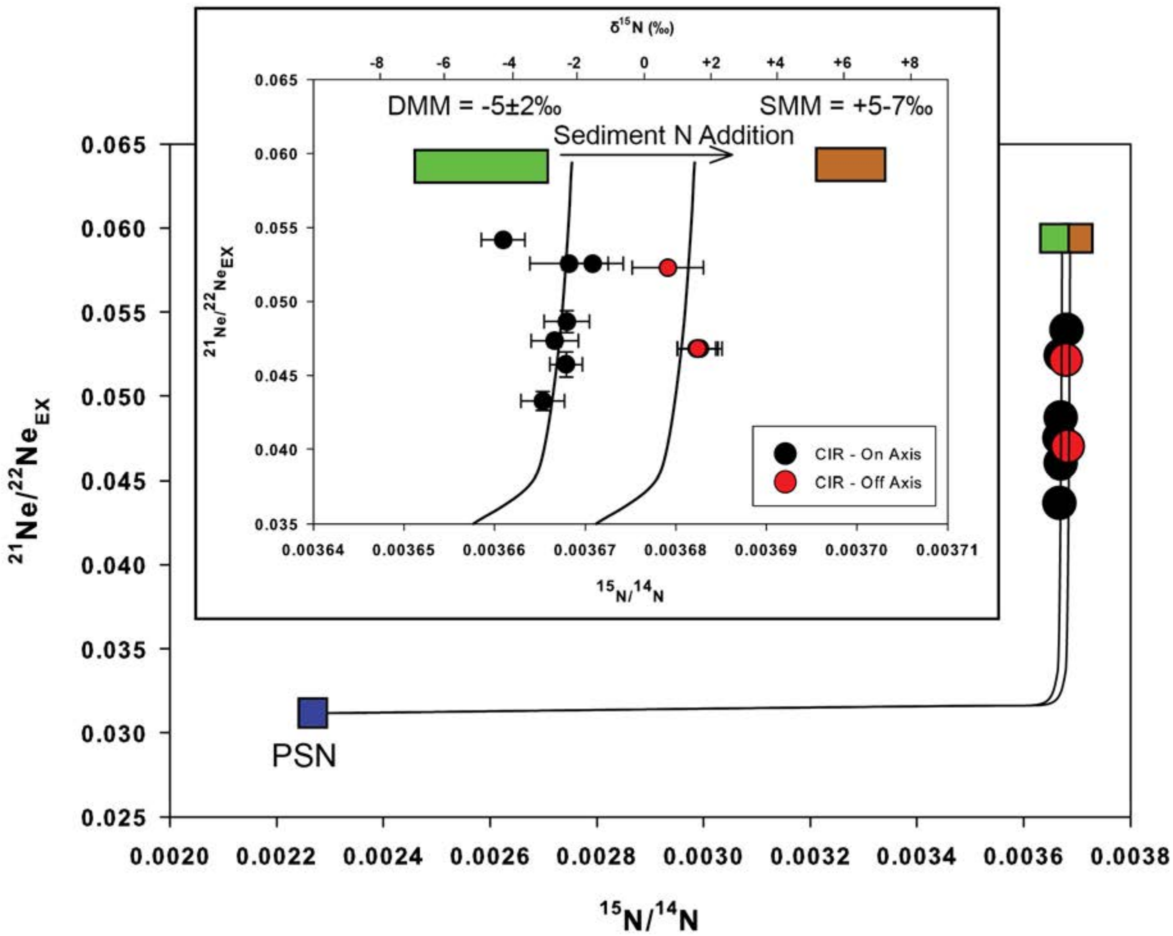

Figure Caption – Extrapolated Ne ($(^{21}Ne/^{22}Ne)_{EX}$, i.e., air-corrected $^{21}Ne/^{22}Ne$ values) versus $^{15}N/^{14}N$ values of CIR basalts, plotted together with binary mixing curves between a pre-solar nitrogen (PSN) component ($^{15}N/^{14}N$ = 0.00227, $\delta^{15}N$ = -373‰) and two mantle endmember components reflecting addition of ^{15}N-enriched sedimentary MORB mantle (SMM; $\delta^{15}N$ = +5‰) to Depleted MORB mantle (DMM) ($\delta^{15}N$ = -5‰). The curvature of the hyperbolic mixing lines is described by the r-value = $(^{14}N/^{22}Ne)_{DMM/SMM}$ /$(^{14}N/^{22}Ne)_{PSN}$. From Barry and Hilton (2016).

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

Research Interests: 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.

A Time-Domain Detection Approach to Identify Small Earthquakes within the Continental U.S. Recorded by the USArray and Regional Networks [Velasco et al., 2016]. Technological advances in combination with the onslaught of data availability allow for large seismic data streams to automatically and systematically be recorded, processed and stored. Here, we develop an automated approach to identify small, local earthquakes within these large continuous seismic data records. Our aim is to automate the process of detecting small seismic events triggered by a distant large earthquake, recorded at a single station (Figure 1). We apply time domain short-term average (STA) to long-term-average (LTA) ratio algorithms to three-component data to create a catalog of detections. We apply these detectors to ±45 hours and ±5 hours of USArray data from the 2011 Japan magnitude 9.0 and the 2010 Chile magnitude 8.8 earthquakes, respectively. Using time-of-day versus number of detection relationships, of the 728 stations we identify 38 that exhibit strong anthropogenic noise. Our detection algorithm identified three regional earthquakes in the Coso region of California that were concurrent with the passage of the *S*- and surface-waves of the Chile mainshock at USArray station R11A, as well as events in Texas following the Japan earthquake.

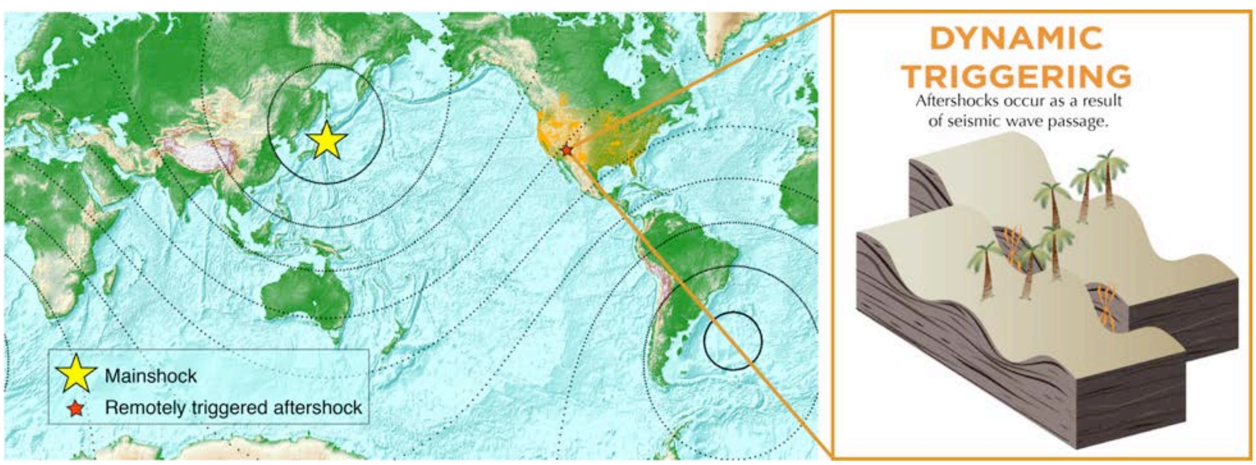

Figure 1: We aim to design an automated detection scheme to catalog local earthquakes recorded by the USArray TA network (points distributed throughout the continental USA), which can be used to help test the hypothesis that a large earthquake (e.g., large star, contours illustrate the mainshock's seismic waves trajectory where the bolder the contour the larger the seismic wave amplitudes) can trigger small aftershocks at remote distances (i.e., small star, many mainshock fault lengths away). These distant aftershocks are assumed to be triggered by dynamic stress changes caused by the mainshock's seismic waves (pull-out cartoon).

Exploring Remote Earthquake Triggering Potential 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), an array of over 400 seismic stations deployed in a grid pattern in the continental US. These stations provide uniform station sampling, similar recording capabilities, large spatial coverage, and in many cases, repeat sampling at each site. Using our new automated method we examine 18 global mainshocks (M≥7) that generate median peak dynamic stress amplitudes of 0.001- 0.028 MPa across the array. We find no evidence of prolific or widespread remote dynamic triggering in the continental U.S. within the mainshock's wavetrain or within the next 2 days following the mainshock stress transients. There is, however, limited evidence of seismicity rate increases 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.

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. This hydraulic fracturing at the base of a glacier can provide a mechanism to track fluid flow within glaciers in near real-time.

Glacier Ambient Noise Study [Walter et al., 2015]: We use seismic ambient noise data from the Greenland Ice Sheet and a Swiss Alpine glacier. Using the direct and scattered wave fields from the vast numbers of icequake records (tens of thousands per month), we can measure small changes in englacial (within the glacier) velocities, and in turn monitor bedrock depth and structural changes within the ice. In this way, seismic networks can be used to monitor a glacier's subsurface structure at sub daily time scales over months or longer. This constitutes a clear advantage over active source techniques that require considerable manpower for data acquisition.

Recent Publications

Heeszel, D., F. Walter and **D.L. Kilb** [2014]. "Humming Glaciers", *Geology,* 1099-1102, doi: 10.1130/G35994.1

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, doi: 10.1785/0220130182.

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. doi: 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.*. doi: 10.1002/2014JB011529. Dynamic Content: interactive visualization of a high-resolution array image http://siogames.ucsd.edu/Zoom/linville_etal_2014

Velasco, A.A., R. Alfaro - Diaz, **D. Kilb**, K.L. Pankow [2016]. "A Time - Domain Detection Approach to Identify Small Earthquakes within the Continental United States Recorded by the USArray and Regional Networks", *Bull. Seism. Soc. Am.*, 106: 512-525, doi: 10.1785/0120150156.

Walter, F., P. Roux, C. Roeoesli, A. Lecointre, **DL Kilb,** P-F. Roux [2015]. "Using glacier seismicity for phase velocity measurements and Green's function retrieval", *Geophysical Journal International*, 201: 1722-1737, doi: 10.1093/gji/ggv069.

Gabi Laske
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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 continues collaboration with Guy Masters and former graduate student Zhitu Ma to compile and distribute global crust and lithosphere models. CRUST1.0, A 1-degree crustal model, was released in 2013. Applications relying on CRUST1.0 are found across multiple disciplines in academia and industry. Laske maintains the distribution website and provides guidance to users.

The PLUME project: For the past decade or so, Laske has analyzed waveforms collected on ocean bottom seismometers (OBSs). She was the lead-PI of the Hawaiian PLUME project (Plume–Lithosphere–Undersea–Mantle Experiment) to study the plumbing system of the Hawaiian hotspot. Results from various body wave, surface wave and receiver function studies were published. A feasibility study with Christine Thomas at Münster University, Germany found new and **previously unmapped D" precursors**. The exceptional quality of PLUME deep-ocean vertical-component records allowed the team to detect PdP waves for some areas and found convincing null-results for other areas. This was the first study of its kind using OBS data. The dataset also provides the basis for PhD student Adrian Doran who studies **seafloor compliance and ambient-noise** Green's functions. His work will help constrain structure in the shallow sediments and crustal layers that were not resolved by previous work. Doran formulated the concept of horizontal compliance and published first-ever application to real OBS data. He also developed a new automated tool to determine OBS instrument orientations using Rayleigh waves, with little interaction by the data analyst. A paper was recently accepted, and the Python computer code will be released shortly.

