CECIL AND IDA GREEN INSTITUTE OF GEOPHYSICS AND PLANETARY PHYSICS

2018 ANNUAL REPORT

SCRIPPS INSTITUTION OF OCEANOGRAPHY | UNIVERSITY OF CALIFORNIA SAN DIEGO

HPWREN Live Stream: Fires, weather conditions, flooding, and other public safety conditions are scenarios where real-time sensor data distributions can become important aspects for situational awareness. HPWREN can now provide live feeds from most of its cameras, in addition to the post-processed videos shown at: www.youtube.com/user/hpwren/videos

IGPP 2018

DIRECTOR'S WELCOME

Here is the 2018 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.

Steven Constable, Director, IGPP

CONTENTS

RESEARCHERS

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

GREEN FOUNDATION

The Cecil H. and Ida M. Green Foundation for Earth Sciences supports visiting scholars and resident scientists at IGPP. Established with a gift from the late Cecil Green in 1971, the Green Foundation holds an endowment managed by the UC San Diego-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: James Badro, IPGP, France

Green Scholar: Brook Tozer, postdoc

Green Scholar: Shunguo Wang, postdoc

Miles Fellow: Adina Püsok, postdoc

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

Calibration of Differential Pressure Gauge: John Orcutt, Glenn Sasagawa, Mark Zumberge

San Diego Trough Seismicity: Gabi Laske

SIGMELTS Electrical Properties Code Development: Anne Pommier

GRADUATE PROGRAM

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 NSF, NASA, NOAA, the USGS, and the Office of Naval Research, and can provide graduates with long-term networking and professional support.

Graduate Students who successfully defended in 2018

Peter Kannberg *(Steven Constable): Marine Electromagnetic Exploration of Gas Hydrate in the California Borderlands*

Shi Joyce Sim *(David Stegman, James Day): The depth of mid-ocean ridges through Earth's evolution and a two-phase study of melt focusing at mid-ocean ridges*

Zhao Chen *(Peter Gerstoft): Seismic Response to Ocean Waves: Microseisms and Plate Waves*

Ekaterina Tymofyeyeva *(Yuri Fialko): Improving the accuracy of space geodetic measurements of tectonic deformation*

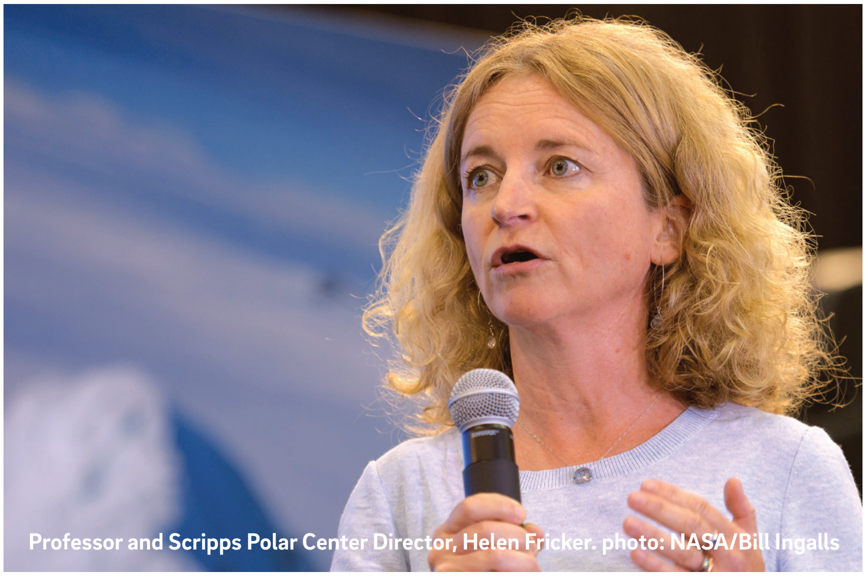
Joanna Sherman *(Steven Constable): Surface-towed controlled source electromagnetic system for mapping extent of subsea permafrost on the Beaufort shelf, Alaska*

John DeSanto *(David Sandwell): Measuring seafloor displacement using repeated sidescan sonar surveys*

Dara Goldberg *(Yehuda Bock): Seismogeodetic Methods for Earthquake and Tsunami Warning and Response*

Mayuri Sadhasivan *(Cathy Constable): Extending Stochastic Representations of the Geomagnetic Field*

ICESat-2 Lauch



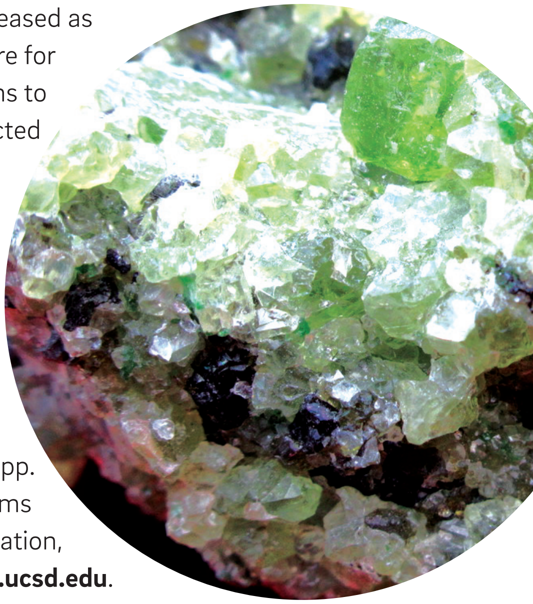
Professor and Scripps Polar Center Director, Helen Fricker. photo: NASA/Bill Ingalls

SEPTEMBER 2018. NASA launched its Ice, Cloud and Land Elevation Satellite (ICESat-2). Several Scripps scientists contributed to the ICESat-2 mission, notably glaciologist Professor and Scrippps Polar Center Director, Helen Fricker, who has served as a member of NASA's Science Definition Team for more than a decade.

Helen Fricker was interviewed on NPR's Here and Now to discuss the ICESat-2 launch—which represented the culimination of ten years of work by Fricker and her collegues. From orbit, the satellite will measure tiny changes in the ice sheets, better help climate researchers understand in real-time the speed of melt, and define the next decade of Antarctic research. The full interview: www.wbur.org/hereandnow/2018/09/20/nasa-icesat-2-satellite-ice-melting.

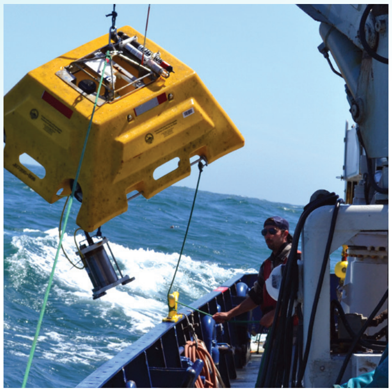
The United Launch Alliance (ULA) Delta II rocket launches with the NASA Ice, Cloud and land Elevation Satellite-2 (ICESat-2) onboard, Saturday, Sept. 15, 2018, from Vandenberg Air Force Base in California. The ICESat-2 mission will measure the changing height of Earth's ice. photo: NASA/Bill Ingalls

SIGMELTS 2.0



The SIGMELTS app, created and built by Anne Pommier and Jeff Roberts, has been updated and released as SIGMELTS 2.0! SIGMELTS, software for geophysicists and petrologists, aims to improve the interpretation of detected magnetotelluric anomalies in Earth's crust and mantle and track the sources of earthquakes and volcanic eruptions. The second addition of SIGMELTS features numerous updates including the capability for users to apply conductivity values to a graph and export results for use outside the app. students collect and study organisms from the seafloor. For more information, or to try out the app, visit **sigmelts.ucsd.edu**.

OBSIP Sensor Licenced



Distiguished Professor of Geophysics John Orcutt and collaborators successfully licensed their ocean bottom seismograph system to Canadian company Nanometrics. The device, the Autonomous Broad Application Low Obstruction Noise Exempt System (ABALONES), will now be marketed, manufactured, and distributed to research institutes worldwide.

DUNCAN CARR AGNEW
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FRANK K. WYATT
Principle Development Engineer, RTAD

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

Since the 1970's we have used long-base laserstrainmeters 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 14km from the Anza section of the San Jacinto fault (2-3m accumulated slip since the last large earthquake) and Salton City (SCS, since 2006) within 15km 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 (4-6m accumulated slip). As of October 31, 2018, all funding for the operation of these instruments ended; as part of the last year of operation, those constructed for the Plate Boundary Observatory were decommisioned in whole or in part. The table shows the operating times, length of operation in years, and cumulative amount of data collected, in instrument years.

SITE	START	END	LEN	TOTAL
PFO NS	1971.29	2018.67	47.38	47.38
PFO EW	1972.05	2018.75	46.70	94.08
PFO NW	1973.16	2018.75	45.59	139.67
DHL NS	1994.21	2018.75	24.54	164.21
YMS	2002.64	2007.16	4.52	168.73
GVS	2002.66	2015.38	12.72	181.45
DHL EW	2005.41	2018.50	13.09	194.53
SCS NS	2006.75	2018.08	11.33	205.87
SCS EW	2006.75	2017.97	11.22	217.09
CHL NS	2008.68	2018.66	9.98	227.07
CHL EW	2008.68	2018.66	9.98	237.05

One unusual signal detected on the two strainmeter installations on either side of the Salton Sea is a periodic and intermittent variation with a period of about three hours. Water level measurements around the Salton Sea show water level variations with this period and also at shorter periods: these are seiching of the Salton Sea, with the three-hour oscillation being the gravest mode, with largest amplitude at the NW and SE ends, and a node running roughly along the line between the SCS and DHL strainmeters.

Figure 1 shows a cross-spectrum between the two strainmeters at SCS, with significant coherence at the frequency of the gravest mode, and a phase relation that shows these two extensions are exactly 180° apart, implying that the strain is pure shear. This is expected, since the areal strains from loads are small (zero for a halfspace). What is most interesting about this peak is that it has clearly shifted with time, with the frequency decreasing about 5% in the 10-year interval between the first three years and the last three. Such behavior is what would be expected if the average depth of water in the Salton Sea has decreased, and it has, with about 1.5 m change in the level. Since frequency depends on $1/\sqrt{h}$, where h is the average depth, a 5% change in frequency corresponds to a 10% change in average depth, implying that the average depth is about 15 m, which is what bathymetric surveys show.

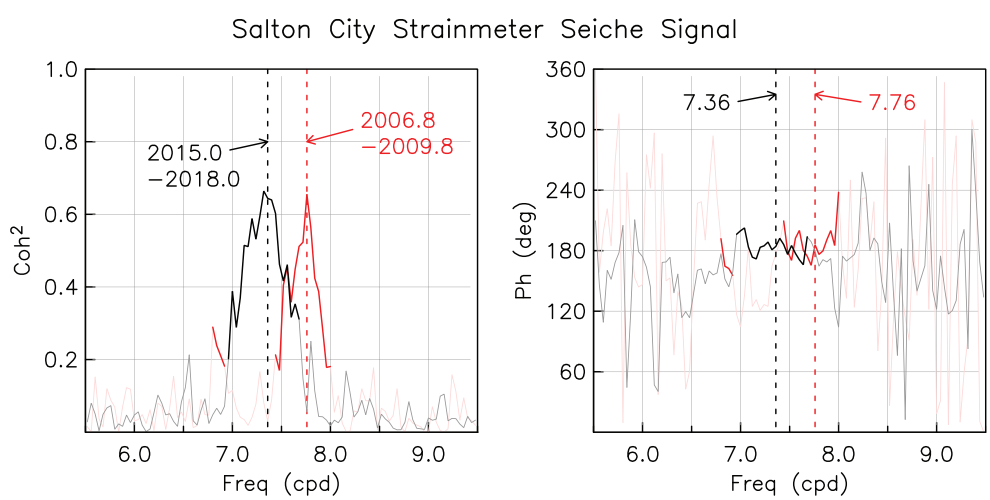

Figure 1. Coherence and phase between the NS and EW strain measurements at Salton City, for the first and last three years of the deployment. The peak in coherence is caused by loading from the gravest mode of oscillation in the Salton Sea.

JONATHAN BERGER

Emeritus Researcher, RTAD

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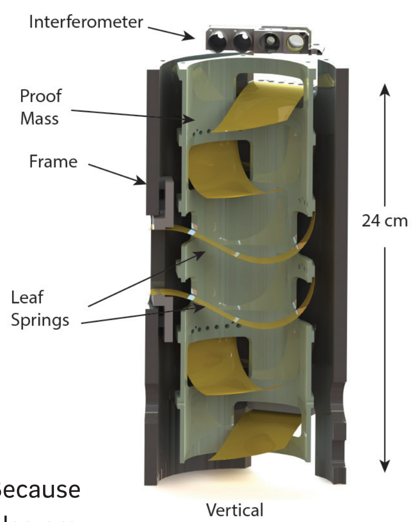
Research Interests: Global seismological observations, marine seismo-acoustics, geophysical instrumentation, deep ocean observing platforms, ocean robotics, global communications systems

This year my colleagues and I reported on the results from a three-component combination seismometer and geodetic sensor suitable for borehole deployment. The instrument uses no electronics at depth in the borehole, rather it relies on optics. While our initial goal was to construct a broadband seismometer, we also succeeded in creating precise and stable geodetic sensors. The wide dynamic range of an interferometric displacement transducer (limited only by the laser coherence length and the alignment range of the optics—normally several centimeters at the very least) allows for very precise proof mass tracking to zero frequency. The mean position of the vertical component' s mass is proportional to gravity and the mean positions of the horizontal mass components are proportional to tilt. The system was installed in a 60-m-deep borehole at the US Geological Survey's Albuquerque Seismology Lab (ASL) for 1 year. The seismic noise floor of the optical seismometer's components compare well with those of a co-located KS54000 borehole seismometer. Because the optical sensors operate to zero frequency (DC), they also provide useful geodetic records.



