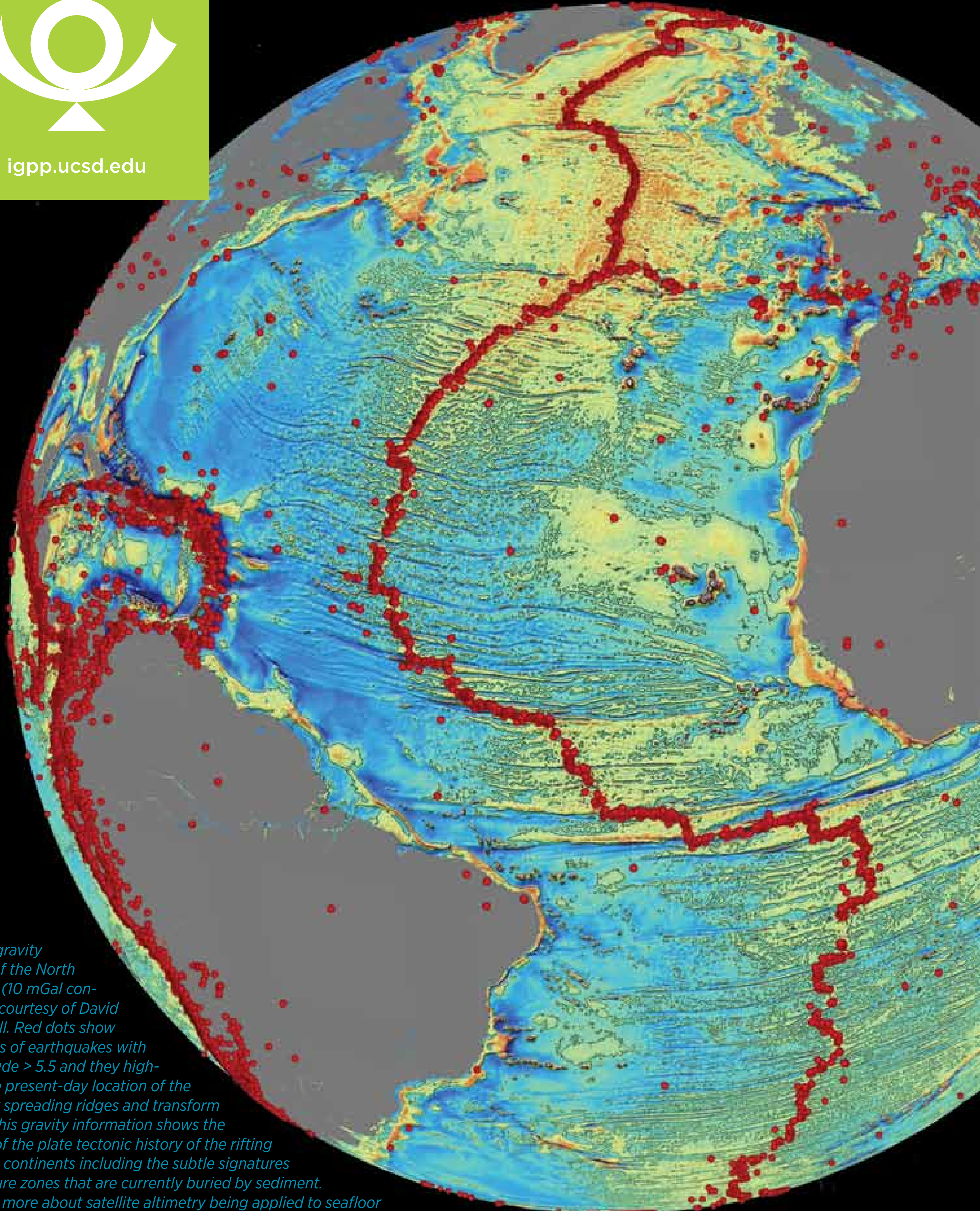
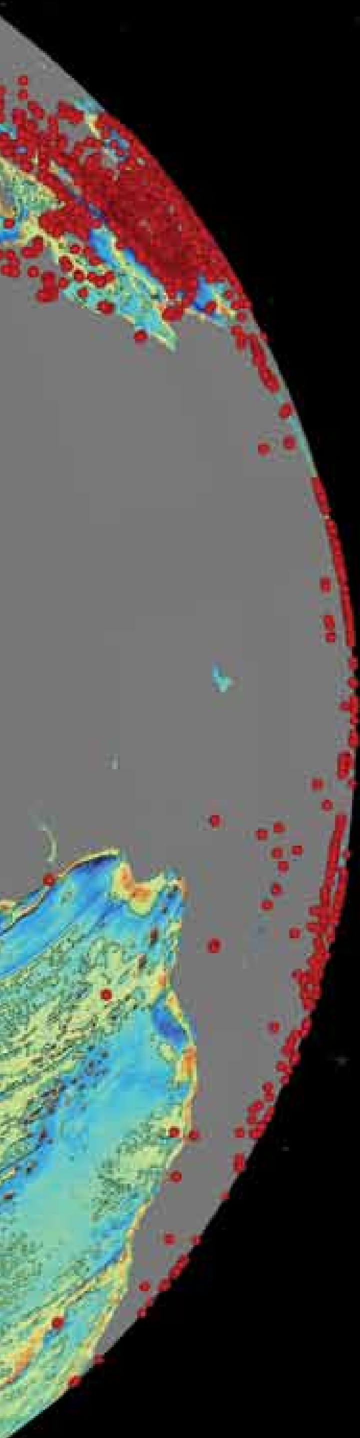
CECIL H. & IDA M. GREEN

INSTITUTE OF GEOPHYSICS AND PLANETARY PHYSICS

SCRIPPS INSTITUTION OF OCEANOGRAPHY **UNIVERSITY OF CALIFORNIA, SAN DIEGO** igpp.ucsd.edu



Marine gravity model of the North Atlantic (10 mGal contours)—courtesy of David Sandwell. Red dots show locations of earthquakes with magnitude > 5.5 and they highlight the present-day location of the seafloor spreading ridges and transform faults. This gravity information shows the details of the plate tectonic history of the rifting of these continents including the subtle signatures of fracture zones that are currently buried by sediment. To learn more about satellite altimetry being applied to seafloor mapping, visit topex.ucsd.edu/grav_outreach.



2014

IGPP Director's Welcome

In this 2014 Annual Report of the **Cecil and Ida Green Institute of Geophysics and Planetary Physics**, we aim to provide a description of our research activities during the past academic year for prospective graduate students and for anyone else who has an interest in the Earth Sciences, particularly geophysics. While most of our research is basic in nature, many, if not most, of the subjects covered are areas of broad societal concern. These include: understanding the earthquake cycle, developing earthquake early warning systems, understanding the behavior of ice sheets, improved methods of energy exploration, monitoring of carbon dioxide sequestration, and so on.

Our work spans a broad range of subject matter in geophysics and oceanography. A wide range of observations are accomplished on global, regional, and local scales by extensive shipboard and ground-based operations and also include remote sensing by satellites and the use of wide-ranging instrument networks. Theoretical developments and modeling play a strong role in data interpretation.

It is our hope that you will find this a useful description of our ongoing work and that you will agree that IGPP continues to be one of the foremost research centers for geophysics in the nation.

Guy Masters, Director, IGPP

IGPP Researchers

* no annual report available

Image: Trekking on Mt. Erebus, Antarctica—courtesy of Hubert Staudigel

HIGHLIGHTS

Many IGPP researchers were recognized for their outstanding work with awards and honors in 2014. They have also provided news agencies with responsive insight to tectonic and climate concerns and have shared scientific testimony in an unprecedented call-to-arms symposium on climate change at the Vatican. What follows is an incomplete compilation of recognized achievement in 2014:

JANUARY

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

Yehuda Bock appears on San Diego's Channel 10 News to share the addition of "small, inexpensive seismic and meteorological sensors" to existing GPS sensors in San Diego and surrounding counties. *www.10news.com/news/new-technologies-merge-for-public-safety-010914*

Hubert Staudigel's exploration of Antarctica's extreme environments featured in the Union Tribune article: "Scientists face frozen world in Antarctica" *www.utsandiego.com/news/2014/jan/17/environment-scripps-antarctica-staudigel*

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

FEBRUARY

Yehuda Bock elected as a fellow of the Explorers Club.

Jean-Bernard Minster becomes an American Association for the Advancement of Science fellow "for distinguished contributions in the areas of plate motion, crustal deformation, and satellite geodesy, as well as for community leadership and teaching the next generation of geophysicists."

MARCH

The Explorer's Club honors Walter Munk's 65 years of Oceanographic achievement with The Explorer's Medal.

Jennifer Haase shares her new airborne GPS system—which detects weather conditions with precision designed to improve storm predition and modeling—with CBS News 8: *goo.gl/35RIr9*

MAY

IGPP Professor Emeritus Walter Munk and Ph.D. student Matthew Siegfried participate in an unprecedented sustainablilty conference, *Sustainable Humanity, Sustainable Nature: Our Responsibility*, hosted by the Vatican

John Orcutt selected to be the inaugural editor for AGU's journal: ***Earth and Space Science!***

JUNE

Diego Melgar is the 19th recipient of the Edward A. Frieman Prize for Excellence in Graduate Student Research.

Adrian Borsa receives 2014 Scripps Best Graduate Teaching award

Helen Fricker discusses the instability of the West Antarctic Ice Sheet on KPBS's Mid-day Edition *goo.gl/llthjo*

JULY

Zhongwen Zhan and Peter Shearer (in collaboration with researchers at Caltech) article *"Supershear Rupture in A Mw 6.7 Aftershock of the 2013 Sea of Okhotsk Earthquake"* appears in July 11, 2014 ***Science***.

AUGUST

Adrian Borsa discusses evidence of uplift, as an aftereffect of severe drought, in the western U.S. on KPBS's Midday Edition *www.kpbs.org/news/2014/aug/25/landrise-connected-drought-linked-earthqukes*

SEPTEMBER

Duncan Agnew and Adrian Borsa's research on drought-related western uplift published in the September 26 issue of Science *"Ongoing drought-induced uplift in the western United States." m.sciencemag.org/content/345/6204/1587.short*

OCTOBER

David Sandwell's article *"New global marine gravity model from CryoSat-2 and Jason-1 reveals buried tectonic structure"* published in the October 3 issue of ***Science***.

Image above: Walter Munk shortly after his presentation at the Vatican sustainablity conference: Sustainable Humanity, Sustainable Nature: Our Responsibility

GRADUATE EXPERIENCE

IGPP's graduate program offers students a unique hands-on, collaborative learning environment. In addition to the core academic curriculum, IGPP emphasizes observational techniques and the collection of novel datasets. Scripps students participate extensively in field experiments, instrument development, laboratory investigations, and shipboard expeditions. Graduate students have access to a world-class faculty whose research include geochemistry, geophysics, geodesy, geology, glaciology, and planetology—and which is renowned for its record of developing instruments. IGPP has strong working relationships with the National Science Foundation, NOAA, the US Geological Survey, and the Office of Naval Research, and can provide graduates with long-term networking and professional support. Located on the San Diego coast in La Jolla, IGPP benefits from an enviable climate and proximity to both the Pacific Ocean and the active tectonics of Southern California. Year-around outdoor activities abound, bwwoth recreational and research focused.

Graduate Students who successfully defended their thesis in 2014

Andrew Barbour *(advisor: Duncan Agnew)*: Investigations of fluid-strain interaction using Plate Boundary Observatory borehole data

currently: Mendenhall Postdoctoral Fellow working with Steve Hickman at U.S. Geological Survey

Scott DeWolf *(advisor: Mark Zumberge)*: Optical Fiber Sensors for Infrasonic Wind Noise Reduction and Earth Strain Measurement

currently: Postdoctoral Researcher at Clemson University

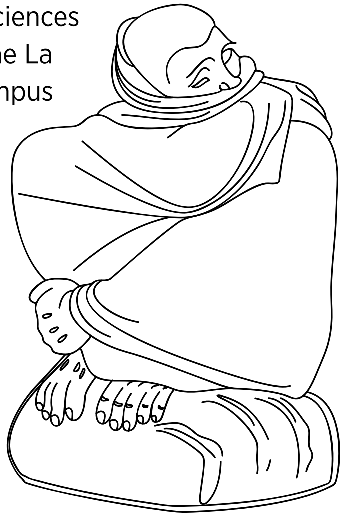
Diego Melgar Moctezuma *(advisor: Yeuhuda Bock)*: Seismogeodesy and Rapid Earthquake and Tsunami Source Assessment

currently: Seismology Laboratory at UC Berkeley

Anandaroop Ray *(advisor: Kerry Key)*: Trans-dimensional Bayesian Inversion of Controlled Source Electromagnetic Data

currently: Research Geophysicist at Chevron U.S.A. Inc.

GREEN FOUNDATION



The Cecil H. and Ida M. Green Foundation for Earth Sciences supports visiting scholars and resident scientists at the La Jolla branch of the University of California's multi-campus Institute of Geophysics and Planetary Physics (IGPP). Established with a gift from the late Cecil Green in 1971, the Green Foundation holds an endowment managed by the UCSD-IGPP Director and overseen by an independent Board of Directors. A selection committee comprised of IGPP faculty screens nominees and applicants for both the Green Scholar and the Miles Fellowship. The scholarship funds come from the income that the Foundation receives on its capital. Being an independent entity, the Foundation has some flexibility in how funds are earmarked within the University of California guidelines. In addition to funding visiting scholars, the selection committee considers requests from IGPP scientists for funds to support research via purchase of equipment or construction of facilities. Such awards are usually directed as seed money for new projects or for equipment that is difficult to obtain via traditional extramural funding sources.

The Green Foundation is currently supporting:

Green Scholar Marine Denolle, postdoc

Miles Fellow Noel Bartlow, postdoc

Green Scholar John Colosi

Green Scholar Chris Davies

UCSD membership in Southern California Earthquake Center *www.scec.org*

Images (clockwise from top): Plate Boundary Observatory GPS station P298, located near Coalinga, California. P298 is mounted on a deep-drilled braced (Wyatt-Agnew) monument, and its displacement data were used in the determination of water loading changes in the western United States—Credit: Andre Basset, UNAVCO. Danny Richter and Matt Siegfried stand with a Swiss Guard at the Vatican; Geoff Davis and Malcolm White participate in a survey trip in Anza, California.