Surface Wave Azimuthal Anisotropy: MS student Chenghao Shen continues the analysis of PLUME Rayleigh-wave **azimuthal anisotropy**. While shear-wave splitting results appear to be sensitive only to the fossil spreading direction "frozen" into the lithosphere, Laske and her students found a clear signal that is suggestive of plume-related flow in the asthenosphere. This past summer German Academic Exchange Service student Lennart Ramme from Münster University, Germany performed extensive forward modelling for local two-layer models. Laske has also collaborated with Donna Blackman to model flow-induced rock texture in the aging ocean lithosphere, and implications for seismic anisotropy. A manuscript is in revision.

The ADDOSS project: For the ADDOSS (Autonomously Deployed Deep-ocean Seismic System) Laske collaborates with Jon Berger, John Orcutt, Jeff Babcock and Liquid Robotics Inc. to develop and test an untethered OBS system that is capable of providing **near-real time data** collected on the ocean floor. A wave glider towing an acoustic mo-

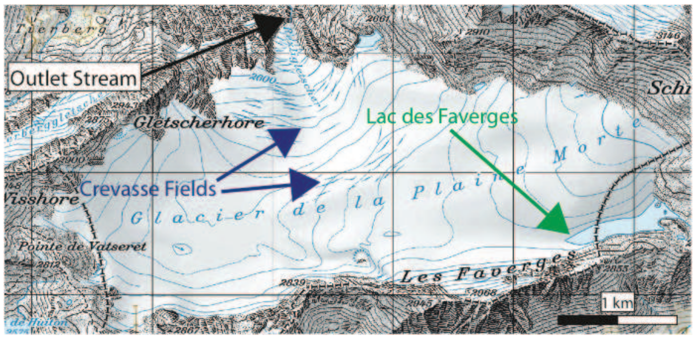

Figure 1: Map of Glacier de la Plaine Morte just south of Wildstrubel, Switzerland. The Rhone valley is to the south. Marked is the outlet stream at the toe of Rexliglacier that drains into the Simme river to the north. Arrows mark Lac des Faverges, a major glacier lake, and the two crevasse fields that Laske and Walter occupied with four arrays of short-period seismometers during the 2016 summer. The instruments were borrowed from the GIPP instrument pool at GFZ, Potsdam, Germany.

dem maintains a communications link to the OBS. The group has performed several tests in shallow (1000 m) and deep (3800 m) water. A 3-month deep-water test about 300 km west of La Jolla in the winter of 2013 revealed never-before seen seismic activity in the Outer California Borderland. Doran and Laske returned in the summer of 2015 on UC ship fund cruises to continue investigation of this seismicity in more detail.

The AnICEotropy project: Laske has been collaborating with Fabian Walter at ETH, Switzerland to study ice quakes on the Glacier de la Plaine Morte, Switzerland. This plateau glacier that separates Cantons Berne and Valais develops a glacier lake, Lac des Faverges, during snow melt that frequently drains and floods the Simme valley to the north. Recent floods have become more frequent and larger, approaching the capacity of the flood control system. Laske and collaborators installed seismometers on the glacier and are trying to identify precursory ice quake activity that helps improve early flood warning. As an academic by-product, the gathered seismicity allows a 'sandbox' azimuthal anisotropy analysis to test the hypothesis that seismic anisotropy is aligned with the crevasses on the glacier. This project provided the basis for an ice-quake localization study for visiting summer student Manuel Krage from Münster University, Germany.

Recent publications:

Thomas, C. and Laske, G., D" observations in the Pacific from PLUME Ocean Bottom Seismometer recordings. *Geophysical Journal International*, 200, 851–862, doi:10.1093/gji/ggu441, 2015.

Berger, J., Laske, G., Babcock, J. and Orcutt, J., An Ocean Bottom Seismic Observatory with Real-time Telemetry. *Earth and Space Science*, 3, 68–77, 2016.

Doran, A. and Laske, G., Infragravity waves and horizontal seafloor compliance. *J. Geophys. Res.*, 121, 260–278, doi:10.1002/2015JB012511, 2016.

Doran, A. and Laske, G., IOcean-bottom seismometer instrument orientations via automated Rayleigh-wave arrival angle measurements. *Bull. Seismol. Soc. Am.*, in press, 2016.

Walter Munk **Research Professor**
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Research Interests: Ocean waves and sea level changes

I am continuing to work on wind-wave interactions and how they can be measured using ambient noise from nonlinear behavior.

Recent Publications

W. E. Farrell, J. Berger, J.-R. Bidlot, M. Dzieciuch, W. Munk, R. A. Stephen, and P. F. Worcester (2016), Wind sea behind a cold front and deep ocean acoustics, *J. Phys. Oceanogr.* **46**, 1705-1716, DOI: 10.1175/JPO-D-15-0221.1

W. Munk (2015) An oceanographic perspective, in *Sustainable Humanity, Sustainable Nature: Our Responsibility* Pontifical Academy of Sciences Extra Series **41** (Vatican City).

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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

Formation of the Isthmus of Panama
There has been controversy in recent years about the timing of the uplift of the Panama Isthmus, the oceanographic separation of the tropical Pacific from the Caribbean, and the interchange of land animals between North and South America. Evidence from zircon dates has been used to suggest that the isthmus formed as early as 12-13 million years ago, considerably older than previous estimates. I participated (as one of 35 authors) in a synthesis of the evidence for the age of the isthmus. My part in the paper was to write a section on the implications of deep ocean oceanography for this controversy. We assembled data from outcrop geology, paleowater depths, deep sea microfossils, light stable isotopes, neodymium isotopes, ocean models, molecular genetics of marine animals, and time of appearance of land mammals in North and South America. These diverse lines of evidence show that the isthmus first had detectable effects on deep oceanography about 10-11 million years ago, severed deep water interchange between the Pacific and Atlantic by 9.2 Ma, altered surface ocean chemistry by 4.2 Ma, and largely isolated surface water plankton populations by 2.7 Ma. Concurrently, land mammal dispersals accelerated across the isthmus by 4-5 Ma and the most recent genetic divergences of shallow marine animals occur by 3 Ma. Finally, there is evidence for intermittent connection between the Pacific and the Atlantic oceans as late as 2.45 Ma, the probable final formation of permanently dry land across Panama.

Recent Publications

O'Dea, A., H. A. Lessios, A. G. Coates, R. I. Eytan, S. A. Restrepo-Moreno, A. L. Cione, L. S. Collins, A. de Queiroz, D. W. Farris, R. D. Norris, R. F. Stallard, M. O. Woodburne, O. Aguilera, M.-P. Aubry, W. A. Berggren, A. F. Budd, M. A. Cozzuol, S. E. Coppard, H. Duque-Caro, S. Finnegan, G. M. Gasparini, E. L. Grossman, K. G. Johnson, L. D. Keigwin, N. Knowlton, E. G. Leigh, J. S. Leonard-Pingel, P. B. Marko, N. D. Pyenson, P. G. Rachello-Dolmen, E. Soibelzon, L. Soibelzon, J. A. Todd, G. J. Vermeij and J. B. C. Jackson (2016). Formation of the Isthmus of Panama. *Science Advances* **2**(8). 10.1126/sciadv.1600883

Sibert, E., R. Norris, J. Cuevas and L. Graves (2016). Eighty-five million years of Pacific Ocean gyre ecosystem structure: long-term stability marked by punctuated change. *Proceedings of the Royal Society Biological Sciences* **283**(1831). 10.1098/rspb.2016.0189

Penman, D. E., S. K. Turner, P. F. Sexton, R. D. Norris, A. J. Dickson, S. Boulila, A. Ridgwell, R. E. Zeebe, J. C. Zachos, A. Cameron, T. Westerhold and U. Rohl (2016). An abyssal carbonate compensation depth overshoot in the aftermath of the Palaeocene-Eocene Thermal Maximum. *Nature Geoscience.* 10.1038/ngeo2757

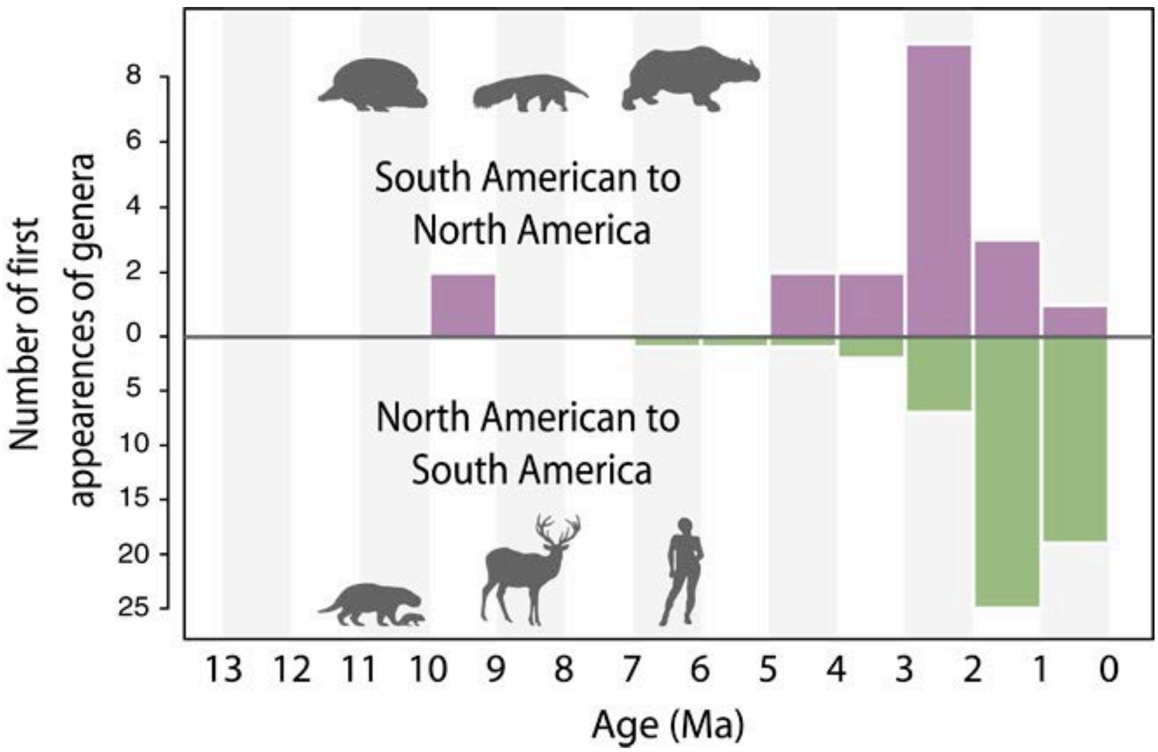

Figure 1 Caption: History of land mammal exchange between North American and South America associated with the formation of the Isthmus of Panama. The major mammalian 'interchange' accelerated between 2 and 3 million years ago. We have shown, in O'Dea et al. 2016, *Science Advances*, that this timing of land mammal exchange is onsistent with diverse geological, geochemical, marine paleontological and genetic evidence for the formation of the Panama Isthmus by 2.45 to 3 million year ago.

John A Orcutt **Distinguished Professor of Geophysics**

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Research Interests*:* My current research interests include the operation of a large number of broadband and wideband ocean bottom seismographs, the extension of seafloor seismology to a global scale using new seismometer technologies. In addition I am working on new cyberinfrastructure for collecting and controlling remote sensors on a local to global scale.

