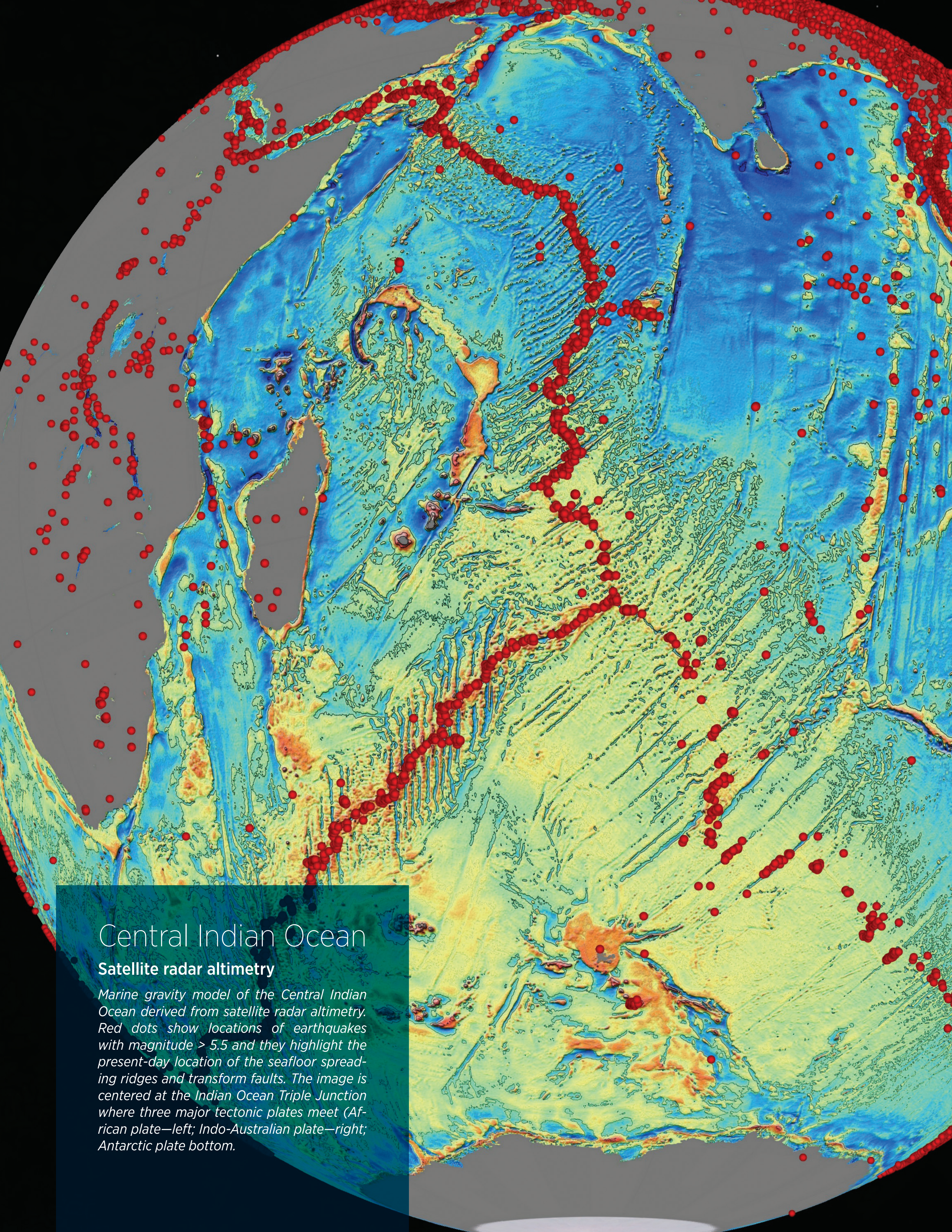
THE CECIL H. AND IDA M. GREEN

INSTITUTE OF GEOPHYSICS AND PLANETARY PHYSICS

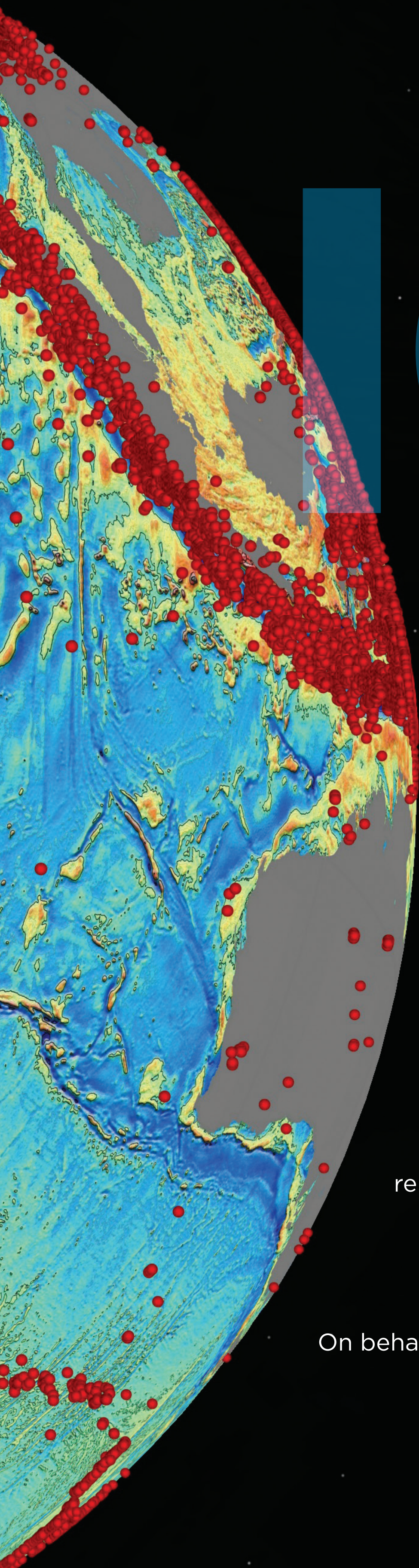
2016



Central Indian Ocean

Satellite radar altimetry

Marine gravity model of the Central Indian Ocean derived from satellite radar altimetry. 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. The image is centered at the Indian Ocean Triple Junction where three major tectonic plates meet (African plate—left; Indo-Australian plate—right; Antarctic plate bottom.



IGPP 2016

DIRECTOR'S WELCOME

Here is the 2016 Annual Report of the Cecil and Ida Green Institute of Geophysics and Planetary Physics, in which we provide descriptions of our research activities carried out during the past year. This report, as well as its predecessors dating back to 2006, is designed to give prospective graduate students, and anyone else who is interested in geophysics, an overview of our research, which spans a broad range of subjects in geophysics, oceanography, geology, and, indeed, planetary science.

Much of our work could be described as pure science, but the subject matter is often of broad societal interest, such as understanding earthquake mechanisms and cycles, studying the behavior of ice sheets, improving methods for energy exploration (both renewable and conventional), monitoring carbon dioxide sequestration, the effects of drought on California groundwater, the effects of atmospheric water on storm systems, modeling Earth's magnetic field, and so on. A lot of what we do involves long-term monitoring of the sea, land, and atmosphere by operating and using a variety of instrument networks as well as shipboard systems. IGPP has a strong history of instrument development, but also the development of theoretical and numerical methods. We hope you find this report useful and agree that IGPP continues to be one of the leading research centers for geophysics.

There has been a recent change of guard at the IGPP Directorship. On April fool's day 2016 I took over from Guy Masters as Director of IGPP. On behalf of the entire IGPP community I would like to extend our thanks to Guy for his many years of solid leadership.

Steven Constable, Director, IGPP

RESEARCHERS

6. Duncan Carr Agnew, *Professor*

Laurence Armi, *Professor**

Jeffrey Babcock, *Associate Project Scientist**

George Backus, *Professor Emeritus**

7. Jonathan Berger, *Research Scientist*

9. Donna Blackman, *Research Scientist*

10. Yehuda Bock, *Research Scientist*

13. Adrian Borsa, *Assistant Research Scientist*

Catherine Constable, *Professor*

15. Steven Constable, *Professor*

17. J. Peter Davis, *Specialist*

18. Catherine deGroot-Hedlin, *Research Scientist*

19. Matthew Dzieciuch, *Project Scientist**

Peng Fang, *Specialist**

20. Yuri Fialko, *Professor*

22. Helen Fricker, *Associate Professor*

24. Jennifer S. Haase, *Associate Research Geophysicist*

26. Alistair Harding, *Research Scientist*

27. Michael Hedlin, *Research Scientist*

Glenn Ierley, *Professor Emeritus**

29. Deborah Kilb, *Associate Project Scientist*

31. M. Gabriele Laske, *Professor in Residence*

T. Guy Masters, *Professor*

Robin Matoza, *Assistant Project Scientist*

32. Jean-Bernard Minster, *Professor*

34. Walter Munk, *Research Professor*

35. John Orcutt, *Professor**

Robert Parker, *Research Professor Emeritus*

37. Anne Pommier, *Assistant Professor*

39. David Sandwell, *Professor*

40. Peter Shearer, *Professor*

Lenord Srnka, *Professor of Practice**

Hubert Staudigel, *Research Scientist*

42. David Stegman, *Associate Professor*

Frank Vernon, *Research Scientist*

44. Peter Worcester, *Research Scientist*

46. Mark Zumberge, *Research Scientist*

Cecil H. and Ida M. Green Institute of Geophysics and Planetary Physics, SIO/UCSD
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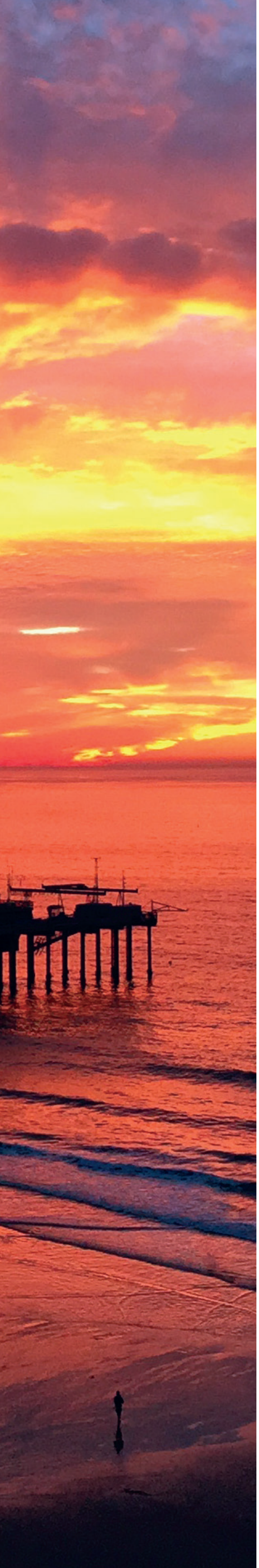
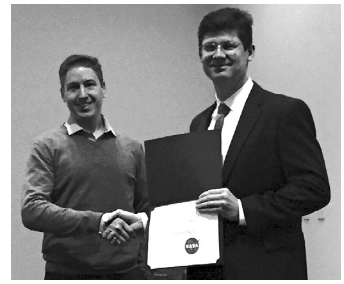


GRADUATE EXPERIENCE

More than the Oceans...



Our multidisciplinary program offers graduate students a unique hands-on, collaborative learning environment. In addition to our core academic curriculum, we emphasize observational techniques and the collection of novel datasets. IGPP students participate extensively in field experiments, instrument development, laboratory investigations, and shipboard expeditions.

Our graduates go on to careers in research, education, industry, and public policy. Scripps has strong working relationships with the National Science Foundation, NASA, NOAA, the US Geological Survey, and the Office of Naval Research, and can provide graduates with long-term networking and professional support.

Graduate Students who successfully defended in 2016

Emmanuel Soliman Garcia *(David Sandwell)*: ***Marine Gravity Variations and the Strength of the Oceanic Lithosphere with Bending***

Evan Hirakawa, SDSU *(Shuo Ma)*: ***Poro-Elasto-Plastic Off-Fault Response and Dynamics of Earthquake Faulting***

Nicholas Mancinelli *(Peter Shearer)*: ***Constraints on Heterogeneity throughout the Earth's Mantle from Observations of Scattered Seismic Waves***

Lindsay Smith-Boughne *(Cathy Constable)*: ***Spectral Estimation Techniques for time series with Long Gaps: Applied to Paleomagnetism and Geomagnetic Depth Sounding***

Kyle Withers, SDSU *(Shuo Ma)*: ***Ground Motion and Variability from 3-D Deterministic Broadband Simulations***

GREEN FOUNDATION

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 Green Foundation is currently supporting:

Green Scholar Shawn (Songqiao) Wei, postdoc

Green Scholar Junle Jiang, postdoc

Green Scholar Anders Damsgaard, postdoc

Green Scholar Dan Bassett, postdoc

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

AnICEotropy seismic study on Alpine glacier, Gabi Laske

Green Scholar Mladen Nedemovic, Summer 2016 and 2017

Miles Fellow Adina Püsok, postdoc

DUNCAN CARR AGNEW, PROFESSOR

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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.

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

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

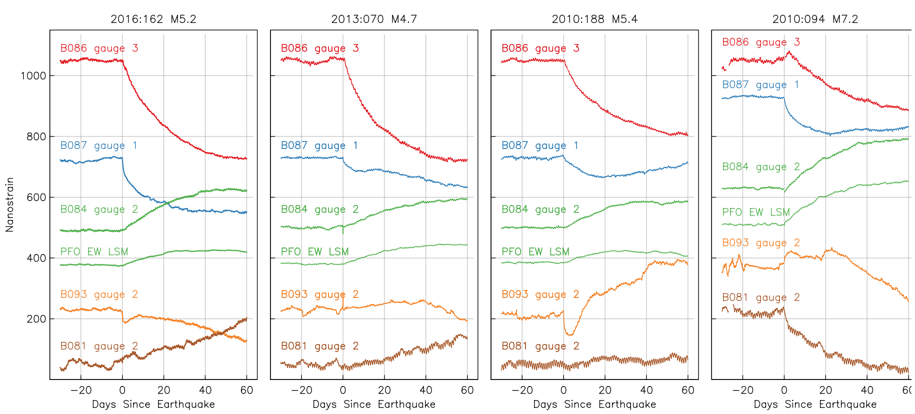

Figure 1. Aseismic strains seen following four earthquakes since 2010, showing one component of each of the laser strainmeters at PFO and five borehole strainmeters in the Anza area (B084 is at PFO).