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FRANK K. WYATT, PRINCIPLE DEV. ENGINEER, RTAD

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

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

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

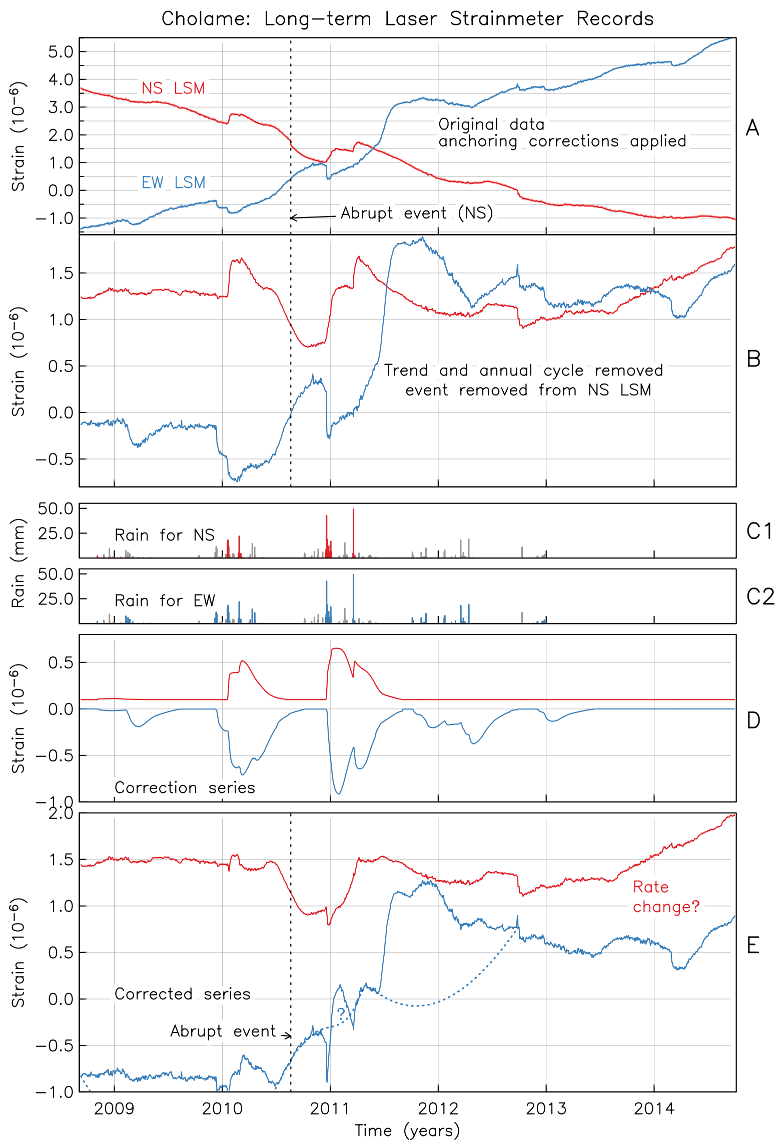

Figure 1: Records from Cholame LSM's, showing empirical corrections for rain eects. Frame A is the data, showing the long-term rate. Frame B is after removing an annual cycle and trend, both based on the data through the end of 2009. Frame C shows the rainfall (gray) and the amounts above a threshold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

LSM data have been used to rule out possible strain signals, often in ways relevant to short-term hazard, as at times of earthquake swarms close to DHL or following large regional events. The CHL data tightly limit aseismic strains at times of deep tremor. And the PFO data rule out large coseismic strains seen on nearby borehole strainmeters. Operating these observatories shows that patience and persistence are needed to learn about the Earth: only a multiyear program captures interesting signals and properly characterizes the Earth's behavior. But this is difficult to do over geophysically useful timescales.

Recent Publications

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

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

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

JONATHAN BERGER EMERITUS RESEARCHER RTAD

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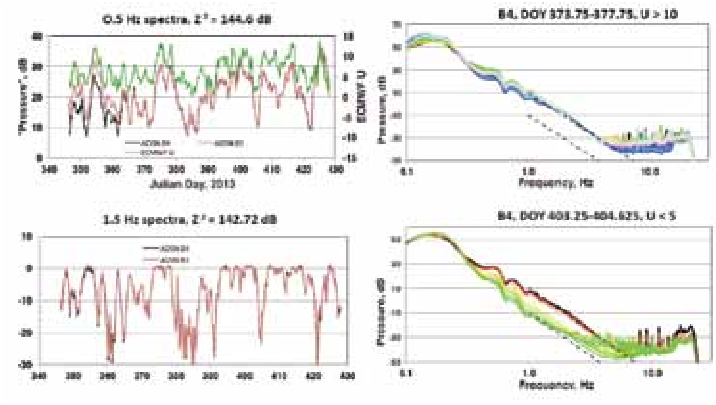
Research Interests: Global seismological observations, marine seismoacoustics, geophysical instrumentation, deep ocean observing platforms, ocean robotics, global communications systems.

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

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

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

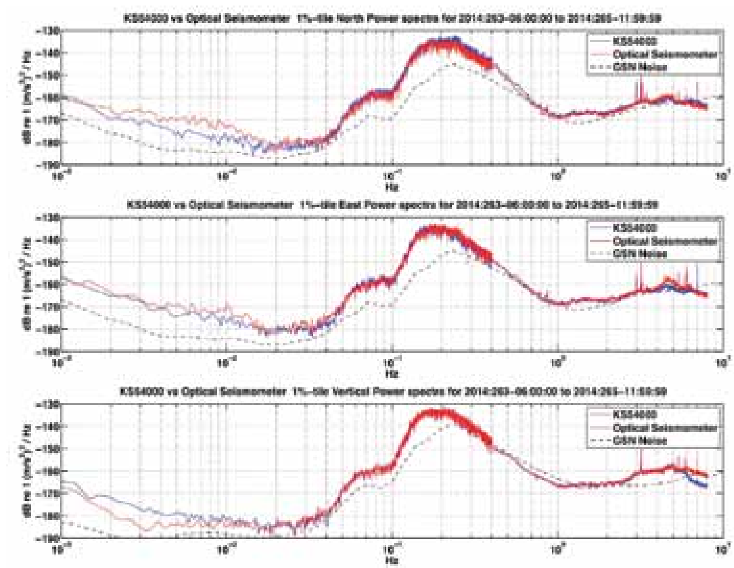
Oceanographers are very interested in methods to infer the state of short ocean waves (10 m down to 10 cm) from deep-sea acoustic measurements. Longer waves are well studied by weather centers because of their economic importance (e.g. ship routing) and models for predicting the ocean swell are quite mature. However, it is the shorter waves that account for most of the energy transfer from the atmosphere to the ocean. These waves are too small to be accurately sensed by satellites, and are also difficult to measure from ships and buoys but can be inferred by pressure measurements on the seafloor. The right top panel in the figure below shows a typical spectrum of bottom pressure (4,000 m) when the overhead wind (U) is strong. There are slight variations in pressure with U at low frequencies and high, but virtually none in the middle range. The lower panel shows 20 dB variations in the spectrum when the wind is variable but low. The left panels compare the wind, for 90 days, (derived from modeling global satellite observations) to the history of bottom pressure and bottom velocity at two frequencies. The two sensors, after an appropriate scaling, differ by only 5% (0.2 dB), except at the start where the hydrophone suffered warping. The black and red traces are practically indistinguishable. The top left panel shows the bottom acoustics moving up and down with the wind. The bottom left panel shows that the spectra are clipped at the top whenever the wind is greater than about 5 m/s.



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

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

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



Recent Publications

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

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

DONNA BLACKMAN, RESEARCH GEOPHYSICIST

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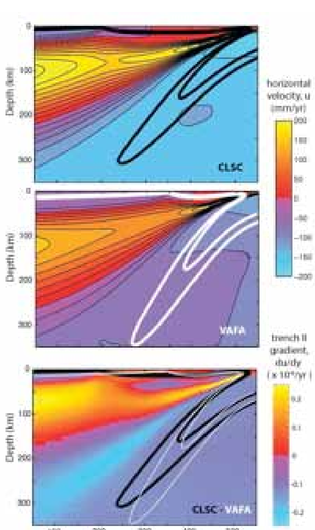
Research Interests: Understanding mantle flow, melting, and plate tectonic evolution along plate boundaries, using marine geophysics and numerical modeling

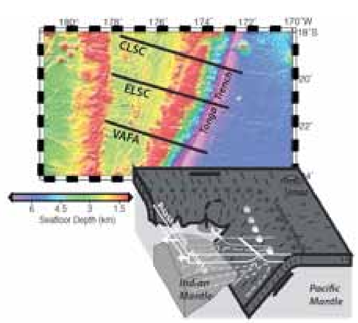
My work this year was dominated by program management, for the Marine Geology & Geophysics program, as I complete a 3-year rotation at the National Science Foundation. However, I was able to do some research in two areas- synthesizing ocean drilling results and numerical modeling of mantle flow and associated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

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

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

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





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

Recent Publications

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

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

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

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

YEHUDA BOCK, RESEARCH GEODESIST, SENIOR LECTURER

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

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

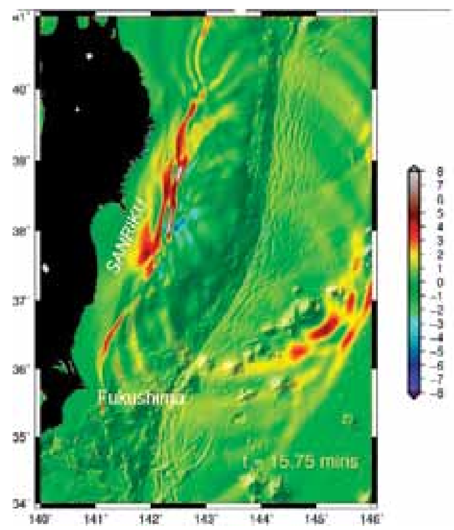

Figure 1. Tsunami wave propagation at 15.75 minutes after origin time of the 2011 Mw 9.0 Tohoku-oki, Japan earthquake based on a kinematic source model (D. Melgar, Ph.D. thesis, 2014). The first waves inundated the shoreline at about 30 minutes, and waves continued to arrive for more than 30 more minutes.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

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

Integration of GNSS and accelerometer data at the observation level provides real-time estimates of seismic displacements, velocities, and point tilts that are more robust and informative than accelerometer or GPS data on their own (*Geng et al.,* 2013). Seismogeodetic data can enhance earthquake early warning, rapid centroid moment tensor (CMT) solutions and finite fault slip models for near-source monitoring of large earthquakes such as the devastating 2011 Mw 9.0 Tohoku-oki earthquake in Japan (*Melgar et al.,* 2013), which triggered a devastating tsunami. Using a kinematic source model to calculate deformation of the seafloor, incorporating seismogeodetic, ocean surface buoy displacements, and seafloor

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

pressure sensor data, and using two-dimensional shallow water equations, Melgar and Bock (2013) demonstrated an accurate tsunami inundation model for the affected Japanese shoreline (Figure 1). This is a significant result for those in the region closest to the earthquake source where loss of life and damage to infrastructure is most severe. As was demonstrated during the actual response to the 2011 Tohoku-oki earthquake, traditional approaches are not accurate enough in the critical time period after the event and may severely underestimate the magnitude and regional extent of damage, to the detriment of rapid response.

Earthquake rapid response, flash flood forecasts and structural health monitoring

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

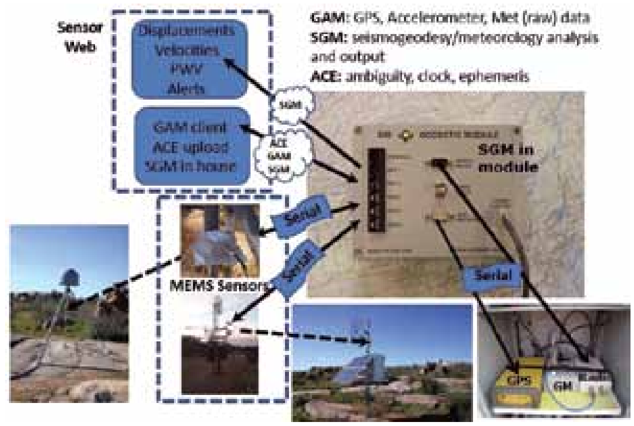

Figure 2. Components of an upgraded GNSS station.

Recent Publications

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

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

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

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

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

ADRIAN BORSA, ASSISTANT RESEARCHER & LECTURER

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

My most recent research involves the characterization of the hydrological cycle using crustal loading observations from GPS, in collaboration with SIO colleagues Duncan Agnew and Dan Cayan. Changes in water storage in lakes, aquifers, soil moisture, and vegetation results in elastic deformation of the crust that yields measurable 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.

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

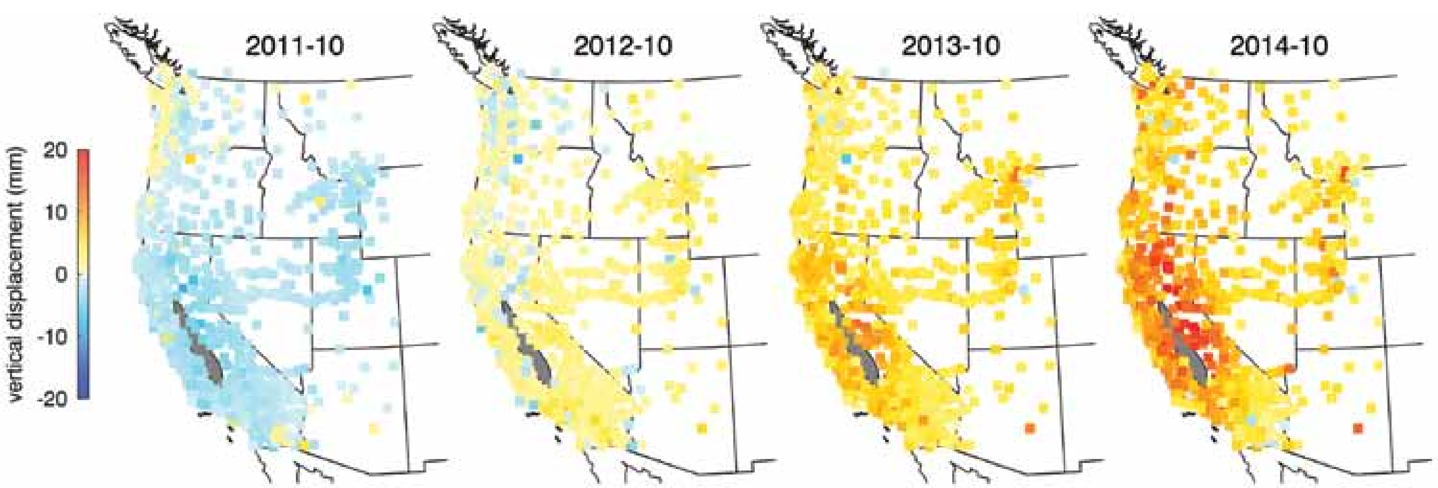

Figure 1: Left: Spatial distribution of vertical displacements from Plate Boundary Observatory continuous GPS stations in the western USA in March of 2013 and 2014. Color indicates deviations of seasonally-adjusted elevations from decadal mean, with blues related to subsidence and yellow-reds related 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.

processing that was the source of large shot-to-shot errors late in the mission period and that significantly changed ICESat-derived elevation change trends for the stable portions of the Greenland and Antarctic ice sheets.