With Frank Vernon, Michael Meisinger and Edward Hunter, we have developed the *Scientific Observatory Network* (*SciON)* software for a scientific *Internet of Things* (IOT). *SciON* was originally envisioned by a team of scientists and technology professionals at Scripps, UC San Diego's Qualcomm Institute, and several collaborating institutions. Previously named *OOINet,* and originally developed to support the National Science Foundation's *Ocean Observatories Initiative* (*OOI*), *SciON* provides reliable, high-volume, secure collection of data and command-and-control of remote sensors, instruments, and platforms. The software, written largely in *Python,* relies heavily on open-source software and is available under an open BSD (Berkeley Standard Distribution) 2-Clause License.

Scripps Institution of Oceanography is an international leader in environmental and geoscience observing systems. Scripps has long-term experience in cutting-edge operational sensor networks, including the *USArray* component of NSF's *EarthScope*, the NSF-supported *Global Seismic Network (GSN)*, the *Southern California Coastal Ocean Observing System (SCCOOS),* and the privately-supported *ANZA Seismic Network* — all of which informed the design of *SciON*. *SciON* builds on expertise with sensor and communications networks, including NSF's *HiSeasNet* and the NSF-initiated *High Performance Wireless Research and Education Network (HPWREN)*. *HiSeasNet*, for example, started as a single Office of Naval Research-supported installation on *R/V Melville* to demonstrate that high-bandwidth telemetry was possible from a buoy, envisioned as a necessary capability for the prospective NSF OOI.

Modern oceanography relies on new software and hardware technologies to enable a remote presence in the oceans, including UNOLS ships and, increasingly, robotic systems such as *Argo*, aerial vehicles launched from ships, and gliders and wave gliders. Sophisticated software is needed to take advantage of remote sensors, instruments, and platforms in multi-disciplinary environments. The software is valuable for oceanographic (and other) applications as initial requirements were informed through community workshops, reviews by the oceanographic community, and software experts.

SciON's Service Oriented Architecture (SOA) is highly extensible and includes important new capabilities. For example, the networking between the software and sensors/platforms relies upon the *Advanced Messaging Queuing Protocol (AMQP)* for secure, high-speed, point-to-point communications. To maintain security, connections to the public Internet are made at a limited number of *Cyberinfrastructure Points of Presence (CyberPoPs)*. *AMQP* was originally designed by the financial sector to support millisecond trading, provide high-level security, and allow passing of large volumes of data and products from point-to-point. Users of the software are able to subscribe to specific remote instruments to provide streaming data to virtual observatories in near-real-time, in some cases with latencies as short as a second from instruments later deployed with the Regional Scale Nodes (RSN). Elasticity is an important design element to ensure support of variable workloads through CyberPoP hardware or academic/commercial clouds. When loads increase, new instances of the appropriate software components are started in these environments; as the loads decrease, the instances are reduced. Elastic computing reduces hardware requirements, resulting in significant cost savings.

Presently we are supporting more than a hundred broadband seismic stations in near-real-time as well as wave height/direction from the global CDIP facility while making data available in HDF5 format. The hardware required is modest in that it includes a single (approx. $7K) Dell R720 with dual Xeon processors with six cores each. There are 192GB of disk storage that support 4-6 virtual machines. Only a small fraction of the compute power available is used normally although the system's capacity increases as the numbers of sensors increase. The software is elastic and scales well as the load increases. The hardware/software system is designed for acceptable scalability, high security through the use of AMQP and ease of modification given that most of the system is written in Python and some in JavaScript.

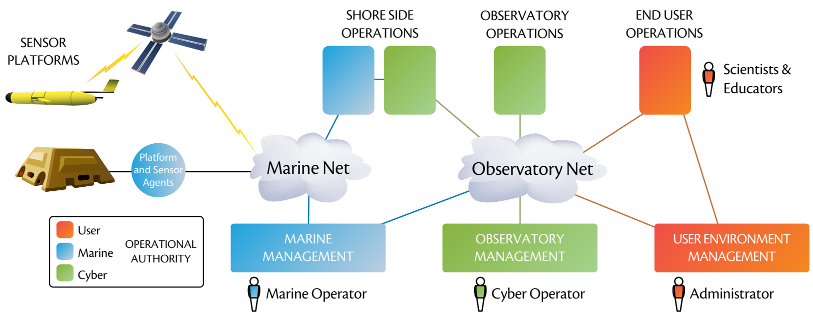

Figure caption: A schematic of an integrated ocean network extending from sensors and tobots on the left to users on the right.

Finally, I have participated in a major effort to build a long-term observatory in the Arctic entitled "Arctic Watch." During the past 20 years, Arctic ice has been disappearing at an accelerated rate; in 2012 the summer ice cover has been reduced to 20% of the cover in 1987. Optimistically, the summer ice cover may last until mid-century. In addition to the loss of new ice, multi-year ice, characterized by significant thicknesses is disappearing even more rapidly with the implication that the volumetric rate of loss of ice is even greater than that for ice surface as observed from space. We have proposed a major effort to establish an observatory in the Arctic centered on a seafloor cable that would extend from Barrow, AK through the North Pole and then to Longyearbyen, Svalbard, Norway. The observatory will include seafloor cable junction boxes situated along the length of the cable for environmental sensors, acoustic thermometry, seafloor current, docking stations for autonomous vehicles and acoustic arrays. SciON would be used for delivering near-real-time data from the Arctic with latencies of a few seconds to researchers ashore. The data collected will be openly available to all researchers and agencies.

Recent Publications

Mikhalevsky, P., H. Sagen, P. Worcester, A. Baggeroer, J. Orcutt, S. Moore, C. Lee, K. Vigness-Raposa. L. Frietag, M. Arrott, K. Atakan, A. Beszczynska-Moller, T. Duda, B. Dushaw, J. Gascard, A. Gavrilov, H. Keers, A. Morozov, W. Munk, M. Rixen, S. Sandven, E. SKarsoulis, K. Stafford, Vernon, F., M. Yuen, (2015), Arctic, 11-17, doi: 10.14430/arctic4449.

Berger, J., G. Laske, J. Babcock, & J. Orcutt, (2016), An Ocean Bottom Seismic Observatory with Near Real-Time Telemetry, Earth Space Sci., 1-10, doi: 10.1002/2015EA000137.

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Research Interests*:* physics and chemistry of silicate melts; 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 evolution) to the present.

Ongoing research projects have mainly focused on (i) the experimental investigation of the electrical properties of sheared rocks in the Earth's upper mantle, (ii) the investigation of the terrestrial cores using high-pressure experiments and numerical modeling.

(i) Under funding from NSF Cooperative Studies Of The Earth's Deep Interior, my collaborators David Kohlstedt, Lars Hansen, Stephen Mackwell, Miki Tasaka, Florian Heidelbach, Kurt Leinenweber, and I conducted a systematic experimental study of the effect of shear deformation on the electrical conductivity of polycrystalline olivine (Pommier et al., EPSL, in rev.). The main objective is to explore the role of plastic shear deformation on electrical properties at upper mantle conditions and thus, to help interpret electromagnetic profiles of the asthenosphere. Although it has been suggested that melt is required to reproduce electrical conductivity and anisotropy in the asthenosphere, electrical properties of the sheared polycrystalline matrix and their contribution to bulk electrical anisotropy at upper-mantle conditions are not fully understood and require further investigation. In this study, samples were initially deformed at 1200°C and 0.3 GPa in a gas-medium apparatus to a shear strain of up to 7.3. Electrical conductivity and anisotropy of the samples were measured at 3 GPa over the temperature range ~700-1400°C in a multi-anvil apparatus using a two-electrode technique. The results demonstrate that shear deformation increases electrical conductivity, even in the absence of melt, and that conductivity is highest in the direction of shear, with the sample deformed to the highest strain being the most conductive. The important role of grain boundaries in the conductivity of sheared materials was mostly assessed by comparing our bulk conductivity values with computed bulk conductivity of grain interiors. The latter was calculated using the conductivity of each grain (known from previous electrical studies on single crystals) depending on its crystallographic orientation (defined using EBSD analyses). We observed a factor of up to 10 between grain interior conductivities from the electrical pole figures and measured bulk conductivities, and the fastest direction ([010]) in the experiments is not the one obtained from the measurements and CPO ([100]), suggesting that grain-boundary conduction best explains electrical anisotropy (up to 4.5) in all samples, with a noticeable effect of grain boundary orientation distribution characterized by a preferential grain-boundary alignment sub-parallel to the shear plane. A strong CPO implies a preferential orientation distribution of grain boundaries, with boundaries in the shear direction having a different crystallography and thus different physical properties than boundaries in an orthogonal direction. We suggest that grain boundary crystallography introduces anisotropy into the mobility of charge carriers and causes electrical anisotropy. These experimental data also suggest that the interpretation of electromagnetic data in the uppermost mantle requires consideration of the effect of rock deformation on the bulk electrical response, instead of attributing high electrical conductivities solely to rock chemistry (presence of hydrogen and/or melt).

(ii) It has been suggested that several wt.% of light elements (e.g., S, C, H, O, N, Si) may compose the metallic core of terrestrial planets, affecting its bulk physical properties (for instance, by lowering density, viscosity, and bulk modulus) and thus the dynamics and thermal history of the core. A combination of light elements is likely part of planetary cores, and sulfur is thought to be present in significant amount. Another major candidate is oxygen because of its abundance in several bulk terrestrial planets, its partitioning behavior into metal at core pressure and temperature, and because oxygen is thought to partition favorably into the liquid phase upon cooling and thereby drive compositional convection. Therefore, understanding the crystallization of O-bearing phases in a metallic core and the partitioning behavior of O between these phases is critical for elucidating its effect on the core's magnetic activity in small planets. Together with collaborators Dan Frost, Vera Laurenz (BGI, Germany) and Christopher Davies (University of Leeds, UK), I conducted an experimental investigation of the phase equilibria in the Fe-S and Fe-S-O systems (Pommier et al., submitted). Experiments were performed at high temperatures (1400-1850°C) and high pressure (15 and 21 GPa) using a multi-anvil apparatus. The results of this study are used to understand the effect of oxygen on core dynamics of small terrestrial planets. Our experiments show that oxygen has little effect on the liquidus temperature and that the formation of FeO occurs in the form of a layer at the Fe-S liquid – Fe solid interface at high temperature (>1400°C at 21 GPa) (see Figure). Oxygen fugacities calculated for each O-bearing sample showed that redox conditions vary from ΔIW=-0.65 to 0. Considering the relative density of each phase and existing evolutionary models of terrestrial cores, we applied our experimental results to the cores of Mars, Mercury, and Ganymede. We show that the presence of FeO in small terrestrial planets tends to contribute to outer-core compositional stratification, due to density contrasts. Depending on the redox and thermal history of the planet, FeO may also help forming a transitional redox zone at the core mantle boundary. This compositional stratification of the core may bear a seismically observable signal as part of future spacecraft missions. This study was supported by the Alexander von Humboldt Foundation.

Related publications: 1- A. Pommier, D. L. Kohlstedt, L. Hansen, S. J. Mackwell, M. Tasaka, F. Heidelbach, and K. Leinenweber, Experimental Investigation of the Effect of Shear on the Electrical Properties of Polycrystalline Olivine, EPSL, in rev. 2 – A. Pommier, V. Laurenz, C. J. Davies, D. J. Frost, Melting Phase Relations in the Fe-S and Fe-S-O Systems at Core Conditions in Small Terrestrial Bodies, JGR Planets, submitted.