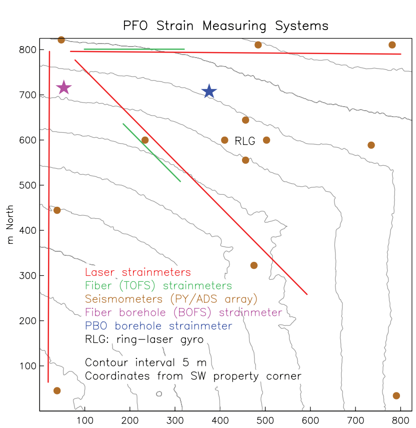

Figure 2: Map of PFO showing the location of various strainmeters and a Ring Laser Gyro.

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

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

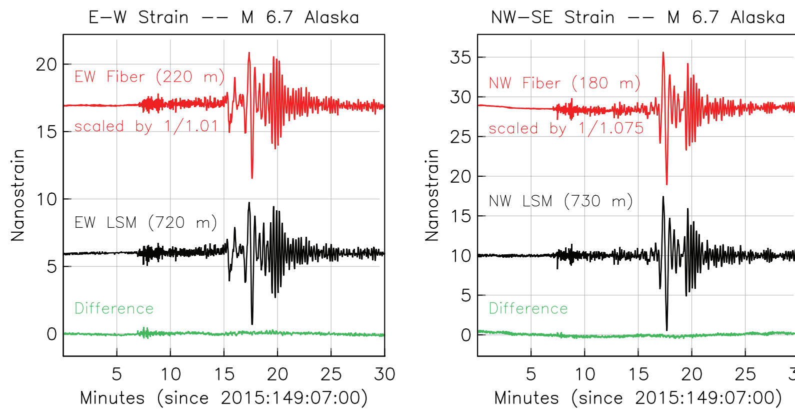

Figure 3: Comparison of the TOFS and long-base vacuum strainmeters.

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

JONATHAN BERGER, EMERITUS RESEARCHER RTAD

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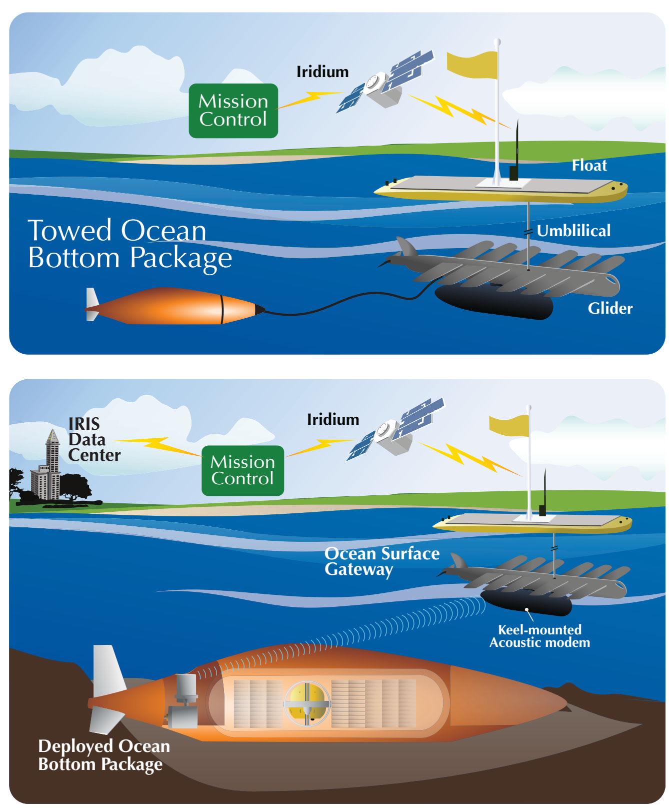
Research Interests: Global seismological observations, marine seismoacoustics, geophysical instrumentation, deep ocean observing platforms, ocean robotics, global communications systems.

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

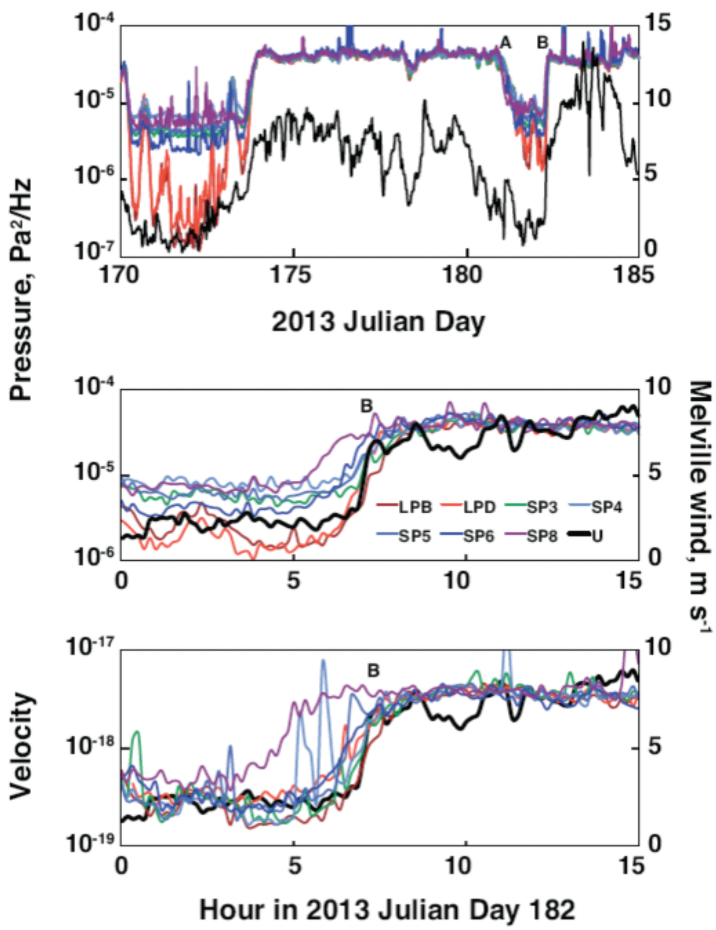


The principal design features of the system are:

1. Be deployable without the use of a ship. The hydrodynamic design of the bottom package is optimized for low drag when towed and to reduce current-induced noise on the bottom. When deployed it does not have the buoyancy to return to the surface—it can be left on the seafloor or be retrieved by a ROV at some convenient time when a ship is ready and available;
2. Provide continuous near-real time streaming of sensor data sampled at one sample per second or faster from the seafloor to land with a latency of less than a few minutes;

3. Provide higher rate data segments telemetered either upon request or automatically after signal detection; and
4. Operate for a two-years while streaming continuous data at one sample per second (sps) plus about 1200 hours of 40 sps data on-request.

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



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

Recent Publications

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

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

DONNA BLACKMAN,
RESEARCH GEOPHYSICIST

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

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

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

Through a series of numerical experiments, we explored the rheologic effects of CPO and evaluated the magnitude of possible impacts on the pattern of flow and associated seismic signals. Stable flow and CPO distributions were obtained after several iterations. The textured olivine polycrystals were found to have anisotropic viscosity tensors in a significant portion of the model space. This directional dependence in strength impacted the pattern of upper mantle flow. For background asthenosphere viscosity of 1020 Pa s and a rigid lithosphere, the modification of the corner flow pattern was found to be modest, but the change could have geologic implications. Feedback in the development of CPO occurred, particularly near and below the base of the lithosphere. Stronger fabric was predicted below the flanks of a spreading center for fully coupled, power-law polycrystals than was previously determined for linear, intermediate coupling polycrystal models. The predicted SKS splitting was found to be modestly different (~0.5 s) between the intermediate and fully coupled cases for oceanic plates less than 20 Myr old. Surface waves, on the other hand, were predicted, in work with Gabi Laske, to have twice the magnitude of Rayleigh wave azimuthal anisotropy for fully coupled power law flow/polycrystals than for linear, intermediate coupled flow/polycrystal models.

The overall flow pattern is still essentially a corner flow, but upwelling rate in the subaxial zone is somewhat reduced. This could result in decreased partial melting. Material starting within 50 km of the spreading axis rises to a level that is a few km shallower when CPO-based anisotropic rheology is incorporated. Material starting at depth outside this zone rises as much as ~20

A

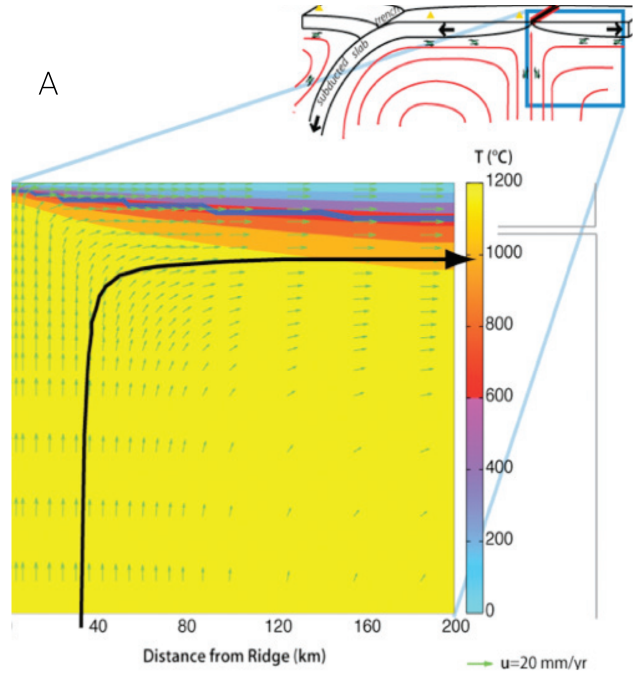
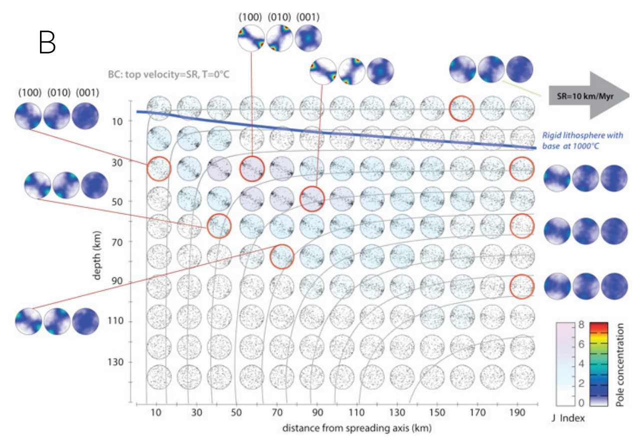
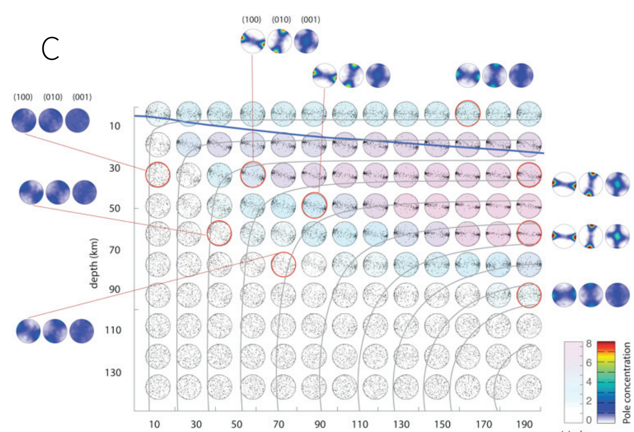


Figure. Model geometry (A) showing basic flow pattern (green vectors) and temperature (color). Reference model (B) and full-coupled, self-consistent model (C) show flowpaths (gray lines) and CPO (pole figures: olivine a-axes throughout model; a-, b-, and c-axis concentrations contoured in a few locations),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

B



C



km shallower, and at higher rates near the inflection point where the flow turns the corner. This could broaden the low-percent partial melting zone compared to the isotropic (scalar) viscosity case. The distribution of CPO differs from past linked flow/anisotropy analyses in strength and alignment direction in key regions of the model space. As off-axis shearing becomes dominant, the sub-lithospheric region develops horizontal preferred direction rather than retaining a diffuse version of the inclined alignment that develops in the flow corner. The strength of the off axis CPO is greater than predicted for the intermediate coupling case. These asthenosphere anisotropy results indicate that proceeding with further modifications to optimize the linked numerical scheme is both warranted and would be necessary, for computational efficiency that would allow finer discretization so that lithosphere anisotropy could be more reliably estimated.

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

Recent Publications

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

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

YEHUDA BOCK, DISTINGUISHED RESEARCHER & SENIOR LECTURER

Director, Scripps Orbit and Permanent Array Center (SOPAC)

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

The SOPAC research group is application oriented with an emphasis on mitigating effects of natural hazards on people and critical infrastructure through improved forecasting, early warning and rapid response to events such as earthquakes, tsunamis, volcanoes and severe weather. We approach this in a holistic manner from the design and deployment of geodetic and other sensors, real-time data collection and analysis, physical modeling, for example a kinematic earthquake source model followed by tsunami prediction, to communicating actionable information the "last mile" to emergency responders and decision makers during disasters. We maintain a global archive of GNSS data including a growing database of high-rate measurements of large earthquakes, with accompanying IT infrastructure and database management system. In 2015-2016, the SOPAC group included Peng Fang, Jennifer Haase, Jianghui Geng, graduate students Dara Goldberg, Jessie Saunders at SIO, Lina Su, Minghua Wang and Jing Qiao (visiting from China), and Mindy Squibb, Anne Sullivan, Maria Turingan, Glen Offield, Allen Nance and Alex Turner.