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

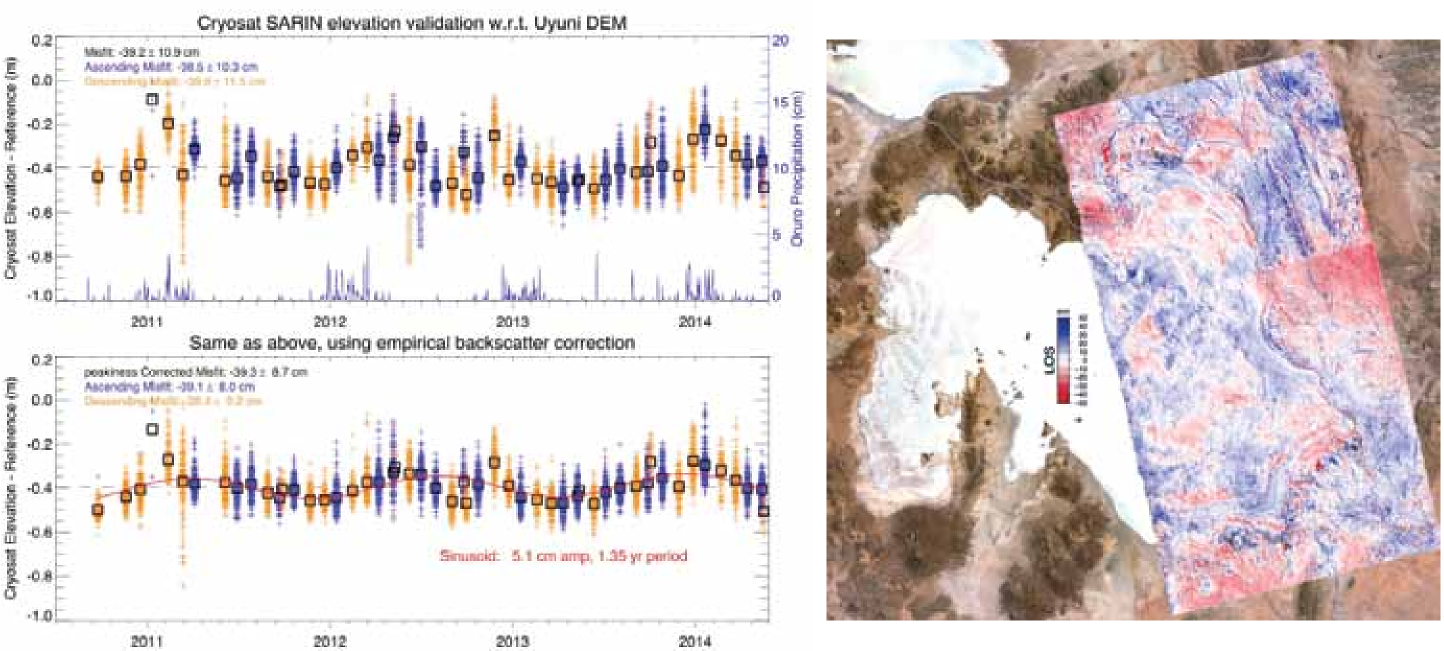

Figure 2: Left: Cryosat SARIN-mode elevation validation relative to the salar de Uyuni DEM, with residuals showing a.) a uniform range bias of -40 cm, b.) an apparent sinusoidal anomaly of 1.35 year period that is still unexplained, and c.) higher range resolution than reported elsewhere, even with the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

Recent Publications

Borsa, Adrian Antal, Duncan Carr Agnew, and Daniel R. Cayan. (2014). "Ongoing drought-induced uplift in the western United States." *Science*, **345**, 6204 (2014): 1587-1590.

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

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

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

CATHERINE CONSTABLE, PROFESSOR

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

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

Linking Dynamo Simulations to Paleomagnetic Field Behavior:

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

Several years ago former graduate student Leah Ziegler and I coauthored a paper in which we analyzed PADM2M, our reconstruction of paleomagnetic axial dipole moment for the past 2 My. By filtering at successively longer periods we uncovered the result shown in Figure 1, that in a frequency band between about 7 and 50/Myr the dipole moment spends more time in decay mode than growing, and speculated that this could reflect dominance of

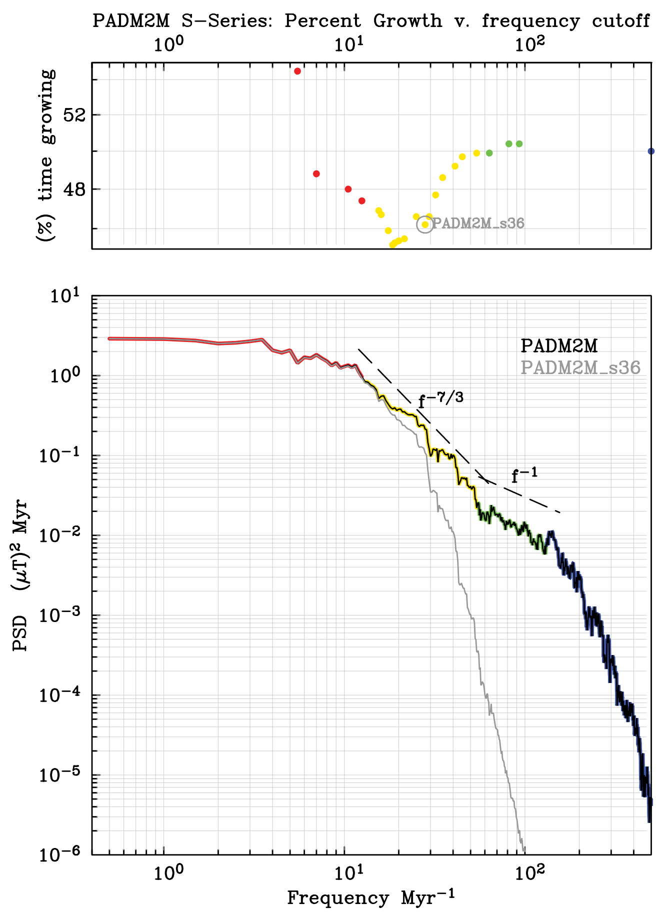

Figure 1: Power spectrum for PADM2M and impact of smoothing on asymmetry in growth and decay: (a) Percentage of time spent in periods of intensity growth versus frequency cuto for the smoothing. (b) PADM2M power spectrum (black) highlighted with colors to show distinct behavioral regimes. Details are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

diffusive processes on these time scales. New estimates of dipole diffusion times (based on revised estimates of conductivity for the core) are compatible with this interpretation. In ongoing studies we (Maggie Avery, Chris Davies, David Gubbins and I) have conducted further analyses of numerical simulations to assess whether this asymmetry in growth and decay times can be identified in numerical simulations and used as a further criterion for Earth-like behavior. Following tests on how long a record is needed we have identified asymmetry in some simulations (and the opposite form with more time growing than decaying in others). A major topic of interest is to determine what visual (see snap shots of magnetic field and flow velocity below) and physical behavior is exhibited in the simulations leads to these different scenarios, and then relate this back to real paleomagnetic field observations.

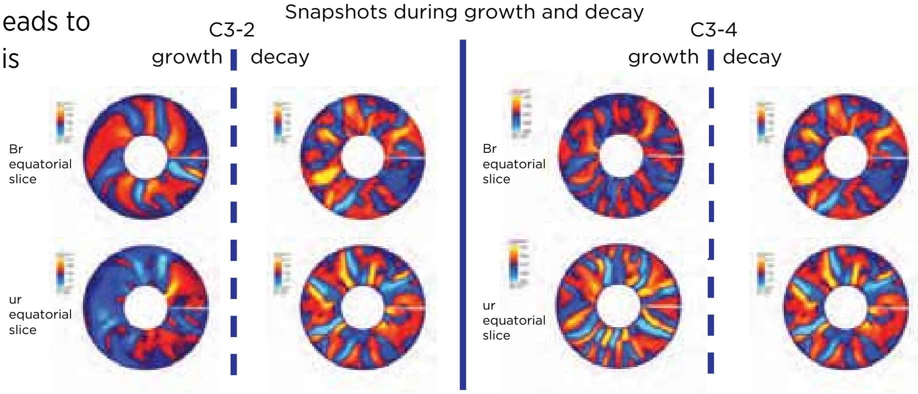

Figure 2

Recent Publications

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

STEVEN CONSTABLE PROFESSOR

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Research Interests: Marine EM methods, electrical conductivity of rocks

Steven Constable runs the SIO Marine Electromagnetic (EM) Laboratory at IGPP, and along with Kerry Key oversees the Seafloor Electromagnetic Methods Consortium, an industry funding umbrella which helps support PhD students and postdocs working in the group. The two main field techniques we use are controlled-source EM (CSEM), in which a deep-towed EM transmitter broadcasts energy to seafloor EM recorders, and magnetotelluric (MT) sounding, in which these same receivers record natural variations in Earth's magnetic field. Both methods can be used to probe the geology of the seafloor, from the near surface to hundreds of kilometers deep, using electrical conductivity as a proxy for rock type.

This year has seen our instrument fleet, consisting of 56 seafloor EM receivers and two deeptowed EM transmitters, in constant use. At around the time last year's annual report was released, we shipped all our gear to Uruguay for a study of sedimentary structure in a frontier (oil) exploration area. We carried out the experiment in January and early February on the R/V Ocean Stalwart out of Montevideo. Our gear did not get back to La Jolla until mid-April, and was immediately put onto trucks to Newport, Oregon, for the MOCHA experiment headed up by Kerry Key to study the tectonics of subduction. The seafloor receivers stayed down until mid-June, and were trucked back just in time to load onto the R/V New Horizon for a study of gas hydrates in the Santa Cruz Basin, offshore

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

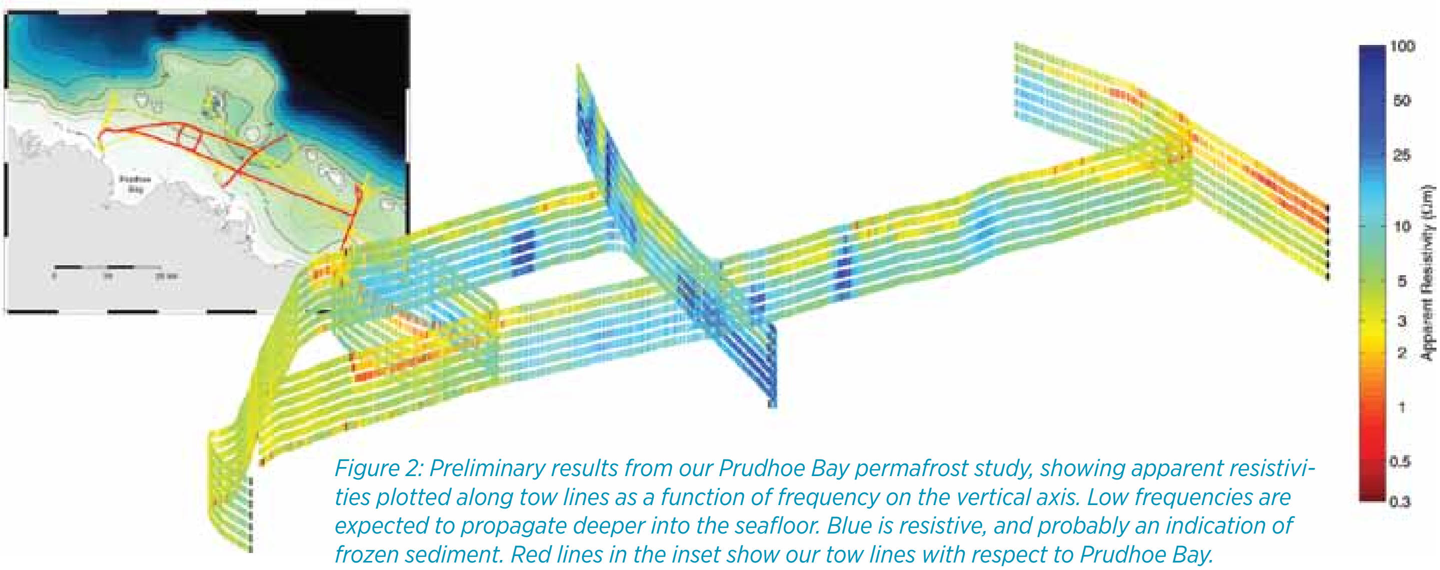
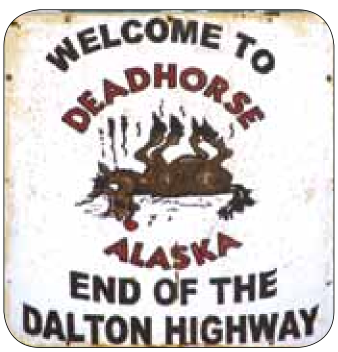


Figure 2: Preliminary results from our Prudhoe Bay permafrost study, showing apparent resistivities plotted along tow lines as a function of frequency on the vertical axis. Low frequencies are expected to propagate deeper into the seafloor. Blue is resistive, and probably an indication of frozen sediment.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

California. After demobilizing the New Horizon at the beginning of July we then shipped some gear to Prudhoe Bay, Alaska, for a study of offshore permafrost. After returning from Prudhoe Bay in late July we then started loading containers to ship our equipment to Japan for another gas hydrate study, which entailed almost three weeks constant use of our EM transmitter in August. The gear returned home from Japan in early October. Thanks to decades of instrument development, and the hard and careful work of our engineers and technicians, we lost only two seafloor receivers in over 200 deployments associated with these various projects, maintaining our excellent record of a long-term instrument loss rate of only 1% of deployments.

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



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

Recent Publications

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

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

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

J. PETER DAVIS, SPECIALIST

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

My research responsibilities at IGPP center upon managing the scientific performance of Project IDA's portion of the Global Seismographic Network (GSN), a collection of 42 seismographic and geophysical data collection stations distributed among 26 countries worldwide. IDA recently concluded upgrading the core data acquisition and power system equipment at all stations using funding provided by NSF via the IRIS Consortium. A map of the network showing upgraded systems denoted by orange triangles is shown in Figure 1. The remaining stations, ABKT and NRIL, are effectively closed.