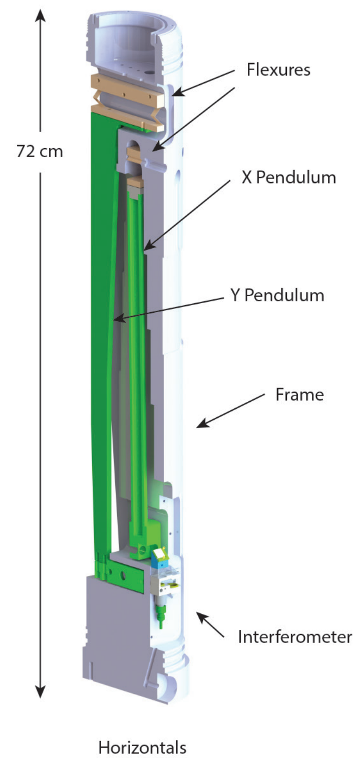


Figure 2.

In other work, I continued my analysis of the seismic and acoustic data collected during the OBSANP experiment in the deep ocean of the subtropical NE Pacific.

The acoustic floor is not unique, but varies with geographic location, observation depth, and time. This report details the acoustic floor during June–July 2013 at station OBSANP [Ocean Bottom Seismometer Augmentation in the North Pacific, 33° 25: 1350°N; 137° 40: 9480°W, Stephen et al. (2014)]. The goal is to understand better the spatial and directional variation of the acoustic floor at one place and time in the deep ocean when the wind overhead is negligible and ship interference least.

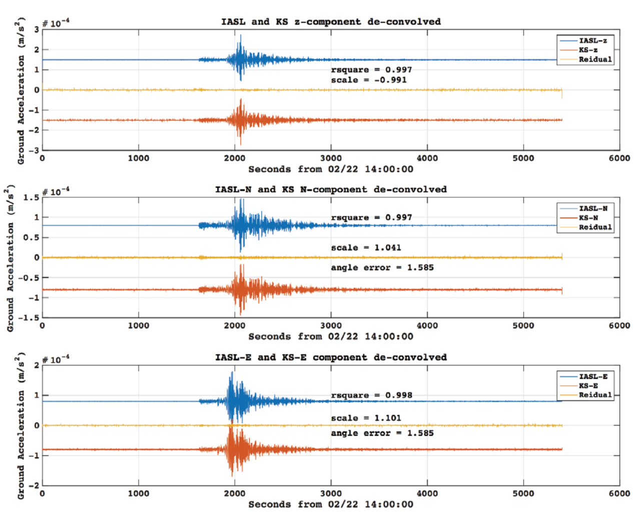


Figure 3. An example of a seismogram showing comparison between the optical seismometer, processed to convert mass position to ground acceleration, and the records from a co-located KS54000.

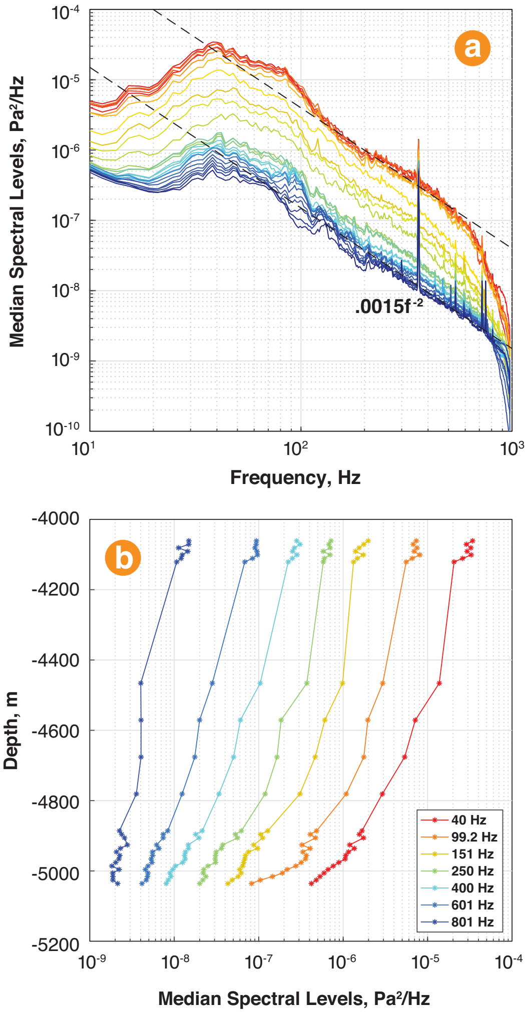


Figure 4. (a) The spectrum of the acoustic floor rises about 16 dB from the bottom element of the VLA (blue, 5036 m) to the top element (red, 4081 m) for frequencies between 40 and 500 Hz. The lower dash line is the function $0.0015 \times f^{-2}$; the upper dash line is parallel and 16 dB higher. (b) The profile of the power up the array at selected frequencies shows the gradient is least at the highest frequency (blue) where the spectrum is smallest.

The deep ocean acoustic floor (taken to be the pressure spectrum observed the few percent of the time when the overhead wind is small, ships are distant and marine life silent) has been measured across a 975 m vertical array anchored at 5048 m in the basin just north of the Murray fracture zone. In the ship-dominated regime ($f > 6$ Hz) the acoustic floor rises about 15 dB up the array. As reported before, the energy is horizontally polarized. From analysis of a 150 m aperture sub-array at the sea floor, the beam width is less than the array resolution (8° at 75 Hz). The beam narrows as f^{-1} for higher frequencies. Furthermore, the power in the beam appears to fall more steeply with frequency than the omnidirectional spectrum, an effect possibly attributable to scattering. Events on the marine-atmosphere boundary layer radiate sound into the ocean. Above about 6 Hz ships are an important source of this sound, and their influence must be discounted in order to study the acoustic signal in this band radiated by windsea processes. The usual approach in studying acoustic "noise" has been to designate the observed spectrum at some frequency as ship-generated or wind-generated by its level, shape and, sometimes, vertical gradient. Here we analyze data from a vertical hydrophone array fortuitously positioned for three days beneath the center of an anticyclone from which there was virtually no windsea acoustic radiation.

RECENT PUBLICATIONS

Mark Zumberge, Jon Berger, William Hatfield, and Erhard Wielandt (2018). A Three-Component Borehole Optical Seismic and Geodetic Sensor. *Bulletin of the Seismological Society of America*, Vol. 108, No. 4, pp. 2022–2031, August 2018, doi: 10.1785/0120180045.

J. Berger, J.R. Bidlot, M. Dzieciuch, W.E. Farrell, P.F. Worcester, and R.A. Stephen. (2018). A deep ocean acoustic noise floor, 1–800 Hz. The *Journal of the Acoustical Society of America*. 143, 1223 (2018); doi: 10.1121/1.5025042

YEHUDA BOCK

Distinguished Researcher and Senior Lecturer; Director, Scripps Orbit and Permanent Array Center (SOPAC); Director, California Spatial Reference Center (CSRC)

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Research Interests: GPS/GNSS, crustal deformation and transients, dynamic geodetic datums, early warning systems for earthquakes and tsunamis, seismogeodesy, GPS meteorology, structural health monitoring, data science, MEMS sensors

The SOPAC group's current focus includes the combined use of traditional seismic and geodetic methods to support natural hazard mitigation for communities affected by earthquakes, tsunamis, volcanoes, or severe weather. We contribute to this goal with in-house instrument design, field deployment of sensor packages, real-time data collection and analysis, development of rapid hazard characterization methods, and interaction with hazard warning centers. Using 20+ years of geodetic displacement time series, we also study tectonic signals of interest, including interseismic, coseismic and postseismic deformation, and transients such as fault creep, subsidence and episodic tremor and slip (ETS). SOPAC also archives GNSS metadata and data products with accompanying IT infrastructure and database management system for the International GNSS Service and the California Spatial Reference Center. The SOPAC group currently includes Peng Fang, Songnian Jiang, Allen Nance, Anne Sullivan, Maria Turingan, graduate students Dara Goldberg and Dorian Golriz, and postdoctoral researcher Emilie Klein, with laboratory and field assistance by Matt Norenberg and Glen Offield.

LOCAL TSUNAMI WARNING SYSTEM

Tsunamis are among the world's most devastating natural disasters. The 2004 Mw9.3 Sumatra-Andaman earthquake and tsunami resulted in a death toll of 250,000. The 2011 Mw9.1 Tohoku-oki earthquake and tsunami caused 25,000 casualties and is one of the most costly and environmentally destructive natural disasters in history. Currently, ocean-basin-wide tsunami warning systems are well developed, providing accurate warnings to far-field coastal regions. However, it remains challenging to characterize the earthquake source fast enough to disseminate a reliable warning to populations of the coastal regions nearest the earthquake source. Accurate estimates of magnitude and primary faulting mechanism are critical metrics for anticipating an earthquake's tsunamigenic potential, yet traditional seismic instrumentation alone is insufficient for near-field evaluation of large earthquake source properties. Using high-rate, near-source GNSS observations in combination with collocated strong-motion accelerometers (seismogeodesy) allows accurate and timely estimates of earthquake properties from the seismic P-wave arrival, rapid magnitude estimation (Figure 5), and permanent deformation, to higher-order source characterizations such as faulting mechanism and distribution of slip, all within a few minutes after earthquake origin time.

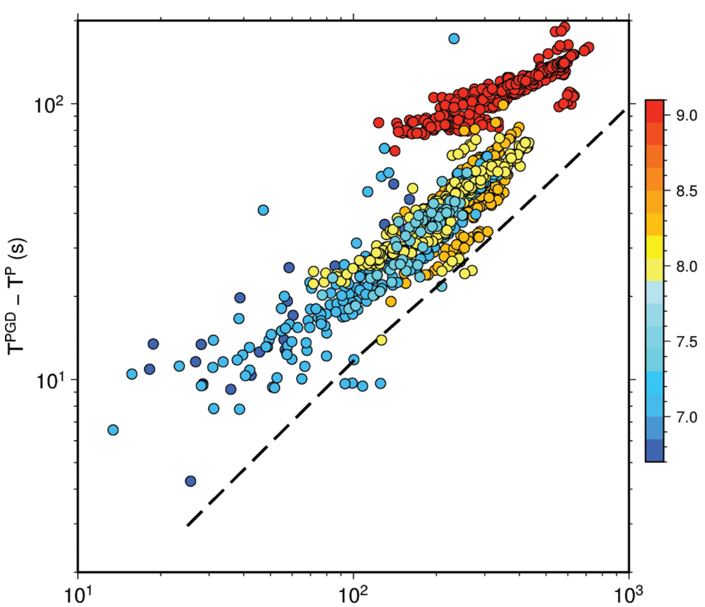

Figure 5. Relationship between hypocentral distance and the time from P-wave arrival to final peak ground displacement (TPGD-TP) for a series of Mw6.7 to Mw9.1 earthquakes in Japan from 2003 to 2016. Peak ground displacement is the first reliable metric for estimation of earthquake magnitude, thus this is indicative of how quickly accurate magnitude estimation is possible for large earthquakes. Black dashed line is the expected S-wave arrival minus P-wave arrival (S-P) time for a 1D velocity model and 25 km source depth. Each colored circle represents an observation from a single GNSS station, and is colored based on the magnitude of the observed earthquake (Goldberg et al., 2018).

Figure 6. Installation of seismogeodetic instrumentation on a structure at the NHERI@UCSD Large High Performance Outdoor Shake Table. (Left) GPS antenna and SIO MEMS accelerometer on the shake table platen. (Right) On roof of the structure. The black tape on the antenna covers serves as targets for geoferencing UAV images of the structure, We use these earthquake simulations to test real-time data collection and earthquake detection algorithms.

Under a NASA-funded project, SOPAC is working with the NOAA Tsunami Warning Centers (TWCs) to transmit real-time seismogeodetic data and implement algorithms to improve the TWC's current practices for local, near-field tsunami warning.

STRUCTURAL MONITORING

Natural hazard mitigation is inextricably linked to the built environment and our ability to reduce risk by properly monitoring structural health before, during, and after a major event. With funding from the U.S. Army Corps of Engineers, SOPAC and collaborators at the UC San Diego Jacobs School of Engineering and Qualcomm Institute are working to develop a multi-sensor, data-driven approach to structural health monitoring. To that end, we have deployed seismogeodetic instrumentation with real-time data collection at the UC San Diego Geisel Library. These continuous observations are supplemented by once-yearly LIDAR and UAV photogrammetry surveys used to create a digital surrogate of the structure and identify any changes to the building over time, particularly following a significant seismic or weather event. We perform additional testing of these monitoring systems by simulating earthquakes and associated structural damage at the NEES @ UCSD Large High Performance Outdoor Shake Table (LHPOST) (Figure 6).

RECENT PUBLICATIONS

Bock, Y. & Melgar, D. (2016), Physical Applications of GPS Geodesy: A Review, Reports on Progress in Physics, 79, 10, doi:10.1088/0034-4885/79/10/106801.

Chen, M. C., Astroza, R., Restrepo, J. I., Conte, J. P., Hutchinson, T., & Bock, Y. (2017). Predominant period and equivalent viscous damping ratio identification for a full-scale building shake table test. *Earthquake Engineering & Structural Dynamics*, 46(14), 2459–2477. doi:10.1002/eqe.2913

Goldberg, D. E., & Bock, Y. (2017). Self-contained local broadband seismogeodetic early warning system: Detection and location. *Journal of Geophysical Research: Solid Earth,* 122(4), 3197–3220. https://doi.org/10.1002/2016JB013766

Goldberg, D. E., Melgar, D., Bock, Y., & Allen, R. M. (2018). Geodetic Observations of Rupture Evolution. *Journal of Geophysical Research: Solid Earth.* doi: 10.1029/2018JB015962.