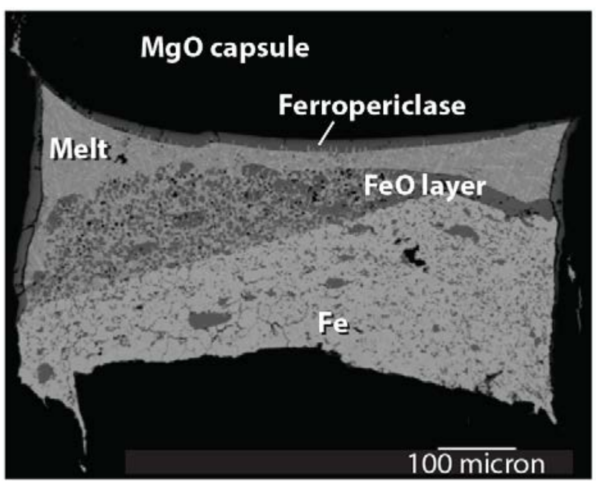

Figure caption: Back-scattered electron images of a retrieved sample after equilibration at high pressure and temperature in the Fe-S-O system. Experiment conducted at 21 GPa, 1600°C, showing the destruction of a continuous FeO layer at the liquid/solid interface. This layer corresponds to an unstable gravitational stage, as the density of FeO is smaller than the density of the Fe-S melt phase and of metallic iron. At the scale of a terrestrial core, the formation and migration (by density contrast) of FeO may influence significantly core dynamics and hence affect the dynamo. Note that the lighter sample contour, corresponding to ferropericlase, was used to estimate the oxygen fugacity of the sample.

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Research Interests*:* Environmental Archaeology, Geoarchaeology, Archaeomalacology, Marine Archaeology, Coastal Heritage, Human Adaptation to Climate and Environmental Change, Landscape reconstruction, Human-Environmental Dynamics, Socioecosystems, Resilience, Risk Perception, Food and Habitat Security

This year I joined UCSD and SIO as new joint hire between GRD and the Department of Anthropology. My most recent research has focused on two areas: the environmental legacies of deep-time human occupation on a tropical island, and the assessment of the impact of Pleistocene and Holocene sea level rise over Caribbean landscapes.

The first research area applies a multi-scalar analysis of biotic, abiotic and cultural data collected from archaeological and ethnographic methods on the hydrological basin of the Grande de Manati River in Puerto Rico. The goal is to investigate social and environmental histories to understand resilience and vulnerability at a local scale. A panarchy model was applied to organize recent and deep-time data to identify landscape use-patterns, use of forest and river resources and to evaluate long-term resilience/vulnerability.

The study is showing that the entire research area has been impacted by human activity, since the earliest of pre-Columbian occupations 5k years ago. In spite of the intensity of human activity, tropical forests show very high resilience. They recover and grow quickly, masking the evidence of human impact and the potential crises caused by reduced biodiversity, extirpation of native species and uncontrolled reproduction of non-native ones. In the context of the case study, social resilience is evidenced as continuation of long-term traditions based on local, regional and long-distance social support networks, and the maintenance of self-sufficient subsistence practices. For the non-elite, this knowledge is rooted in the deep-time memory of pre-Columbian traditions. Flexibility and adaptation allowed for the continuation in spite social, or environmental changes through time. More recent changes are increasing social vulnerability at all scales, suggesting that, upon facing the projected climate and environmental changes in the present and near future, the studied communities will be highly vulnerable and prone to social crises.

My second research area focuses on human adaptation to coastal environments in the Caribbean. The distribution of Late Pleistocene sites along Northern South America and Panama suggests that entry routes to South America occurred along the coasts and penetration inland followed large river basins, such as the Magdalena or the Cauca in Colombia. Patterns of settlement and discarded projectile points suggests that people during this period and until the Pleistocene / Holocene transition, used to live near aquatic environments, favoring ecotonal areas, carrying exploratory incursions inland and modifying the rainforests. Sites with very early radiocarbon dates, such as Pubenza (ca. 16.5k BP), Taima-Taima (ca. 14.4k BP), El Abra (ca. 12.4k BP) and Tibitó (ca. 11.8k BP) are kill-sites or specialized sites associated to hunting and butchering, but there is no evidence of coastal settlements of the same time periods along modern shorelines.

Global eustatic sea-level has risen 120 – 130m since the end of the Last Glacial Maximum (LGM) between ca. 26 and 19ka (Fig.1). The rate of sea level rise after the end of the LGM was outstanding. It is estimated that between 15 and 10ka sea level rose at a rate of over 10m every thousand years. Yearly change of coastlines would have been perceptible. We have no modern equivalent to compare the magnitude of sea level change, but we might be facing similar rates in the near future.

Figure 1: The Caribbean during the LGM, ca. 20ka. The light colored areas mark the bathymetric zones between 130 and 1.3m below modern sea level. All these areas would have been dry land during lower sea levels. Note that, with the exception of Trinidad and Tobago, all of the islands in the Caribbean Archipelago were detached from the mainland even during the LGM. Many of the islands, however, were merged to each other and some islands completely disappeared with post LGM sea level rise.

Data-modelling of sea-level rise in the Caribbean Region indicate that by 10ka eustatic sea level was at 24.6m below modern levels, and reached -1.3m by 5ka. Sea level rise submerged vast expanses of land causing the loss of productive coastal terrain, and the reshaping of cultural territories. Similar to the evidence recovered from Doggerland – the drowned landscapes between northern Europe and Britain – it can be expected that, when the sea level was lower, these terrains used to be dry landscapes covered in diverse ecosystems with rivers, estuaries, swamps and forests, as well as associated human settlements.

The picture we can recover from the human colonization of Caribbean lowlands is incomplete, as what we see as coasts today used to be inland locations. The prime, preferred locations at the time are today located underwater. This research project begins a quest to understand the impact that very rapid sea level rise had on coastal landscapes and on maritime societies in the past. This understanding will provide us with lessons from beneath the oceans, that will help us explore how rapid sea level rise will affect coastal natural and cultural landscapes in the near future. Developing on from this theme, I am also working on the evaluation of the threat that expected sea level rise poses to coastal heritage in Puerto Rico, and what can actions have to be taken regarding its potential loss. This research is developed for the 2018 assessment of the Puerto Rico Climate Change Council with the collaboration of SIO's graduate student Paula Ezcurra and on the context of the Society of American Archaeology's Committee on Climate Change Strategies and Archaeology Resources.

Recent Publications

Rivera-Collazo, Isabel. 2015. "Por El Camino Verde: Long-Term Tropical Socioecosystem Dynamics and the Anthropocene as Seen from Puerto Rico." The Holocene 25 (10): 1604–11. doi:10.1177/0959683615588373.

Rivera-Collazo, Isabel C. 2015. "Looking at the 'Continent Divided by Water': Coastal and Human Dynamics, and the Potential for Submerged Landscapes in the Caribbean." In 2015 IEEE/OES Acoustics in Underwater Geosciences Symposium (RIO Acoustics), 1–10. Rio de Janeiro, Brazil.

Rivera-Collazo, Isabel, Amos Winter, Denis Scholz, Augusto Mangini, Thomas Miller, Yochanan Kushnir, and D. Black. 2015. "Human Adaptation Strategies to Abrupt Climate Change in Puerto Rico Ca. 3.5 Ka." The Holocene 25 (4): 627–40. doi:10.1177/0959683614565951.

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Research Interests: Geodynamics, global marine gravity, crustal motion modeling, space geodesy

Students and Funding - Research for the 2015-16 academic year was focused on understanding the dynamics of the crust and lithosphere. Our group comprises three graduate students Soli Garcia (PhD 2016), Eric Xu, and John Desanto, one postdoc Dan Bassett and one lab assistants Ben Tea. Our research on improvement in the marine gravity field is co-funded by the National Science Foundation (NSF) and NASA. In addition, we are funded by Google to improve the accuracy and coverage of the global bathymetry. The NASA Earth Surface and Interior Program as well as the Southern California Earthquake Center provides funding our research on 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 AltiKa). 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 (*Garcia et al.,* 2013). The improved marine gravity is important for exploring unknown tectonics in the deep oceans (Figure 1) as well as revealing thousands of uncharted seamounts (*Sandwell et al.,* 2014, *Matthews et al*., 2016).

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. 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. These combined GPS/InSAR data are critical for understanding the along-strike variations in stress accumulation rate and associated earthquake hazard (*Tong et al.,* 2015; *Xu et al.,* 2015). The InSAR processing was performed with new software called GMTSAR developed at SIO (http://topex.ucsd.edu/gmtsar).

Crustal Motion Modeling – Over the past two years, three new InSAR satellites became operational. Sentinel 1A and 1B are the first of a series of European Space Agency (ESA) SAR satellites to provide an operational mapping program for crustal deformation along all zones having high tectonic strain. The three new satellite is ALOS-2, launched by JAXA. The L-band radar aboard ALOS-2 operates in a ScanSAR mode having a 350 km wide swath (Figure 2). **These satellites have the measurement cadence and spatial coverage needed to revolutionize our understanding of earthquake cycle processes both globally and along the San Andreas Fault System**.

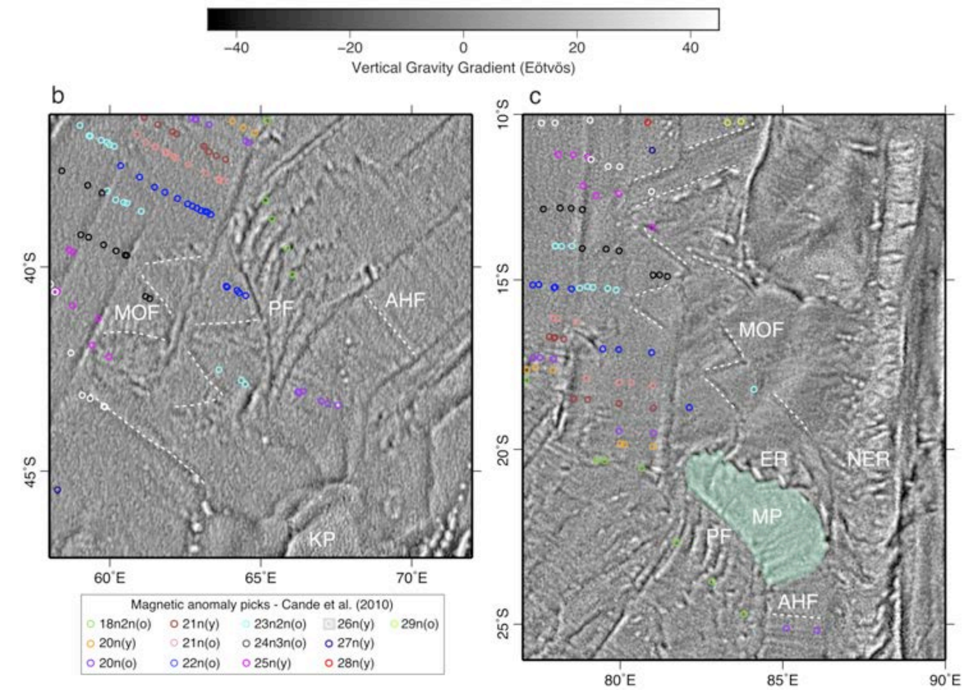

Figure 1. Vertical gradient of the marine gravity field reveals the detailed tectonics in the Indian Ocean (*Sandwell et al.,* 2014; *Matthews et al.,* 2016). These gravity data were used along with plate reconstructions to discover the Mammerickx Microplate which is the size of West Virginia (green shading on right figure).