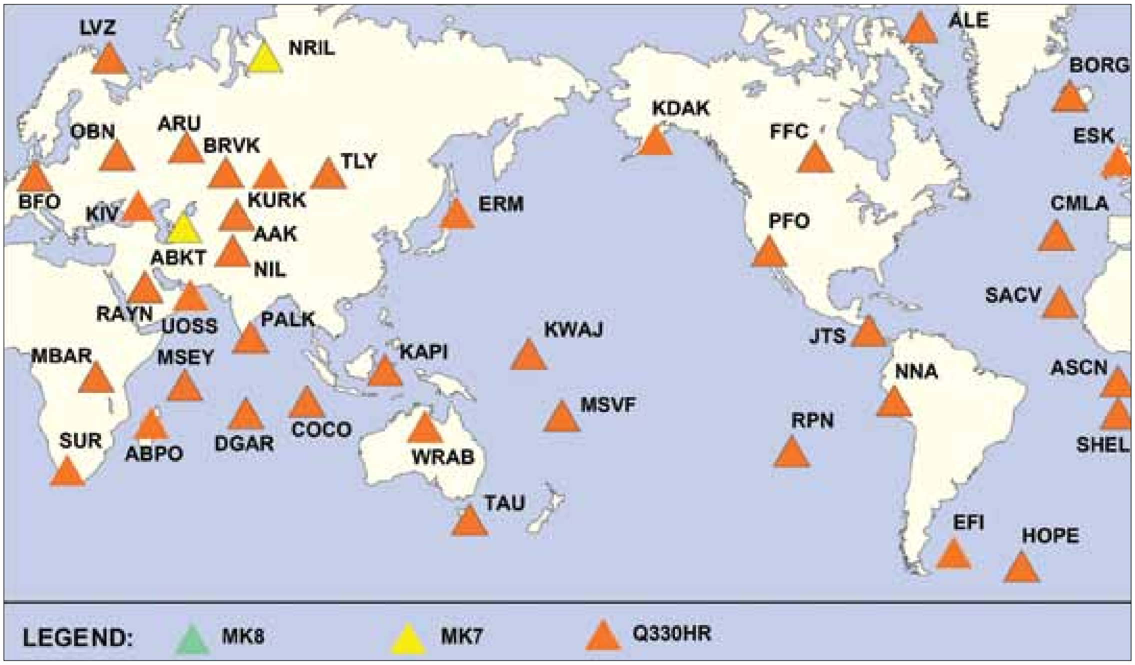
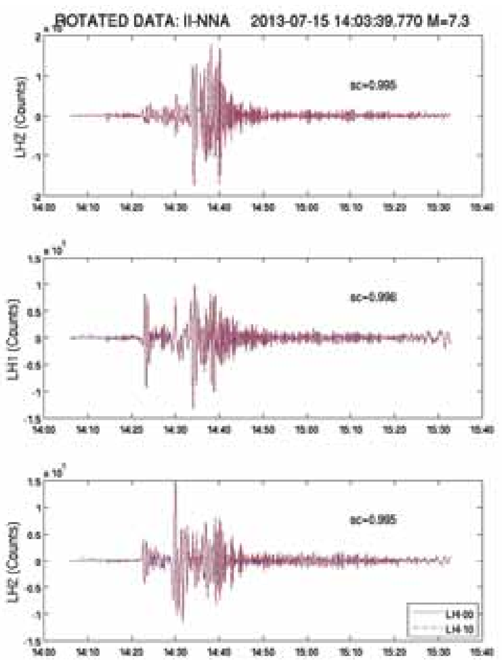


Figure 1. Current global seismic stations operated by Project IDA.



During the next phase of network operation, IDA's staff will fine-tune each station's instruments to enable scientists to extract the most accurate information possible from the data collected. One method for accomplishing this task is by examining key phenomena such as Earth tides and normal modes that should register the same on these important geophysical sensors. To the extent that measurements made with multiple instruments that have been calibrated in very different fashions match, we may have greater confidence that the instrument response information IDA distributes with GSN waveform data is accurate. Investigators use this information to compensate for the frequency-dependent sensitivity of sensors so that they may study true ground motion and its underlying physical causes.

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

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

Recent Publications

Berger, J., P. Davis, R. Widmer-Schnidrig and M. Zumberge, Performance of an Optical Seismometer from 1μHz to 10 Hz. BSSA. **104** (5), 2422-2429, Oct. 2014, doi:10.1785/0120140052

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

CATHERINE DE GROOT-HEDLIN, RESEARCH SCIENTIST

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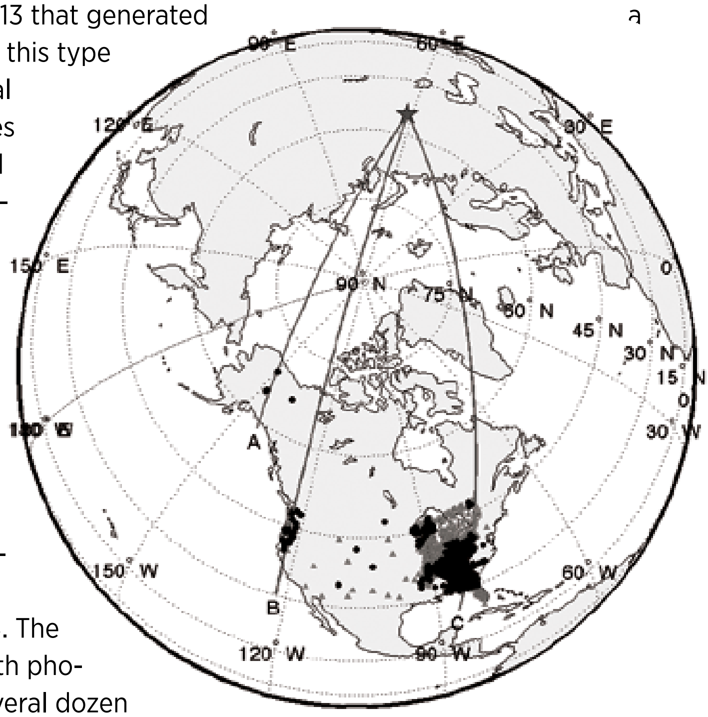
Research Interests: Acoustic propagation modeling with application to infrasound and hydroacoustics; application of hydroacoustics and infrasound to nuclear test-ban verification and hazard monitoring; use of dense seismic and infrasound networks to analyze infrasound signals.

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

Meteor Detection

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



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

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

Gravity Waves

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

Numerical Modeling

A basic research goal in infrasound is to understand the transmission of infrasound through variable atmospheric conditions. To this end I have developed a computationally efficient numerical method to synthesize the propagation of nonlinear acoustic waves through the atmosphere – this nonlinearity arises when pressure perturbations associated with acoustic waves are a significant fraction of the ambient atmospheric pressure. Such situations can arise from meteoroid explosions in the upper atmosphere, volcanic eruptions, or nuclear and chemical explosions. With support from the Air Force Research Laboratory (AFRL), work on this code is continuing so that, in future, it will allow for the incorporation of more realistic atmospheric effects, such as topography, atmospheric absorption, and both spatially and temporally varying sound speeds and wind speeds. The current goal is to determine to what extent nonlinearity affects the estimated source yields for anthropogenic explosions.

Recent Publications

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

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

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

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

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

de Groot-Hedlin, C., 2012, Nonlinear synthesis of infrasound propagation through an inhomogeneous, absorbing atmosphere," *J. Acoust. Soc. Am.,* **132**, p646-656.

MATTHEW DZIECIUCH, PROJECT SCIENTIST

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

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

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

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

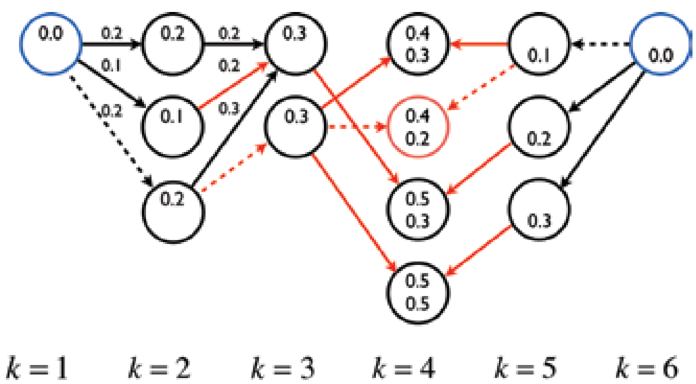

Figure 1: The nodes represent detected peaks at different transmission times k. The arrows represent transition costs between nodes. The total cost of a path from the left/right is the sum of the costs along the path and is shown in the top/bottom number at a node. The most likely node at a particular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

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

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

Peak tracking has been a limiting factor in tomographic experiments because of the time and energy required by manual analysis. Since the number of paths to be tracked scales as the product of the number of sources and receivers, even a moderate sized experiment with six transceiv-

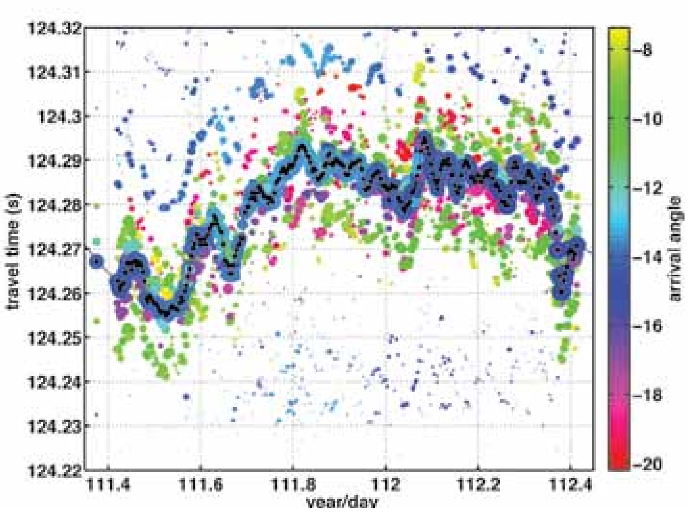

Figure 2: Philippine Sea 2009 arrival-time vs. transmission time. Arrival-angle is represented by the dot color, and arrival strength is represented by dot size.

ers represents a large amount of labor. The Viterbi algorithm solves this problem, while also providing a rational and repeatable method of analysis. While the definition of the transition probabilities is complicated, the process is direct and programmable.

Recent Publications

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

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

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

YURI FIALKO, PROFESSOR

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

Professor Fialko's research is focused on understanding the mechanics of seismogenic faults and magma migration in the Earth's crust, through application of principles of continuum and fracture mechanics to earthquakes and volcanic phenomena. Prof. Fialko is using observations from space-borne radar satellites and the Global Positioning System (GPS) to investigate the response of the Earth's crust to seismic and magmatic loading.

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

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

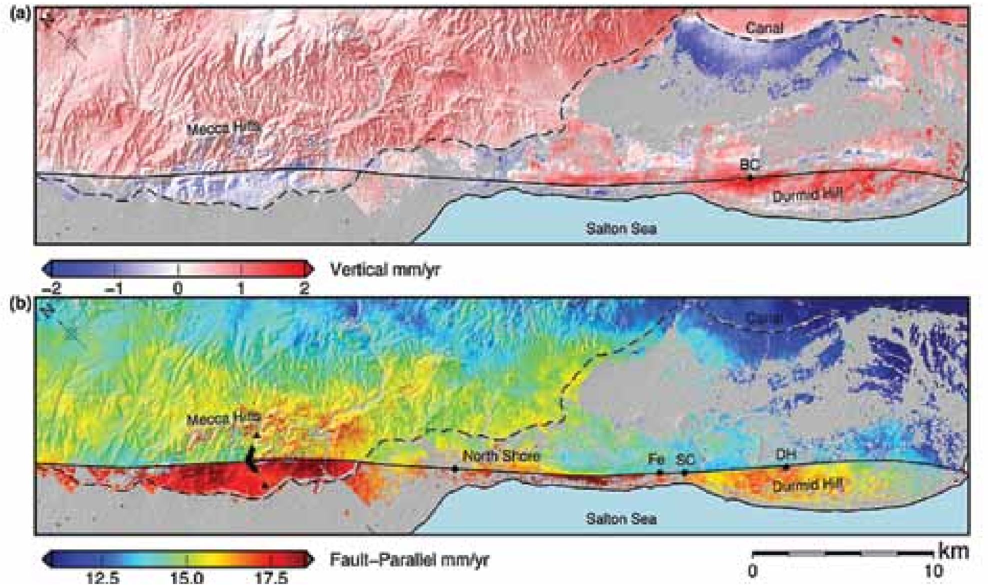

Figure 1: (a) Vertical and (b) horizontal (fault-parallel) velocities of the Earth's surface along the Southern San Andreas fault inferred from Envisat InSAR observations. BC denotes location of Bat Caves Buttes leveling line. Black line denotes trace of the SAF. Diamonds indicate locations of creepmeters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

sible minor contribution of poroelastic rebound. Far-field data require an additional mechanism, most likely viscoelastic relaxation in the ductile substrate.

Other areas of prof. Fialko interests include interseismic deformation and mechanics of damage zones associated with major crustal faults. In a series of recent studies Prof. Fialko and graduate student Eric Lindsey investigated the spatial pattern and rates of deformation due to active faults in southern California such as the San Andreas and San Jacinto faults. Radar observations using data from the Envisat satellite were used to construct a high-resolution map of surface motion near the fault traces. In case of San Andreas, the data reveal pervasive shallow creep along the southernmost 50 km of the fault. Creep is localized on a well-defined fault trace only in the Mecca Hills and Durmid Hill areas, while elsewhere creep appears to be distributed over a 1-2 km wide zone surrounding the fault. The degree of strain localization is correlated with variations in the local fault strike.

The occurrence of shallow, localized interseismic fault creep within mature fault zones may thus be partly controlled by the local fault geometry and normal stress, with implications for models of fault zone evolution, shallow coseismic slip deficit, and geologic estimates of long-term slip rates.

Recent Publications

Lindsey, E., V. Sahakian, Y. Fialko, Y. Bock, S. Barbot, and T. Rockwell, Interseismic Strain Localization in the San Jacinto Fault Zone, *Pure and Appl. Geophys.,* doi:10.1007/s00024013-0753-z, 2014a.

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

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

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

HELEN AMANDA FRICKER, PROFESSOR

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

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

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

i) Antarctic Subglacial Water

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

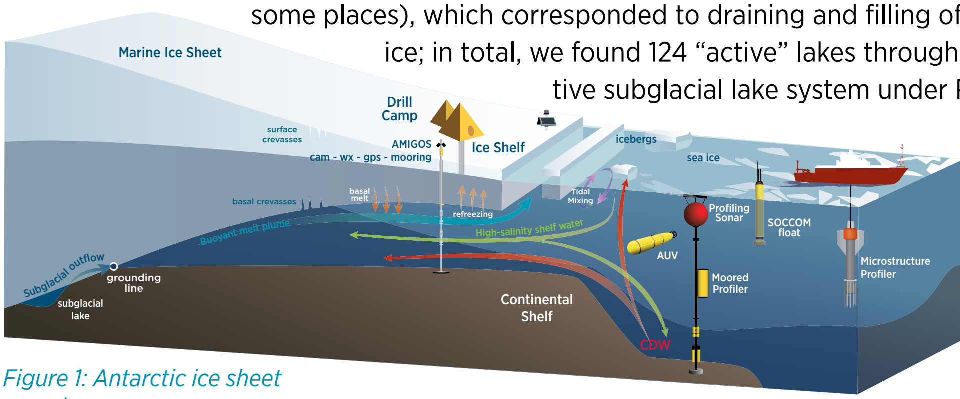

Figure 1: Antarctic ice sheet mass loss processes

Changing the basal conditions of an ice sheet, particularly beneath fast flowing ice streams and outlet glaciers, is one possible mechanism to increase its contribution to sea level rise, through increased ice flow speeds in the ice streams. With the current interest in Antarctic ice sheet mass balance and its potential impact on sea-level rise, it is important to understand the subglacial water process so that it can become incorporated into models; Sasha Carter works with me on this aspect of the problem. I am a PI on the Whillans Ice Stream Subglacial Access Research Drilling (WISSARD) project, a large, interdisciplinary NSF project to drill into one of the subglacial lakes that I discovered – Subglacial Lake Whillans (SLW) on Whillans Ice Stream, lead PI is Slawek Tulaczyk at UCSC. IGPP student Matt Siegfried took part in the surface geophysics fieldwork 2011-2012/2012-2013/2013-2014 (team leader), and installed GPS on the lakes to monitor their activity. SLW was drilled during the 2012-2013 field season (5). Matt will return to Whillans Ice Stream in 2014-2015, along with IGPP postdoc Oliver Marsh. UCSC graduate student Lucas Beem published a paper on the slowing of Whillans Ice Stream (10). A paper describing the biological discoveries from WISSARD was published in Nature (2).

ii) Ice shelf Grounding Zones

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

iii) Ice shelf stability and change

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

iv) Glacio-seismology

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

Recent Publications

1. Moholdt, G., H.A. Fricker, L. Padman (2014) Basal mass budget of Ross and Filchner-Ronne ice shelves, Antarctica, derived from Lagrangian analysis of ICESat altimetry, *J. Geophys. Res.: Earth Surface,* doi: 10.1002/2014JF003171.