Goldberg, D. E. (2018). Seismogeodetic Methods for Earthquake and Tsunami Warning and Response. PhD dissertation, University of California San Diego.

Ruhl, C. et al. (2018), A Global Database of Strong Motion Displacement GNSS Recordings and an Example Application to PGD Scaling, *Seismological Research Letters.*

Watanabe, S., Bock, Y., Melgar, D., & Tadokoro, K. (2018). Tsunami Scenarios Based on Interseismic Models Along the Nankai Trough, Japan, From Seafloor and Onshore Geodesy. *Journal of Geophysical Research: Solid Earth,* 123(3), 2448–2461. https://doi.org/10.1002/2017JB014799

ADRIAN BORSA
Assistant Professor

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Remote hydrology from joint analysis of GPS/GNSS, GRACE and InSAR. Transient surface deformation from natural and anthropogenic sources using InSAR and GNSS. Noise sources in geodetic remote sensing, calibration/validation of geodetic observations, and optimal combinations of geodetic information. Differential lidar techniques applied to problems in geomorphology and tectonic geodesy. Dry lake geomorphology. Socioeconomic responses to water scarcity and implications for public policy.

Much of my current research involves the characterization of the hydrological cycle using observations of Earth surface deformation and mass distribution. Specifically, I am interested in observing and analyzing changes in terrestrial water storage (the total water in glaciers, snowpack, lakes, soil, and groundwater) which are critical to closing the water budget but which have been poorly observed until recently. My group combines satellite gravity measurements of water mass change (from the GRACE mission) with GNSS observations of crustal deformation associated with these water mass changes to recover the evolution of water storage across the continental USA and beyond. While seasonal signals from hydrology have been extensively studied, changes over both shorter and longer periods have not been broadly documented. We use a variety of techniques to investigate spatio-temporal patterns of water storage in watersheds across the United States, the extent and duration of droughts, and watershed flooding/recovery from storms such as Hurricane Harvey.

We are also investigating linkages between water and the solid earth, including possible triggering of seismicity (the L'Aquila, South Napa and El Mayor–Cucapah earthquakes) and volcanism (Long Valley Caldera) by water-related crustal stresses. These studies often incorporate InSAR (interferometric synthetic aperture radar) observations of subsidence from groundwater extraction, which provide high spatial resolution and broad coverage of impacted areas. Additionally, we are using our InSAR time series over California's Central Valley in a collaboration with colleagues at UCSD's School of Global Policy and Strategy to study crop selection and planting decisions in response to changes in rainfall, surface water deliveries, and groundwater availability.

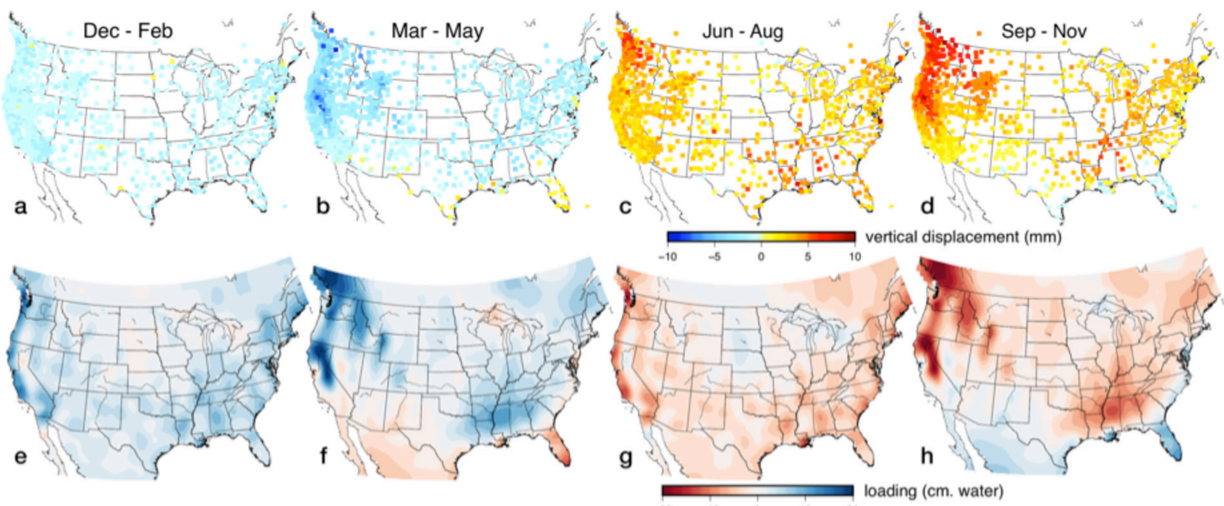

Figure 7. (a-d) Seasonal vertical displacements from GPS across the continental United States (CONUS), showing overall subsidence (cool colors) in the winter and spring, and uplift (warm colors) in the summer and fall. (e-h) Estimated terrestrial water storage anomalies (TWSA) corresponding to panels a-d, from joint analysis of GPS and GRACE data. TWSA typically peaks in winter-spring and is smallest in summer-fall, except on the southern/southeastern CONUS boundary (e.g. Florida and the Gulf and Atlantic coasts), where the seasonal phase is advanced by 3 months.

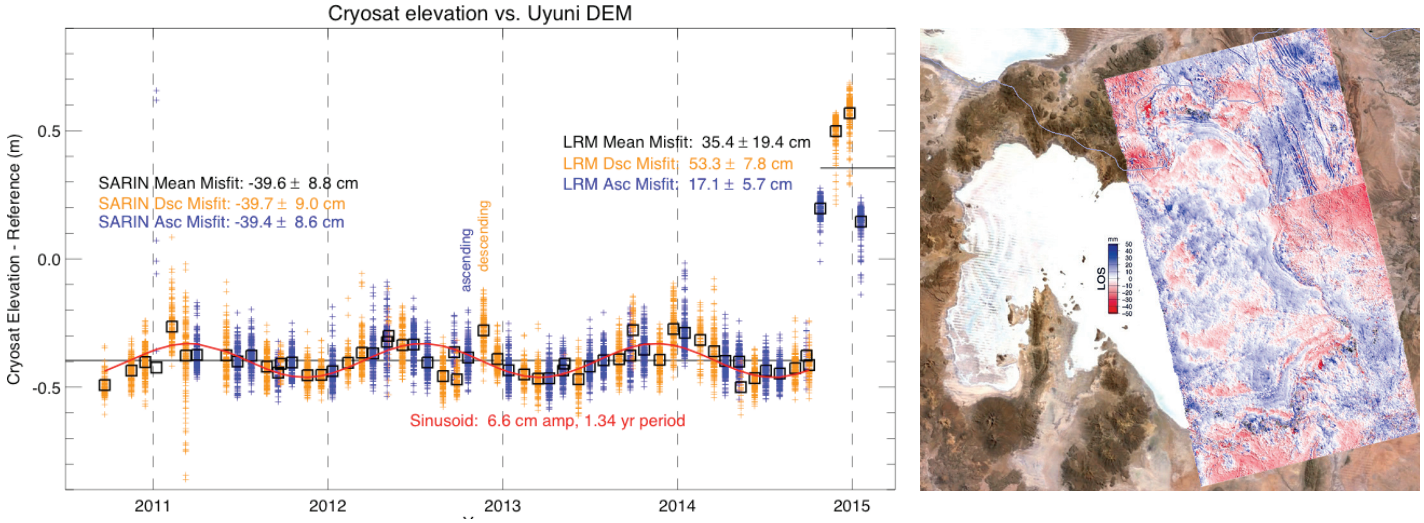

Figure 8. Left: Cryosat elevation validation relative to the salar de Uyuni DEM, with residuals showing a.) a uniform range bias of -40 cm for SARIN mode and +35 cm for LRM mode, b.) an 7 cm amplitude sinusoidal anomaly of 1.34 yr period that is still unexplained, and c.) higher range resolution than 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.

Another primary area of research has been the calibration and validation (cal/val) of satellite altimeter measurements. In collaboration with SIO colleague Helen Fricker, my group used kinematic GNSS to survey Bolivia's salar de Uyuni in 2002, 2009 and 2012 to create a digital elevation model (DEM) of the surface. Using this reference DEM, we identified a significant error in ICESat processing whose correction changes ICESat-derived elevation change trends for the stable portions of the Greenland and Antarctic ice sheets. We later found a previously unidentified 5 cm bias between ICESat's lasers, whose magnitude is larger than the elevation error budget for the mission.

We are now linking absolute GPS measurements with relative motions provided by InSAR to provide a time series of surface displacements for cal/val and for studying salar geomorphology. We have also expanded our cal/val activity to the CryoSat mission, are currently collaborating with European investigators doing cal/val for SWOT, and are about to begin cal/val analysis for ICESat-2.

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

CATHERINE CONSTABLE

Professor

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Earth's magnetic field and electromagnetic environment; Paleo and geomag- netic secular variation; Linking paleomag-netic observations to geodynamo simulations; Paleomagnetic databases; Electrical conductivity of Earth's mantle; Inverse problems; Statistical techniques.

The natural spectrum of geomagnetic variations at Earth's surface extends across an enormous frequency range. The overall shape of the spectrum in Figure 9 is red, and shows the time scales of variations in the predominantly dipolar internal field produced by the geodynamo in Earth's liquid outer core. Fluid flow in the highly electrically conductive (~10^6 Sm^{-1}), core produces a secular variation in the magnetic field. The secular variation is most visible at periods of a year or longer. The dipole part of the field has the longest term changes, associated with geomagnetic excursions and reversals which require the axial dipole part of the field to vanish as it changes sign. Finite electrical conductivity of the mantle effectively filters variations in the core field on time scales much less than a year. Satellite observations and ground based observatory data can be used to study geomagnetic variations on the timescales of the solar cycle, and are used for studies of deep mantle electrical conductivity. Paleomagnetic data from volcanics, archeomagnetic artifacts, and sediments provide information on longer time periods ranging from hundreds to millions of years.

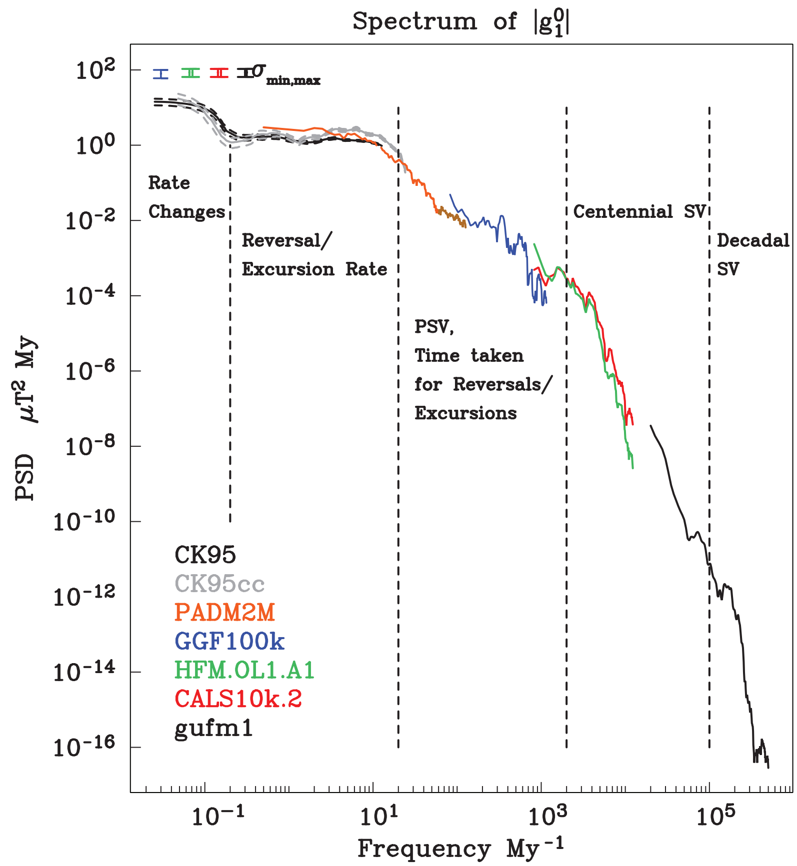

Figure 9. Power spectral density (PSD) estimates of the geomagnetic dipole moment from 0–160 Ma reversal record (CK95), 0–83 Ma reversal record including cryptochrons (CK95cc) 2 Ma paleomagnetic axial dipole moment recostruction PADM2M, Holocene geomagnetic field models HFM.OL1.A1 and CALS10k.2, historical field model gufm1*, and the new geomagnetic field model over the past 100 ka–GGF100k.*

Ongoing research projects (with Sanja Panovska and Monika Korte of GeoForschungs Zentrum, Helmholtz Center, Potsdam) have been concerned with analysis of behavior of the geomagnetic field on centennial to 100 kyr timescales helping to fill previous gaps in Figure 9 between 1 ky and 10 ky periods. A new time varying geomagnetic field model, GGF100k, spans the 0–100 ka interval, and Figure 10 shows the dipole moment has changed by as much as a factor of 4 over this time. The 100 ky model also allows a study of field structure during the Laschamps excursion which occurred around 40 ka and of other extreme events noted by the black bars shown in Figure 10.