Relevant Publications

Garcia, E. S., D. T. Sandwell, and K. M. Luttrell, An Iterative Spectral Solution Method for Thin Elastic Plate Flexure with Variable Rigidity, *Geophys. J. Int., 200*, 1012-1028, doi: 10.1093/gji/ggu449, 2014.

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, An integral method to estimate the moment accumulation rate on the Creeping Section of the San Andreas Fault, Geophys. J. Int., 203, 48-62, doi: 10.1093/gji/gjis140783, 2015.

Xu, X., X. Tong, D. T. Sandwell, C. Millner, J. F. Dolan, J. Hollingsworth, S. Leprince, F. Ayoub, Refining the shallow slip deficit, Geophys. J. Int., 203, 48-62, doi: 10.1093/gji/ggv269, 2015.

K.J. Matthews, R.D. Müller, D.T. Sandwell, Oceanic microplate formation records the onset of India–Eurasia collision, Earth and Planetary Science Letters 433, 204-214 , 2016.

Basset, D. D. T. Sandwell, Y. Fialko, and A. B. Watts, Upper-plate controls on co-seismic slip in the 2011 magnitude 9.0 Tohoku-oki earthquake, Nature, 531, 92-96, doi:10.1038/nature16945. 2016.

DeSanto, J. B., D. T. Sandwell, and C. D. Chadwell, Seafloor geodesy from repeated sidescan sonar surveys, J. Geophys. Res. Solid Earth, 121, 4800–4813, doi:10.1002/2016JB013025, 2016.

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Research Interests: Radiolarian taxonomy, evolution, and biostratigraphy, correlation of Cenozoic marine sequences to investigate extinction and diversification patterns associated with climate change.

Current and Ongoing Efforts: Focusing on oceanographic and climatic constraints on the Eocene radiolarian record during the Paleocene-Eocene Thermal Maximum (PETM), Early Eocene Climatic Optimum (EECO), Middle Eocene Climatic Optimum (MECO) and Middle Eocene Cooling Trend (MECT).

Together with SIO Geological Collections manager Alex Hangsterfer progress is being made toward revitalization and inventory of unique, retired and/or orphaned paleontological collections acquired over the years, to make them available to future scientists.

To provide accessibility to the Riedel and Sanfilippo radiolarian slide collection (started in 1950) a database of the existing data (locality, age, radiolarian abundance, preservation, slide storage, sample storage etc.) has been initiated.

My paleontological research is intimately linked to the geological collections and their proper curation. As curator for the U.S. West Coast Repository for the DSDP/ODP/IODP Micropaleontological References Centers (MRC) I continue to inventory new radiolarian slides that are periodically added to the MRC collection.

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.

Recent Publications

Lazarus, D., Suzuki, N, Caulet, J.-P., Nigrini, C., Goll, I., Goll, R., Dolven, J.K., Diver, P. and Sanfilippo, A., 2015. An evaluated list of Cenozoic-Recent radiolarian species names (Polycystinea), based on those used in the DSDP, ODP and IODP deep-sea drilling programs. Zootaxa 3999 (3): 301-333, (http://dx.doi.org/10.11646/zootaxa.3999.3.1)
Abstract: A first reasonably comprehensive evaluated list of radiolarian names in current use is presented, covering Cenozoic fossil to Recent species of the primary fossilising subgroup Polycystinea. It is based on those species names that have appeared in the literature of the Deep Sea Drilling Project and its successor programs, the Ocean Drilling Program and Integrated Ocean Drilling Program, plus additional information from the published literature, and several unpublished taxonomic database projects. 1192 names are recognized as valid, and several hundred additional names including synonyms and misspellings are given as well. A brief list of valid names is provided in the main paper, while the full list, with synonyms, author, year of publication, family assignment, geologic interval and notes is provided as a SOM spreadsheet.

The abstract of the above paper was presented as a poster at the GSA meeting in Vancouver, BC, Oct. 20-24, 2014. (Ref: Abstract No: 247919)

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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, systematically estimating small-earthquake stress drops from *P*-wave spectra, and studying properties of earthquake clustering, especially swarms and foreshock sequences. Postdoc Qiong Zhang recently developed an automated method to detect swarms and applied it to the San Jacinto Fault Zone (*Zhang and Shearer*, 2016). She identified 89 swarm-like seismicity clusters, which are more common on the northern and southern ends of the fault than its central portions. The swarms appear driven by fluid flow because their estimated migration velocities are far smaller than those of typical fault creep events.

Graduate student Wenyuan Fan has been applying back-projection to study large earthquakes recorded by the global seismic network. His results for the enigmatic 2009 Tonga-Samoa earthquake (*Fan et al*., 2016) reveal multiple rupture branches, with a *Mw* 8.0 normal-faulting earthquake east of the trench axis (seaward) followed by a *Mw* 8.1 reverse-faulting earthquake along the subduction interface west of the trench axis. Comparisons to high-resolution swath bathymetry suggest that the faulting stages are controlled by bending-related faults on the Pacific plate and along-strike fore-arc segmentation. Detailed analysis of the 2012 *Mw* 7.2 Sumatra earthquake detected two previously unknown early aftershocks (*Fan and Shearer*, 2016a). This motivated a comprehensive search for such early aftershocks in records from 88 large earthquakes, which detected a total of 48 aftershocks within a few fault lengths of 27 mainshocks during the times that high-amplitude surface waves arrived from the mainshocks (less than 200 seconds). The observations indicate that near-to-intermediate-field dynamic triggering commonly exists and fundamentally promotes aftershock occurrence (*Fan and Shearer*, 2016b).

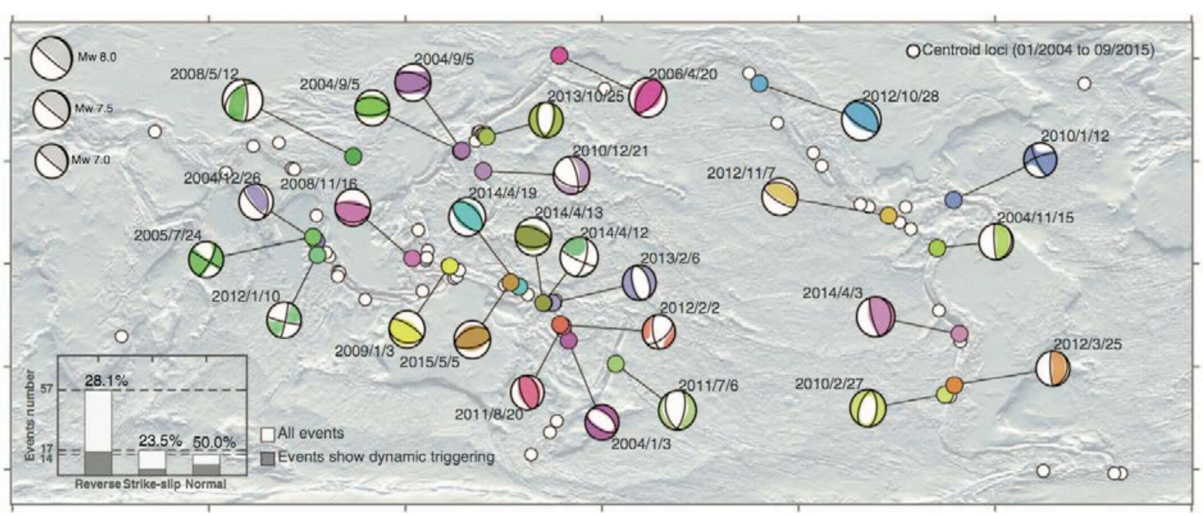

Figure 1. Twenty-seven early-aftershock–triggering mainshocks and their focal mechanisms. The 27 triggering mainshocks are color-coded at their GCMT centroid locations (colored circles). The white circles show the rest of the 88 large earthquakes (7 ≤ Mw < 8) that we investigated with back-projection. (Inset) Triggering rates for strike-slip, normal, and reverse faulting earthquakes. Figure from *Fan and Shearer* (2016b).

Graduate student Nicholas Mancinelli, who received his PhD last year, studied seismic wave scattering in the mantle in order to constrain the strength of mantle heterogeneity at short wavelengths. One of his projects involved an analysis of PKKP precursor observations, which placed important new constraints on small-scale CMB topography and provided support for models with a reduced seismic velocity gradient at the base of the liquid core, just above the inner-core boundary (*Mancinelli and Shearer*, 2016). Another of his projects involved stacking broadband global seismic data to measure the average amplitude of the scattered wave energy between the direct seismic phases, and then modeling this energy using synthetic seismograms for random 3D Earth models. This approach is useful in filling in the gap at intermediate scale lengths in our knowledge of the power spectrum of mantle heterogeneity, that is between the very long wavelengths (~1000 km) resolved with global mantle tomography and the short wavelengths (~10 km) constrained by PKP precursor studies. The results show that upper-mantle heterogeneity is nearly self-similar over a very wide range of scale lengths (1 to 1000 km), consistent with simple mixing models of basalt and harzburgite (*Mancinelli et al.*, 2016).

Finally, postdoc Marine Denolle analyzed teleseismic P-wave spectra from 942 shallow thrust earthquakes and found that the data are best fit with a double-corner frequency model with a break in self-similar scaling at about Mw 7. The departure from self-similarity for larger earthquakes likely is caused by a change in rupture aspect ratio rather than differences in average stress drop or scaled energy (*Denolle and Shearer*, 2016).

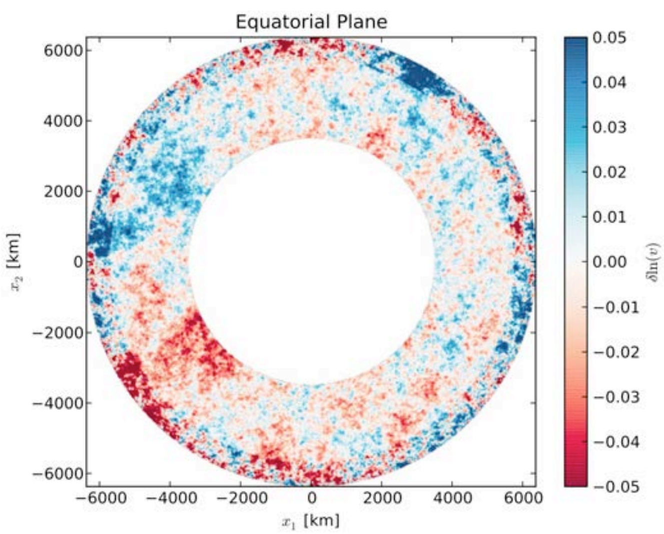

Figure 2. Cross section through an example 3-D mantle model with random heterogeneity. The 600-km-thick upper mantle has stronger heterogeneity than the lower mantle. The heterogeneity in both layers is a random realization of a Von Kármán autocorrelation function. The model shown here has much stronger lower mantle heterogeneity than we found is required to explain our P coda observations. Figure from *Mancinelli et al.* (2016).

Selected Recent Publications

Denolle, M. A., and P. M. Shearer, New perspectives on self-similarity for shallow thrust earthquakes, *J. Geophys. Res*., **121**, doi: 10.1002/2016JB013105, 2016.

Fan, W., and P. M. Shearer, Fault interactions and triggering during the 10 January 2012 Mw 7.2 Sumatra earthquake, *Geophys. Res. Lett.*, **43**, doi: 10.1002/2015GL067785, 2016a.