2. B.C. Christner, J.C. Priscu, A.M. Achberger, C. Barbante, S.P. Carter, K. Christianson, A.B. Michaud, J.A. Mikucki, A.C. Mitchell, M.L. Skidmore, T.J. Vick-Majors & the WISSARD Science Team (2014). A microbial ecosystem beneath the West Antarctic ice sheet. *Nature,* doi:10.1038/nature13667.

3. Fricker, H.A., S. P. Carter, R.E. Bell, T.A. Scambos (2014) Active lakes of Recovery Glacier, East Antarctica: a bedrock-controlled subglacial hydrological system, *Journal of Glaciology*, **60** (223), doi: 10.3189/2014JoG14J063..

4. Holt, T.O., N.F. Glasser, H.A. Fricker, L. Padman, A. Luckman, O. King, D.J. Quincey, M.R. Siegfried, The structural and dynamic responses of Stange Ice Shelf to recent environmental change, *Antarctic Science,* doi:10.1017/S095410201400039X, 15pp.

5. Tulaczyk, S., J.A. Mikucki, M.R. Siegfried, J.C. Priscu, C.G. Barcheck, L.H. Beem, A. Behar, J. Burnett, B.C. Christner, A. T. Fisher, H.A. Fricker, K. D. Mankoff, R.D. Powell, F. Rack, D. Sampson, R.P. Scherer, S.Y. Schwartz And The Wissard Science Team (2014), WISSARD at Subglacial Lake Whillans, West Antarctica: scientific operations and initial observations, *Annals of Glaciology,* **55**(65) 2014 doi: 10.3189/2014AoG65A009.

6. Christoffersen, P., M. Bougamont, S.P. Carter, H.A. Fricker, S. Tulaczyk, 2014. Significant groundwater contribution to Antarctic ice streams hydrologic budget, *Geophysical Research Letters,* 2014GL059250 doi:10.1002/2014GL059250.

7. Münchow, A., L. Padman And H. A. Fricker (2014) Interannual Changes of the Floating Ice Shelf of Petermann Gletscher, North Greenland from 2000 to 2012, *Journal of Glaciology,* **60**, (221), 498-499, doi: 10.3189/2014JoG13J135.

8. Heeszel, D. S., H. A. Fricker, J. N. Bassis, S. O'Neel, And F. Walter (2014), Seismicity within a propagating ice shelf rift: The relationship between icequake locations and ice shelf structure, *J. Geophys. Res. Earth Surf.,* **119**, 731–744, doi:10.1002/2013JF002849.

9. Siegfried, M.R. H.A. Fricker, M. Roberts, T.A. Scambos, S. Tulaczyk (2014) A decade of West Antarctic subglacial lake interactions from combined ICESat and CryoSat-2 altimetry, *Geophysical Research Letters*, http://dx.doi.org/10.1002/2013GL058616.

10. Beem, L.H., S.M. Tulaczyk, M.A. King, M. Bougamont, H.A. Fricker, P. Christoffersen (2014) Variable Deceleration of Whillans Ice Stream, West Antarctica, *J. Geophys. Res.: Earth Surface*, **119** (2), 212-224, doi: 10.1002/2013JF002958.

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

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

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

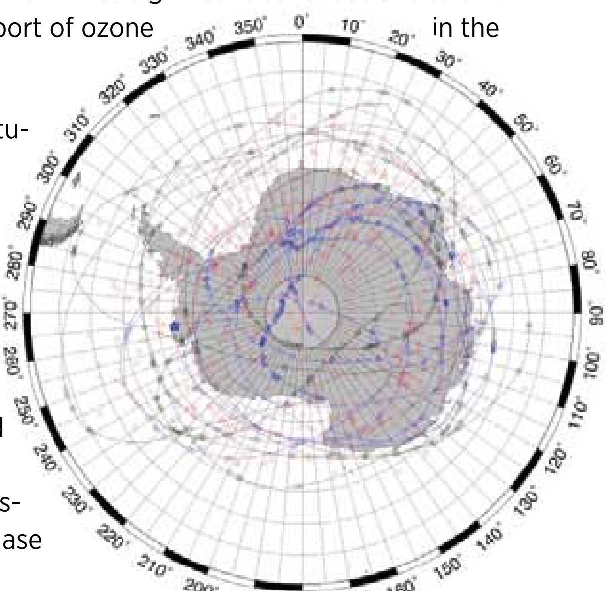

Figure 1 Paths of the two stratospheric balloons carrying GPS radio occultation sensors showing profile locations (black and blue diamonds), and profile locations from 13 balloons carrying dropsondes (red diamonds).

Recent Publications

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

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

Haase, J. S., B. J. Murphy, P. Muradyan, F. Nievinski, K. M. Larson, J. L. Garrison, and K.-N. Wang (2014), First Results from an Airborne GPS Radio Occultation System for Atmospheric Profiling, *Geophysical Research Letters,* **40**, 10.1002/2013GL058681.

Crowell, B. W., D. Melgar, Y. Bock, J. S. Haase, and J. Geng (2013). Earthquake magnitude scaling using seismogeodetic data, *Geophysical Research Letters,* **40**, 6089-6094.

Symithe, S. J., E. Calais, J. S. Haase, A. M. Freed, and R. Douilly (2013), Coseismic slip distribution of the 2010 M7.0 Haiti earthquake and resulting stress changes on regional faults, *Bull. Seis. Soc. Am,* **103**(4), 2326-2343.

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

Geng, J., Y. Bock, D. Melgar, B. W. Crowell, and J. S. Haase (2013), A new seismogeodetic approach applied to GPS and accelerometer observations of the 2012 Brawley seismic swarm: Implications for earthquake early warning, *G-cubed,* **14**(7), 2124-2142.

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

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

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

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

The borehole velocity profiles derived from the sonic log and from inverting the first arrival travel times of the VSP are used to benchmark the accuracy of different velocity inversions of the nearby surface MCS data, Figure 1. The initial inversion applied travel time tomography to shot gathers downward continued to a horizon just above the seafloor simulating an extended on-bottom experiment (*Henig et al.,* 2012). The more recent inversion extends this analysis and applies waveform inversion to the same downward continued dataset (e.g. *Arnulf et al.,* 2014). Although the travel time

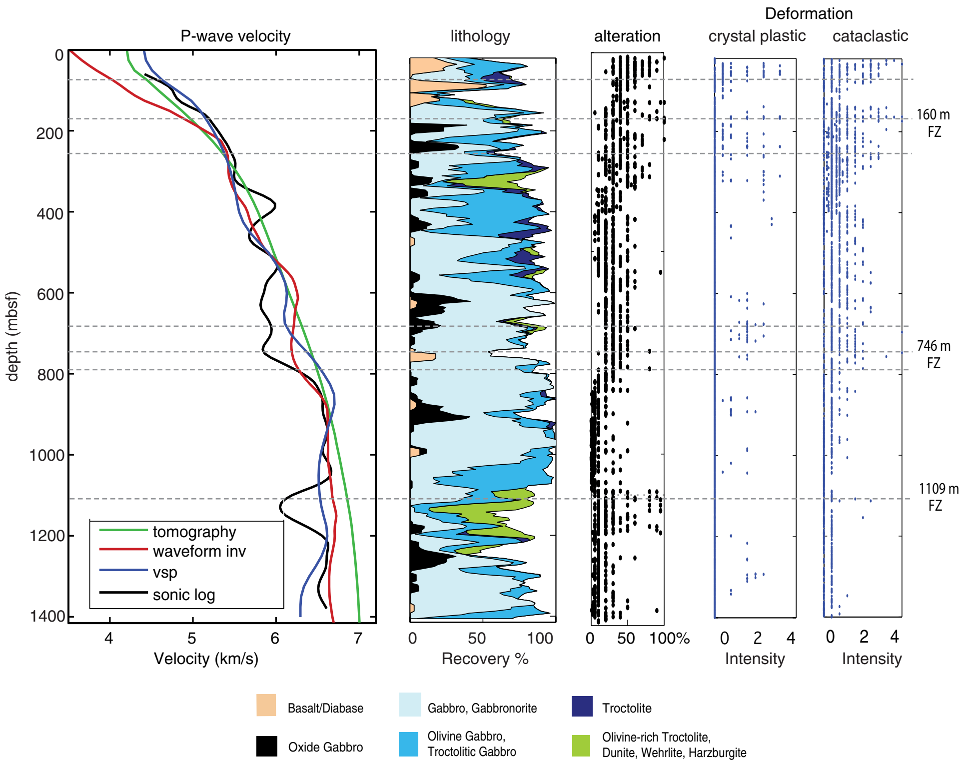

Figure 1 Vertical velocity profiles for Hole U1309D compared with logs of lithology, alteration and deformation. The changes in velocity due to lithology are expected to be minor except for the intervals of olivine-rich rocks. Instead velocity changes are closely correlated with changes in alteration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

tomography result matches the general trend of the velocity profiles recorded in the borehole, it is unable to resolve the changes in vertical velocity gradient that are captured by the waveform inversion result. The vertical velocity structure can be split into three zones with dividing horizons at 250-300 m and 750-800 m, which correlate to drops in the degree of deformation and alteration. The top horizon corresponds to the base of intense detachment related deformation of the footwall, while the second horizon, based on other analysis marks the overall limit of such deformation. The second horizon also corresponds to the current base of advective fluid flow with the borehole temperature gradient being conductive below this level (*Blackman et al.,* 2014). It these horizons that can be extrapolated beyond the borehole in the waveform inversion results to help map deformation and alteration.

Arnulf, A. F., A. J. Harding, S. C. Singh, G. M. Kent, and W. C. Crawford (2014), Nature of upper crust beneath the Lucky Strike volcano using elastic full waveform inversion of streamer data, *Geophys. J. Int.,* **196**(3), 1471–1491, doi:10.1093/gji/ggt461.

Blackman, D. K., A. Slagle, A. J. Harding, and G. Guerin (2012), IODP expedition 340T: Borehole logging at Atlantis Massif oceanic core complex, Preliminary Report 340T, Integrated Ocean Drilling Management International, doi:10.2204/iodp.pr.340T.

Blackman, D. K., A. Slagle, G. Guerin, and A. Harding (2014), Geophysical signatures of past and present hydration within a young oceanic core complex, *Geophys. Res. Lett.,* **41**(4), 1179–1186, doi: 10.1002/2013GL058111.

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**(5), Q0AG07, doi:10.1029/2012GC004059.

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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

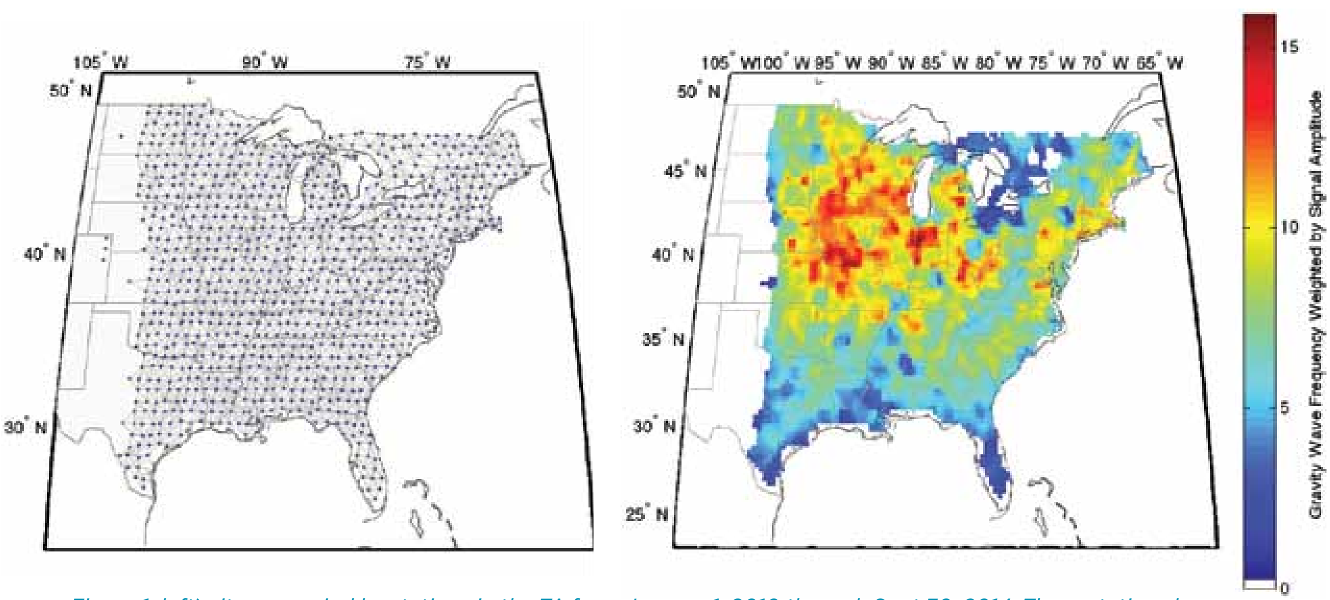

Figure 1. left) sites occupied by stations in the TA from January 1, 2010 through Sept 30, 2014. These stations have been grouped into 3-element arrays (triads) for the study of long-period atmospheric gravity waves. The panel on the right shows the frequency of gravity waves in this time period with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

the western United States similar to commonly used seismic event catalogs. The acoustic catalog is used in part to find sources of interest for further study and to use the recorded signals to study long-range infrasound propagation. Recorded signals from instantaneous sources are commonly dispersed in time to several 10's of seconds. Modeling indicates that this is due to interaction of the sound waves with fine-scale structure in the atmosphere due to gravity waves. We are currently using infrasound to constrain the statistics of this time-varying structure.

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

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.