Earthquake Early Warning and Seismogeodesy

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

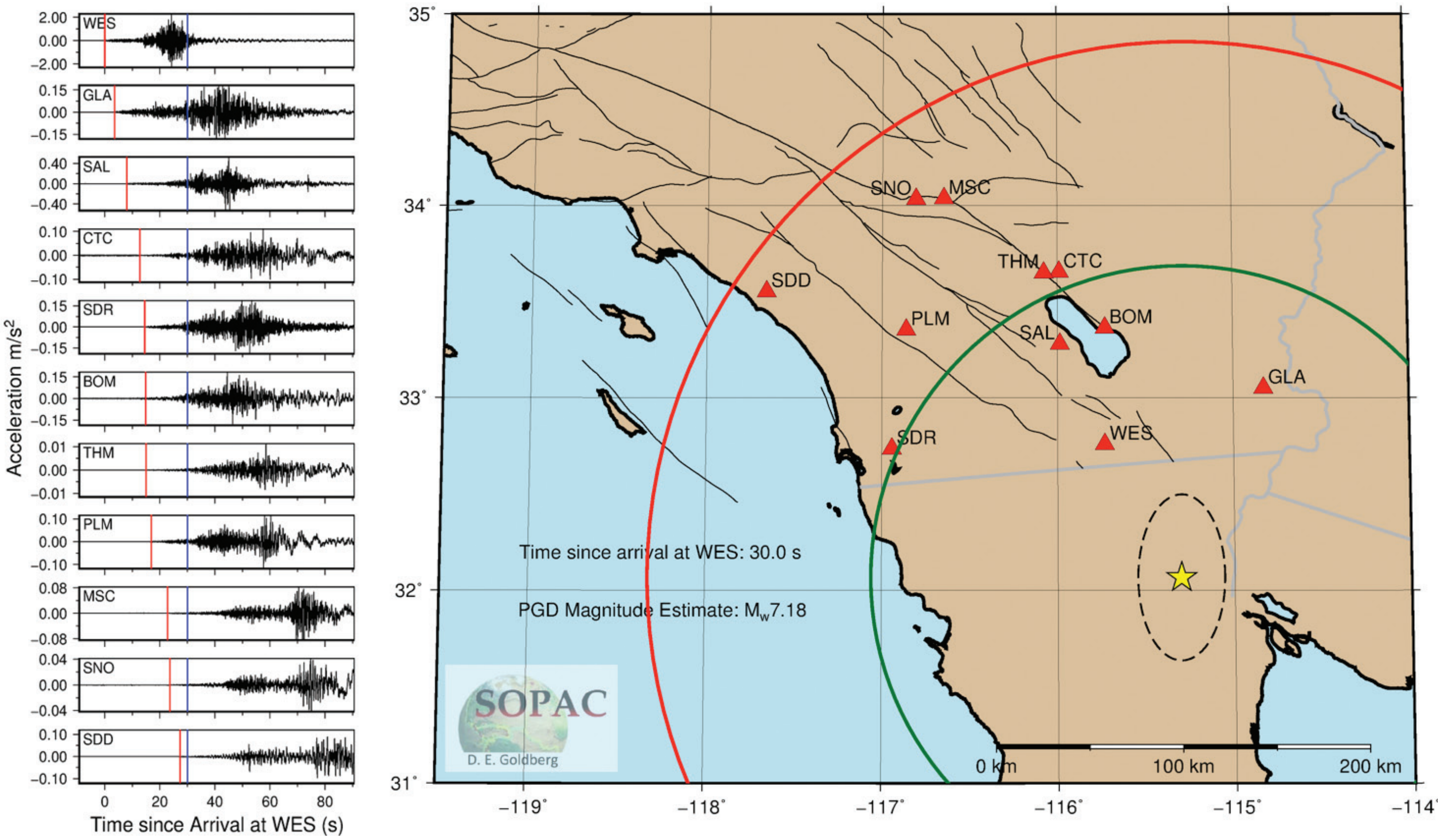

Figure 1. Example of SOPAC's seismogeodetic earthquake early warning system for the 2016 Mw5.2 Borrego Springs earthquake. Shown is the warning information available 20.0 s after the first detection at station P797 closest to the epicenter. Once 4 stations have triggered, an estimate of the hypocenter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

the SIO Geodetic Module and low-cost MEMS accelerometer packages ("GAPs"), designed as a simple plug-in for existing GNSS stations. The Geodetic Module is an instrument that receives, time tags, buffers, analyzes and transmits data from multiple sensors, including a GNSS receiver, MEMS accelerometer, and MEMS meteorological instruments (pressure, temperature and humidity). The MEMS meteorological data allows us to estimate the variations in water vapor content in the lower atmosphere (troposphere), a critical driver of extreme weather such as the southern California summer monsoons. NOAA's weather forecasting offices in San Diego and Los Angeles Counties successfully used our data to forecast and track a monsoon in the summer of 2013 and issue an accurate flash flood warning for the region (Moore et al., 2015).

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

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

Recent Publications

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

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

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

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

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

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

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

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

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

ADRIAN BORSA, ASSISTANT PROFESSOR

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

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

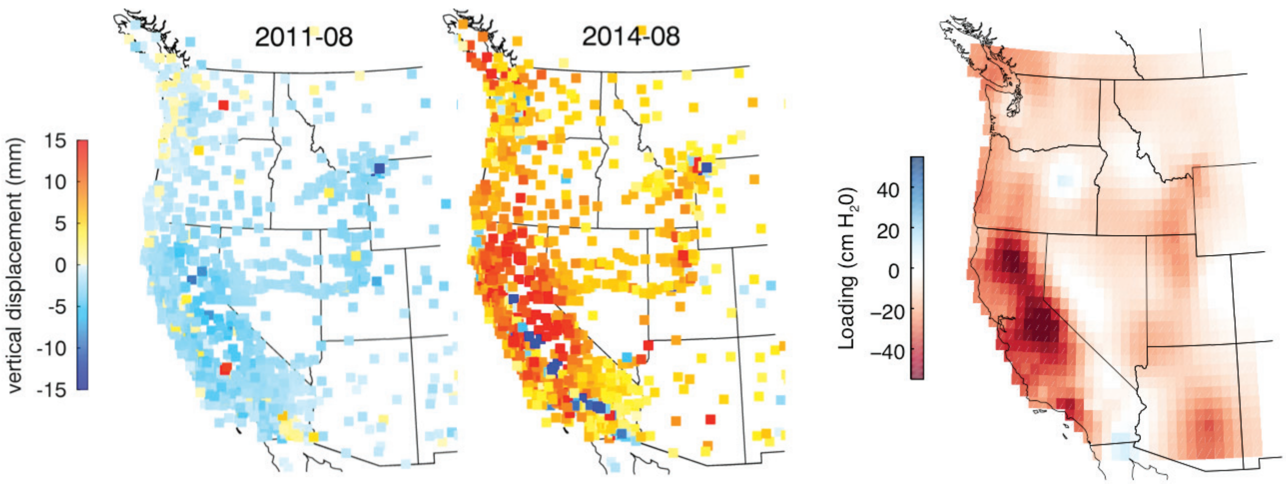

Figure 1: Left: Spatial distribution of vertical displacements from Plate Boundary Observatory continuous GPS stations in the western USA in March of 2013 and 2014. Color indicates deviations of seasonally-adjusted elevations from decadal mean, with blues related to subsidence and yellow-reds related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

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 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 displace-

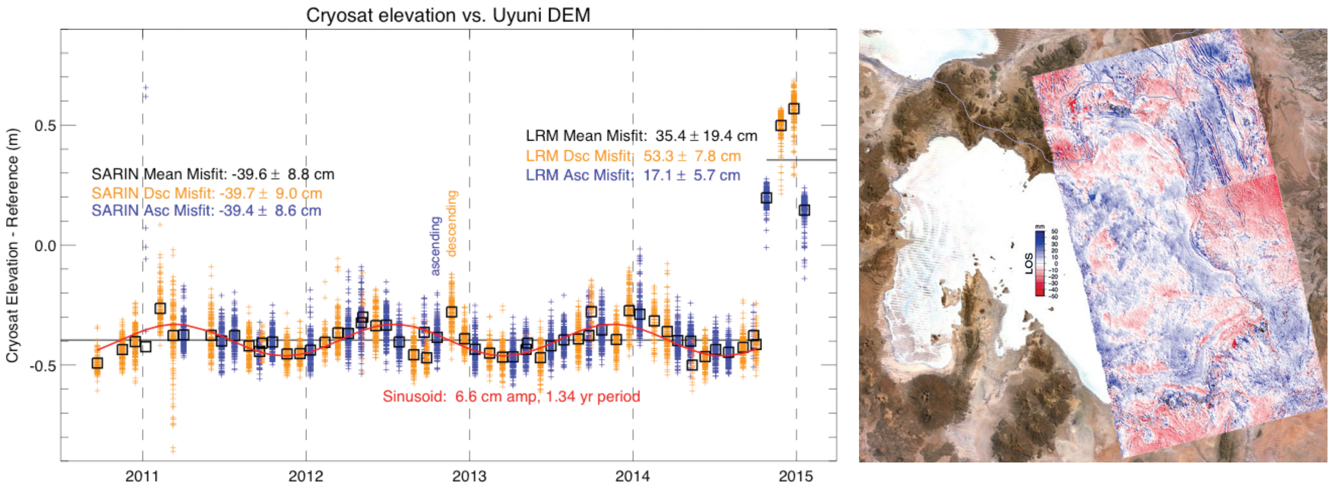

Figure 2: Left: Cryosat elevation validation relative to the salar de Uyuni DEM, with residuals showing a.) a uniform range bias of -40 cm for SARIN mode and +35 cm for LRM mode, b.) an 7 cm amplitude sinusoidal anomaly of 1.34 yr period that is still unexplained, and c.) higher range resolution than reported elsewhere, even with the sinusoidal anomaly. Right: ALOS InSAR results over the salar de Uyuni for the period 8/27/2010 ~ 1/12/2011, indicating that seasonal elevation change is <1 cm averaged over the salar surface.

ment for calibration purposes. We have also expanded our cal/val activity to the CryoSat mission and are currently evaluating improvements between Baseline B and Baseline C datasets. Our ongoing interaction with the CryoSat mission team has led ESA to switch CryoSat from SARIN to LRM mode for all passes over the salar de Uyuni from 2015 onward, allowing us to provide a cross-calibration of elevations from these different operational modes.

Recent Publications

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

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

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

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

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 post-docs. The two main field techniques we use are controlled-source EM (CSEM), in which a deep-towed EM transmitter broadcasts energy to seafloor EM recorders, and magnetotelluric (MT) sounding, in which these same receivers record natural variations in Earth's magnetic field. Both methods can be used to probe the geology of the seafloor, from the near surface to hundreds of kilometers deep, using electrical conductivity as a proxy for rock type.

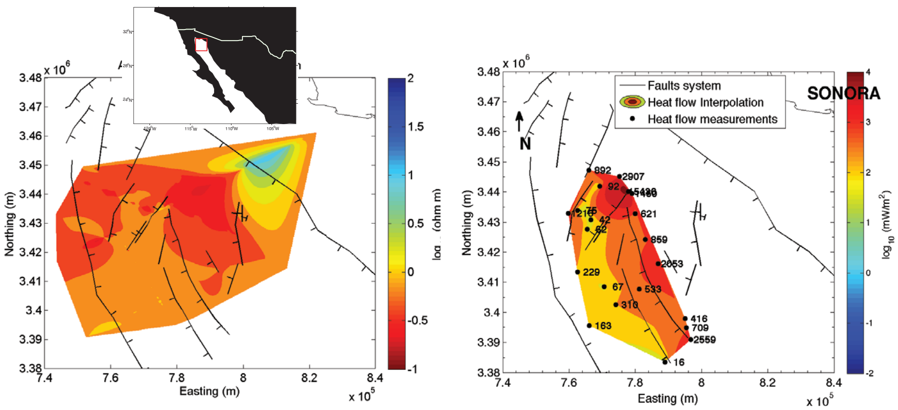

Figure 1. Left: Electrical resistivity at a depth of 500 m in the northern Gulf of California, interpolated from inversions of surface-towed EM data. Red indicates high conductivity/high temperature. Right: Heatflow, interpolated from seafloor measurements. From the MSc thesis of Valeria Reyes-Ortega, 2016.

There are many applications for EM methods in geophysics, and some of our recent efforts have been directed towards offshore geothermal energy, in collaboration with Centro de Investigaci´on Cientifici y de Educaci´on Superior de Ensenada (CICESE). Last year we carried out MT and CSEM surveys in the northern Gulf of California, o San Felipe, and this year we made measurements in the central Gulf out of Santa Rosalia. We used the research vessel Alpha Helix, originally operated by Scripps from 1965–1980 and recently purchased and refurbished by CICESE (Background Image). The 2015 data were used in the masters theses of Thalia Anaid Aviles Esquivel and Valeria Reyes-Ortega. Thalia used MT data to estimate the location of the spreading center which extends from the East Pacific Rise to the northern Gulf of California, where its location becomes obscured by a thick sequence of sediments. Valeria (now at IGPP as a PhD student)

used surface-towed CSEM measurements, collected with the system developed for permafrost studies and described in the 2014 annual report, to look for areas of increased conductivity due to hot fluids in the sediments. Her results (Figure 1) are in good agreement with heat flow measurements, but extend the area studied significantly.

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

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

Recent Publications

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

Naif, S., K. Key, S. Constable, and R.L. Evans (2015) Water-rich bending faults at the Middle America Trench, *Geochemistry, Geophysics, Geosystems* **16,** 2582–2597, 10.1002/2015GC005927 Further information can be found at the lab's website, http://marineemlab.ucsd.edu/

J. PETER DAVIS, SPECIALIST

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

My research responsibilities at IGPP center upon managing the scientific performance of Project IDA's portion of the IRIS/USGS Global Seismographic Network (GSN), a collection of 41 seismographic and geophysical data collection stations distributed among 26 countries worldwide. IDA recently concluded upgrading the core data acquisition and power system equipment at all stations using funding provided by NSF via the IRIS Consortium.