Fan, W., and P. M. Shearer, Local near instantaneously dynamically triggered aftershocks of large earthquakes, *Science*, **353**, 1133-1136, doi: 10.1126/science.aag0013, 2016b.

Fan, W., P. M. Shearer, C. Ji, and D. Bassett, Multiple branching rupture of the 2009 Tonga-Samoa earthquake, *J. Geophys. Res*., **121**, doi: 10.1002/2016JB012945, 2016.

Mancinelli, N., and P. Shearer, Scattered energy from a rough core-mantle boundary modeled by a Monte Carlo seismic particle method: Application to *PKKP* precursors, *Geophys. Res. Lett.*, **43**, doi: 10.1002/2016GL070286, 2016.

Mancinelli, N., P. Shearer, and Q. Liu, Constraints on the heterogeneity spectrum of Earth's upper mantle, *J. Geophys. Res*., **121**, 1-19, doi: 10.1002/2015JB012641, 2016.

Zhang, Q., and P. M. Shearer, A new method to identify earthquake swarms applied to seismicity near the San Jacinto Fault, California, *Geophys. J. Int*., **205**, doi: 10.1093/gji/ggw073, 2016.

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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.

Over the past year I have continued to work with graduate students on topics related to computational geodynamics at both global scale as well as plate tectonic boundaries. Working with PhD student Joyce Sim and collaborators Marc Spiegelman and Cian Wilson (LDEO), we are using two-phase flow models to investigate mid-ocean ridge (MOR) volcanism. The goal of the proposed work is to compare numerical models subjected to various upper mantle conditions with information of melting conditions derived from abyssal peridotites. We plan to use numerical models to make predictions of the resulting lithology of crust-mantle sections underneath MORs and directly compare those with geochemical information from estimates of degrees of partial melting in abyssal peridotites that reflect a residue of the melting processes under MORs. Joyce has successfully developed a working ridge model using the advanced geodynamics software TerraFERMA that was developed by Spiegelman and Wilson.

I continued working with PhD student Robert Petersen, building upon the models of subduction Petersen et al. (2015) and Petersen et al. (2016). I hosted an REU student, Molly James, in my research group for 10 weeks of the summer and she successfully mapped out additional parameter space to that which Robert had identified as potentially interesting. Together, the 3 of us worked as a team to discover the key parameters that controlled the subduction system, those of the yield stress and viscosity of the weak crust in the models. This work will be presented at the AGU meeting.

I have also worked with researchers that were previously post-doctoral scholars in my group. Thomas Chaparro is a graduate student in my lab pursuing an MS by thesis, and for his project we teamed up with former Miles post-doctoral scholar Lijun Liu (now at UIUC) and his graduate students. This project aims to better understand the mantle flow underneath the western United States. As a starting point we use the velocity field from the mantle flow model of Liu and Stegman (2011) which provides a good match with the seismic tomography under western US. This velocity field is used for computing the deformation of aggregates of mineral assemblages by employing a version of the D-REX code that has been adapted for 3D geometry (Faccenda and Capitanio, 2012). The results provide a forward model prediction of the LPO anisotropy that develops as a result of the mantle flow during the past 10 million years. We are able to then make a direct comparison of the predicted mantle flow and the observed pattern in SKS observations of western US (Figure 1). One of the most prominent features in the pattern is a quasi-circular swirl pattern centered around central Nevada, and this pattern is clearly seen in our results (blue lines in Figure 1). We have investigated the amount of time the features take to develop as well as the depth that contribute most to this feature. We have found that if only the present day velocity is used to predict LPO, the center of prominent swirl pattern is

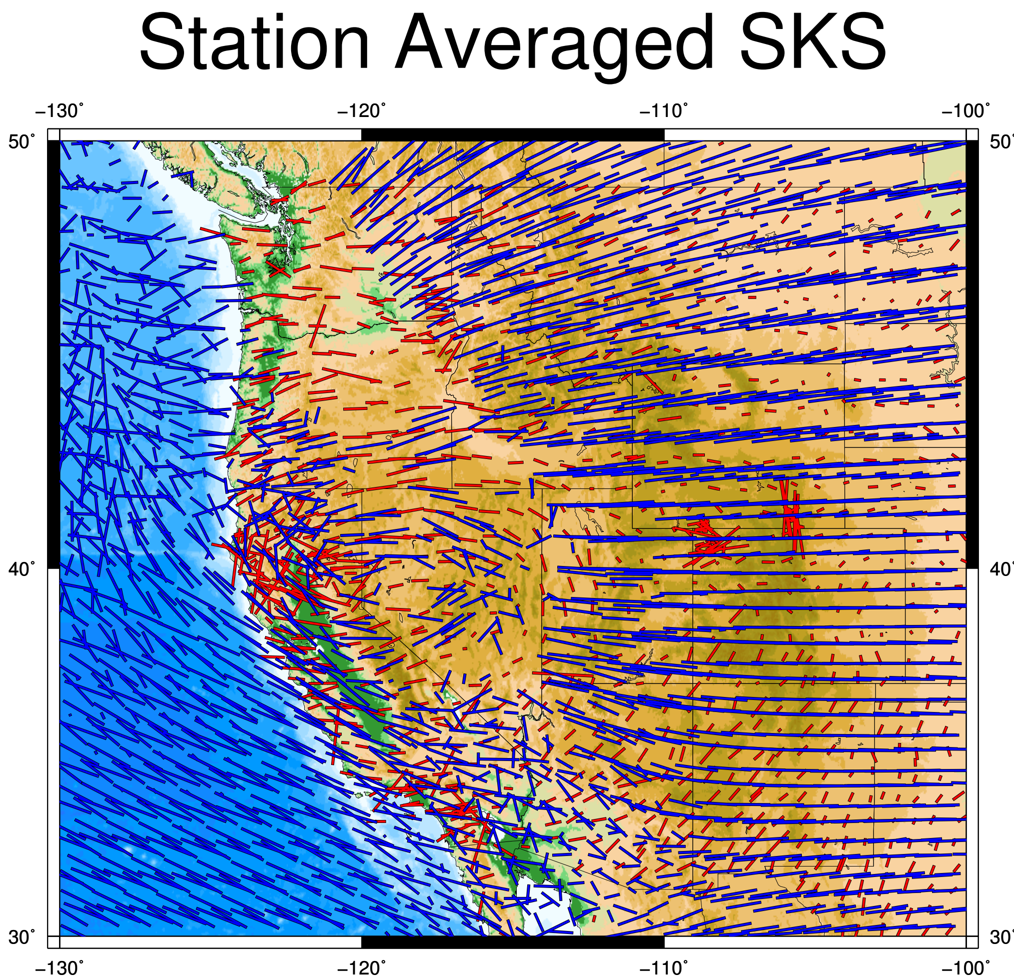

Figure 1: Fig 1. Comparison of predicted LPO anisotropy resulting from mantle flow (blue) with SKS observations from Walpole et al (2013) shown in red. The SKS data is scaled by magnitude of delay time. The LPO is vertically integrated between 200-400km depth.

shifted and located about 500 km northwest of the center of the observed pattern. We conclude that the observed feature must be mostly fossil in nature, having been developed by integrating the velocity field over the past 10 Million years. It is also possible to predict the SKS delay times that would results from such a pattern (Faccenda and Capitanio, 2013), and we have been investigating these as well.

Lastly, I worked on a project that includes former Green Scholar Chris Davies and Dr. Leah Ziegler in which we are developing an entropy-based parameterized thermal evolution model to further evaluate the hypothetical basal magma ocean dynamo, as was proposed by Ziegler and Stegman (2013).

Recent Publications

Petersen, R.I., **D.R. Stegman**, and P.J. Tackley (2015) A Regime Diagram of Mobile lid Convection with Plate-like Behaviour, *Physics of the Earth and Planetary Interiors* **241**, 65-76.

Petersen, R.I., **D.R. Stegman**, and P.J. Tackley (2016) The Subduction Dichotomy of Strong Plates and Weak Slabs, *Solid Earth* doi:10.5194/se-2016-56.

Sim, S., **D.R. Stegman** and N. Coltice (2016) Influence of continental growth on mid-ocean ridge depth, *Geochem. Geophys. Geosyst.,* **17**, doi:10.1002/2016GC006629.

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Research Interests:

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

The research during 2015 of myself and my students and post-docs continued several recent threads and began several new ones. We continued to work on improving the methods by which we determine the ancient field strength (e.g, Cromwell et al., 2015a) and it seems we may have finally hit on an accurate and precise way of doing it. The key is first finding the appropriate materials (those that contain only the finest grained magnetic particles) and applying strict selection criteria. The need for using only so-called single-domain material was underscored by the work of Shaar and Tauxe (2015) who showed for the first time the danger of using samples with larger grain sizes as the remanences are not stable over time and the answers retrieved from such material is likely to be incorrect. Happily this non-ideal behavior is easily recognized by using the selection criteria proposed by Cromwell et al. (2015a), if all the measurements are available for analysis.

Using our newly revised approach, Cromwell et al. (2015b) sampled and analyzed sub-glacially erupted lava flows on Iceland in an attempt to constrain better the behavior of the Earth's magnetic field over the last few million years as witnessed at high latitudes (Figure 1). We found that the field strength is approximately equal to that implied by published data from lower latitudes - an impossible result if the field is largely that of a magnetic dipole, as presumed since the 1600s! Because of the work of Cromwell et al. (2015a) and Shaar and Tauxe (2015), we strongly suspect that it is the data from lower latitudes (based on what can now be viewed as fatally flawed samples) which is the problem. Naturally, we will be returning to lovely Hawaii in the near future to try to sort this out.

In addition to constraining field behavior over the last five million years, we had several other projects come to fruition. We continue to produce high quality data for the more recent past (e.g., Cai et al., 2015). Another project concluded work on the IODP Expedition 318 (Tauxe et al., 2015). This latter study applied rock and paleomagnetic techniques to the understanding of the melting history during the Pliocene of the East Antarctic Ice Sheet, which underwent startling melting during the Pliocene, a period of time with CO_2 levels thought to be as high as today's.

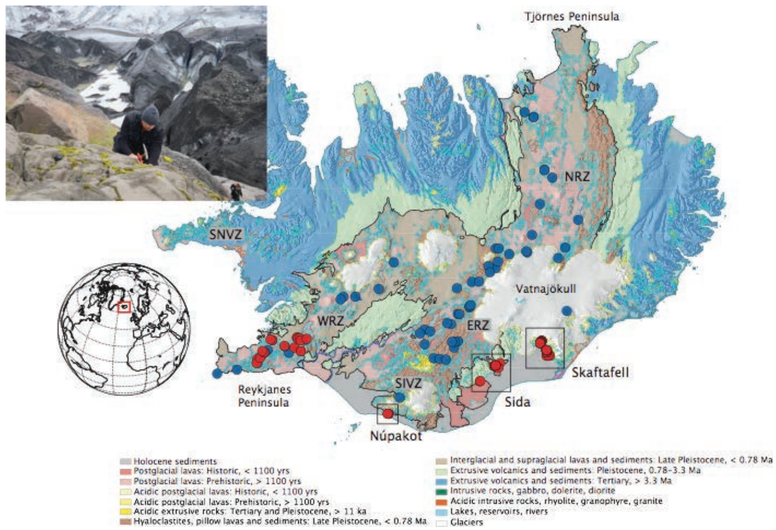

Figure 1: Sampling sites from study of Cromwell et al., 2015b. Inset shows Geoff Cromwell at work sampling sub-glacially erupted pillow lavas.