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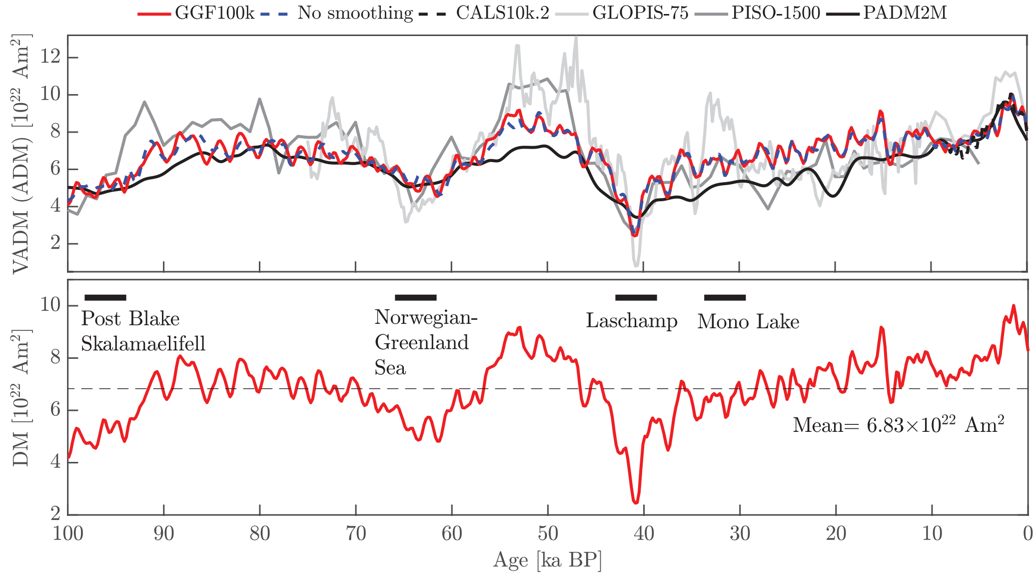

Figure 10. Dipole moment variations from 0-100 ka for GGF100k compared with earlier field models.

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STEVEN CONSTABLE

Distinguished Professor

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Research Interests: Marine EM methods

Steven Constable heads the SIO Marine EM (Electromagnetic) Laboratory at IGPP. EM methods can be used to probe the geology of the seafloor, from the near surface to hundreds of kilome- ters deep, using electrical conductivity as a proxy for rock type. We have used these methods to study plate boundaries, marine gas hydrate, offshore geothermal prospects, permafrost, hydrothermal venting and associated massive sulfides, groundwater, and conventional oil and gas reservoirs.

Two years ago we carried out some novel tests using an autonomous underwater vehicle (AUV) to collect data over a hydrothermal vent field off Japan (background image). We mes- sured electric self potentials, which are gener- ated by hydrothermal vents and also submarine massive sulfides (SMS), observing signals above seafloor features that are likely vents. We also deployed seafloor battery powered EM transmitters to measure seafloor electrical conductivity. We measured conduc- tivities that are ten times higher than seawater, likely a hydrothermal system and/or an SMS deposit. This work was published this year in Constable et al. (2018).

We deployed and recovered 21 MT instruments across the Mendocino Fracture Zone on a project supported by UC Shipfunds during transits of the RV R*oger Revelle* from Newport, Oregon, to her home port in San Diego. These instruments recorded both EM data and seismic signals for about 2 months with the goal to study differences in the lithosphere and mantle associated with the 26.5 million age difference across the fracture zone. PhD student Valeria Reyes-Ortega was chief scientist for the recovery cruise and is working on these data.

Last year we collected MT data in Mono Lake, California, in collaboration with the USGS, which has been using MT to image hydrothermal and magmatic systems in the Mammoth Lakes area. Initial analysis of the data showed a shallow conductor north side of the lake, likely a hydrothermal system, so in October we collected some land MT sites in the area north of the lake.

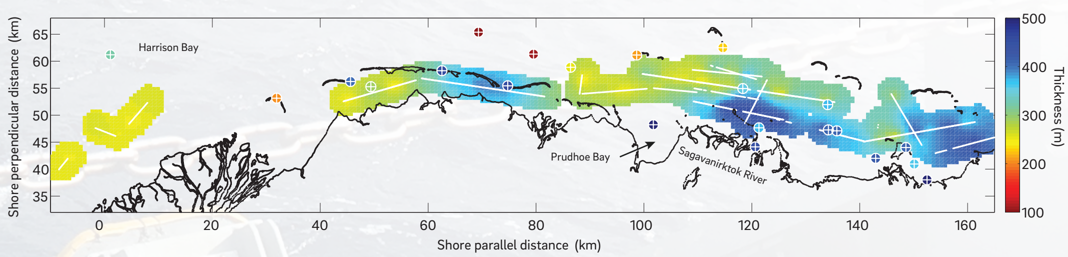
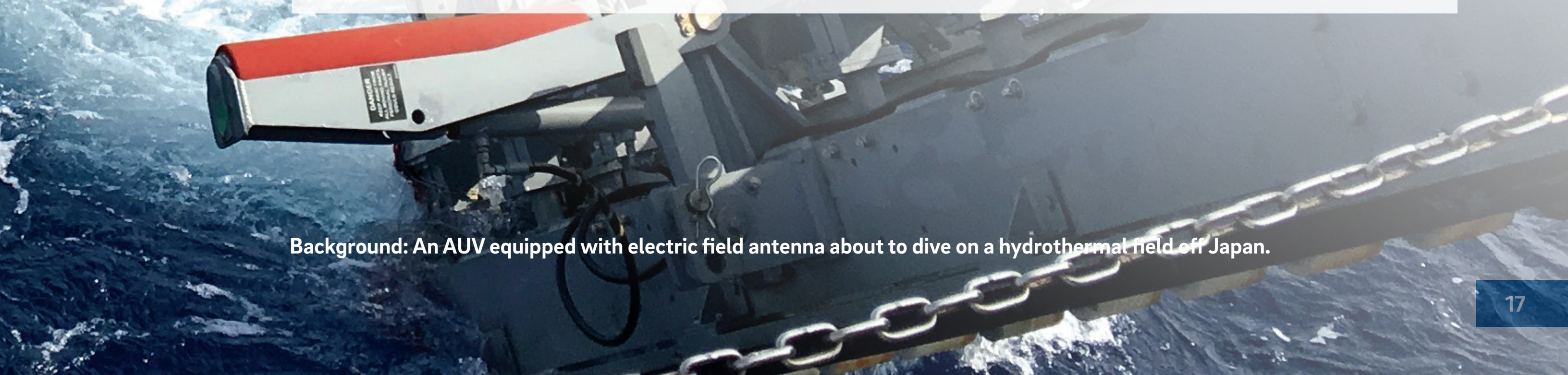


Figure 11. Map of permafrost thickness, offshore Prudhoe Bay, Alaska, measured using a novel surface-towed marine EM system developed by the marine EM lab.



Background: An AUV equipped with electric field antenna about to dive on a hydrothermal field off Japan.

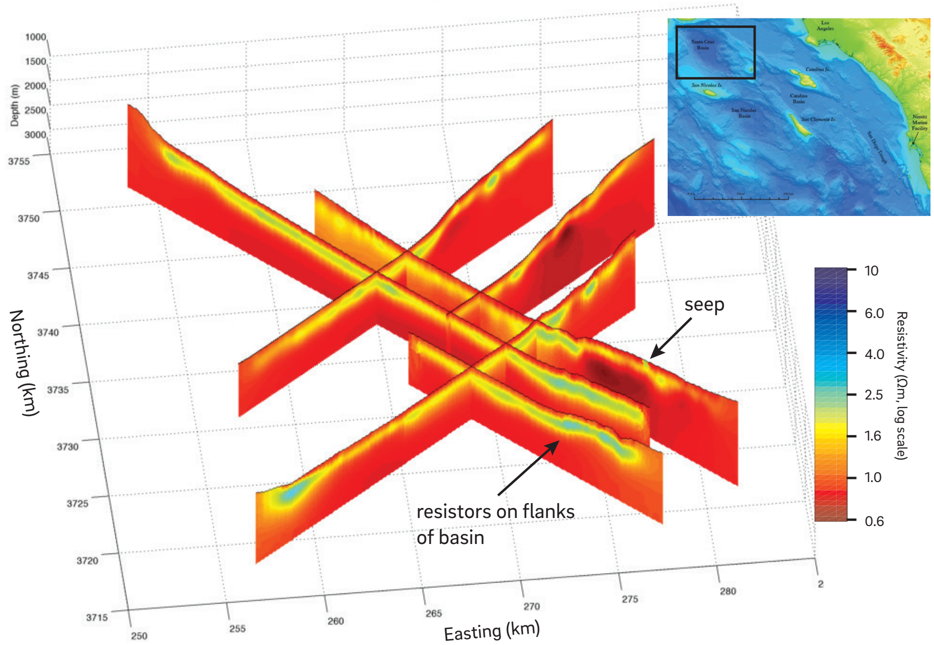


Figure 12. Electrical resistivity of the Santa Cruz Basin. Cool colors are resistors, showing that gas hydrate is associated with the flanks of the basin.

Dallas Sherman finished up her work on mapping arctic permafrost offshore Prudhoe Bay, Alaska, and graduated in March this year. Her results were published in Sherman and Constable (2018), which includes maps of depth and thickness of permafrost along nearly 200 km of coastline (Figure 11). The instrument we developed for this project was used off the west (Kona) coast of Hawaii in September this year to map offshore groundwater.

Peter Kannberg also graduated this year. Peter has been working on applying EM methods to mapping gas hydrate in the marine environment. He has been involved in several projects, some ongoing, which includes a comprehensive survey of the Santa Cruz Basin, offshore southern California. Although there are bottom-simulating reflectors, a seismic indicator of hydrate, throughout the middle of the Santa Cruz Basin, our results (Figure 12) show that gas hydrate, which is elec- trically more resistive than the host sediments, appears to accumulate at the margins of the basin, probably as a result of gas migrating along faults bounding the basin. We also see a vertical resistor that looks very similar to the resistor we imaged at the Del Mar Seep in the San Diego Trough, so we think we might have discovered a previously unknown seep in this basin.

RECENT PUBLICATIONS

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Barak, O., K. Key, S. Constable, and S. Ronen (2018): Recording active-ground rotations using induction-coil magnetometers, *Geophysics*, **83**, 1–24, 10.1190/GEO2017-0281.1

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. NSF recently renewed funding for an additional five years of GSN network operations via the IRIS Consortium.

To maintain the network in optimal working condition, IDA is in the process of replacing obsolete primary sensors with new models provided by our funding agency. Figure 13 shows one of these sensors being lowered into a 100m deep borehole to insure the quietest possible setting for recording distant earthquakes.

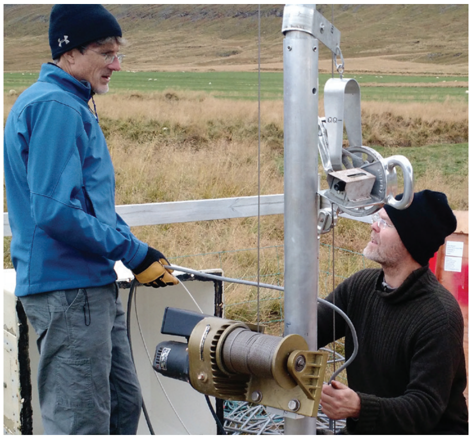


Figure 13. Dr. Carl Ebeling (left), IDA's chief engineer, and Bergur Bergsson (right) of the host Iceland Meteorological Office carefully lower a new seismometer package into the borehole at GSN station BORG (Borganes, Iceland). Photo courtesy C. Sites.

We are also installing infrasound sensors at several of our sites. In order to maximize data quality, we experimented with several types of spatial filters to suppress local wind noise. Figure 14 shows the test results of two such filters when they recorded signals created by a the launch of the Mars InSight probe from nearby Vandenberg AFB. We expect to record infrasonic waves from a wide variety of phenomena using these instruments.

IDA staff members are working to 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.

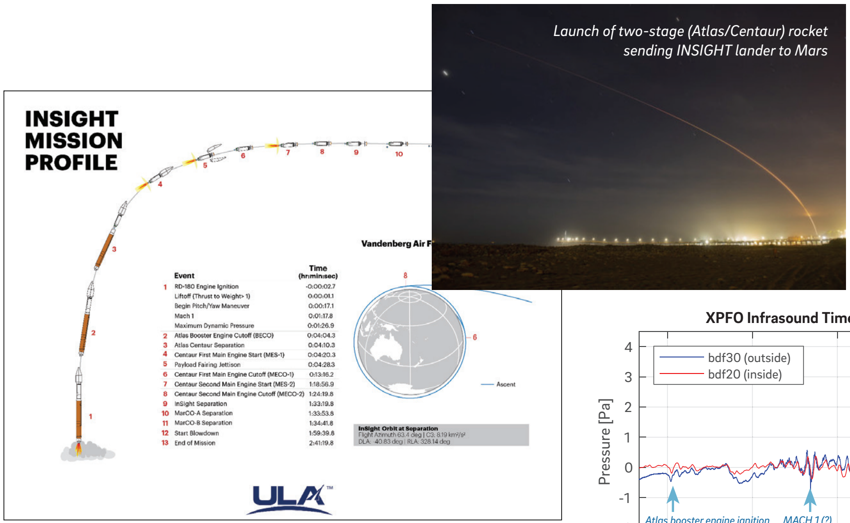
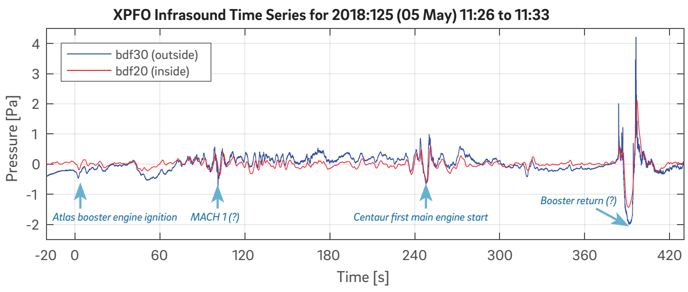


Figure 14. Infrasound sensors located at Pinyon Flat Observatory recorded the successful launch of the Mars INSIGHT mission from Vandenburg AFB on May 5, 2018. The pair of sensors, one with a flexible rosette hose filter (shown in red) and one with a rock pile noise reduction filter (shown in blue), recorded the event with differing quality. Courtesy C. Ebeling.Iceland). Photo courtesy C. Sites.