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

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

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

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

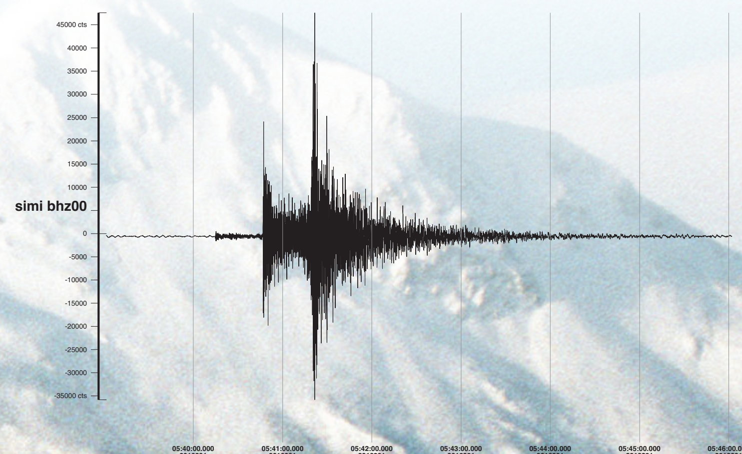

Figure 2. Recording of a magnitude Mw=4.6 earthquake 150 km deep beneath the Pamir Mountains at a distance of 284 km, the first of many such events we expect to capture.

Recent Publications

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

CATHERINE DE GROOT-HEDLIN, RESEARCH SCIENTIST

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

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

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

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

In a recent project, this code has been used to compute the penetration of sound into areas typically thought of as being in a "shadow zone", where sound refracts upwards, away from the Earth's surface due to the decrease in sound speed with altitude, much as light bends as it travels between air and water. In the summer of 2016, rocket motor were detonated at the Utah Test and Training Range (UTTR), and sound sensors were placed at up to 14 sites eastward of the blasts. Numerical codes were used to create a map to predict the peak sound levels in areas to the east of the detonations. Predicted peak sound levels are compared to observed levels in Figure 1.

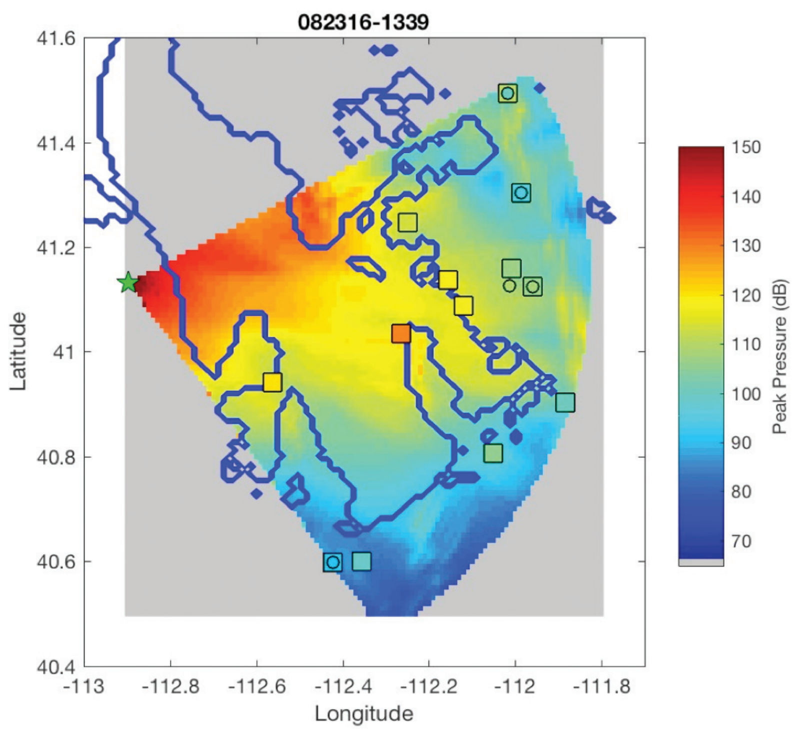

Figure 1. A map of predicted peak sound pressures for a 17,700 kg detonation at UTTR, which is marked by a green star. Winds carry the peak sound off to the northwest. Sound sensor sites, marked by squares and circles, are color-coded by the recorded peak sound pressure levels. Results show agreement within about 6 dB.

Recent Publications

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

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

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

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

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

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

MATTHEW DZIECIUCH, PROJECT SCIENTIST

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

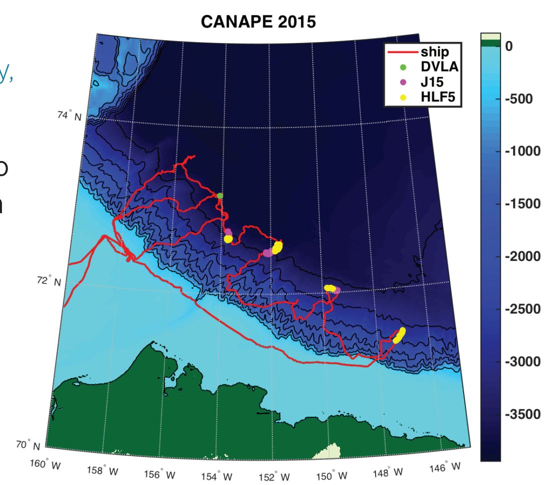

Figure 1: A vertical line array of hydrophones (DVLA) was deployed at axed location and then two sound sources, at 125Hz (J-15) and at 250 Hz (HLF-5) were deployed at various ranges to learn about the relationship between attenuation and range. Ship tracks reflect the tortuous route taken to avoid thick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

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

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

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

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

Recent Publications

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

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

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

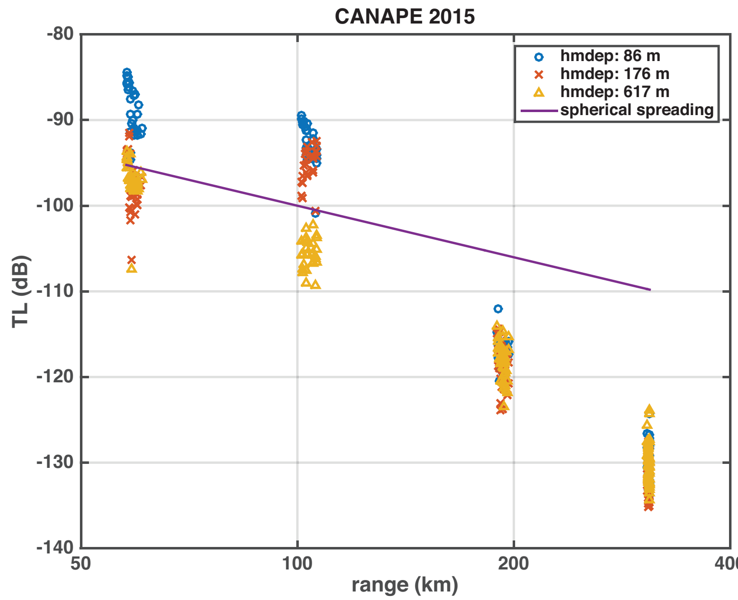

Figure 2: CANAPE2015 sound attenuation or transmission loss (TL) vs range. Deep hydrophones show a loss greater than spherical spreading (purple).

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

Other areas of Prof. Fialko interests include rock mechanics and physics of earthquakes. In a series of recent studies

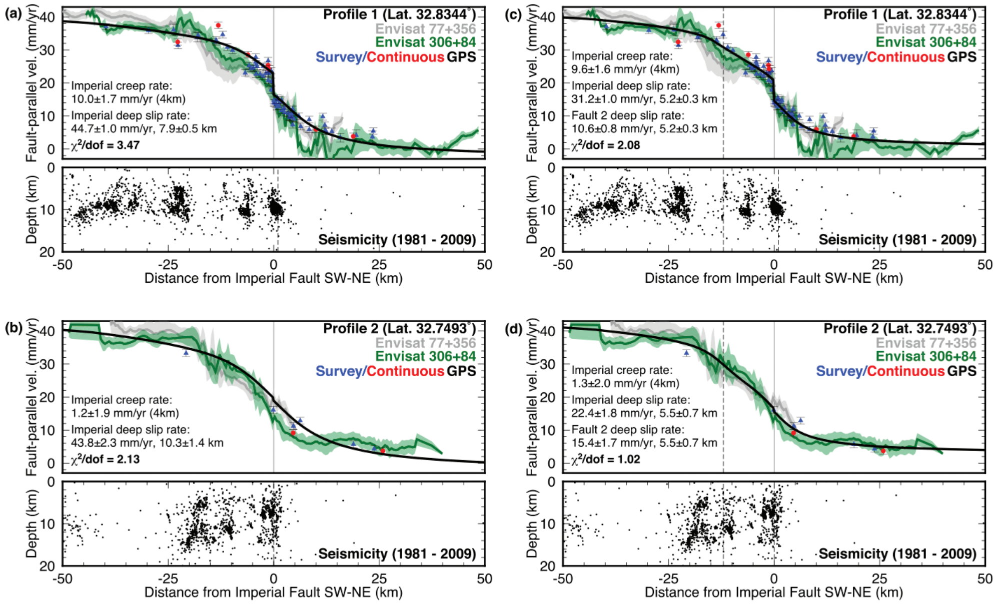

Figure 1: Proles across the Imperial Fault showing InSAR-derived fault-parallel velocities (gray and green curves), and GPS velocities from campaign (blue) and continuous stations (red). Black curves denote best-tting models assuming one fault (a, b), and two faults (c, d). Fault locations are denoted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

Prof. Fialko in collaboration with Prof. Brown and graduate student Erica Mitchell investigated the effect of temperature on slip stability of typical crystalline rocks such as granite and gabbro. The study included laboratory experiments on both solid samples and simulated gouge over a wide range of temperatures and loading conditions. Previous experimental data on granite suggest a transition from unstable slip to creep at about 350°C. Assuming a reasonable geotherm, this corresponds to depth of 2115 km, close to the deep limit to seismicity in the Western US. This is consistent with a view that the thickness of the seismogenic layer is controlled by a transition from velocity-weakening to velocity-strengthening friction. However, the new results from direct shear experiments on Westerly granite at both dry and hydrated conditions show increasingly unstable slip (velocity-weakening behavior) at temperature up to 600°C. A comparison of previously published experimental results with the new data suggests that the rate and state friction parameters strongly depend on normal stress and pore pressure high (>400°C) temperature. The new study suggests that the depth extent of the seismogenic zone in continental crust may not be fully controlled by the onset of plasticity in either quartz or plagioclase, and that frictional properties of common crustal rocks can be velocity-weakening over a wider depth range than previously believed, in particular under dry conditions or low pore pressure. This may help explain the observed regional variations in the depth distribution of earthquakes in continental crust. The measured temperature dependence of the rate and state friction parameters may also contribute to strong dynamic weakening observed in high-speed friction experiments, with important implications for the dynamics of earthquake ruptures.

Recent Publications

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

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

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

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

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

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HELEN AMANDA FRICKER, PROFESSOR, *John Dove Isaacs Chair*

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

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

1. Antarctica's floating ice shelves. Antarctica's floating ice shelves surrounded the entire continent and this is where most of the mass loss takes place. Since ice shelves displace their own weight in water, their melting does not contribute directly to sea level. However, ice shelves provide mechanical support to 'buttress' seaward flow of grounded ice, so that ice-shelf thinning and retreat result in enhanced ice discharge to

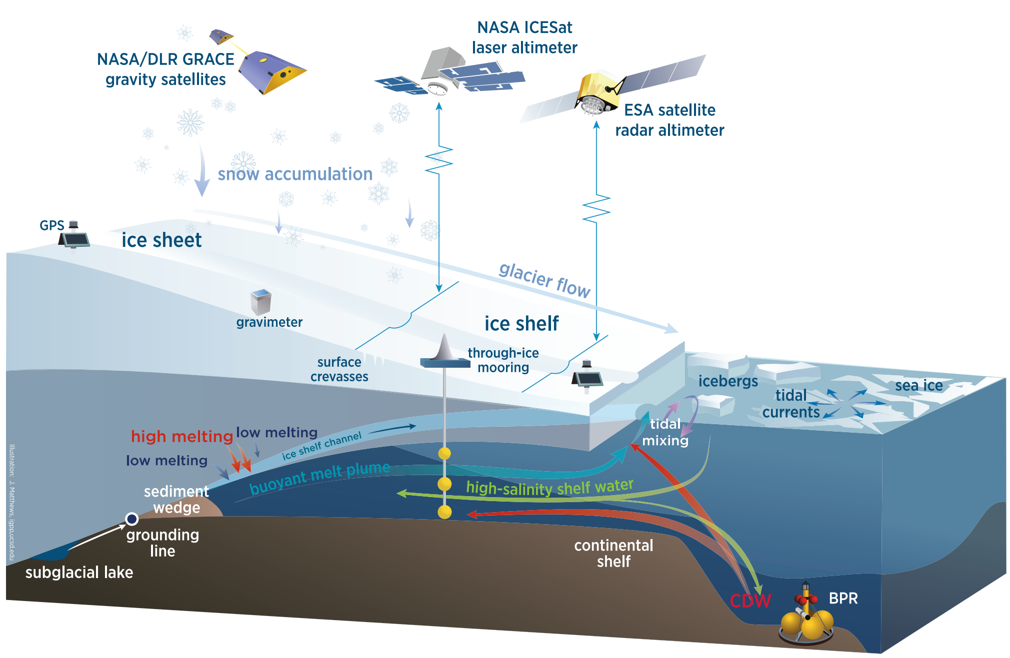

Figure 1: Schematic of the marine margin of an ice sheet where there is a floating ice shelf. The ice shelf's mass budget is the sum of inputs from glacier flow across the grounding line and snow accumulation, and losses by net basal melting and iceberg production. Basal melting depends on ocean heat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

the ocean. Our group specializes in monitoring Antarctic ice shelves from satellite altimetry (radar and laser), and we also work on understanding the mass loss processes from ice shelves; we are funded by NASA to do this work. I am also a PI on a large NSF project ROSETTA to investigate the Ross Ice Shelf using airborne geophysical techniques (gravity, laser and radar). Matthew Siegfried took part in the 2015/2016 season of ROSETTA and was part of the airborne field team, and 2nd year student Maya Becker is taking part in the 2016/2017 season.