Selected Publications from 2015

Cromwell, G., Tauxe, L., Staudigel, H., Ron, H., Paleointensity estimates from historic and modern Hawaiian lava flows using volcanic glass as a primary source material, Phys. Earth Planet. Int., 241, 44-56, `http://dx.doi.org/10.1016/j.pepi.2014.12.007`, 2015a.

Tauxe, L., S. Sugisaki, F. Jimenez-Espejo, C. Escutia, C. P. Cook, T. van de Flierdt, M. Iwai, Geology of the Wilkes Land Sub-basin and Stability of the East Antarctic Ice Sheet: Insights from rock magnetism at IODP Site U1361, Earth Planet. Sci. Lett., 4123, 61-69, `http://dx.doi.org/10.1016/j.epsl.2014.12.034`, 2015.

Shaar, R., Tauxe, L., Ben-Yosef, E., Kassianidou, V., Lorentzen, B., Feinberg, J., Levy, T.E., Decadal-scale variations in geomagnetic field intensity from ancient Cypriot slag mounds, Geochem. Geophys., Geosyst., 15, `http://dx.doi.org/10.1002/2014GC005455`, 2015a.

Cai, S., Chen, W., Tauxe, L., Deng, C., Qin, H., Pan, Y., Zhu, R., New constraints on variation of the geomagnetic field during the late Neolithic period: Archaeointensity results from Sichuan, southwestern China, J. Geophysical Res., 120, 20562069, `http://dx.doi.org/10.1002/2014JB011618`, 2015.

Cromwell, G., Tauxe, L., Halldorsson, S.A., New paleointensity results from rapidly cooled Icelandic lavas: Implications for Arctic geomagnetic field strength, J. Geophys. Res., 120, 29132934, `http://dx.doi.org/10.1002/2014JB011828`, 2015b.

Shaar, R., Tauxe, L., Instability of thermoremanence and the problem of estimating the ancient geomagnetic field strength from non-single-domain recorders, Proc. Nat. Acad. Sciences, 112, 11187-11192, `http://dx.doi.org/0.1073/pnas.1507986112`, 2015b.

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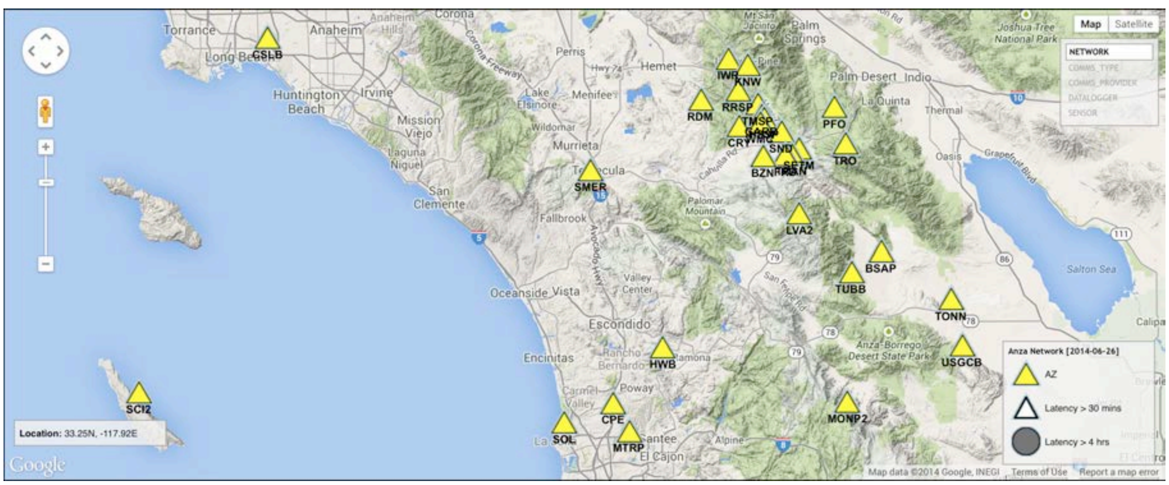
Research Interests:

1. Earthquake source physics and ground motion estimation.
2. Time series analysis applied to terrestrial and space data.
3. Development of instrumentation that improves the observation and understanding of seismic measurements.
4. Realtime environmental sensor networks and wireless networking.

I am the principal investigator for the ANZA Seismic Network (http://eqinfo.ucsd.edu) that monitors local and regional seismicity in southernmost California. The ANZA seismic network currently consists of twenty-eight operational stations. Most of the stations are located along the San Jacinto fault starting with IWR and RDM towards the top of the map, and TONN and USGCB on the right side of the map. The San Jacinto fault is one of the two most dangerous faults in southern California, the other being the San Andreas Fault.



The ANZA network is the foundation for the San Jacinto Fault Zone project in collaboration with Yehuda Ben-Zion to examine the dynamics associated with earthquake rupture. The studies being carried out are providing much more comprehensive constraints on the way that a major fault zone behaves. Specifically, the project combines detailed imaging of the San Jacinto Fault (SJF) in Southern California using multiple seismic arrays to characterize the fault zone in the subsurface. In the late Spring of 2014, we had the opportunity to deploy the first complete academic “Large N” experiment to observe the unaliased two dimensional seismic wavefield. This experiment deployed 1108 high frequency instruments in an area 600 meters by 600 meters, spanning the surface trace of San Jacinto Fault at Sage Brush Flats. This is a whole new methodology being introduced into earthquake seismology, which is enabled by the technological evolution of petroleum industry instrumentation.

I am also the PI on for the Array Network Facility for the USArray project Transportable Array. The core of the USArray project is known as the Transportable Array (TA) comprised of ~500 broadband seismic stations deployed in a nominal 70 km grid bounded by the borders of the lower 48 states. Each station was deployed ~2 years and the TA is moved in a rolling manner to the east. At present, the ANF facility is already operating the largest broadband seismology system in the world. USArray finished up in the Lower 48 and is now deploying instruments in Alaska, creating a whole new set of challenges. USArray was the foundation of the Central and Eastern US Network, which is continuing to operate in the eastern United States.

Recent Publications

Li, Z., Z. Peng, Y. Ben-Zion and F. L. Vernon (2015). Spatial variations of Shear-wave Anisotropy Near the San Jacinto Fault Zone in Southern California, J. Geophys. Res., 120, doi: 10.1002/2015JB012483

Tytell, J., F. Vernon, M. Hedlin, C. de Groot Hedlin, J. Reyes, B. Busby, K. Hafner, and J. Eakins, 2016: The USArray Transportable Array as a Platform for Weather Observation and Research. Bull. Amer. Meteor. Soc., 97, 603–619, doi: 10.1175/BAMS-D-14-00204.1.

Jacques, A. A., Horel, J. D., Crosman, E. T., Vernon, F. and Tytell, J. (2016). The Earthscope US transportable array 1 Hz surface pressure dataset. Geosci. Data J., 3: 29–36. doi:10.1002/gdj3.37

Philippe Roux, Ludovic Moreau, Albanne Lecointre, Gregor Hillers, Michel Campillo, Yehuda Ben-Zion, Dimitri Zigone, and Frank Vernon (2016). A methodological approach towards high-resolution surface wave imaging of the San Jacinto Fault Zone using ambient-noise recordings at a spatially dense array. Geophys. J. Int. 206 (2): 980-992 doi:10.1093/gji/ggw193

David J. Thomson and Frank L. Vernon (2016). Some Comments on the Analysis of “Big” Scientific Time Series. Proceedings of the IEEE 104, 11, 2220–2249. DOI: 10.1109/JPROC.2016.2598218

Z. E. Ross, M. C. White, F. L. Vernon, Y. Ben-Zion (2016). An Improved Algorithm for Real-Time S-Wave Picking with Application to the (Augmented) ANZA Network in Southern California. Bulletin of the Seismological Society of America, Vol. 106, No. 5, pp. 2013–2022, doi: 10.1785/0120150230

Kerkez, B., Daniels, M., Graves, S., Chandrasekar, V., Keiser, K., Martin, C., Dye, M., Maskey, M. and Vernon, F. (2016), Cloud Hosted Real-time Data Services for the Geosciences (CHORDS). Geosci. Data J., 3: 4–8. doi:10.1002/gdj3.36

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Research Interests*:* geomorphology, paleoclimate, geochemistry, cosmogenic nuclides, environmental toxicology, citizen science

Tectonics, erosion, chemical weathering, and life work together to form the Earth's surface environment where we live and work. As scientists continue to break traditional disciplinary boundaries, we find that little of nature can be fully understood in isolation. For example, weathering in soil liberates nutrients from minerals and disaggregates rock to make soil. The breakdown of silicate minerals regulates global temperatures in a habitable limit through feedbacks within the carbon cycle. John Muir best said it when he wrote in 1911 in My Life in the Sierras, "When we try to pick out anything by itself, we find it hitched to everything else in the Universe."

How does the Earth's surface respond to perturbations – anthropogenic and natural? How much does Earth change over time (Willenbring and Jerolmack, 2016)? Studies of modern landscapes provide valuable insights into these processes, help to identify primary controls, and contribute to unraveling potential feedback mechanisms. Understanding the magnitudes of past and modern fluxes and rates of surface processes provide empirical data with which we can begin to understand the extent of human alteration of the environment and possible geomorphic effects of a warmer Earth in the geologic past and in the future (Garcin et al., in press).

My group uses geochemical techniques, high-resolution topographic data, field observations, and, when possible, I couple these data to landscape evolution numerical models and ice sheet models. The geochemical tools I use and develop often include cosmogenic nuclide systems, which provide powerful, novel methods to constrain rates of erosion and mineral weathering. Beryllium isotopes can quantify the rates of soil production, erosion, and remobilization and recent work develops one beryllium isotope as a proxy for the flux of weathering products to the oceans. These geochemical tools have revolutionized our understanding of the evolving earth surface for decades. Although beryllium isotopes sorbed to sediments are now being measured extensively to understand movement of soil particles and the natural feedbacks that operate in the Earth system, we lack of an understanding of the mechanisms of adsorption and desorption processes that are critical for the interpretation of new data produced (Boschi and Willenbring, 2016a,b).

Recent landscape and ecosystem research from 2016 (Brocard et al., 2016; Wolf et al., 2016) was focused on understanding how river erosion and soil properties regulate many ecosystem processes in tropical forests. Rapid upslope migrations of plant species are occurring on tropical mountains, but the drivers of current community composition and community reassembly during upslope migration remain poorly understood. We use indicators of landscape transience, such as waterfalls and the shapes of longitudinal profiles of rivers, and cosmogenic nuclides to understand real, natural barriers to ecosystem response to climate change (Fig. 1). We also are starting to learn about what are the principle controls on landscape evolution and river network rearrangements, and how these processes contribute to the formation of highly biodiverse tropical aquatic ecosystems? We currently lack an integrated understanding of the geomorphological controls on lineage diversification at regional and continental scales. We exploit a natural laboratory of the Amazon basin that has experienced both large shifts in river networks and has unparalleled, unexplained biological richness to learn about these processes in the coming years.