IDA is also 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 evaluate 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.

RECENT PUBLICATIONS

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

http://dx.doi.org/doi:10.1785/0220170280

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). There are two main reasons to develop this catalog. 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.

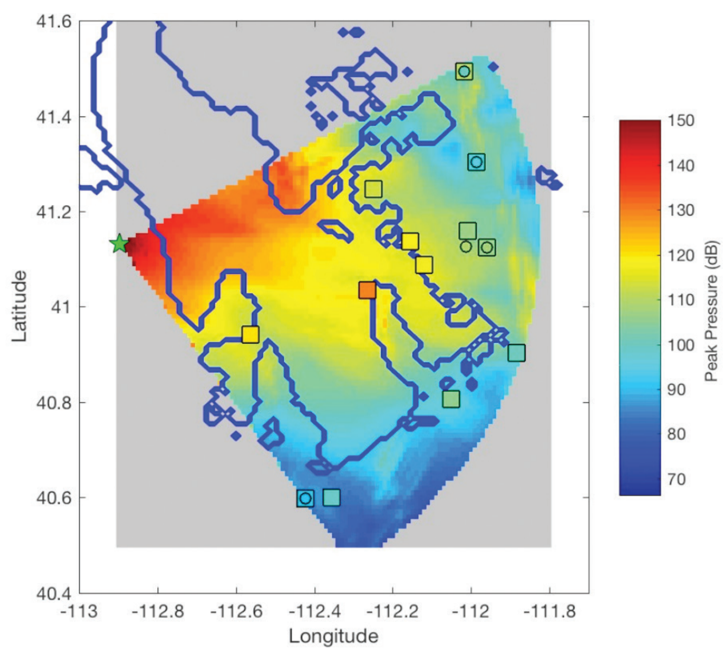

Figure 15. A map of predicted peak sound pressures for a 17,700 kg detonation at UTTR, which is marked by a green star. Winds carry the peak sound off to the northwest. Sound sensor sites, marked by squares and circles, are color-coded by the recorded peak sound pressure levels. Results show agreement within about 6 dB.

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 15.

RECENT PUBLICATIONS

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Hedlin, M.A.H., C.D. de Groot-Hedlin, J.M. Forbes, D.P. Drob, Solar Terminator Waves in Surface Pressure Observations, *Geop. Res. Lett,* https://doi.org/10.1029/2018GL078528

MATTHEW DZIECIUCH

Project Scientist

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

Low-frequency, long-range ocean acoustics experiments provide a wealth of knowledge about an otherwise opaque environment. The travel-time of sound waves propagating through the depths is affected by both small-scale and large-scale ocean processes. Acous.tical 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.

At the moment we are planning a new experimental program in the Arctic that would measure the heat content along a trans-Arctic path extending from near Svalbard to near the North Slope of Alaska. A map of the planned 2019 deployment is shown in Figure 16. Part of the motivation is to repeat a measurement done 25 years ago by Mikhalevsky et al. in order to see how much the acoustic propagation (and by inference, the heat content) has changed.

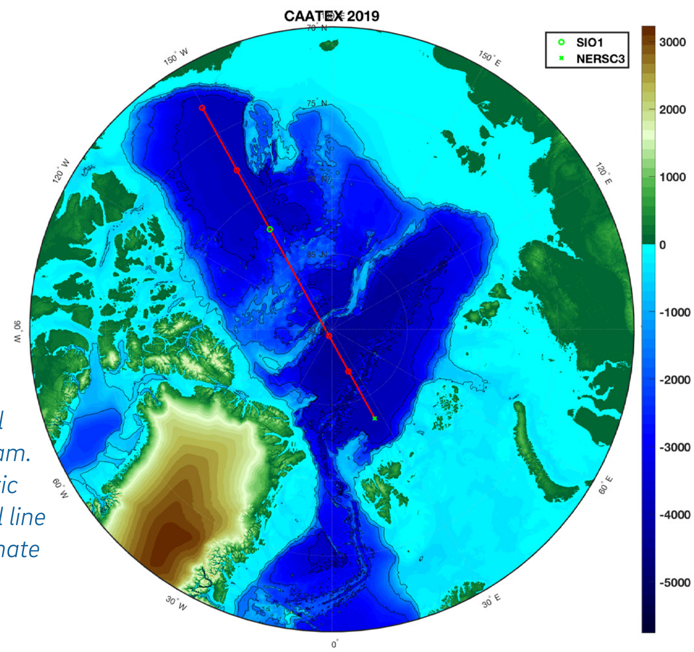

Figure 16. Proposed experimental layout of the CAATEX field program. The green dots desiginate acoustic transceivers (sources and vertical line arrays.) While the red dots designate acoustic receivers only.

A second motivation is that the acoustic equipment has much improved in the past twenty-five years and thus we will be able to obtain much finer detailed measurements. In.creased source effciency will allow us to produce a year long time-series from fixed moorings rather than a few transmissions from a drifting ice camp. Furthermore, advances in storage and clocks will allow for a much denser sampling of the acoustic field with 40 element vertical line arrays and an accurate time base will produce meaningful acoustic travel-times.

The sound source will operate near 35 Hz in order to avoid the rough ice-cover scattering losses associated with higher frequencies. The stratification of the Arctic is complicated has been changing rapidly in past few years. Above the deep Arctic water, there is the warm, salty Atlantic layer, the less salty but cold Pacific winter water, then the warmer Pacific summer water, while on top is fresher but cold water either from the melting ice or from the large amount of river inflows. The composition and thicknesses of these layers have been greatly affected by climate change and thus acoustic propagation through these layers has also been affect. The experiment has been designed to learn the most possible from the acoustic travel-time, transmission loss, and scattering loss as the sound interacts with the stratification and with the rough ice-cover.

The field program will deploy in 2019, collect data for one year and then be recovered in 2020. This experiment is being conducted with funding from the Office of Naval Research, they have supported the CAATEX preparations as well as previously deployed experiments, to further our ability to monitor and understand the changing Arctic.

RECENT PUBLICATIONS

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Ozanich, E., Gerstoft, P., Worcester, P., Dzieciuch, M., and Thode, A., (2017) Eastern Arctic ambient noise on a drifting vertical array, *J. Acoust. Soc. Am.,* 142, 1997-2006.

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 seismo-genic 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 how the Earth's crust responds to seismic and magmatic loading.

One of the long-term research interests of Prof. Fialko is the interseismic deformation due to active faults in Southern California. Southern California hosts a number of active faults, including major plate boundary faults such as the San Andreas and the San Jacinto faults. A recent report by the USGS estimates a 60% probability of a major (magnitude greater than 6.7) event in Southern California over the next 30 years. Evaluation of seismic hazard is based primarily on historic seismicity and long-term fault slip rates inferred from paleoseismic data. Geodetic observations provide an important ad- ditional source of information about present-day accumulation of strain in the seismogenic upper crust. A major outstanding question is whether geodetic observations can help identify areas of seismic hazard that haven't been recognized based on available seismic and geologic data. While mature faults such as the San Andreas fault by and large have clear expression in geomorphology, young developing faults and fault zones may be more difficult to recognize. In order to better understand a potential contribution of geodetic observations to estimates of seismic hazard in the region, Prof. Fialko and a former graduate student Katia Tymofyeyeva (now a postdoc at JPL/Caltech) used Interferometric Synthetic Aperture Radar (InSAR) and GPS data to map surface deformation at the southern end of the San Jacinto fault zone. Fialko and Tymofyeyeva combined data from the ascending and descending satellite orbits with an additional constraint provided by the azimuth of the horizontal component of secular velocities from GPS data to obtain horizontal and vertical components of the surface velocity field. The resulting high-resolution surface velocities were then differentiated to obtain a map of shear strain rates (Figure 17a).

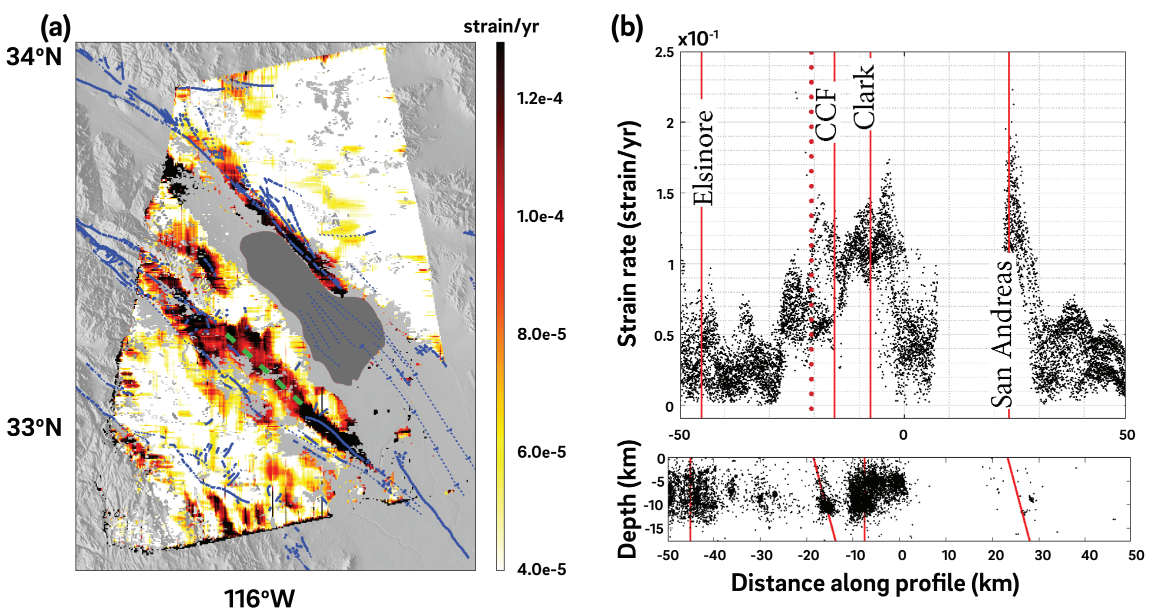

Figure 17. a) Maximum shear strain rates, obtained from regularized differentiation of the horizontal velocity data. The green rectangle outlines the profile across the faults, and the selected data points from the profile are shown in the next panels. b) Top panel shows the strain rate data selected from within the same area as the profile in panel a). The vertical red lines show the locations of each of the modeled faults at depth. The bottom panel shows the cross-section with seismicity denoted by black dots. From Tymofyeyeva and Fialko (2018).

The computed shear strain rates reveal localized deformation along known active faults. Some of these faults are associated with shallow creep, for example the southern San Andreas and the Superstition Hills faults, which may contribute to high apparent strain rates at small spatial wavelengths on the order of pixel size (< 1 km). However, the computed strain rate anomalies are sufficiently broad to indicate interseismic deformation within the locked seismogenic layer. The spatial pattern and location of the deformation zone at the southern end of the San Jacinto fault lend support to the hypothesized active blind segment that connects the Clark fault to the Superstition Hills fault. This interpretation is further supported by a localized lineament of seismicity extending to the south-west from the southern tip of the mapped trace of the Clark fault. The blind southern segment of the Clark fault thus appears to be the main active strand of the San Jacinto fault, posing a currently unrecognized seismic hazard.

In another recent study Prof. Fialko and a former graduate student Kang Wang (now a postdoc at UC Berkeley) investigated how the Tibetan lithosphere responded to the 2015 M_W 7.8 Gorkha (Nepal) earthquake that occurred along the central Himalayan arc. This study involved analysis of space geodetic observations including InSAR data from Sentinel-1A/B and ALOS-2 satellites, as well as GPS data from a local network.

InSAR observations revealed an uplift of up to ~70 mm over ~20 months after the mainshock, concentrated primarily at the downdip edge of the ruptured asperity. This is in agreement with the GPS observations that also show uplift, as well as southward movement in the epicentral area, qualitatively similar to the coseismic deformation pattern. Kinematic inversions of GPS and InSAR data, and forward models of stress-driven creep suggest that the observed postseismic transient is dominated by afterslip on a down-dip extension of the seismic rupture. All tested visco-elastic models predict opposite signs of horizontal and vertical displacements compared to those observed. Available surface deformation data therefore appear to rule out a hypothesis of a low viscosity channel beneath the Tibetan Plateau which has been previously invoked to explain the lon-term uplift and variations in topography at the plateau margins

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Wang, K. and Y. Fialko, Observations and modeling of co- and post-seismic deformation due to the 2015 M_W 7.8 Gorkha (Nepal) earthquake, *J. Geophys. Res.,* **123**, 761-779, 2018.

Tymofyeyeva, E. and Y. Fialko, Geodetic evidence for a blind fault segment at the Southern end of the San Jacinto Fault Zone, *J. Geophys. Res.,* **123**, 878-891, 2018.