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

2. Subglacial lakes. The Antarctic Ice Sheet is on average 2.2 km thick and rests on top of bedrock; the insulation, high pressures, and geothermal heat flux at the ice-bed interface leads to melting of the basal ice layers on the order of mm/year. When averaged over the entire ice sheet, this produces high volumes of subglacial water (estimated volume is 65 Gt/yr), much of which is stored in subglacial lakes and subglacial aquifers. In 2006 I discovered active subglacial water systems under the fast-flowing ice streams of Antarctica using ICESat data. This was inferred from observations of large height changes (up to 10m in some places) in repeat-track ICESat data, which corresponded to draining and filling of subglacial lakes beneath 1-2 km of ice. We continue to monitor active lakes, and we have found 124 in total throughout Antarctica. In the decade since the discovery of active Antarctic subglacial water systems, much progress has been made in our understanding of these dynamic systems. Matt Siegfried extended the record of volume change for all lakes under the CryoSat-2 mask up to 2016.

I was a PI on a large, interdisciplinary 6-year NSF project (Whillans Ice Stream Subglacial Access Research Drilling (WISSARD)) to drill into one of the subglacial lakes that I discovered—Subglacial Lake Whillans (SLW) on Whillans Ice Stream (WIS)—and the region of the grounding line across which the subglacial water flows and enters the ocean. The final field season was 2015-2016 and my graduate student Matthew Siegfried led the GPS survey, which was centred on the lakes themselves, and the grounding line downstream. A new NSF-funded 4-year project Subglacial Antarctic Lakes Scientific Access (SALSA) began in the 2016-17 field season, and Matt Siegfried is leading the geophysics team. The Scripps Glaciology Group has 3 postdocs and 2 graduate students.

Recent Publications

Carter, S. P., Fricker, H. A., Siegfried, M. R. (2016) Antarctic subglacial lakes drain through sediment-floored canals: Theory and model testing on real and idealized domains, *The Cryosphere,* doi:10.5194/tc-2016-74.

Paolo, F.S., Fricker H.A., Padman L. 2016. Constructing improved decadal records of Antarctic ice shelf height change from multiple satellite radar altimeter. *Remote Sensing of Environment*. **177**:192-205.

Siegfried, M. R, Fricker H. A, Carter S. P., Tulaczyk S. 2016. Episodic ice velocity fluctuations triggered by a subglacial flood in West Antarctica. *Geophysical Research Letters.* **43**:2640-2648.

Alley, K. E., T. A. Scambos, M. R. Siegfried, H. A Fricker (2016) Impacts of warm water on Antarctic ice shelf stability through basal channel formation, *Nature Geoscience* **9**, (4), 290-293.

Fricker, H. A., Siegfried M. R., Carter S. P., Scambos T. A. 2016. A decade of progress in observing and modelling Antarctic subglacial water systems. *Philosophical Transactions of the Royal Society a-Mathematical Physical and Engineering Sciences.* **374**.

Marsh, O. J., Fricker H. A., Siegfried M. R., Christianson K., Nicholls K. W., Corr H. F.J ., Catania G. 2016. High basal melting forming a channel at the grounding line of Ross Ice Shelf, Antarctica. *Geophysical Research Letters*. **43**: 250-255.

Mikucki, J. A., Lee P. A., Ghosh D., Purcell A. M., Mitchell A. C., Mankoff K. D., Fisher A. T., Tulaczyk S., Carter S., Siegfried M. R., Fricker H. A., et al. 2016. Subglacial Lake Whillans microbial biogeochemistry: a synthesis of current knowledge. *Philosophical Transactions of the Royal Society a-Mathematical Physical and Engineering Sciences*. **374**

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

Recent Research Results: Airborne Radio Occultation & Hurricane Forecasting

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

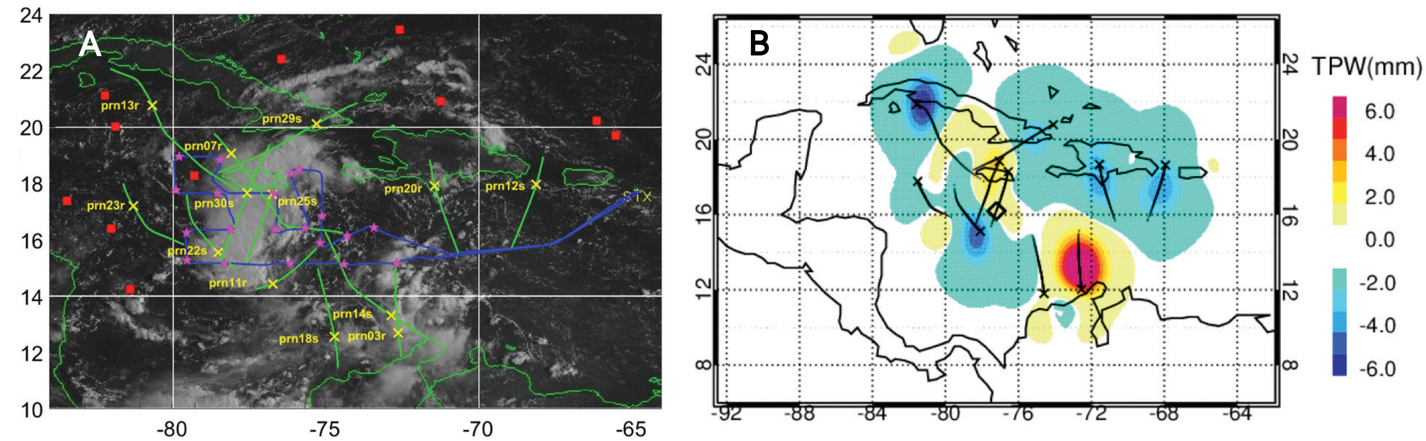
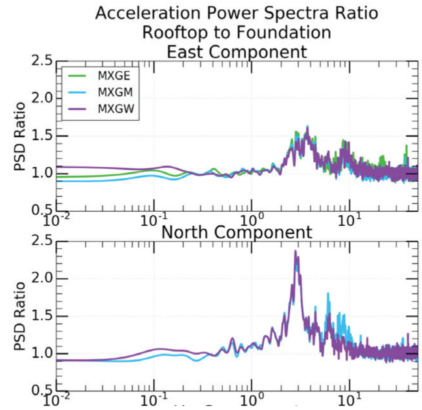


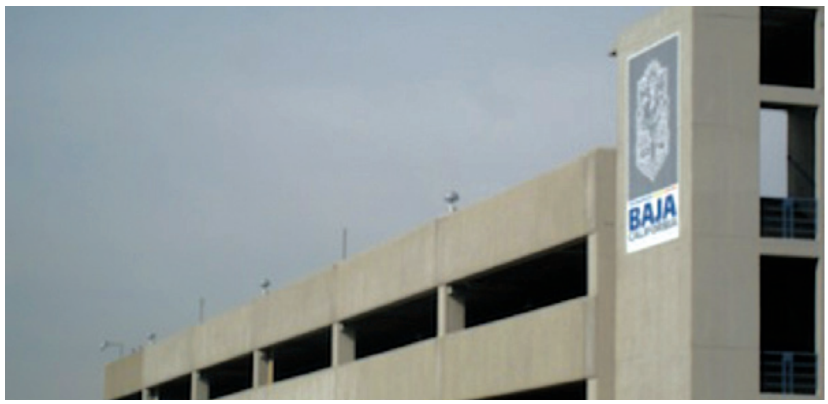
Figure 1 a) Aircraft flight track (blue) and visible GOES image on 13 Sep 2016 12Z, the day prior to development of 2010 hurricane Karl. Occultation tangent point sampling points (green), dropsondes (pink stars) and COSMIC RO profiles (red squares) show the complementary nature of the ARO observations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

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

Recent Research Results: High Rate GPS-seismic Structural Monitoring

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





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

Recent Publications

Wang, K.-N., J. L. Garrison, U. Acikoz, J. S. Haase, B. J. Murphy, P. Muradyan, and T. Lulich (2016), Open-loop tracking of rising and setting GNSS radio-occultation signals from an airborne platform: signal model and error analysis, *IEEE Transactions on Geosciences and Remote Sensing,* **54**, 3967-3984.

Zhang, W., J. S. Haase, A. Hertzog, Y. Lou, and R. Vincent (2016), Improvement of stratospheric balloon positioning and the impact on gravity wave parameter estimation for the Concordiasi campaign in Antarctica, *Journal of Geophysical Research Atmospheres*, 121, 9977-9997.

Adhikari, L., F. Xie, and J. S. Haase (2016), Application of the Full Spectrum Inversion Algorithm for Airborne GPS Radio Occultation Measurements, *Atmospheric Measurement Technology,* **9**, 5077-5087.

Aiken, C., K. Chao, H. Gonzalez-Huizar, R. Douilly, Z. Peng, A. Deschamps, E. Calais, and J. S. Haase (2016), Exploration of remote triggering: A survey of multiple fault structures in Haiti, *Earth and Planetary Science Letters,* **455**, 14-24.

Saunders, J. K., D. E. Goldberg, J. S. Haase, Y. Bock, D. G. Offield, D. Melgar, J. Restrepo, R. B. Fleischman, A. Nema, J. Geng, C. Walls, D. Mann, and G. Mattioli (2016), Seismogeodesy using GPS and low-cost MEMS accelerometers: Perspectives for earthquake early warning and rapid response, *Bull. Seis. Soc. Am,* **106**.

Zhang, W., Y. Lou, J. S. Haase, R. Zhang, G. Zheng, J. Huang, C. Shi, and J. Liu (2016), The use of ground-based GPS precipitable water measurements over China to assess radiosonde and ERA-Interim moisture trends and errors from 1999-2015, *J. Geoph. Res.,* submitted.

Wang, K.-N., J. L. Garrison, J. S. Haase, and B. J. Murphy (2016), Implementation of the phase matching (PM) method for the GPS airborne radio occultation (ARO) system, *Journal of Geophysical Research,* submitted.

Chen, X.-M., S.-H. Chen, J. S. Haase, B. J. Murphy, K.-N. Wang, J. L. Garrison, S.-Y. Chen, C. Y. Huang, L. Adhikari, and F. Xie (2016), Assimilation of Airborne Radio Occultation Measurements and Their Impact on the Prediction of Hurricane Karl in 2010, *Journal of Advances in Modeling Earth Systems,* submitted.

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

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

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

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

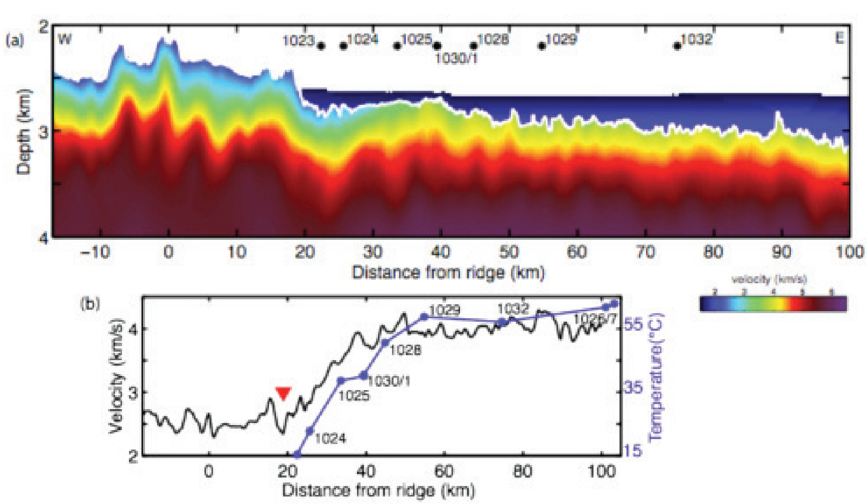

Figure 1 (a) Seismic tomography model of the Endeavour transect. White line is top of igneous basement. Numbered black dots are locations of ODP Leg 168 holes on or near the seismic profile. (b) Average velocity of the top 200 m of basement, upper layer 2A, left axis. Basement temperatures of the ODP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

Recent Publications

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

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

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

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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 sub-audible 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

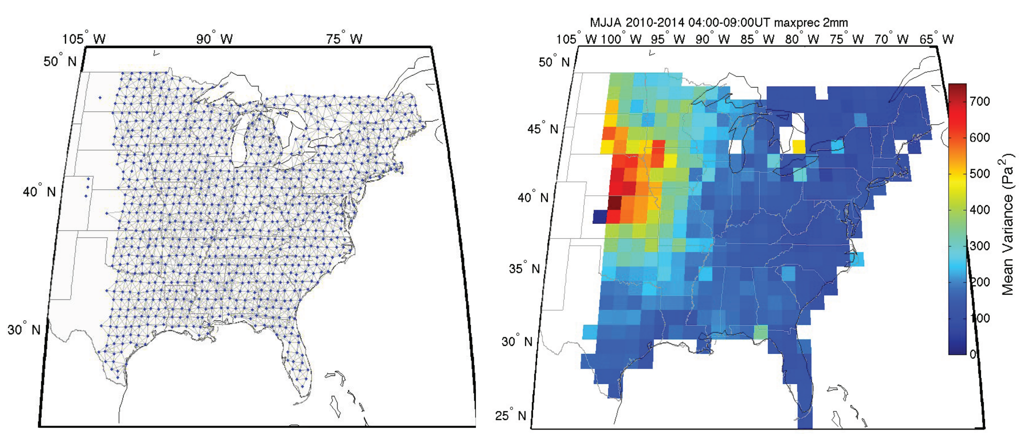

Figure 1. left) sites occupied by stations in the TA from January 1, 2010 through Sept 30, 2014. These stations have been grouped into 3-element arrays (triads) for the study of long-period atmospheric gravity waves. The panel on the right shows the variance of atmospheric pressure in the 2-6 hr passband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

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

The National Science Foundation funded our group to upgrade the entire TA with infrasound microphones and barometers. Our sensor package is sensitive to air pressure variations from D.C. to 20 Hz, at the lower end of the audible range. The upgrade converted the TA into the first-ever semi-continental-scale seismo-acoustic network. The network has moved east across the US as stations are redeployed. Figure 1 (left panel) shows station locations from January 1, 2010 through the end of September, 2014. We have divided this collection of stations into 3,600 elemental arrays (triads) to study atmospheric gravity waves. An early result is shown in the right panel of figure 1. This map shows the variance of atmospheric pressure in the 2-6 hour pass-band at local night. Elevated variance of atmospheric pressure is due to the presence of atmospheric gravity waves. As expected, large gravity waves are common to the west of the Great Lakes and are from convective activity.