Recent Publications

Boschi**, V., **Willenbring, J.K.** 2016. Beryllium Desorption from Minerals and Organic Ligands Over Time. *Chemical Geology* 439(7) 52–58. *doi:10.1016/j.chemgeo.2016.06.009*

Boschi**, V., **Willenbring, J.K.** 2016. The role of pH, organic matter composition and mineralogy on the sorption behavior of beryllium. *Environmental Chemistry 13, 711-722. doi:10.1071/EN15107*

Brocard**, G.Y., **Willenbring. J.K**., Miller, T., Scatena, F.N. 2016. Resilience of a transport-limited relict landscape to dissection by upstream migrating knickpoints. *Journal of Geophysical Research – Earth Surface* 121(6): 1182–1203. *doi:10.1002/2015JF003678*

Garcin, Y., Acosta, V.T., Melnick, D., Schildgen, T.F., Guillemoteau, J., **Willenbring, J.K.,** Strecker, M.R. in press. Increased erosion during the African Humid Period: evidence from the northern Kenya Rift. *Earth and Planetary Science Letters.*

Salamatipour**, A., Mohanty**, S.K., Pietrofesa, R.A., Vann, D., Christofidou-Solomidou, M., **Willenbring, J.K.** 2016. Asbestos fiber preparation methods affect fiber toxicity. Environmental Science & Technology Letters 3: 270-274. doi:10.1021/acs.estlett.6b00174

Willenbring, J.K. Jerolmack, D.J. 2016. The null hypothesis: steady rates of erosion, weathering and sediment accumulation during Late Cenozoic mountain uplift and glaciation. *Terra Nova 'Debates' article*. 28(1): 11-18. doi:10.1111/ter.12185

Wolf, J., Brocard**, G.Y., **Willenbring, J.K.,** Porder, S., Uriarte, M. 2016. Abrupt change in forest height along a tropical elevation gradient detected using airborne LiDAR. *Remote Sensing* 8(10), 864. doi:10.3390/rs8100864

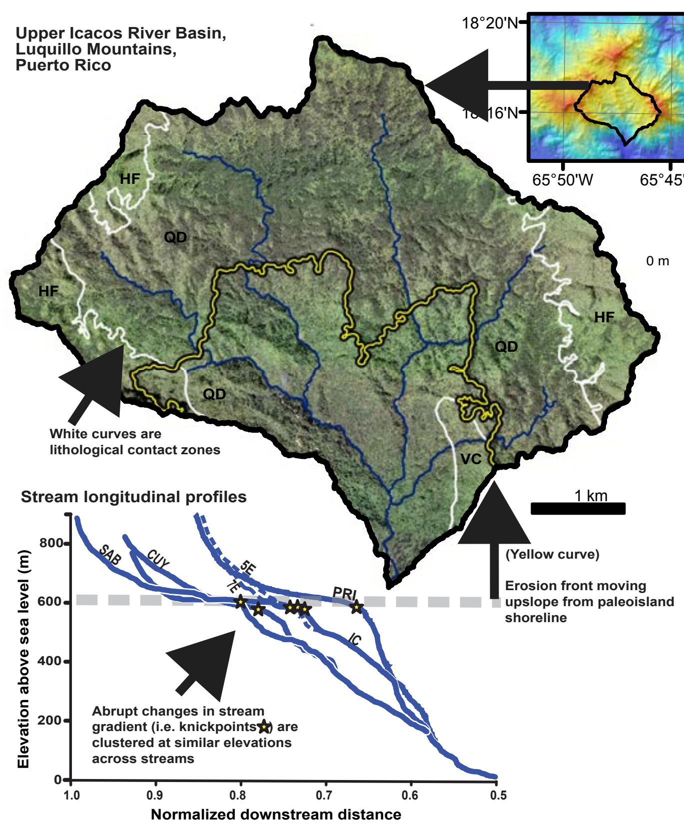

Fig 1. The Rio Icacos River drains a tropical forest landscape in Puerto Rico containing different rock types (abbrev. QD, VC, HF). The landscape is made up of two regimes: an upper 'relict landscape' with low erosionrate and shorter tree canopies and a lower landscape that has experienced renewed erosion and hosts taller tree canopies. The yellow line marks the front of erosion moving through the system. Upper Inset: Elevation. Lower inset: river long profiles.

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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.

Borehole Optical Fiber Strainmeters for Measuring Ground Compaction (with Frank Wyatt and William Hatfield)

We have expanded the use of tensioned optical fibers for the measurement of Earth strain to the Mississippi River Delta, where high subsidence rates threaten a large land area with inundation from the Gulf of Mexico. As part of a U.S. Army Corps of Engineers funded superstation near Myrtle Grove, Louisiana, two boreholes to depths of 10 m and 40 m have been instrumented with interferometric optical fiber sensors which continuously record the displacement of surface monuments to cemented-in anchors at depth. The measurements allow partitioning of the subsidence to layers at various depths above the Pleistocene basement. A third intermediate depth installation is planned for the near future. Correlation between tidal loading and vertical strain reveals variations in rheological properties with depth locally. GPS stations attached to the same surface monuments tie the local compaction measurements to an absolute reference frame.

At the end of the last ice age approximately 7000 years ago, very little of what we call today the Mississippi River Delta existed. As the Laurentide Ice Sheet covering much of North America retreated, water flow in the Mississippi River increased and created the Mississippi River Delta over many centuries. The Delta is formed by a meandering path of the river as it empties into the Gulf of Mexico, providing a constant supply of sediment and distributing it over millions of acres in the triangularly shaped feature in southern Louisiana south of New Orleans. In 1920, the slow but constant variation in the Mississippi River's path proved problematic for navigation and the maintenance of ports, prompting officials at the time to construct levees to keep the river's course constant. One unintended consequence of this action has been to starve the supply of new sediment to the River Delta. The existing sediment is compacting at a rate estimated to be 4 mm per year and, without new sediment to accommodate the compaction, results in land sinking below sea level and inundation by Gulf of Mexico waters. Coupled with sea level rise of 2 mm per year, land of the Mississippi River Delta, much of it valuable agricultural real estate, is disappearing into the ocean at an alarming average rate of an acre per hour.

Colleagues at Tulane University in New Orleans recognized the need for more coordinated efforts to reconstruct, monitor, and predict subsidence in the Mississippi River Delta and proposed to the Army Corps of Engineers a program to establish focused sites with state of the art instrumentation. In particular, the distribution of subsidence with depth is not known, or the extent to which subsidence determined at the land surface is caused by processes in the shallow subsurface of deeper down.

In collaboration with Tulane scientists, we have introduced our new technology of optical fiber strain sensing to a site 1 mile away from the Mississippi River some 30 miles south of New Orleans in a wetland marsh to monitor subsidence with depth. Two instruments to 10 m and 40 m have were installed in July of 2016 and are providing continuous realtime data with micron resolution. A third borehole sensor to an intermediate depth is planned for early 2017. The data to date reveal daily cycles of compaction associated with tidal loading of the marsh sediments, and perhaps a secular term from an annual thermal expansion and contraction of the upper layers (although with only a few months of data in hand it is premature to judge this). Much work remains to understand the measurements, including making corrections for the near surface settling of the casings which form the upper termination of the strain sensors.

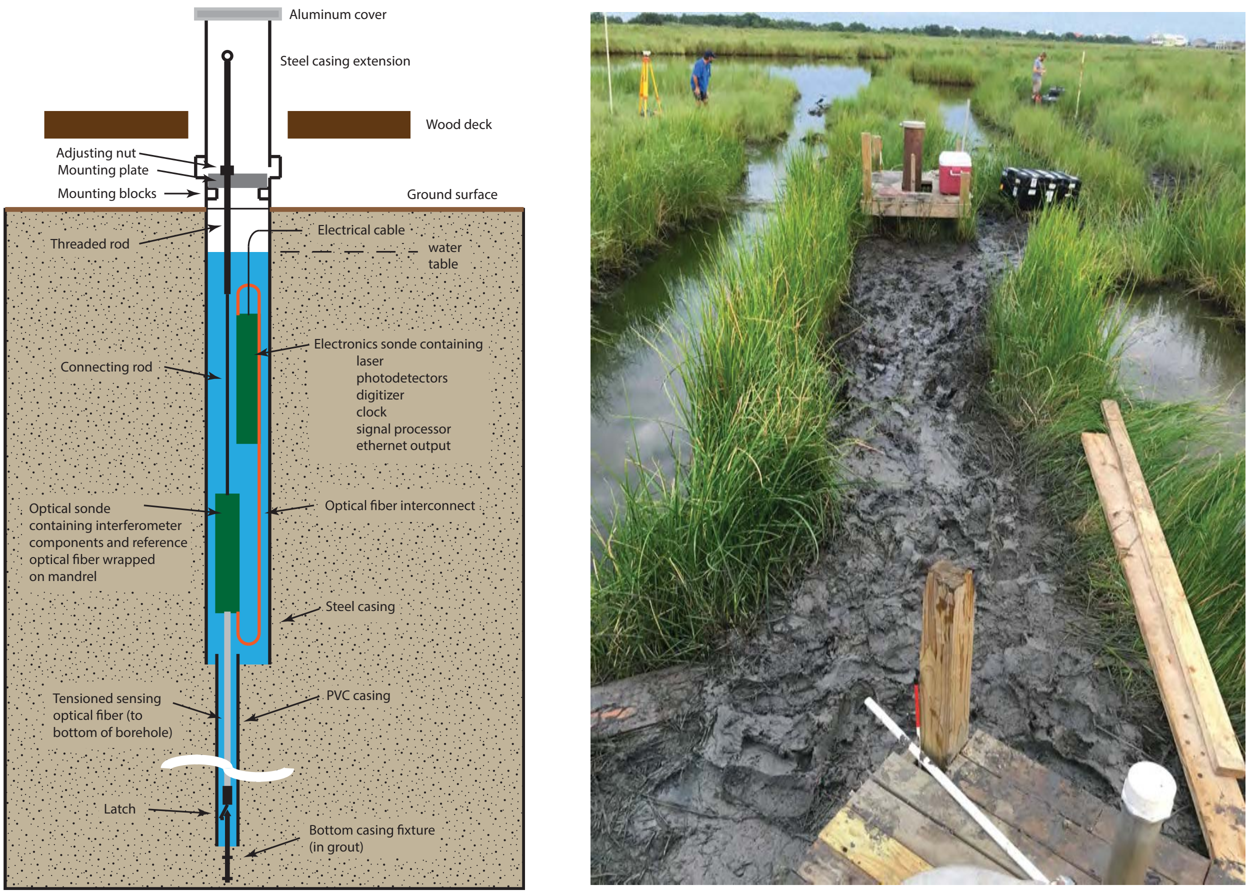

Figure 1. On the left is a schematic of one of the instruments. Two sondes are in each borehole, one housing the recording electronics and a laser to illuminate an optical fiber interferometer, the second holding the interferometer components. They are connected by optical fibers. A tensioned optical fiber running to the bottom of the borehole senses changes in the borehole length caused by soil compaction. On the right is a photograph showing one of the installations being surveyed to reference points by team members Don Elliott and William Hatfield.

Recent Publications

DeWolf, S., Wyatt, F. K., Zumberge, M. A., and Hatfield, W. (2015). Improved vertical optical fiber borehole strainmeter design for measuring Earth strain, *Rev. Sci. Instrum*., 86, 114502, doi:10.1063/1.4935923.

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Background Images: (Cover, left to right) Piston coring in California Borderlans—courtesy of Neal Driscoll; Geoff Cromwell at work sampling sub-glacially erupted pillow lavas in Iceland—courtesy of Lisa Tauxe; Google Earth image of pyroclastic flows on Mt. St. Helens—courtesy of Jeff Gee; (Inside) Multi-phase flow model of a mid-ocean ridge with depth of the computational domain of 100 km—courtesy of David Stegman