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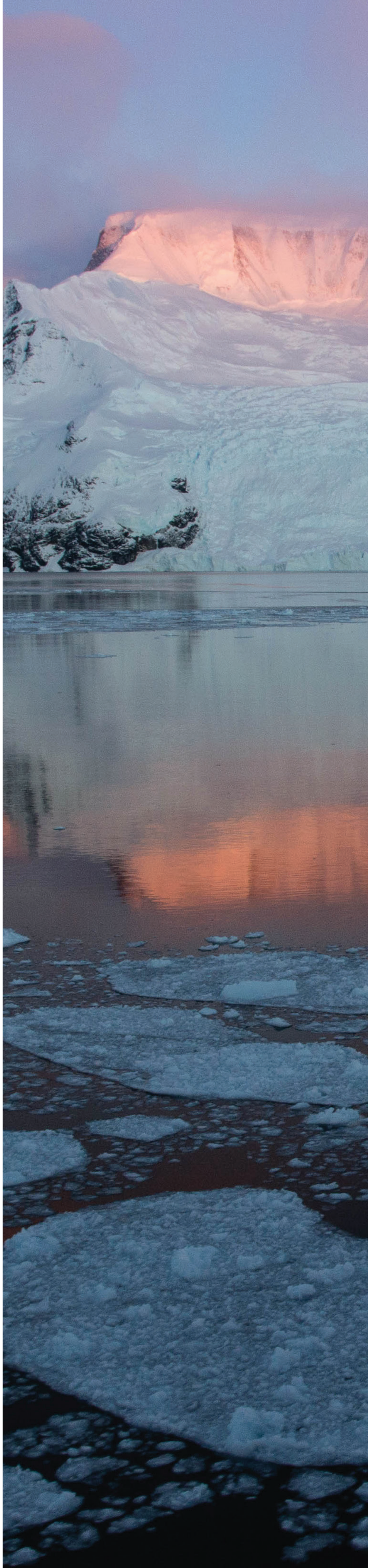

HELEN AMANDA FRICKER

Professor, John Dove Isaacs Chair

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

We are located in MESOM with OA Prof Fiamma Straneo, forming the core of the Scripps Polar Center, which will roll out in 2019. I was on sabbatical at IMAS, Hobart, from January to July 2018. I was a member of the ICESat Science Team & am a member of ICESat-2 Science Team. I was on the Steering Committee of the NAS Decadal Survey Earth Science & Applications from Space. I became an AGU Fellow in December 2017.

My group's research focuses on understanding the processes driving changes on the Antarctic ice sheet. One of the main unknowns is Antarctica's current contribution to global sea level rise, and predicting how that will change in the future. Because Antarctica is so large, and the time scales on which it changes are so long (decades to centuries), the only viable way to monitor it is with satellites. The main techniques we use are satellite altimetry (radar altimetry from ESA's ERS-1/ERS-2/Envisat (1994-2012) or laser altimetry from NASA's Ice, Cloud & land Elevation Satellite (ICESat 2003-2009) & ICESat-2 (launched 15 September 2018); together these multiple missions have provided height data for ice sheet change detection for 25 years. We validate ICESat and ICESat-2 elevations using ground-truth data in places like the salar de Uyuni in Bolivia (with IGPP Prof Adrian Borsa). Using the long, continuous altimeter records we can learn about the processes that are leading to accelerated mass loss. **We focus mainly on two key dynamic components of the Antarctic ice-sheet system: (i) floating ice shelves & (ii) active subglacial lakes.**

i. Ice Shelves: ice shelves surround Antarctica and are where most of the mass loss takes place. Since ice shelves are floating, 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 & retreat result in enhanced ice discharge across the grounding line (GL) to the ocean (Figure 18). Our group specializes in monitoring Antarctic ice shelves from satellite altimetry (radar and laser). Funded by NASA, we generate estimates of ice-shelf surface height continuously since the early 1990s and use these to understand the mass loss processes from ice shelves. These data revealed accelerated losses in total Antarctic ice-shelf volume from 1994 to 2012. In East Antarctica, the first half of the record showed a mass increase, likely a result of increased accumulation. In West Antarctica,

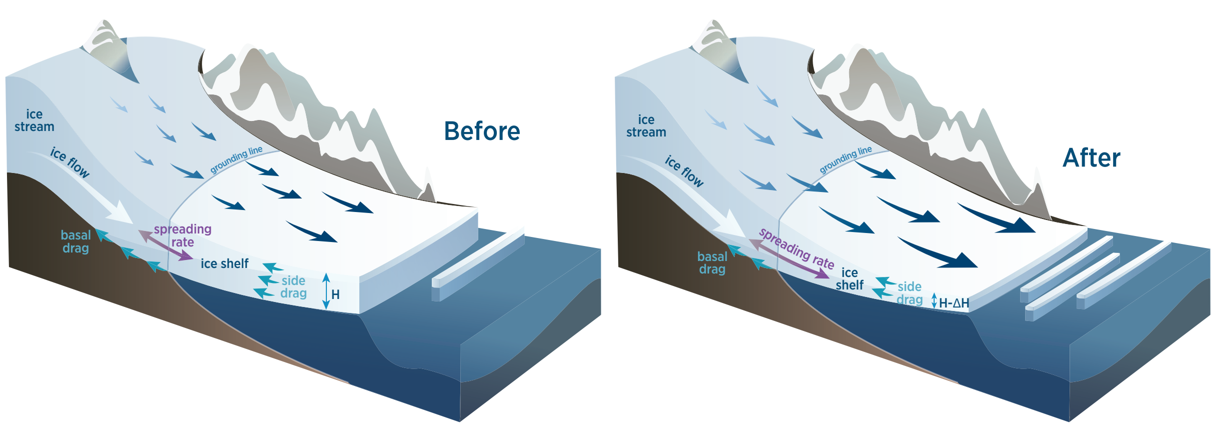

Figure 18. ***Ice shelf buttressing and GL flux.*** *Confined ice shelves restrain the flow of upstream tributaries. Ice-shelf thinning increases the longitudinal stress and with it the spreading rate at the GL. This effect is felt some distance upstream, and net result is an increase in GL ice-flux.*

in particular the Bellingshausen and Amundsen Sea regions, ice shelves lost mass throughout the record with changes on multi-year time scales[4]. 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 & resulting sea level. GP student Susheel Adusumilli generated updated time series for 1994 to 2017, & published in a paper in GRL for the Antarctic Peninsula[3]. In West Antarctica, the height changes 1994-2017 are correlated with ENSO[7]. We wrote an article in *The Conversation* **"Short-term changes in Antarctica's ice shelves are key to predicting their long-term fate"** (June 2018) to coincide with a Special Issue of *Nature*[1,2].

I am a PI on an NSF project ROSETTA-Ice to investigate the Ross Ice Shelf using airborne geophysics (gravity, laser & radar). GP student Maya Becker participated in the 2016-17 & 2017-18 field seasons and is comparing those data with ICESat & ICESat-2 data. Postdoc Cyrille Mosbeux is an ice-sheet modeler looking at how the grounded ice responds to change in the ice shelf.

ii. Subglacial Lakes: The Antarctic Ice Sheet is on average 2.2 km thick & rests on top of bedrock; the insulation, high pressure & 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 & subglacial aquifers. In 2006, I discovered active subglacial water systems under the fast-flowing ice streams of Antarctica using ICESat. This was inferred from observations of large height changes (up to 10m in some places) in repeat-track ICESat data, which corresponded to draining & filling of subglacial lakes beneath 1-2 km of ice. We continue to monitor active lakes & have found 124 in total throughout Antarctica. Much progress has been made in our understanding of these dynamic systems; in 2018 we extended the record of volume change for all lakes under the CryoSat-2 mask up to 2017[5].

I was PI on an interdisciplinary 6-year NSF project (Whillans Ice Stream Subglacial Access Research Drilling (WISSARD)) to drill (in January 2013) into one of the subglacial lakes–Subglacial Lake Whillans (SLW) on Whillans Ice Stream (WIS)–and the region of the GL across which the subglacial water flows & enters the ocean. A current NSF-funded 5-year project Subglacial Antarctic Lakes Scientific Access (SALSA) is about to undergo its main field season & Matt Siegfried is leading the geophysics team, which includes former IGPP Professor Kerry Key and GSR Chloe Gustafson to make EM measurements, and will culminate in drilling of Mercer Subglacial Lake in December 2018.

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[1] Rintoul, S. R., S. L. Chown, R. M. Deconto, M. H. England, H. A. Fricker, V. Masson-Delmotte, T. R. Naish, M. J. Siegert, & J. C. Xavier (2018). Choosing the future of Antarctica. *Nature.* **558**: 233-247. https://doi.org/10.1038/s41586-018-0173-4.

[2] Shepherd, A., Fricker H.A., Farrell S.L. (2018) Trends & connections across the Antarctic cryosphere. *Nature.* **558**:223-232. 10.1038/s41586-018-0171-6.

[3] Adusumilli, S., Fricker H.A., Siegfried M.R., Padman L., Paolo F.S., Ligtenberg Srm (2018) Variable basal melt rates of Antarctic Peninsula ice shelves, 1994-2016. *Geophysical Research Letters.* **45**:4086-4095. 10.1002/2017gl076652.

[4] Minchew, B.M., Gudmundsson G.H., Gardner A.S., Paolo F.S., Fricker H.A. (2018) Modeling the dynamic response of outlet glaciers to observed ice-shelf thinning in the Bellingshausen Sea Sector, West Antarctica. *Journal of Glaciology.* **64**:333-342. 10.1017/jog.2018.24.

[5] Siegfried, M.R., Fricker H.A. (2018) Thirteen years of subglacial lake activity in Antarctica from multi-mission satellite altimetry. *Annals of Glaciology.* **59**:42-55. 10.1017/aog.2017.36.

[6] Padman, L., Siegfried M.R, Fricker H.A. (2018) Ocean tide influences on the Antarctic & Greenland ice sheets. *Reviews of Geophysics.* **56**:142-184. 10.1002/2016rg000546.

[7] Paolo, F. S., L. Padman, H.A. Fricker, S. Adusumilli, S. Howard, M. R. Siegfried (2018) Rapid response of West Antarctic ice shelves to ENSO variability, 1994-2017, *Nature Geoscience,* **11**:121-+. 10.1038/s41561-017-0033-0.

[8] Roberts, J. B. K. Galton-Fenzi, F. S. Paolo, C. Donnelly, D. E. Gwyther, L. Padman, D. Young, R. Warner, J. Greenbaum, H. A. Fricker, A. J. Payne, S. Cornford, A. Le Brocq, T. Van Ommen, D. Blankenship & M. Siegert (2018). Ocean forced variability of Totten Glacier mass loss. *Geological Society, London, Special Publications,* **461**(1), 175-186.

MICHAEL A.H. HEDLIN

Research Geophysicist

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

INFRASOUND: The study of subaudible sound, or infrasound, has emerged as a new frontier in geophysics and acoustics. We have known of infrasound since 1883 with the eruption of Krakatoa, as signals from that event registered on barometers around the globe. Initially a scientific curiosity, the field briefly rose to prominence during the 1950's and 1960's during the age of atmospheric nuclear testing. With the recent Comprehensive Test-Ban Treaty, which bans nuclear tests of all yields in all environments, we have seen renewed interest in infrasound. A worldwide network of infrasound arrays, being constructed for nuclear monitoring, is fueling basic research into man-made and natural sources of infrasound, how sound propagates through our dynamic atmosphere and how best to detect infrasonic signals amid noise due to atmospheric circulation. This network has been supplemented with deployments, such as the 400-station seismo-acoustic USArray Transportable Array (TA), for basic research and enhanced monitoring of regions of great interest.

RESEARCH AT L2A: The Laboratory for Atmospheric Acoustics (L2A) is the home of research in this field at IGPP. Several faculty, post-docs and PhD students work full or part time in L2A, supported by engineers and technicians in the lab and the field. More information about this lab can be found at l2a.ucsd.edu. Presently we study a broad suite of problems related to both natural and man-made sources.

DENSE NETWORK STUDIES: The global infrasound network is unprecedented in scale however it is still very sparse, with ~ 100 stations operating worldwide. To increase the density of sampling of the infrasonic wavefield we have used acoustic–to-seismic coupled signals recorded by dense networks, such as the 400-station USArray Transportable Array (TA) and various PASSCAL deployments. We have used the original (seismic-only) TA network to create a catalog of atmospheric events in the western United States similar to commonly used seismic event catalogs. The acoustic catalog is used in part to find sources of interest for further study and to use the recorded signals to study long-range infrasound propagation. Recorded signals

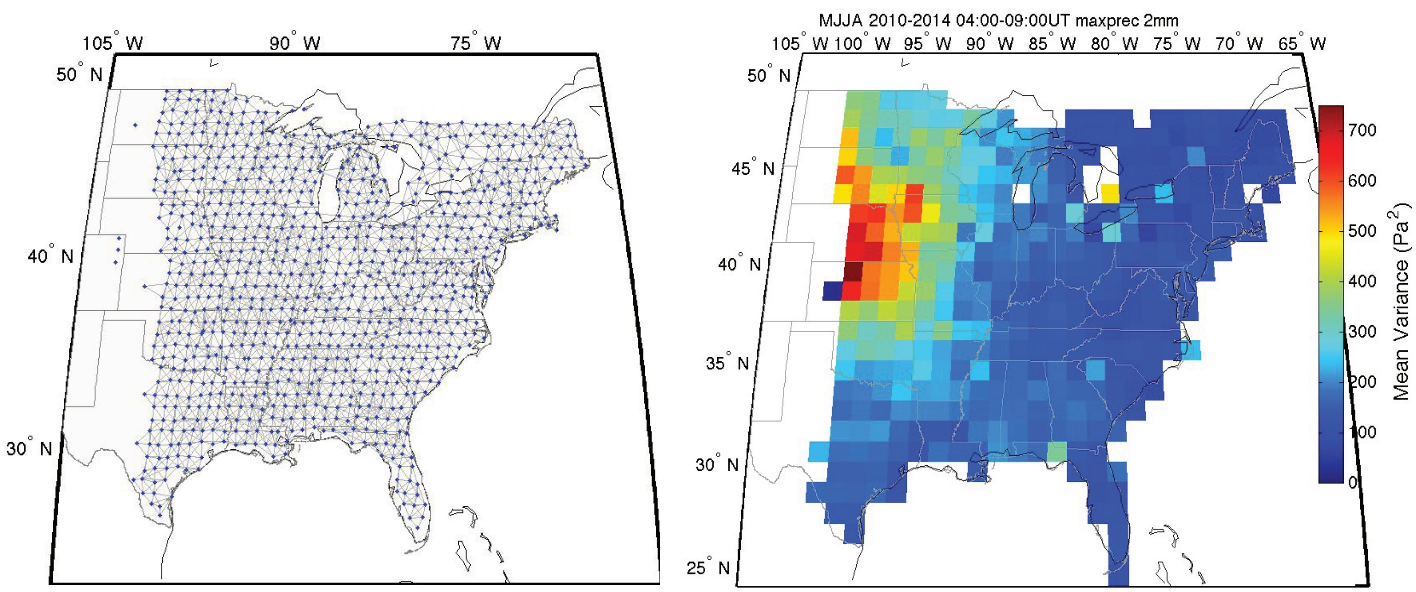

Figure 19. (left) sites occupied by stations in the TA from January 1, 2010 through Sept 30, 2014. These stations have been grouped into 3-element arrays (triads) for the study of long-period atmospheric gravity waves. The panel on the right shows the variance of atmospheric pressure in the 2-6 hr passband 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.