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

Recent Publications

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

de Groot-Hedlin, C.D. and Hedlin, M.A.H., 2015, A method for detecting and locating geophysical events using groups of arrays, *Geophys. J. Int.,* **203,** 960-971, doi: 10.1093/gji/ggv345

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

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

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

Stephan, C., Alexander, M.J., Hedlin, M.A.H., de Groot-Hedlin, C.D. and Hoffmann, L., 2016, A case study on the far-field properties of propagating tropospheric gravity waves, *Monthly Weather Review,* **144**, p2947-2961, DOI: 10.1175/MWR-D-16-0054.1.

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Research Interests: crustal seismology and earthquake and icequake source physics, with an emphasis on understanding how one quake can influence another.

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

EXPLORING REMOTE EARTHQUAKE TRIGGERING POTENTIAL USING FREQUENCY DOMAIN ARRAY VISUALIZATION *[Linville et al., 2014]*. To better understand earthquake source processes involved in dynamically triggering remote aftershocks, we use data from the EarthScope Transportable Array (TA), an array of over 400 seismic stations deployed in a grid pattern in the continental US. These stations provide uniform station sampling, similar recording capabilities, large spatial coverage, and in many cases, repeat sampling at each site. Using our new automated method we examine 18 global mainshocks (M≥7) that generate median peak dynamic stress amplitudes of 0.001- 0.028 MPa across the array. We find no evidence of prolific or widespread remote dynamic triggering in the continental U.S. within the mainshock's wavetrain or within the next 2 days following the mainshock stress transients. There is, however, limited evidence of seismicity rate increases in localized source regions. These results suggest that for these data, prolific, remote earthquake triggering is a rare phenomenon. We further conclude that within the lower range of previously reported triggering thresholds, surface wave amplitude does not correlate well with observed cases of dynamic triggering. Therefore, other characteristics of the triggering wavefield, in addition to specific site conditions, must contribute to triggering at these amplitudes.

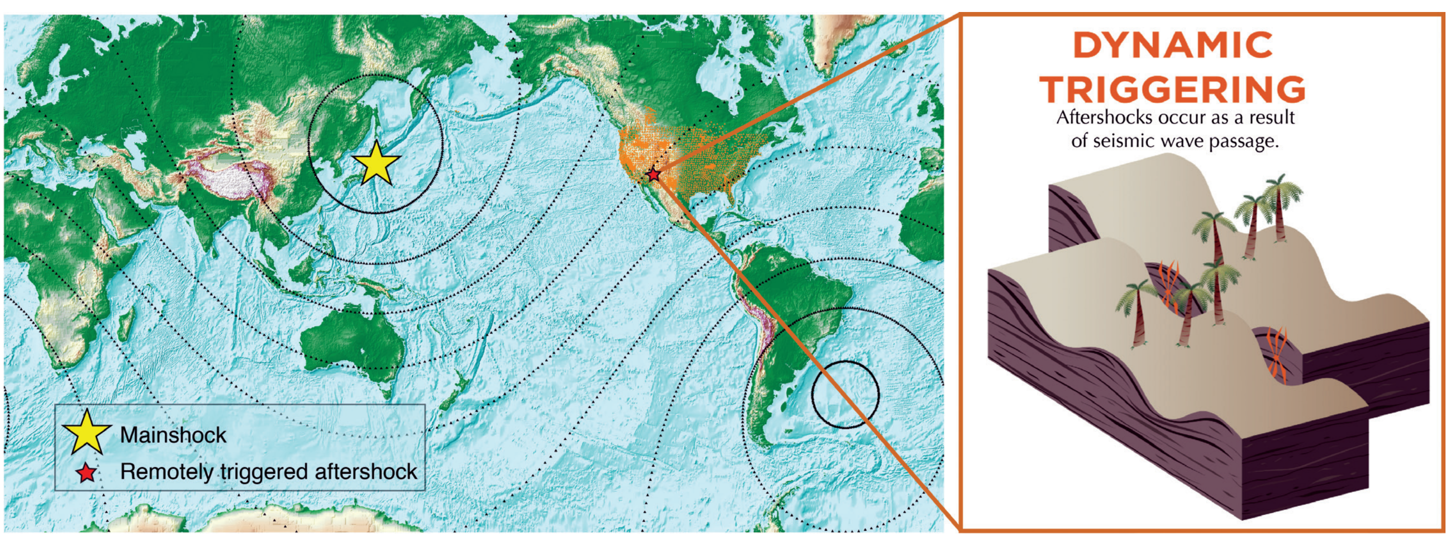

Figure 1: We aim to design an automated detection scheme to catalog local earthquakes recorded by the USArray TA network (points distributed throughout the continental USA), which can be used to help test the hypothesis that a large earthquake (e.g., large star, contours illustrate the mainshock's seismic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

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

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

Recent Publications

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

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

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

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

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

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

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

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

GLOBAL REFERENCE MODELS: Laske continues collaboration with Guy Masters and former graduate student Zhitu Ma to compile and distribute global crust and lithosphere models. CRUST1.0, A 1-degree crustal model, was released in 2013. Applications relying on CRUST1.0 are found across multiple disciplines in academia and industry. Laske maintains the distribution website and provides guidance to users. The PLUME project: For the past decade or so, Laske has analyzed waveforms collected on ocean bottom seismometers (OBSs). She was the lead-PI of the Hawaiian PLUME project (Plume–Lithosphere–Undersea–Mantle Experiment) to study the plumbing system of the Hawaiian hotspot. Results from various body wave, surface wave and receiver function studies were published. A feasibility study with Christine Thomas at Munster University, Germany found new and previously unmapped D" precursors. The exceptional quality of PLUME deep-ocean vertical-component records allowed the team to detect PdP waves for some areas and found convincing null-results for other areas. This was the first study of its kind using OBS data. The dataset also provides the basis for PhD student Adrian Doran who studies seafloor compliance and ambient-noise Green's functions. His work will help constrain structure in the shallow sediments and crustal layers that were not resolved by previous work. Doran formulated the concept of horizontal compliance and published first-ever application to real OBS data. He also developed a new automated tool to determine OBS instrument orientations using Rayleigh waves, with little interaction by the data analyst. A paper was recently accepted, and the Python computer code will be released shortly.

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

THE ADDOSS PROJECT: For the ADDOSS (Autonomously Deployed Deep-ocean Seismic System) Laske collaborates with Jon Berger, John Orcutt, Jeff Babcock and Liquid Robotics Inc. to develop and test an untethered OBS system that is capable of providing near-real time data collected on the ocean floor. A wave glider towing an acoustic modem maintains a communications link to the OBS. The group has performed several tests in shallow (1000 m) and deep (3800 m) water. A 3-month deep-water test about 300 km west of

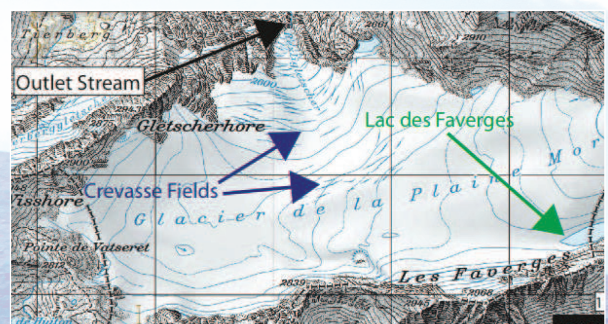

Figure 1: Map of Glacier de la Plaine Morte just south of Wildstrubel, Switzerland. The Rhone valley is to the south. Marked is the outlet stream at the toe of Rexliglacier that drains into the Simme river to the north. Arrows mark Lac des Faverges, a major glacier lake, and the two crevasse fields that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

La Jolla in the winter of 2013 revealed never-before seen seismic activity in the Outer California Borderland. Doran and Laske returned in the summer of 2015 on UC ship fund cruises to continue investigation of this seismicity in more detail. The AnICEotropy project: Laske has been collaborating with Fabian Walter at ETH, Switzerland to study ice quakes on the Glacier de la Plaine Morte, Switzerland. This plateau glacier that separates Cantons Berne and Valais develops a glacier lake, Lac des Faverges, during snow melt that frequently drains and floods the Simme valley to the north. Recent floods have become more frequent and larger, approaching the capacity of the flood control system. Laske and collaborators installed seismometers on the glacier and are trying to identify precursory ice quake activity that helps improve early flood warning. As an academic by-product, the gathered seismicity allows a 'sandbox' azimuthal anisotropy analysis to test the hypothesis that seismic anisotropy is aligned with the crevasses on the glacier. This project provided the basis for an ice-quake localization study for visiting summer student Manuel Krage from Munster University, Germany.

Recent Publications

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

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

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

JEAN BERNARD MINSTER, DISTINGUISHED PROFESSOR OF GEOPHYSICS

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Research Interests: Seismology, Geodesy, Data Science and Policy

As reported last year, I stepped down from my long-held role as chair of the ICSU World Data System (ICSU-WDS) Scientific Committee (SC) in July 2015. This did not end my participation, however, and I have attended all teleconferences and several meetings, chaired by Professor Sandy Harrison of the University of Reading.

As Chair Emeritus for WDS, I have served as liaison with the ICSU Committee for Data in Science and Technology (CODATA www.codata.org). This is a completely different aspect of the emerging words of data policies and data sharing. I was elected to the Research Data Alliance (RDA: www.rd-alliance.org) Council in early 2016, and have served since then. My specific assignments include:

- RDA Council
- Council Strategy
- Sustainablity and Funding
- Engagement and Communications
- Operations and Coordination

A major event, first in history, took place in Denver, CO, on September 10-17 2016. It was called *"International Data Week"* (IDW: www.internationaldataweek.org). For the first time, several events were synchronized:

- The ICSU World Data System and ICSU CODATA held their international conference SciDataCon-2016, including business meeting, together with
  - the WDS member forum,
  - the CODATA Data Science conference
- The RDA plenary meeting (P#8) was held in the same venue immediately afterwords

An important component of IDW was held mid-week, labeled *International Data Forum* (IDF). It featured senior speakers from various governments, and agencies. As a member of the organizing committee, I spend innumerable hours on the phone coordinating the activities and obligations of three very different international organizations, based on different continents, all focused on data issues. This was surprisingly challenging, and convergence did not happen until very late in the planning process.

I organized and chaired a session entitled *"Data Stories"* that dealt with Citizen Science (such as Great Barrier Reef Coral bleaching survey and OpenStreetMap), and Health Science *(Doctors without Borders).* That session was extremely well received. Ultimately, the IDW and IDF were remarkably successful, and there is an emerging strong consensus to repeat such an event in a couple of years, probably on a different continent, with South America and Africa as serious contenders. I will surely participate.

A recent entrant on the international data scene is the *Research Data Alliance* (RDA). As a newly minted member of the RDA Council, I continue to be an active participant in a number of the innumerable RDA Working Groups and Interest Groups, in particular:

- Repository Audit and Certification DSA–WDS Partnership WG
- Libraries for Research Data IG
- RDA/CODATA Legal Interoperability IG
- RDA/WDS Certification of Digital Repositories IG
- RDA/WDS Publishing Data IG
- Digital Practices in History and Ethnography IG

Although I am a silent participant in most of these, I have been very active in a couple which have turned out to be very demanding. The two most demanding ones are the DSA-WDS, and the Legal Interoperability groups. In the former case, the task was to coordinate the criteria used by the World Data System and the Data Seal of Approval organizations to certify their respective data facilities. What looked initially like a simple process turned into a protracted discussion. A main difficulty arose because Humanities and Social Science data centers notion of data curation is to preserve the data exactly as submitted, whereas physical sciences and in particular, astronomy allow updating of the metadata records as more information (e.g. calibration) becomes available. After 18 months of effort, a common set of criteria was arrived at, that is undergoing the RDA process of adoption, and that is being presented at a variety of venues, notably the AGU meetings.

The Legal Interoperability Interest Group was the object of well over 65 teleconferences, involving primarily lawyers from several continents. Except for one librarian, I was the only non-legal participant and the only scientist. The main issues discussed involved intellectual property rights, and the licensing of scholarly works and the associated data. Profound differences existing between US laws and practices notably the *fair use* doctrine, the *European Database Directive,* which has been adopted by almost all EU members, and the Australian intellectual property laws. The final report was reviewed by no fewer than 20 reviewers. The six principles listed below were arrived at after considerable discussion. They seem to be uncontroversial, yet had to be reworded more than once in response to the reviews. The final document includes a lengthy attachment outlining implementation guidelines. Of special note is the recommendation that the Creative Commons CC-By license be used (instead of the oft quoted CC-0) in order to improve legal interoperability among various jurisdictions. Again the RDA adoption process is underway, and the material is being circulated among National Academies, Learned societies, and data facilities worldwide, with a target date of April, 2017.

Finally, I continue my service on the EarthCube Council of Data Facilities as well as my participation in the NASA planning and review activities surrounding two Low-Earth-Orbit geophysical missions planned for the end of the decade: ICESAT-2 and NISAR.

References

Legal Interoperability of Research Data: Principles and Implementation Guidelines

https://rd-alliance.org/rda-codata-legal-interoperability-research-data-principles-and-implementation-guidelines-now

https://www.rd-alliance.org/wds-and-dsa-announce-unified-requirements-core-certification-trustworthy-data-repositories-developed

WALTER MUNK'S 99TH BIRTHDAY...

WALTER MUNK, RESEARCH PROFESSOR

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Research Interests: Ocean waves and sea level changes

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

Recent Publications

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

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

JOHN ORCUTT, Distinguished Professor of Geophysics

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Research Interests: operation of a large number of broadband and wideband ocean bottom seismographs, extension of seafloor seismology to a global scale using new seismometer technologies, cyberinfrastructure for collecting and controlling remote sensors on a local to global scale.

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

Scripps Institution of Oceanography is an international leader in environmental and geoscience observing systems. Scripps has long-term experience in cutting-edge operational sensor networks, including the *USArray* component of NSF's *EarthScope*, the NSF-supported *Global Seismic Network* (GSN), the *Southern California Coastal Ocean Observing System* (SCCOOS), and the privately-supported *ANZA Seismic Network*—all of which informed the design of *SciON*.