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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

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

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

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

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

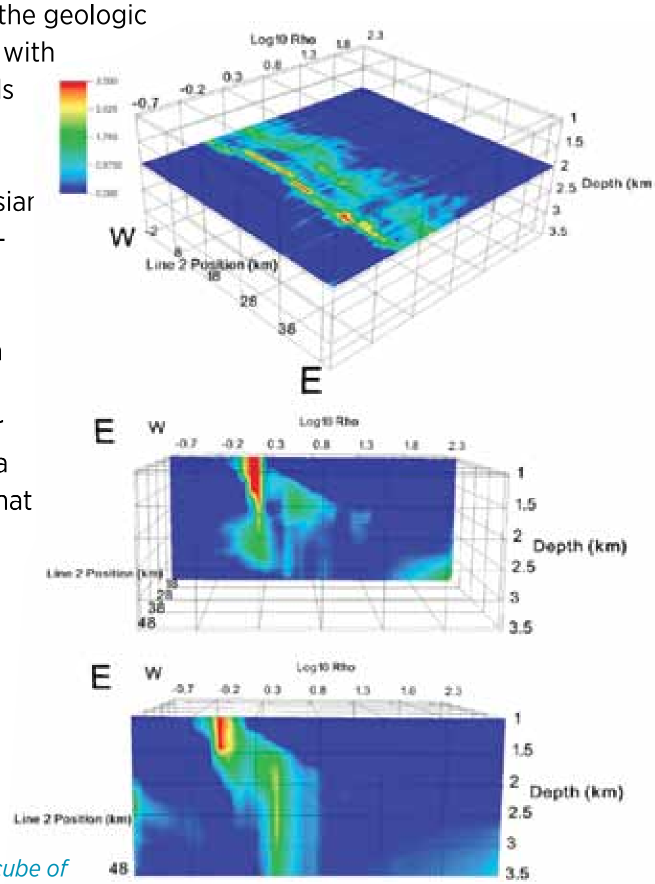

Figure 1. Bayesian inversion of data from the Scripps marine CSEM survey of the Scarborough gas field. All three panels show slices through a probability cube of resistivity as a function of depth and position along the survey profile. Brighter colors correspond to more probable resistivity values. Top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

Background: Marine EM Lab preparing seafloor geophysical equipment for Project MOCHA.

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

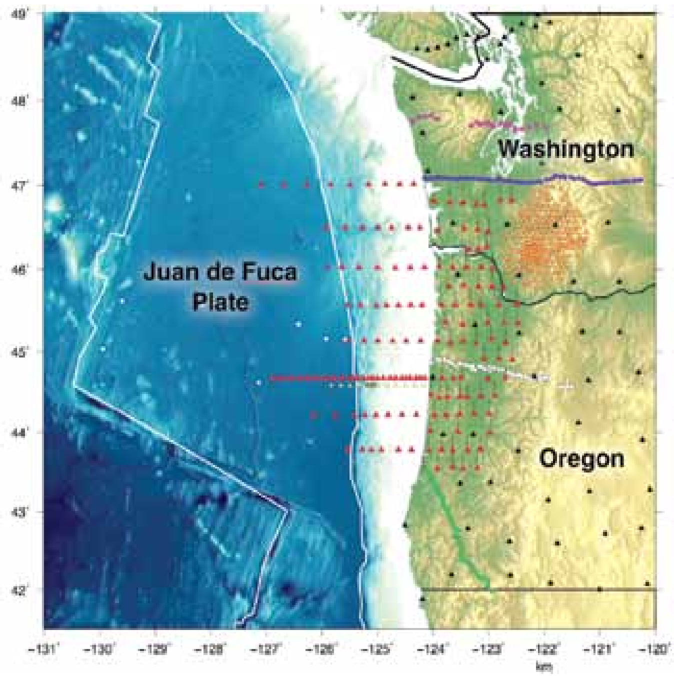

Figure 2. The amphibious magnetotelluric stations collected for the MOCHA project (red triangles) include 71 offshore and 75 onshore stations. This large scale 3D data set fits into a broader context of MT stations collected by other researchers in the Pacific northwest, including the US Array MT (black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

Photos and videos from the MOCHA deployment and recovery cruises can be viewed on our website: marineemlab.ucsd.edu/Projects/MOCHA

Recent Publications

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

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

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

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

Humming Icequakes (Heeszel et al., 2014)

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

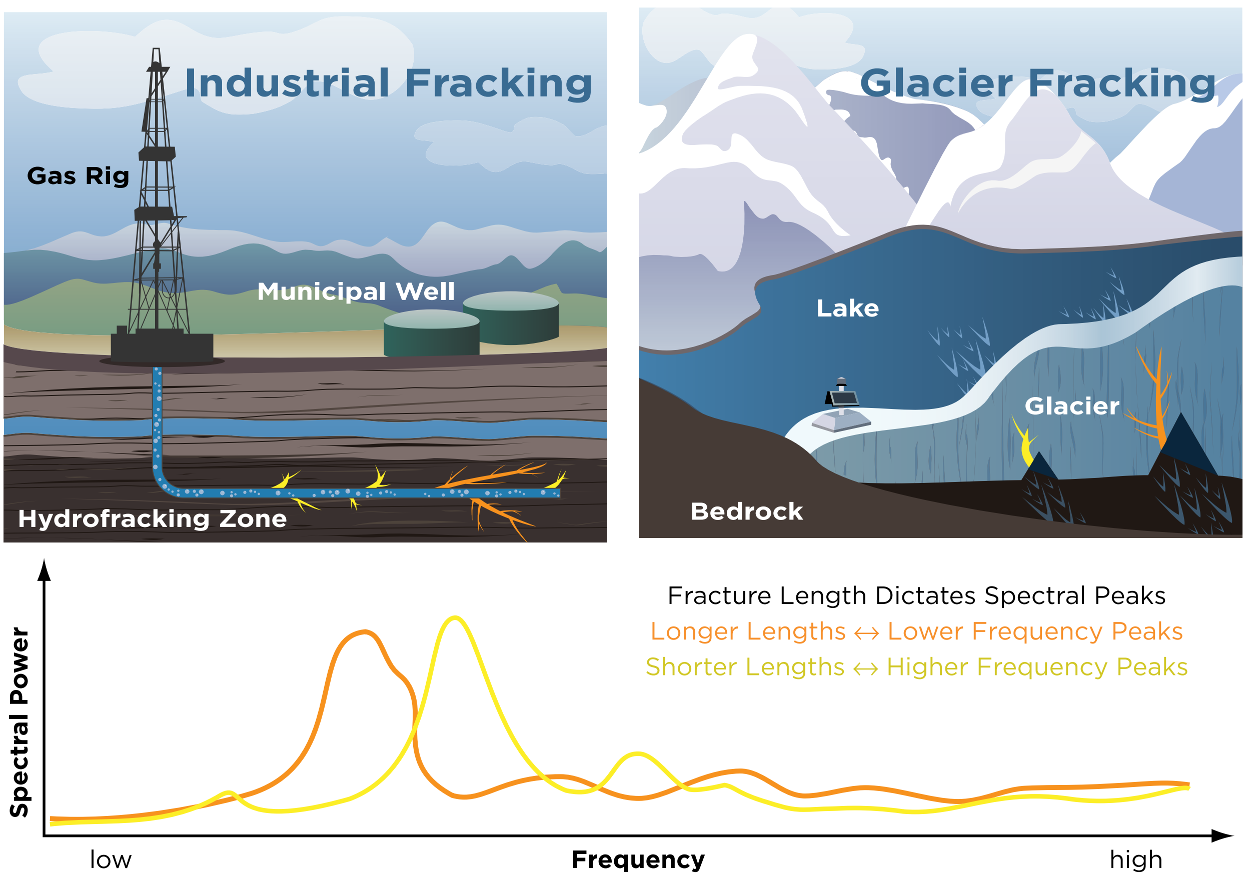

Figure 1: Cartoon depicting the relationship between hydrofracture length and spectral resonance peaks. (A) Industrial fracking within a geothermal reservoir showing both short (yellow) and long (orange) fracture lengths. (B) Fracking within a glacier near a draining lake (dark blue), again both short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

Exploring Remote Earthquake Triggering Potential Across using Frequency Domain Array Visualization (Linville et al., 2014)

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

Selecting Empirical Green's Functions in Regions of Fault Complexity: A Study of Data From the San Jacinto Fault Zone, Southern California (Kane et al., 2013)

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

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

Recent Publications

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

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

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

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Research interests: regional and global seismology; surface waves and free oscillations; seismology on the ocean floor; observation and causes of seismic noise; natural disasters and the environment

Gabi Laske's main research area is the analysis of seismic surface waves and free oscillations, and the assembly of global and regional seismic models. She has gone to sea to collect seismic data on the ocean floor. Laske's global surface wave database has provided key upper mantle information in the quest to define whole mantle structure. Graduate students Christine Houser and Zhitu Ma as well as students from other universities have used her data to compile improved mantle models.

Global Reference Models

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

The PLUME Project

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

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

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

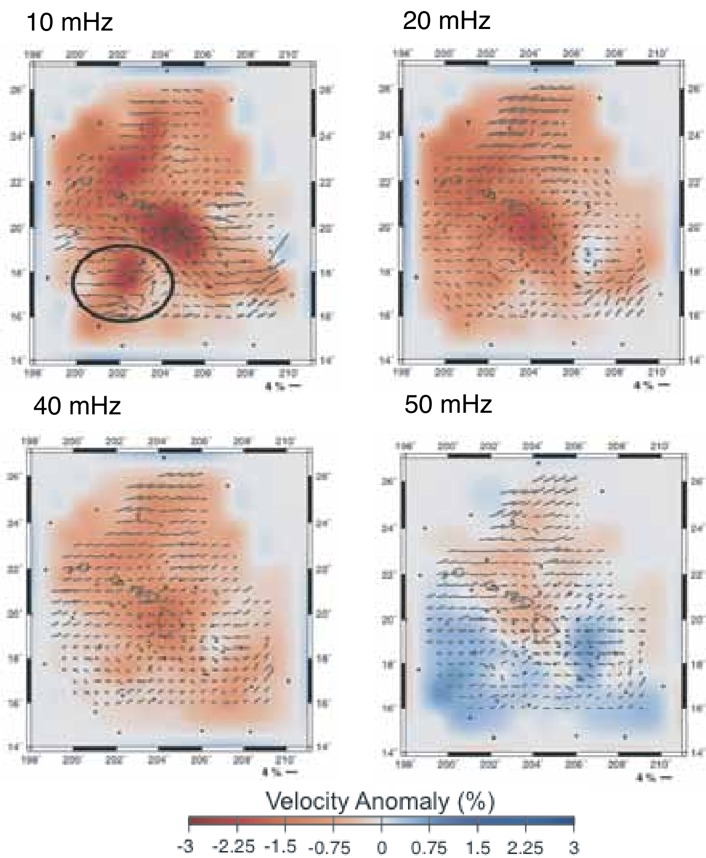

Figure 1: Frequency-dependent Rayleigh-wave azimuthal anisotropy as observed during the PLUME deployments. Data were binned into 1 x 1° cells. Higher frequencies are sensitive to upper-lithosphere structure, while lower frequencies reach into the asthenosphere. The signal for lower frequencies suggest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

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

The ADDOSS Project

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

Recent Publications

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Thomas, C. and Laske, G., D" observations in the Pacific from PLUME Ocean Bottom Seismometer recordings. *Geophysical Journal International,* in press, 2014.

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

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

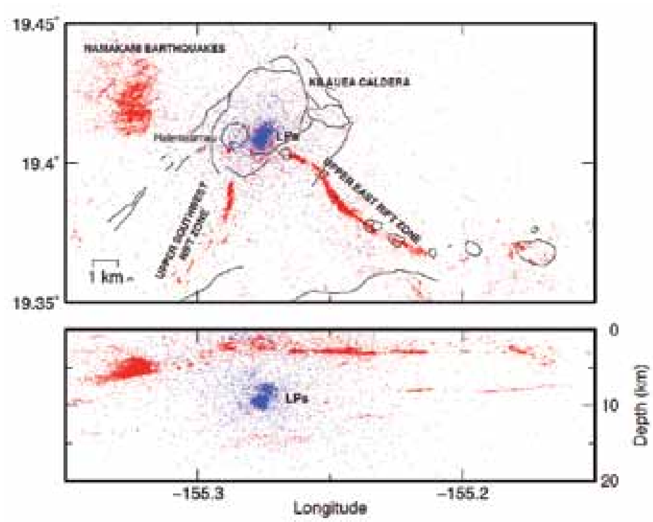

Figure 1: High-precision relocations of seismicity in the summit region of Kilauea Volcano, Hawaii from 1986 to 2009 [Matoza et al., 2013, 2014a]. Blue dots are events we automatically classify as LP and red dots are non-LP. We produce a dramatic sharpening of earthquake locations along faults and magmatic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

The analysis and interpretation of seismicity from mantle depths to the surface plays a key role in understanding how volcanoes work. Together with Peter Shearer, IGPP and Paul Okubo of the USGS

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

Atmospheric infrasound is acoustic waves with frequencies from 380.01-20 Hz, which are inaudible to the human ear. Infrasound is useful for studying volcanic eruptions for two main reasons: (1) Shallow and subaerial volcanic processes radiate sound directly into the atmosphere; sampling this sound complements seismic data, which record subsurface processes, and (2) Infrasound propagates long distances in the atmosphere and is routinely detected on sparse ground-based infrasound networks. There are numerous types of volcano infrasound resulting from a broad spectrum of volcanic eruption styles, but I am currently focused on powerful blast-waves and roaring jet-noise sounds from volcanic explosions. In the past year, I have worked on characterizing volcanic explosion complexity using campaign infrasound datasets from volcanoes Sakurajima, Japan; Karymsky, Russian Federation; and Tungurahua, Ecuador (*Matoza et al.,* 2014b). I have also worked on airground coupling of strong acoustic signals from volcanic eruptions to understand how this complicates seismic tremor recordings during eruptions (*Matoza and Fee,* 2014). I am beginning a new project, funded by a research award from the Comprehensive Test-Ban Treaty Organization, to catalog the global detection of explosive volcanic infrasound on the International Monitoring System (IMS). The IMS infrasound network is designed to detect atmospheric nuclear tests anywhere on the planet, and this project will assess its utility for global volcano monitoring.

Recent Publications

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

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

Matoza, R.S., P.M. Shearer, and P.G. Okubo (2014a) High-precision relocation of long-period events beneath the summit region of Kilauea Volcano, Hawaii, from 1986 to 2009, *Geophys. Res. Lett.,* **41**, 3413-3421, 10.1002/2014GL059819.

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

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

JEAN-BERNARD MINSTER, PROFESSOR OF GEOPHYSICS

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

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

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

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

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

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

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

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

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

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

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

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

3. Improve the *funding* environment

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

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

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

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

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

References

ICSU-WDS 2014 Report to ICSU: *www.icsu-wds.org/news/news-archive/wds-at-the-31st-general-assembly-of-icsu*; *www.icsu-wds.org/publications/annual-reports*

ICSU-WDS Strategic Plan 2014-2018: *www.icsu-wds.org/organization/strategic-plan*

Polar forum declaration, Kyoto, 2013: *www.icsu-wds.org/publications/press-releases*

WALTER MUNK RESEARCH PROFESSOR

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I have returned to the classical problem on WIND DRAG. This is due to viscous shear forces and normal pressures on ocean roughness. There are some new results. At winds of less than U10 =3D 2 m/s it is entirely viscous. At winds of 7 m/s it is 2/3 normal pressures. This has implications on a number of problems.