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 19 (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 19. 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.

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Hedlin, M.A.H., de Groot-Hedlin, C.D., Ritsema, J., Hetland, E., 2018, A multidisciplinary study of the January 17, 2018 bolide terminal burst over southeast Michigan, *Seismological Research Letters*, **89** (6): 2183-2192, https://doi.org/10.1785/0220180157.

DEBORAH LYMAN KILB
Project Scientist

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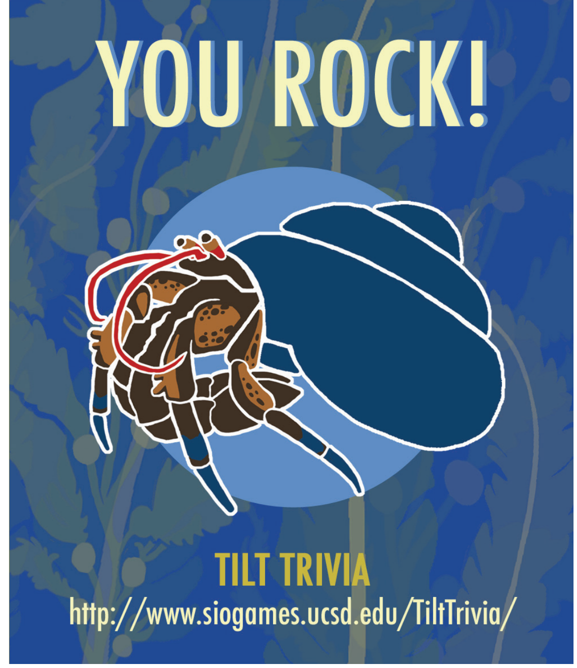
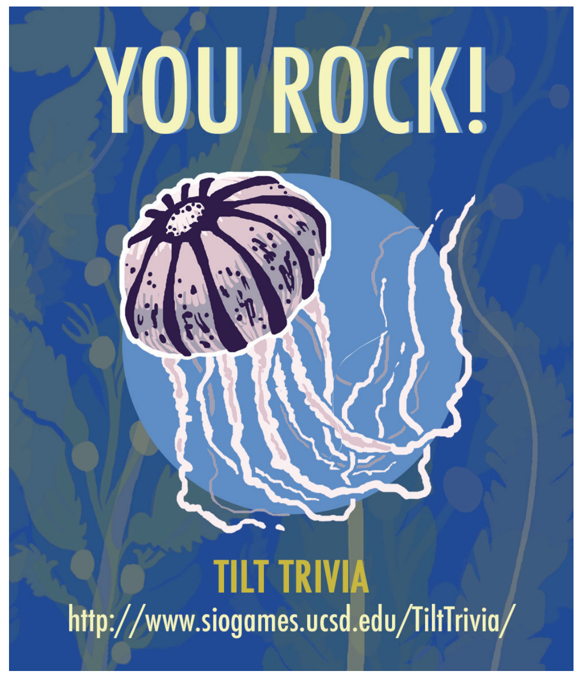
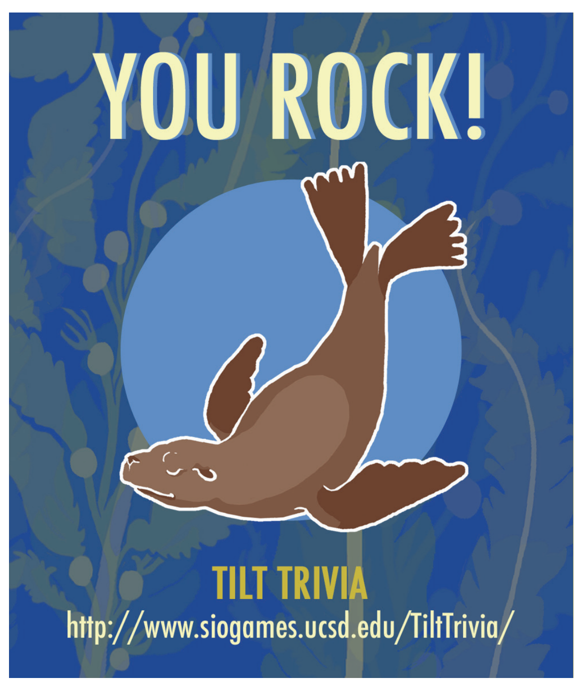
Research Interests: Crustal seismology, earthquake triggering, and earthquake source physics. Diversity Interests: Improving how science is communicated to students and the public

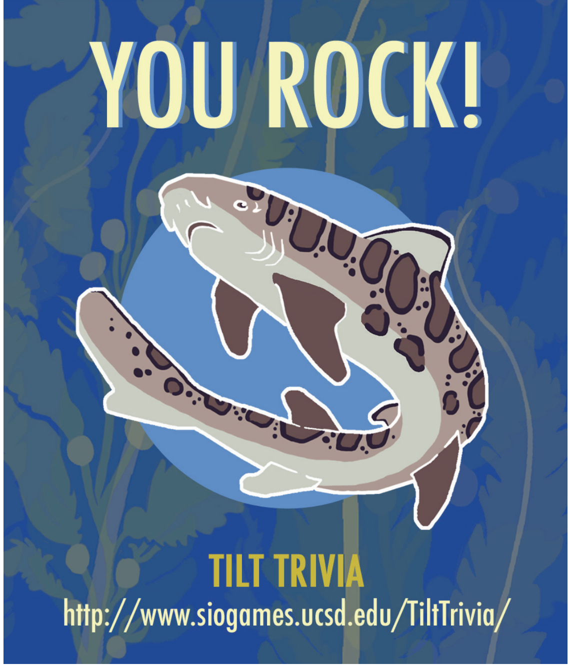
A frequency-domain approach to identify small earthquakes [Linville et al., 2018]. We develop a frequency-domain, array-based detection algorithm, which exploits the gridded nature of the Transportable Array network (~400 stations), to detect and locate small (-0.25≤ M< 2) earthquakes. Applying our new method to data from three sedimentary basins in the Central United States, we can increase the catalog size three-fold (from 140 to 562 events). A majority of the newly detected seismicity in the Permian and Denver-Juleseburg basins may be linked with induced seismicity, while in the Williston Basin there continues to be little evidence of induced sequences. We apply single-link clustering and sub-space detection methods to our data and find some regions have very similar sources (i.e., a limited number of subspace families) while others are extremely variable (up to 38 subspace families). Because our method requires no preconceived assumptions about the source waveform characteristics, our algorithm can be used to successfully find signals of unknown source types.

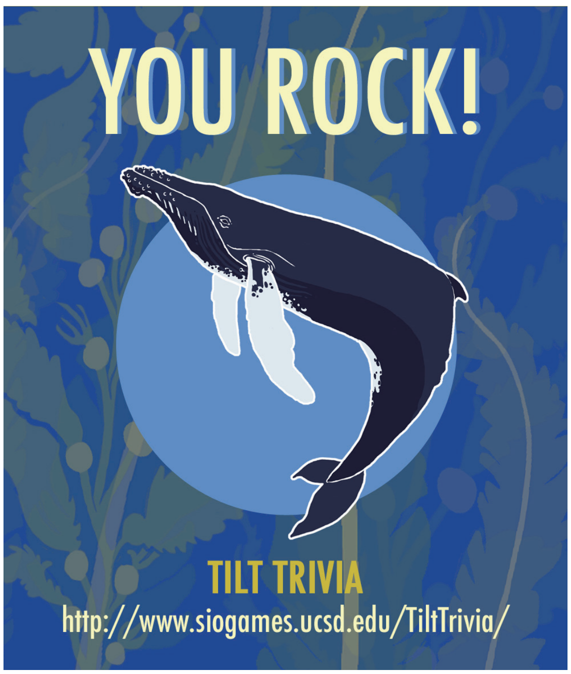
Ground motion prediction equations [Sahakian et al. 2018a; Sahakian et al., 2018b]. Ground-motion prediction equations (GMPEs) are critical elements of probabilistic seismic hazard analysis (PSHA). To improve models of ground-motion estimation and PSHA, the engineering seismology field is moving towards developing fully non-ergodic ground-motion models, or models of ground-motion estimation that are specific to individual earthquake-to-station paths. Previous work on this topic has been in a purely empirical sense, by examining systematic variations in ground-motion along particular paths (from either recorded or simulated earthquake data) and has not included physical properties of the path within the ground-motion models. In our work, we present a framework that includes path properties, by seeking relationships between ground-motion amplitudes along specific paths, and crustal properties along that path. This allows us to obtain crustal models in a seismically quiet region and apply the relationships identified in a forward sense. We apply our method to Southern California data, and find that path effects are primarily controlled by the heterogeneity in the regional velocity model. We also find, however, that the time-averaged shear-wave velocity in the top 30 meters at a site (VS30) has minimal correlation with the site terms, exhibiting correlation coefficients (Pearson's R-values) below 0.03. These results suggest future ground-motion studies should incorporate peak ground acceleration site correction terms.

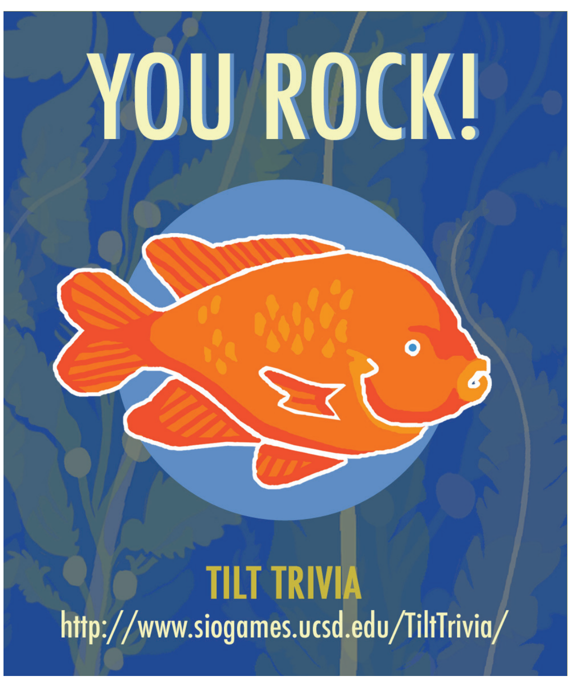












DIVERSITY ACTIVITIES (October 2017-September 2018)

Sally Ride Science Summer Academy for Girls [SRS 2017]: We designed a TILT TRIVIA app that has a suite of quiz-style, multiplayer games for use on mobile devices and tablets (Android or Apple) to help students learn simple definitions and facts. A single game consists of 6-10 questions and takes 3-7 minutes to complete, allowing up to 5 players to play simultaneously in the same game space. To begin, players select a topical avatar to represent them in the game (Figure 20). While in the competitive playing field, players are presented with a question and then they simply "tilt" their tablets until their avatar rests on the correct answer marker (i.e., true or false). Because the playing field is constantly tilting, keeping your avatar on the correct answer requires a continual counter-tilting motion of the tablet to maintain your position within the game. Players have the option of jostling other players off of the correct answer in the hopes of netting the highest score.

Sally Ride Science Summer Academy for Girls: I was integral in putting in place the classes and instructors for the 2018 Sally Ride Science (SRS) Summer Junior Academy that took place at Mission Bay High School. In this capacity I selected and vetted the instructors and classes. The 2018 Academy ran for 4-weeks, offering 123 classes. A total of 692 middle- and high-school age students enrolled in the classes. Of the 38 instructors in the 2018 Academy, 14 were SIO affiliated.

Library NExT: Hired instructors and vetted classes for the Library NExT (Network of Education x Training) program. This program offers free classes for middle- and high-school students at local libraries. Since its launch in January 2017, the program has provided ~600 hours of instruction to ~1500 students.

The Great California Shake Out: For the sixth year in a row, I partnered with the Birch Aquarium at Scripps participating in their annual Great California Shake Out event. I was on site to discuss current seismology research at Scripps, real-time seismic data and earthquake preparedness.

Invited speaker: UCSD Women's Conference (speaker and panelist).

Invited speaker: Panelist for Q&A discussion following a showing of the block-buster movie SAN ANDREAS, Elementary Institute of Science.

Outreach: STEM club (Ocean Knoll Elementary; presenter), Science Nights (assisted with 5 programs).

Figure 20. Sample cartoon avatars used to represent a TILT TRIVIA player. We align the genre of the avatars with the game topic. These avatars are used in our oceanographic TILT TRIVIA games, and were designed by SIO GAMES Caroline Fleet.

RECENT PUBLICATIONS

Kilb D., A. Yang, N. Garrett, K. Pankow, J. Rubinstein and L. Linville [2018]. “Tilt trivia: a free multiplayer app to learn geoscience concepts and definitions”, *Seismological Research Letters,* **89**: 1908-1915. https://doi.org/10.1785/0220180049. (http://siogames.ucsd.edu/TiltTrivia/index.html).