SciON builds on expertise with sensor and communications networks, including NSF's *HiSeasNet* and the NSF-initiated *High Performance Wireless Research and Education Network* (HPWREN). HiSeasNet, for example, started as a single Office of Naval Research-supported installation on R/V *Melville* to demonstrate that high-bandwidth telemetry was possible from a buoy, envisioned as a necessary capability for the prospective NSF OOI.

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

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

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

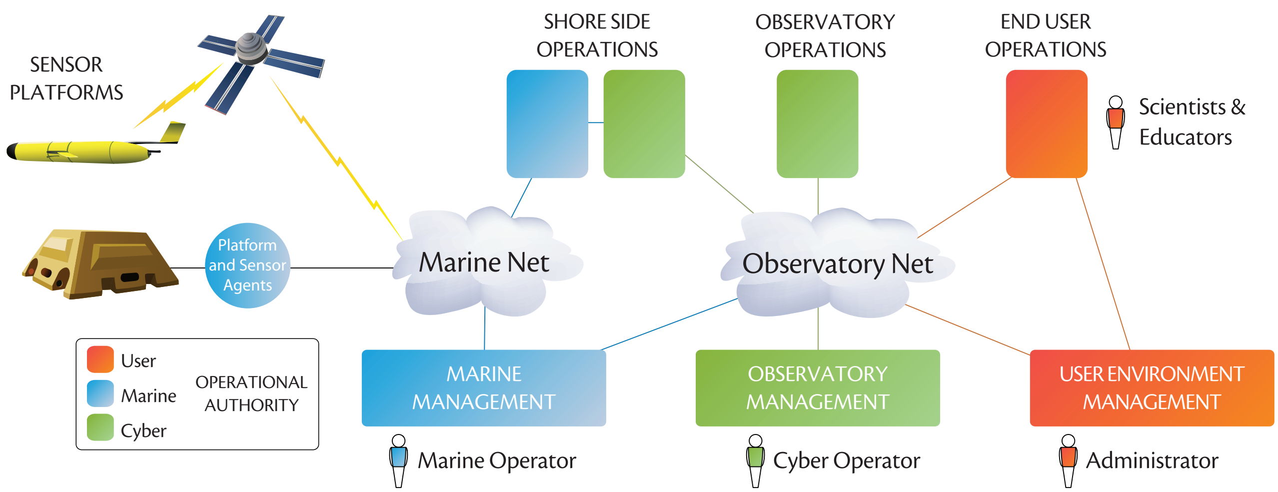

Figure 1: A schematic of an integrated ocean network extending from sensors and robots on the left to users on the right.

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

Recent Publications

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

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

ANNE POMMIER, ASSISTANT PROFESSOR

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

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

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

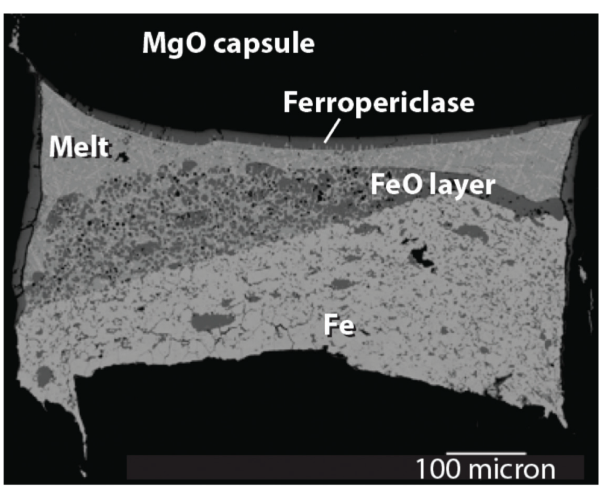
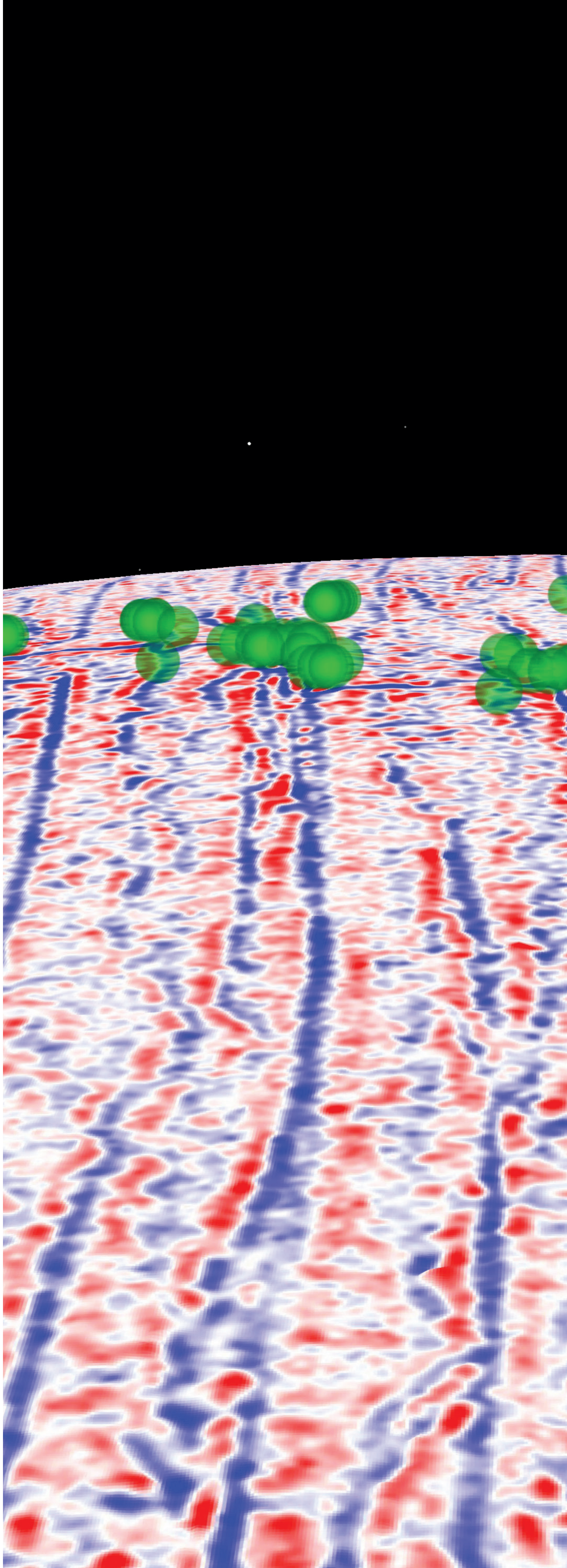


Figure 1: Back-scattered electron images of a retrieved sample after equilibration at high pressure and temperature in the Fe-S-O system. Experiment conducted at 21 GPa, 1600°C, showing the destruction of a continuous FeO layer at the liquid/solid interface. This layer corresponds to an unstable gravitational stage, as the density of FeO is smaller than the density of the Fe-S melt phase and of metallic iron. At the scale of a terrestrial core, the formation and migration (by density contrast) of FeO may influence significantly core dynamics and hence affect the dynamo. Note that the lighter sample contour, corresponding to ferropericlase, was used to estimate the oxygen fugacity of the sample.

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



Recent Publications

A. Pommier, D. L. Kohlstedt, L. Hansen, S. J. Mackwell, M. Tasaka, F. Heidelbach, and K. Leinenweber, Experimental Investigation of the Effect of Shear on the Electrical Properties of Polycrystalline Olivine, *EPSL,* in rev.

A. Pommier, V. Laurenz, C. J. Davies, D. J. Frost, Melting Phase Relations in the Fe-S and Fe-S-O Systems at Core Conditions in Small Terrestrial Bodies, *JGR Planets,* submitted.

DAVID T. SANDWELL, PROFESSOR OF GEOPHYSICS

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

STUDENTS AND FUNDING: Research for the 2015-16 academic year was focused on understanding the dynamics of the crust and lithosphere. Our group comprises three graduate students Soli Garcia (PhD 2016), Eric Xu, and John Desanto, one postdoc Dan Bassett and one lab assistants Ben Tea. Our research on improvement in the marine gravity field is co-funded by the National Science Foundation (NSF) and NASA. In addition, we are funded by Google to improve the accuracy and coverage of the global bathymetry. The NASA Earth Surface and Interior Program as well as the Southern California Earthquake Center provides funding our research on the strain rate and moment accumulation rate along the San Andreas Fault System from InSAR and GPS.

GLOBAL GRAVITY AND BATHYMETRY: We are improving the accuracy and spatial resolution of the marine gravity field using data from three new satellite radar altimeters (CryoSat-2, Jason-1, and AltiKa). This is resulting in a factor of 2-4 improvement in the global marine gravity field. Most of the improvement is in the 12 to 40 km wavelength band, which is of interest for investigation of seafloor structures as small as 6 km (*Garcia et al.,* 2013). The improved marine gravity is important for exploring unknown tectonics in the deep oceans (Figure 1) as well as revealing thousands of uncharted seamounts (*Sandwell et al.,* 2014, *Matthews et al.,* 2016).

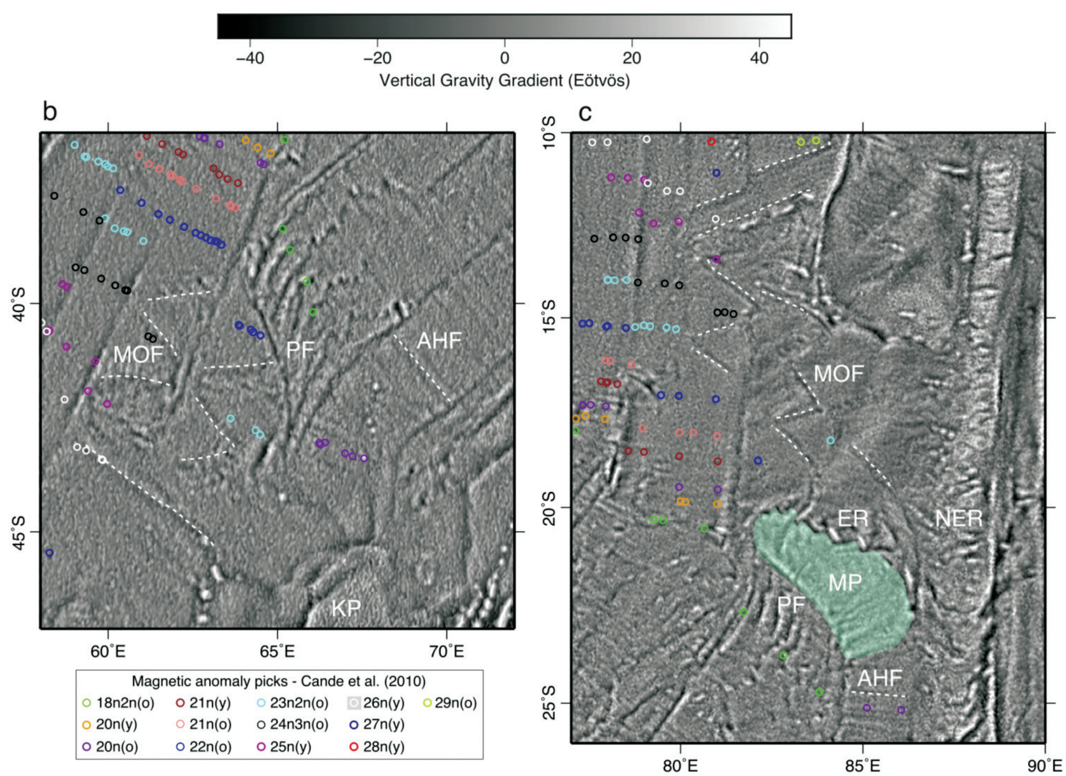

Figure 1. Vertical gradient of the marine gravity field reveals the detailed tectonics in the Indian Ocean (Sandwell et al., 2014; Matthews et al., 2016). These gravity data were used along with plate reconstructions to discover the Mammerickx Microplate which is the size of West Virginia (green shading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

INTEGRATION OF RADAR INTERFEROMETRY AND GPS: We are developing methods to combine the high accuracy of point GPS measurements with the high spatial resolution from radar interferometry to measure interseismic velocity along the San Andreas Fault system. We analyzed InSAR observations, initially from ALOS ascending data, spanning from the middle of 2006 to the end of 2010, and totaling more than 1100 interferograms. These combined GPS/InSAR data are critical for understanding the along-strike variations in stress accumulation rate and associated earthquake hazard (*Tong et al.,* 2015; *Xu et al.,* 2015). The InSAR processing was performed with new software called GMTSAR developed at SIO (topex.ucsd.edu/gmtsar).