Acoustic noise at depth (deeper than 1 km, say) is highly correlated with surface winds, but the physics of the noise generation is not clear. There is some excellent new observational material (see report by J. Berger) and we are looking into a variety of possible physical processes.

Matthew Siegfried, Walter Munk, Mary Coakley Munk, Emily Kelly, and Danny Richter at the at the Vatican sustainablity conference: Sustainable Humanity, Sustainable Nature: Our Responsibility

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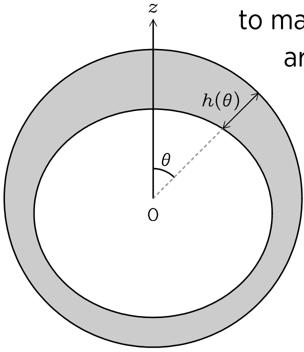
Research Interests: Inverse theory, geomagnetism, spectral analysis, electromagnetic induction.

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

But such a distribution has no external effect, because $\boldsymbol{U} = 0$ on the surface and therefore it vanishes exactly everywhere outside. Because of the linearity of the problem, the function $\boldsymbol{\rho}$ can be added to any solution (scaled if necessary

$$\rho = -\frac{\nabla^2 \mathrm{U}}{4\pi \mathrm{G}} \,. \qquad (1)$$



to maintain positivity), without affecting the match of the original model to the data. Recall $\boldsymbol{U}$ is an arbitrary function, subject only to its being smooth and vanishing on $\partial\boldsymbol{S}$. This represents an huge family of alternative densities whose gravitational fields are identical with the observed one.

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

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

then

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

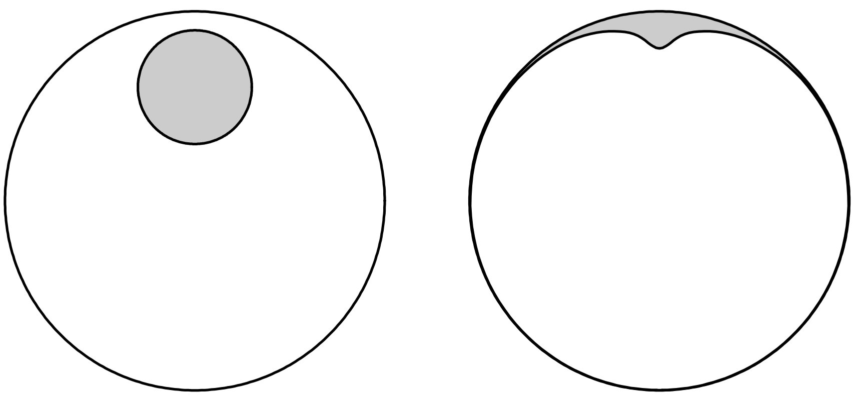
$$= -\frac{4\pi G \varrho a}{2l+1} h_l + \Delta_l[h] \tag{4}$$

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

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

When the layer is very thin, Δ_l can be neglected and (5) gives an approximate solution for the inverse problem in that case; when it is not thin, (5) can be employed as the basis for a fixed point iteration in which successive approximations from the right side are substituted into Δ_l on the left. While a rigorous convergence theory has not be discovered (except for a very simple case), in practice the scheme converges in a satisfactory manner, allowing matching of given potentials to a few parts in 107 by layer models.

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



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

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

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

(B). Fluids influence electrical conductivity and seismic velocity in different ways. These physical properties are measured using electromagnetic and seismic methods, respectively, and offer a unique way to map in situ fluid distribution in real time in the Earth's crust and mantle. When interpreted together with petrological results, geophysical data can be used to constrain fluid chemistry, temperature, fraction, and connectivity. Seismic and magnetotelluric (MT) studies do not necessarily agree on melt fraction estimates, a possible explanation being the assumptions made about melt chemistry as part of MT data interpretation. Melt fraction estimates from electrical anomalies usually assume a basaltic melt phase, whereas petrological knowledge suggests that the first liquids produced have a different chemistry, and thus a different conductivity. Together with Ed Garnero, I explored melt properties by interpreting geophysical data sets sensitive to the presence of melt (electromagnetic and seismic) with considerations of petrology and, in particular, peridotite partial melting (Pommier and Garnero, 2014). We developed a petrology-based model of the electrical conductivity of fertile and depleted peridotites during partial melting. Our results showed that melts produced by low-degree peridotite melting (i15 vol%) are up to 5 times more conductive than basaltic liquids. Such conductive melts significantly affect bulk rock conductivity. Application of our electrical model to magnetotelluric results suggested melt fractions that are in good agreement with seismic estimates (Figure 1.B).With the aim of a simultaneous interpretation of electrical and seismic data, we combined our electrical results with seismic velocity considerations in a joint model of partial melting. We observed that field electrical and seismic anomalies can be explained by ~1 vol% melt beneath Hawaii and ~1–8 vol% melt beneath the Afar Ridge. As part of another study compiling electromagnetic and seismic results from various subduction zones, I observed a possible correlation between electrical conductivity and seismic wave attenuation anomalies in the mantle wedge is observed, consistent with fluid accumulation (Pommier, 2014). A possible relationship between geophysical properties and the slab age is also suggested, whereas no significant trend is observed between electrical conductivity or seismic wave attenuation and estimates of water flux in the mantle wedge. These field-based relationships require further constrains, emphasizing the need for new measurements in the laboratory.

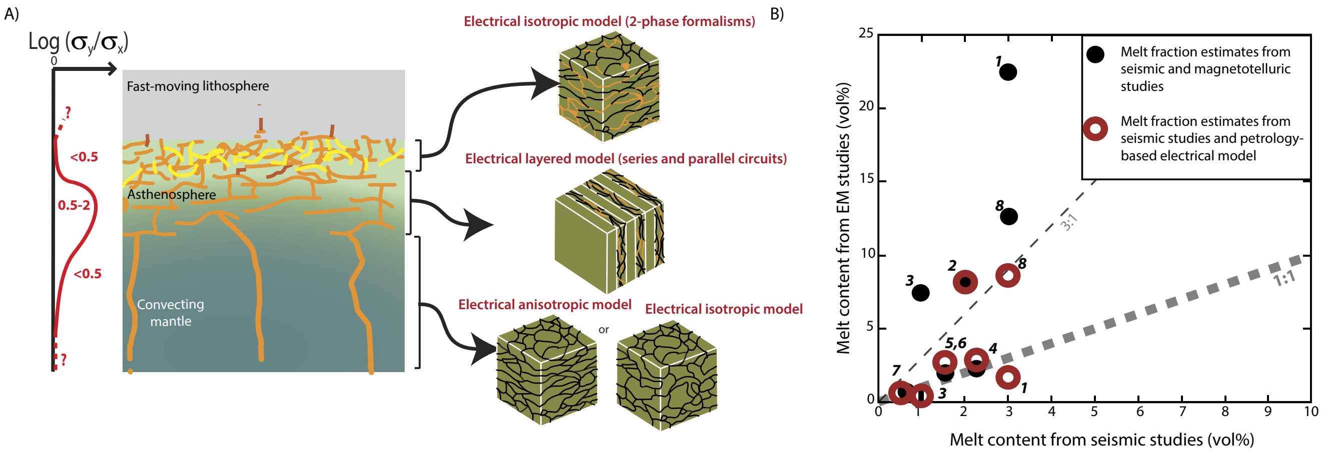

Figure 1: A) Cross-section portrayal of the electrical conductivity (σ) of the uppermost mantle in melt-bearing context (fast-moving plates), with corresponding conductivity ratio for the lowest conductivity direction (σ_y) to the highest conductivity direction (σ_x). Melt reaches the asthenosphere from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

Recent Publications

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

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

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

DAVID T. SANDWELL, PROFESSOR OF GEOPHYSICS

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Research Interests: Geodynamics, global bathymetry, crustal motion modeling

Students and Funding

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

Global Gravity and Bathymetry

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

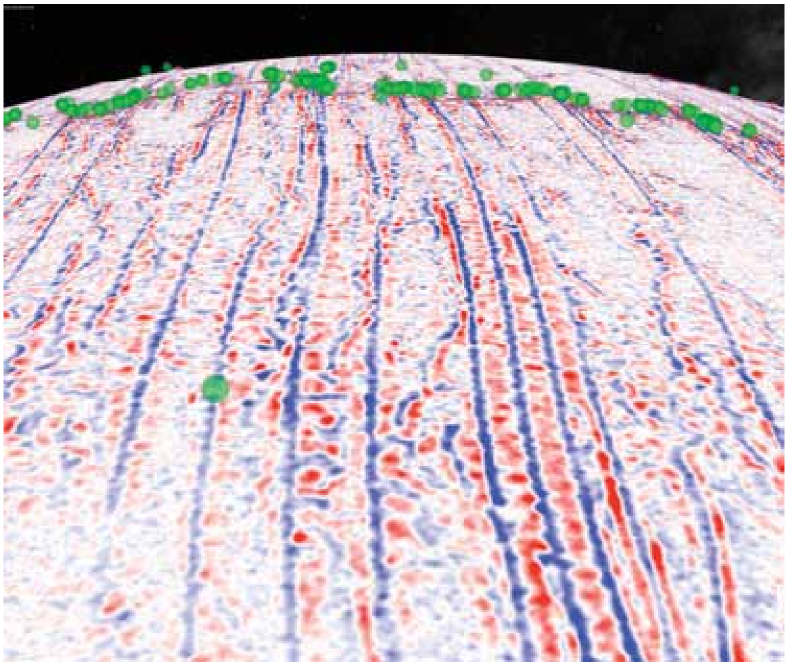

Figure 1. Vertical gravity gradient (VGG) model of the southern mid-Atlantic Ridge. Earthquakes with magnitude > 5.5 are shown as green dots and highlight the current location of the spreading ridges and transform faults. The linear fracture zone signatures record the rifting and spreading between South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

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

Crustal Motion Modeling

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

Relevant Publications

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

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

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

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

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

PETER SHEARER, DISTINGUISHED PROFESSOR OF GEOPHYSICS

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Research Interests: seismology, Earth structure, earthquake physics

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

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

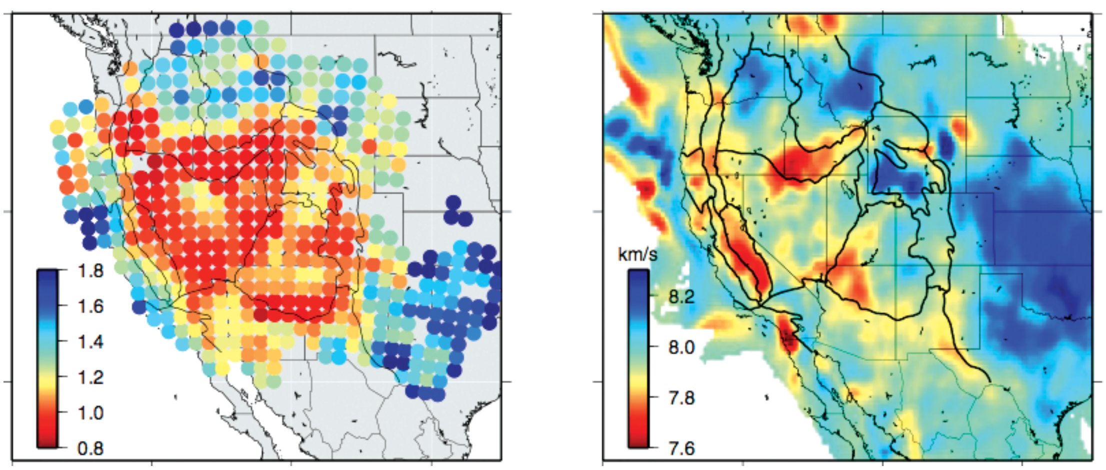

Figure 1. (left) Sn *signal strength at 3.5 degrees from envelope function stacks of USArray data. Note that the weak Sn signals in the central Great Basin.(right) Uppermost mantle* P *velocity from Pn tomography. Figure from* Buehler and Shearer *(2013).*

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

I am also interested in new approaches to imaging large earthquake ruptures, including waveform back-projection and other approaches. Work with graduate student Wenyuan Fan and Peter Gerstoft tested a regularized frequency-domain approach to the finite-slip inversion problem, obtaining good results for the synthetic test data of the Source Inversion Validation Exercise 1 (Fan et al., 2014). IGPP postdoc Zhongwen Zhan has been studying deep earthquake ruptures and

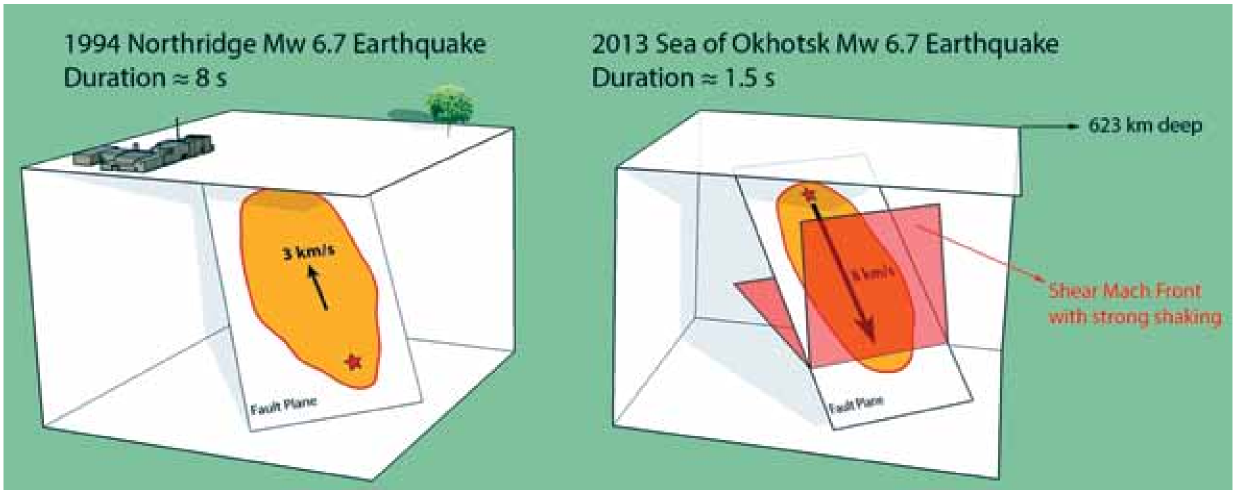

Figure 2. A comparison between the 1994 Northridge earthquake in southern California and the 2013 M 6.7 deep earthquake in the Sea of Okhotsk. Although both earthquakes had similar dimensions and moment (Mw 6.7), the Okhotsk event had a much shorter duration and a very high rupture velocity, exceeding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

recently identified supershear rupture in a M 6.7 aftershock of the 2013 Sea of Okhotsk earthquake (Zhan et al., 2014). This earthquake had a very short duration compared to most earthquakes of similar size (see Fig. 2). Comparisons to the Okhotsk mainshock and the 1994 Bolivian earthquake suggest there is more than one rupture mechanism for deep earthquakes.

Selected Recent Publications

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

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

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

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

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

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

LEONARD J. SRNKA, PROFESSOR OF PRACTICE

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

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

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

Recent Publications

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

HUBERT STAUDIGEL RESEARCHER, RTAD

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Research Interests: Seamounts, mid-ocean ridges, water-rock interaction, low-temperature geochemical fluxes, volcanology, biogeoscience, science education (K-16)

My long-term scientific interests aim broadly at volcanoes, how they work, exploring their impact on the geochemistry of the hydrosphere, the lithosphere and biosphere. My most recent focus aims at the biogeosciences of volcanic systems in particular seamounts and in the extreme environments of McMurdo/Antarctica. I am teaching field methods and I have worked with graduate students developing lesson plans for middle and high schools. References to my broader research interests and other prior work can be found in the bibliography at my website: *earthref.org/whoswho/ER/hstaudigel/index.html.*

Microbes in Volcanoes: In collaboration with colleagues in Oregon and Maine, I study the biogeosciences of volcanoes using geological and microbiological approaches. In the geological record we study trace fossils of microbes drilling into volcanic glass and explore specific morphological features of these trace fossils might give us some leads on the physiological traits of the microbes that cause them. This work demonstrated that microbes

are active in any ocean crust section studied to date and that these fossils can be trace back in time to the time period of the origin of life on earth 3.5 Ga ago. While we are still in the dark about the actual microbes involved, I am working with microbiologists to explore microbe—rock interaction inside volcanoes and their hydrothermal systems. We studied Vailulu'u seamounts in the Samoan archipelago and Loihi Seamount o the Big Island on Hawaii. There we characterized and isolated microbes from natural rock surfaces and exposure experiments for future experiments. My current field work on microbe-basalt interaction now focuses on extreme environments of the McMurdo area in Antarctica, including volcanic terrains in the Royal Society Range, the Dry Valleys, and in particular on Mt Erebus on Ross Island.

Most of our 2012/13 field season was spent in ice caves on Erebus and sub-ice diving. Details are on our expedition website: (*earthref.org/ERESE/projects/GOLF439/2012/*), in an on-line lecture I gave at Birch Aquarium (*www.uctv.tv/search-details.aspx?showID=16074* and we put together a movie on our diving on Youtube: *www.youtube.com/watch?v=CSIHYIbVh1c* (footage by Henry Kaiser, famed Antarctic diver and movie director).

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

Teaching

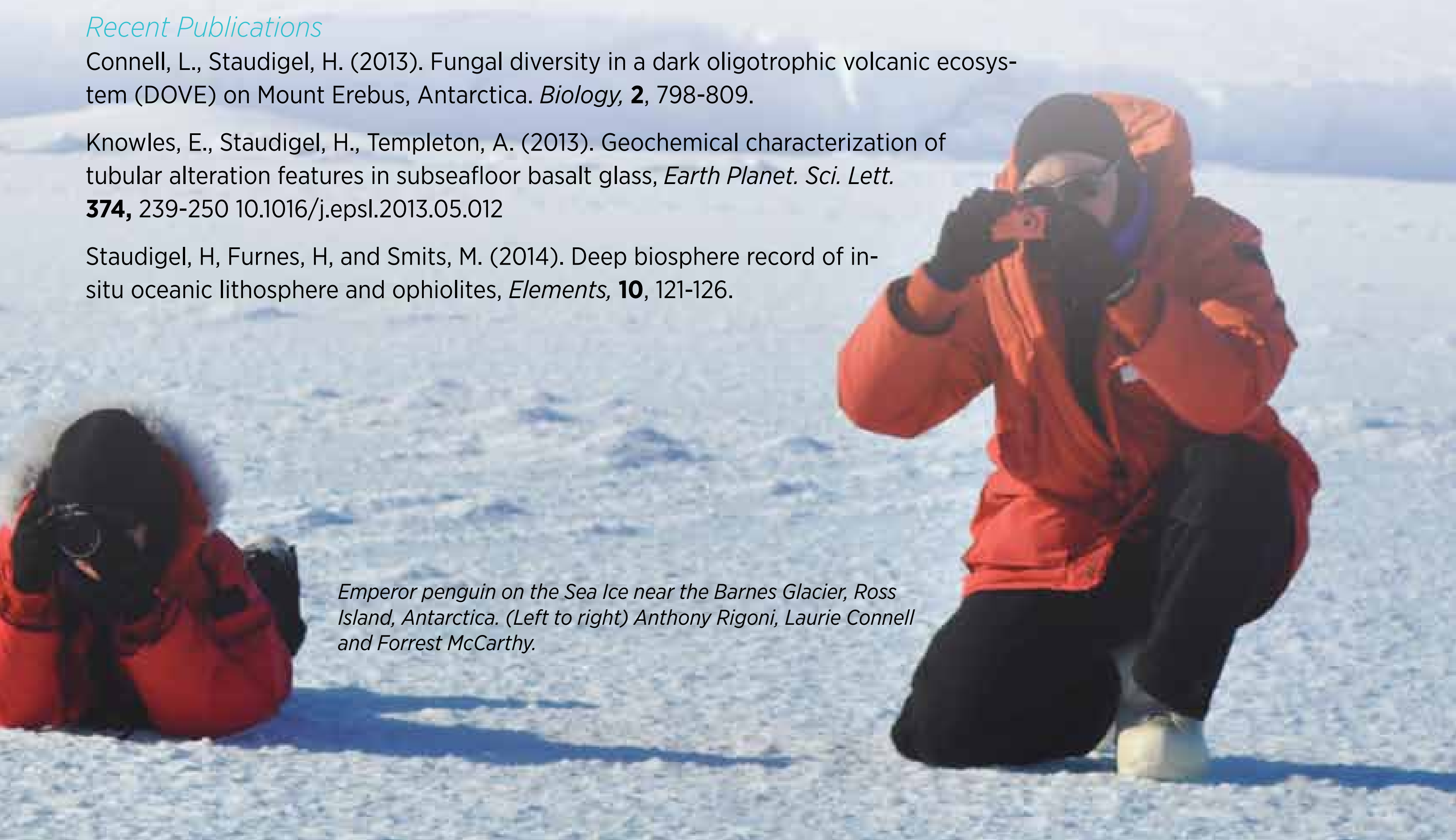
I am teaching SIO 239, an introduction to geological field methods for Geophysicists and, in collaboration with Cheryl Peach, I am also running a NSF educational program for graduate students to work with K-12 students ("GK-12"). This program, the "Scripps Classroom Connection" (*earthref.org/SCC/*) offers nine graduate fellowships to Scripps graduate students each year to improve their communication skills by teaching in middle and high school classrooms. Fellows receive full support for an overall one-third effort in SCC, including a four week Summer Institute and the teaching in classrooms during the school year. Fellows are chosen from all science sections at Scripps.

Recent Publications

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

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

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



Emperor penguin on the Sea Ice near the Barnes Glacier, Ross Island, Antarctica. (Left to right) Anthony Rigoni, Laurie Connell and Forrest McCarthy.

DAVID STEGMAN, ASSOCIATE PROFESSOR

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

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

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

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

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

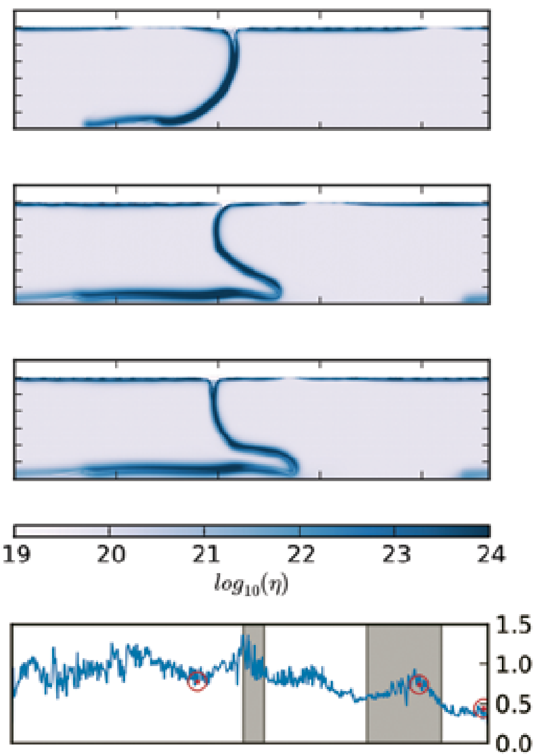

Figure 1: Time evolution of a mantle convection model that is predominantly 2-sided but includes 1-sided episodes (shaded regions on bottom panel) that occur when the overriding plate becomes thin. The top three panels show viscosity as the model evolves from young to old, top to bottom, corresponding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

Recent Publications

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

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

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

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

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

FRANK VERNON, RESEARCH SEISMOLOGIST

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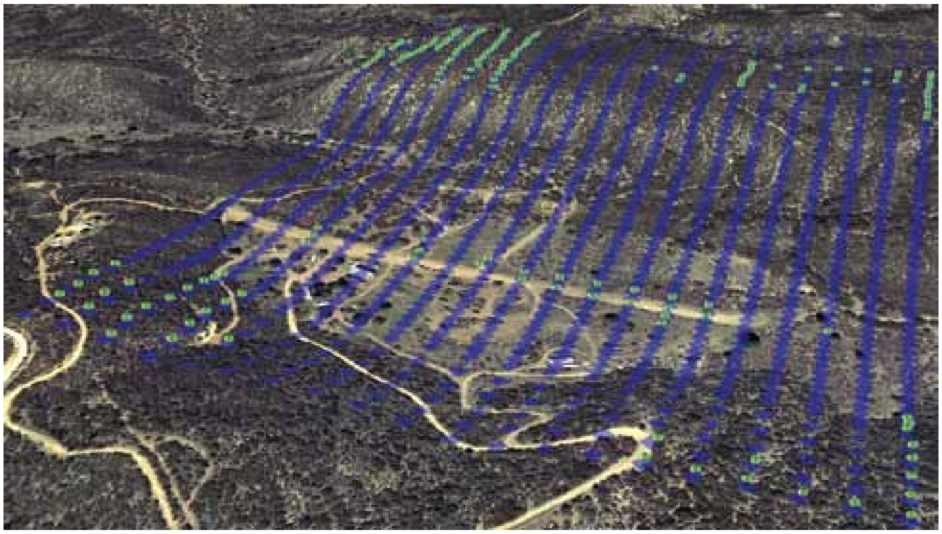
Research Interests: Real-Time Sensor Networks, Time Series Analysis, Earthquake Source Physics, Seismic Instrumentation

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



The ANF group recently completed a survey trip in Anza, California—in collaboration with USC Geophysicists led by Yehuda Ben-Zion. The survey area: Every blue dot is a sensor. Green dots are stations the ANF group surveyed during their first attempt. The remainder were surveyed during a second pass.

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

Recent Publications

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

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

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

Acoustic Propagation in the Philippine Sea.

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

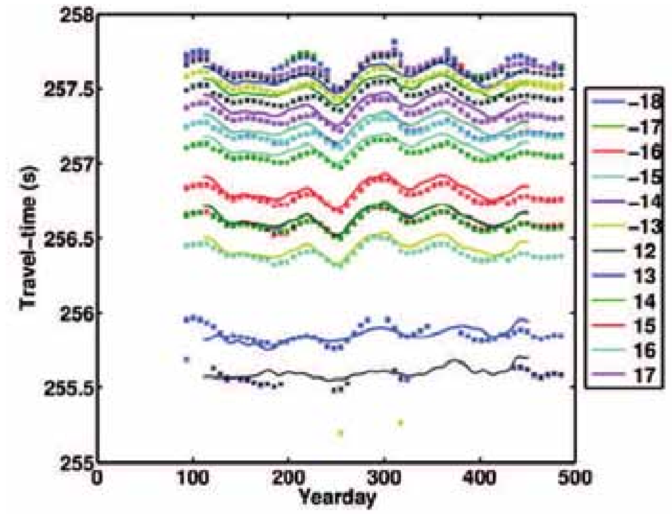

Figure 1: Measured low-frequency travel-time series (solid lines) for transmissions from T2 to T3 compared with travel times (symbols) computed from an ocean state estimate. The colors correspond to dierent ray identifiers.

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

The measured low-frequency travel-time series compare remarkably well with time series computed from an ocean state estimate made using a high-resolution regional implementation of the MIT Ocean General Circulation Model (MITgcm) that was constrained by satellite altimetric and Argo (but not acoustic) data (Fig. 1). Significant (5330 ms) differences remain, however. *Thin-ice Arctic Acoustic Window (THAAW).*

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

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

Recent Publications

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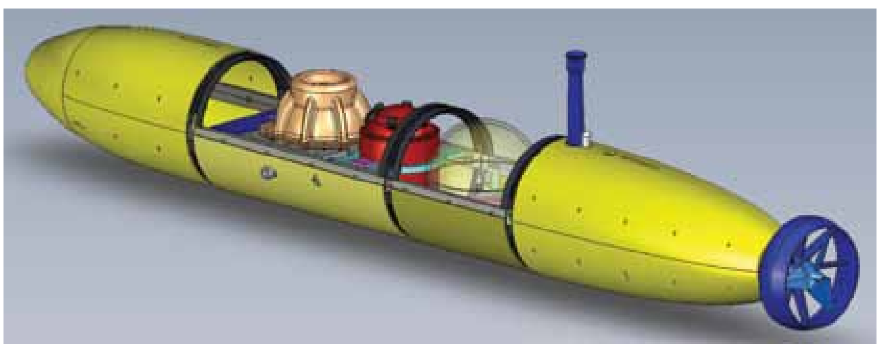
Research Interests: Measurement of gravity and pressure in the marine and subaerial environments, development of new seismic instrumentation, optical fiber measurements of strain and pressure Gravity measurements from an Autonomous Underwater Vehicle (with Gerald D'Spain, Glenn Sasagawa, and Jeff Ridgway)

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

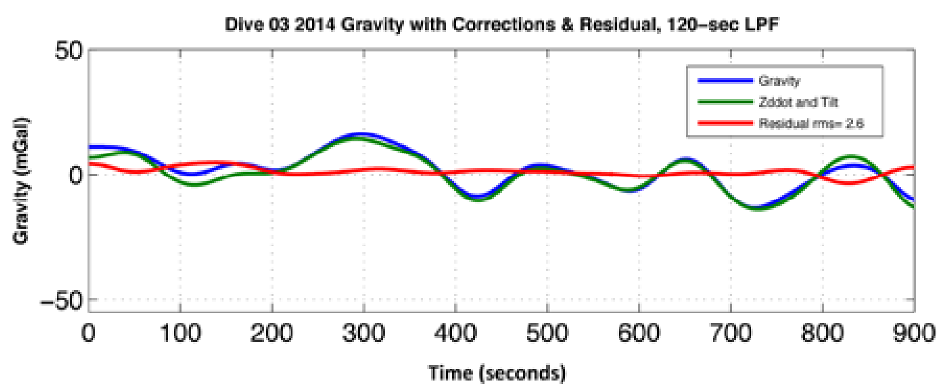


A BlueFin 21 AUV carries an inertial guidance system and a land gravity meter modified for submerged, underway use. (For scale the "21" in the model refers to its 21 inch diameter.)

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

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

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



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