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

Recent Publications

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

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

Graduate student Wenyuan Fan has been applying back-projection to study large earthquakes recorded by the global seismic network. His results for the enigmatic 2009 Tonga-Samoa earthquake (Fan et al., 2016) reveal multiple rupture branches, with a Mw 8.0 normal-faulting earthquake east of the trench axis (seaward) followed by a Mw 8.1 reverse-faulting earthquake along the subduction interface west of the trench axis. Comparisons to high-resolution swath ba-

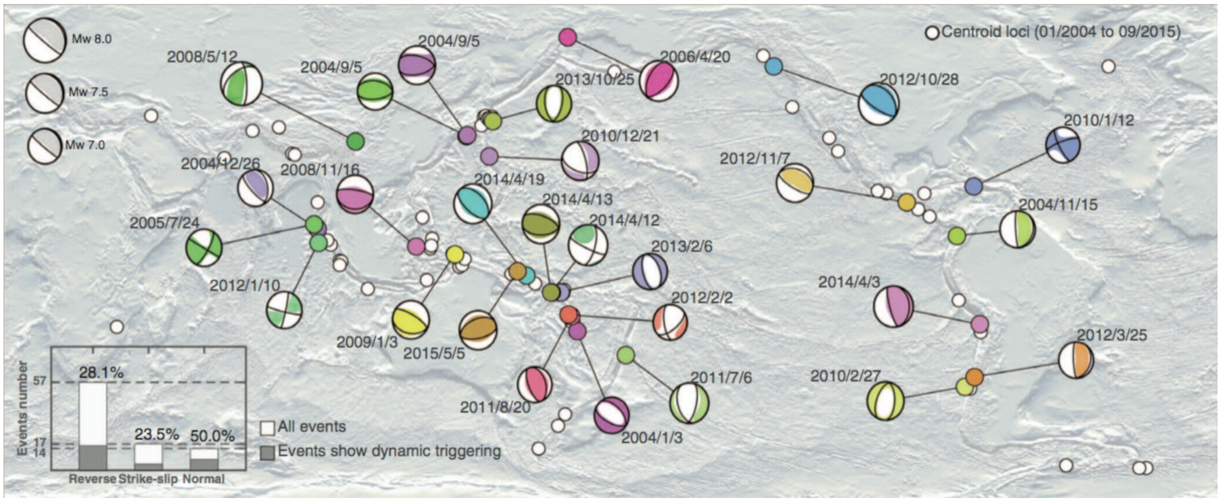

Figure 1. Twenty-seven early-aftershock–triggering mainshocks and their focal mechanisms. The 27 triggering mainshocks are color-coded at their GCMT centroid locations (colored circles). The white circles show the rest of the 88 large earthquakes (7 ≤ Mw < 8) that we investigated with back-projection.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

thymetry suggest that the faulting stages are controlled by bending-related faults on the Pacific plate and along-strike fore-arc segmentation. Detailed analysis of the 2012 Mw 7.2 Sumatra earthquake detected two previously unknown early aftershocks (*Fan and Shearer,* 2016a). This motivated a comprehensive search for such early aftershocks in records from 88 large earthquakes, which detected a total of 48 aftershocks within a few fault lengths of 27 mainshocks during the times that high-amplitude surface waves arrived from the mainshocks (less than 200 seconds). The observations indicate that near-to-intermediate-field dynamic triggering commonly exists and fundamentally promotes aftershock occurrence (*Fan and Shearer,* 2016b).

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

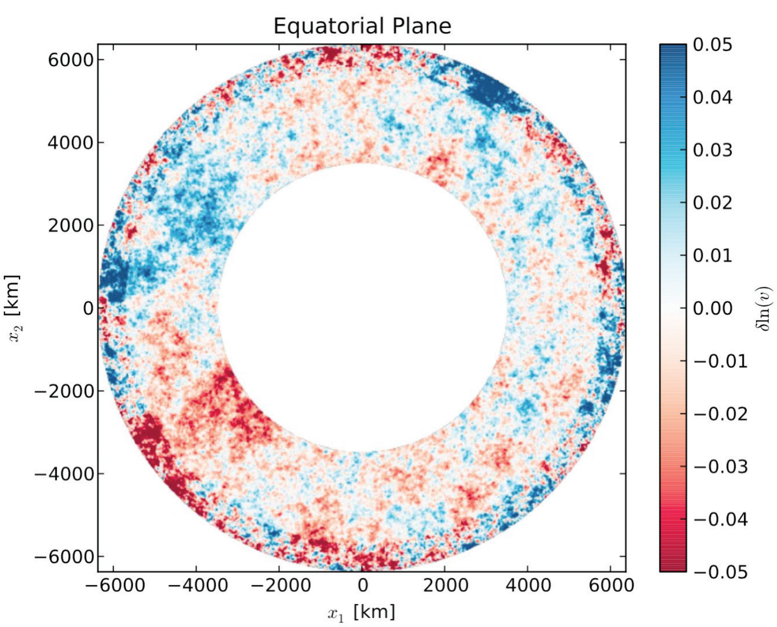

Figure 2. Cross section through an example 3-D mantle model with random heterogeneity. The 600-km-thick upper mantle has stronger heterogeneity than the lower mantle. The heterogeneity in both layers is a random realization of a Von Kármán autocorrelation function. The model shown here has much stronger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

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

Recent Publications

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

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

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

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

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

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

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

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

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

I have also worked with researchers that were previously post-doctoral scholars in my group. Thomas Chaparro is a graduate student in my lab pursuing an MS by thesis, and for his project we teamed up with former Miles post-doctoral scholar Lijun Liu (now at UIUC) and his graduate students. This project aims to better understand the mantle flow underneath the western United States. As a starting point we use the velocity field from the mantle flow model of Liu and Stegman (2011) which provides a good match with the seismic tomography under western US.

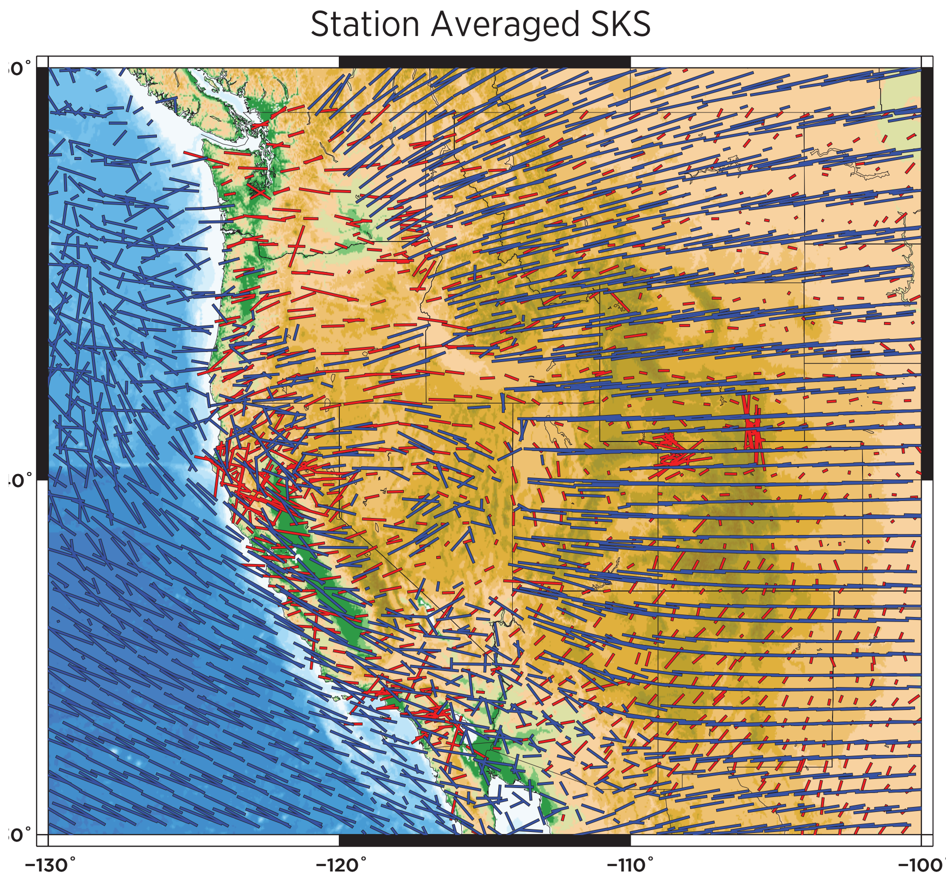

Figure 1: Comparison of predicted LPO anisotropy resulting from mantle flow (blue) with SKS observations from Walpole et al (2013) shown in red. The SKS data is scaled by magnitude of delay time.The LPO is vertically integrated between 200-400km depth.

This velocity field is used for computing the deformation of aggregates of mineral assemblages by employing a version of the D-REX code that has been adapted for 3D geometry (Faccenda and Capitanio, 2012). The results provide a forward model prediction of the LPO anisotropy that develops as a result of the mantle flow during the past 10 million years. We are able to then make a direct comparison of the predicted mantle flow and the observed pattern in SKS observations of western US (Figure 1). One of the most prominent features in the pattern is a quasi-circular swirl pattern centered around central Nevada, and this pattern is clearly seen in our results (blue lines in Figure 1). We have investigated the amount of time the features take to develop as well as the depth that contribute most to this feature. We have found that if only the present day velocity is used to predict LPO, the center of prominent swirl pattern is shifted and located about 500 km northwest of the center of the observed pattern. We conclude that the observed feature must be mostly fossil in nature, having been developed by integrating the velocity field over the past 10 Million years. It is also possible to predict the SKS delay times that would results from such a pattern (Faccenda and Capitanio, 2013), and we have been investigating these as well.

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

Recent Publications

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

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

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

FRANK VERNON, RESEARCH GEOPHYSICIST

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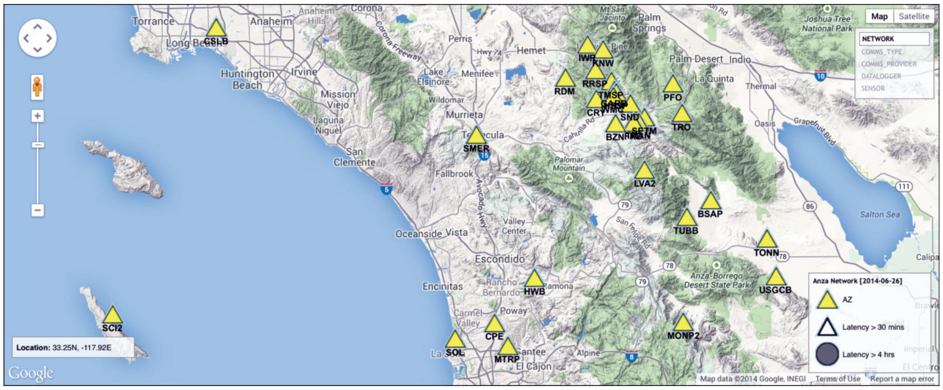
Research Interests: Earthquake source physics and ground motion estimation. Time series analysis applied to terrestrial and space data. Development of instrumentation that improves the observation and understanding of seismic measurements. Realtime environmental sensor networks and wireless networking.

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

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

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



Recent Publications

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

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

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

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

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

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

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

MARK ZUMBERGE, RESEARCH GEOPHYSICIST

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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.

A Seafloor Optical Fiber Strainmeter:

(with Frank Wyatt and William Hatfield)

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

At the end of the last ice age approximately 7000 years ago, very little of what we call today the Mississippi River Delta existed. As the Laurentide Ice Sheet covering much of North America retreated, water flow in the Mississippi River increased and created the Mississippi River Delta over many centuries. The Delta is formed by a meandering path of the river as it empties into the Gulf of Mexico, providing a constant supply of sediment and distributing it over millions of acres in the triangularly shaped feature in southern Louisiana south of New Orleans. In 1920, the slow but constant varia-

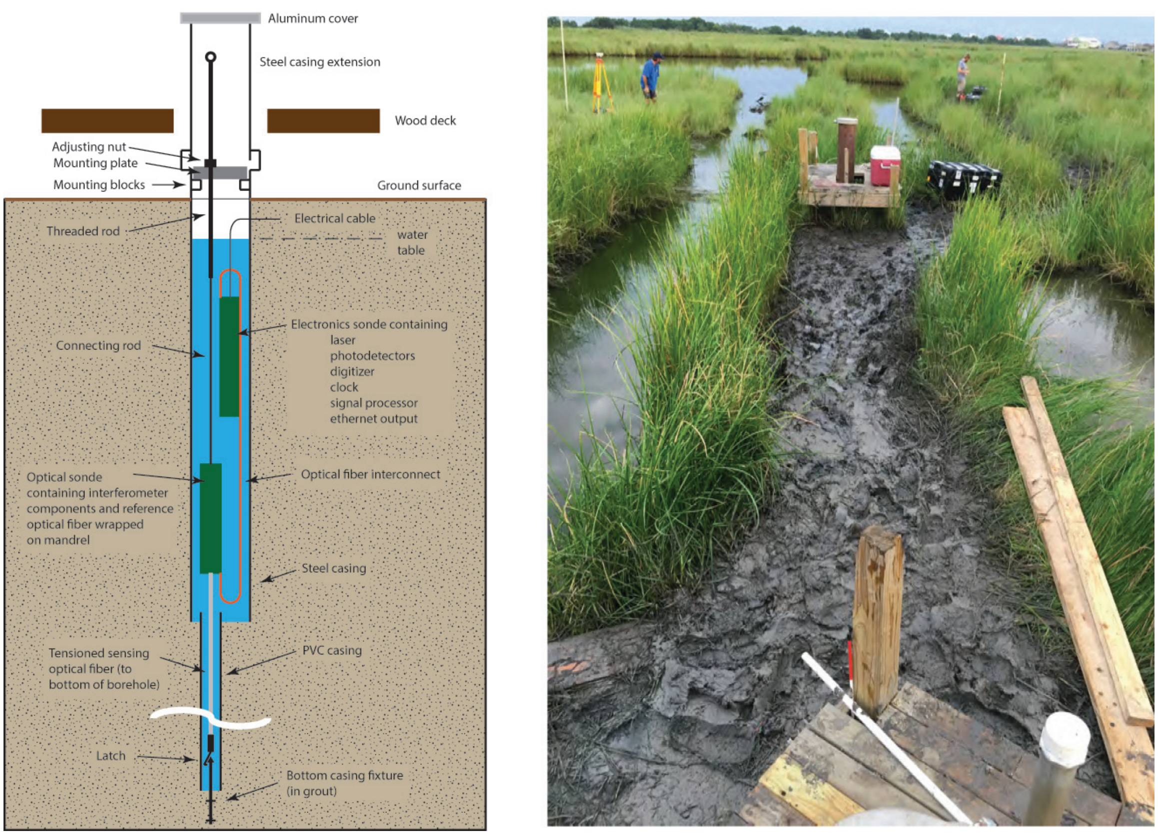

Figure 1. On the left is a schematic of one of the instruments. Two sondes are in each borehole, one housing the recording electronics and a laser to illuminate an optical fiber interferometer, the second holding the interferometer components. They are connected by optical fibers. A tensioned optical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

tion in the Mississippi River's path proved problematic for navigation and the maintenance of ports, prompting officials at the time to construct levees to keep the river's course constant. One unintended consequence of this action has been to starve the supply of new sediment to the River Delta. The existing sediment is compacting at a rate estimated to be 4 mm per year and, without new sediment to accommodate the compaction, results in land sinking below sea level and inundation by Gulf of Mexico waters. Coupled with sea level rise of 2 mm per year, land of the Mississippi River Delta, much of it valuable agricultural real estate, is disappearing into the ocean at an alarming average rate of an acre per hour.

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

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

Recent Publications

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

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