Linville L.M., K. L. Pankow, D. Kilb [2018]. “Contour-based Frequency-domain Event Detection for Seismic Arrays”, *Seismological Research Letters,* **89**: 1514-1523, doi: 10.1785/0220170242 2018.

Sahakian V., A. Baltay, T. Hanks, J. Buehler, F. Vernon, and D. Kilb [2018]. “Decomposing leftovers: Event, path, and site residuals for a small-magnitude ANZA region GMPE”, *Bull. Seism. Soc. Am.,* **108**: 2478-2492. https://doi.org/10.1785/0120170376.

Sahakian V., A. Baltay, T. Hanks, J. Buehler, F. Vernon, D. Kilb and Norm Abrahamson [2018]. “Ground-Motion Residuals, Path Effects, and Crustal Properties: A Pilot Study in Southern California”, *Journal of Geophysical Research,* In Press.

GABI LASKE

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Research interests: Regional and global seismology; surface waves and free oscillations; seis- mology 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 assemble improved mantle models.

Global reference models: Laske continues collaboration with Guy Masters and for- mer 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 rely- ing on CRUST1.0 are found across multiple disciplines in academia and industry. Laske maintains the distribution website and provides guidance to users.

The AnICEotropy project: Laske has been collaborating with Fabian Walter and his grad- uate student Fabian Lindner at ETH, Switzerland to study ice quakes on the Glacier de la Plaine Morte, Switzerland (Figure 21). 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

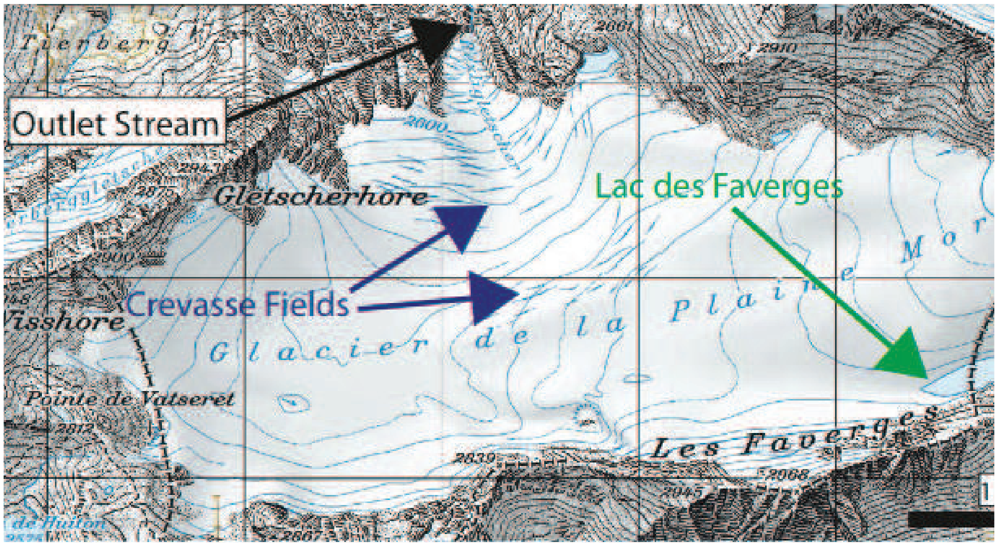

Figure 21. Map of Glacier de la Plaine Morte just south of Wildstrubel, Switzerland. The Rhone valley is to the south. Marked is the outlet stream at the toe of Rexliglacier that drains into the Simme river to the north. Arrows mark Lac des Faverges, a major glacier lake, and the two crevasse fields 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.

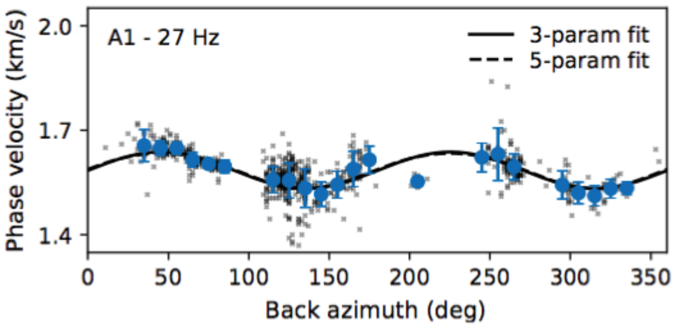

Figure 22. Measured azimuthal anisotropy at 27 Hz at array A1. Azimuthal anisotropy is mod- eled by a truncated trigonometric polynomial of degrees 2 and 4 in back azimuth. A decline of az- imuthal anisotropy with decreasing frequency (not shown) indicates a shallow (20-30 m) origin for the anisotropy.

Simme valley to the north. Recent floods have become more frequent and larger, approaching the capacity of the flood control system. In 2016, Laske, her student

Adrian Doran, and collaborators conducted an field experiment to identify precursory ice quake activity that helps improve early flood warning. As a by-product, the gathered seis- micity allowed a 'sandbox' azimuthal anisotropy analysis to test the hypothesis that seismic anisotropy is aligned with the crevasses on the glacier. Laske was the lead mentor for Fabian Lindner in the analysis of azimuthal anisotropy. She and student Adrian Doran took over modeling for anisotropy with depth (Figure 22). A paper is in press.

The PLUME project: For the past decade or so, Laske has analyzed waveforms col- lected 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 func- tion studies were published. The PLUME dataset also provides the basis for PhD student Adrian Doran who studies seafloor compliance and ambient-noise Green's functions. His work helps 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 a first-ever application to real OBS data, and a paper was published previously. He has presented his work at several domestic conferences as well as the 2018 EGU general assembly. A new manuscript is under review. 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 published last year, and the Python computer code is available on our website for general use.

The CABOOSE project: The California Borderland Ocean Seismicity project (CA- BOOSE) is a collection of past present and future small OBS deployments to assess seismic- ity off-shore Southern California. For the ADDOSS (Autonomously Deployed Deep-ocean Seismic System) project, Laske collaborated 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. During the 3-month deep-water test about 300 km west of La Jolla, never-be- fore seen seismic activity was observed in the Outer Borderland. Doran and Laske returned in the summers of 2015, 2017 and 2018 on UC ship fund cruises to continue investigation of the Borderland seismicity in more detail. this year, they collected data on the San Clemente Fault while two M=3.0 quakes occurred in close proximity. Analysis of these data are underway. For the most recent deployment, mechanical engineer Martin Rapa developed an in-situ calibration frame for the pressure sensor to help better understand the still poorly known instrument response of that sensor. Laske's graduate student Adrian Doran is leading the data analysis.

RECENT PUBLICATIONS

Lindner, F., Laske, G., Walter, F. and Doran, A.K., Crevasse-induced Rayleigh-wave azimuthal anisotropy on Glacier de la Plaine Morte, Switzerland. *Annals of Glaciology*, in press, 2018.

Doran, A.K. and Laske, G., Lateral heterogeneity of the upper oceanic crust and sediments. *Geophys. Res. Abstr.,* **20**, EGU2018-1903, 2018.

JOHN ORCUTT

Distinguished Professor of Geophysics, Editor-in-Chief of AGU Earth and Space Science

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Research Interests: Seafloor seismology and acoustics including applications to nuclear test ban treaty verification. Large scale data management and access.

Students and Funding: Research for thI completed my term as Editor-in-Chief of AGU's new journal Earth & Space Sciences at the end of 2018. I started the journal five years ago as an experiment in open access that bypassed the need for scientific paper fees for any reader. The content focused on the publication of details of instrument construction, testing and applications in order to provide a peer-reviewed journal for scientists and engineers that were involved in developing, testing, calibrating and deploying new instruments. The journal was quite successful and grew throughout the five years including an excellent citation index in 2018. One of the most successful areas involved the Mars Rovers and the use of the instruments for collecting data that were used in unanticipated ways including the collection of dust on the vehicles and implications for Martian winds.

Differential Pressure Gauges (DPG) were developed in the mid 1980's at Scripps by Charles (Chip) Cox, Tom Deaton and Spahr Webb. The pressure gauge relied upon measuring the differential pressure between the deep ocean and a confined pressure chamber in the gauge. The differential pressure was measured with a small strain gauge while the reference chamber was connected to ambient pressure via a capillary leak formed with a standard hypodermic needle. The leak ensured that the reference chamber did not deform as pressures increased. The DPG has been effectively used to measure deformation at the seafloor caused by long waves

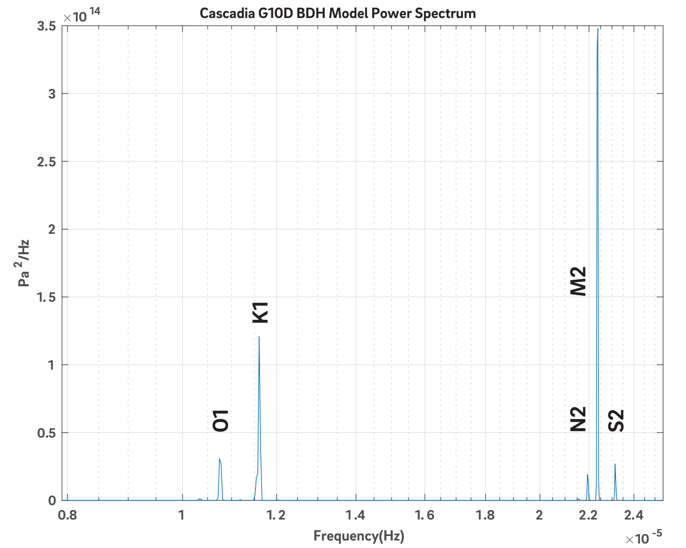


Figure 23. The power spectrum for the best fit tidal model obtained by using the Welsh method is plotted in this figure.

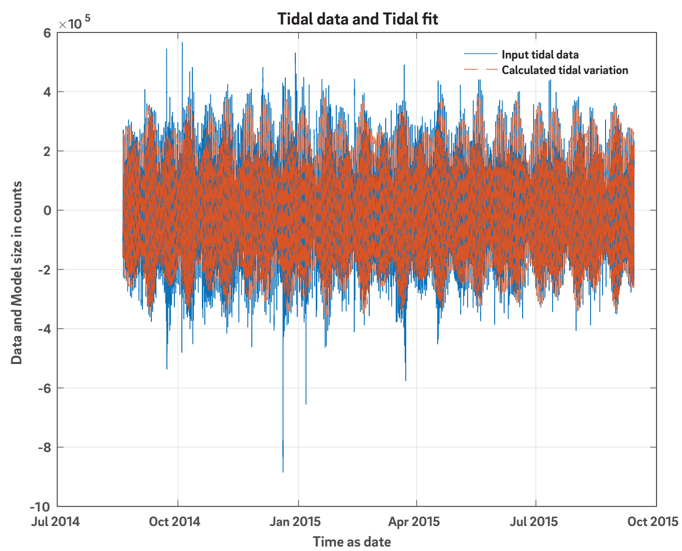
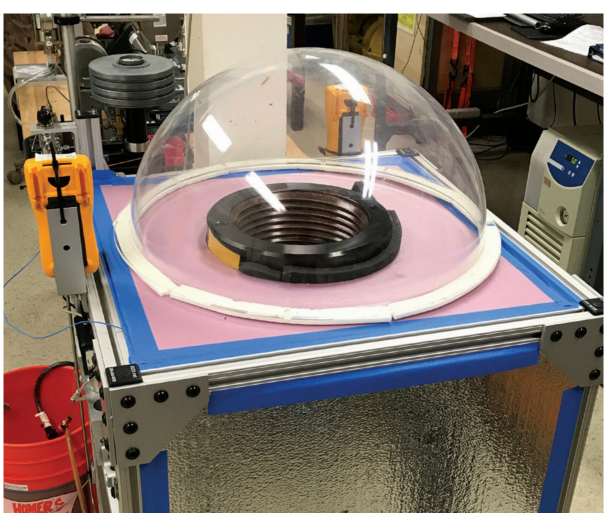


Figure 24. This figure overlays the best fitting tidal model (red) with the raw data (blue).



passing overhead at frequencies >1mHz. Jon Berger and I found that the gauges were also effective in recording tides at semidiurnal and diurnal frequencies as well as the fortnightly tides. Since the great successes of radar altimetry have provided accurate tidal models, we have been able to use measurements of times (in particular) to calibrate seafloor DPG's with considerable accuracy at very low frequencies >20μHz. The tides M2, K1, O1, S2, and N2 are particularly useful in this calibration. These tidal lines are apparent in the power spectrum in Figure 23. Figure 24 is a plot of the tidal signal on an ocean bottom seismograph deployed for a year offshore Oregon—the fit of the observed tides are nearly identical to the measured tides although many earthquakes were observed with signals larger than the tides. Using this information, we have been able to calibrate the instruments in-situ and we've been able to significantly extend the calibration to frequencies as low as 1μHz. Glenn Sasagawa, Martin Rapa and I have constructed a laboratory device that is capable of calibrating the DPGs at higher frequencies. The instrument is shown in Figure 25. We have found problems associated with the mechanical system and we're working to replace critical components with higher-quality hardware. We anticipate that we will be able to measure accurately the calibration of the DPGs over a very useful band.

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Berger, J., Laske, G., Babcock, J. and Orcutt, J., An Ocean Bottom Seismic Observatory with Near Real-time Telemetry, *Earth and Space Sci.,* doi: 10.1002/2015EA000137, 2016.

Figure 25. We have constructed a laboratory DPG calibration chamber, with support from the Navy based on unexpended funds from a previous design contract for nuclear test detection. This required the construction of a reaction vessel large enough to accommodate a DPG. This figure shows the vessel with the top plug removed. The vessel is placed inside an insulated enclosure; cooling liquid hoses and a liquid cooking refrigerator are shown in the right-hand frame of the photograph. A Paroscientific 410K gauge is visible in the center. Digital voltmeters and temperature sensors are used to measure the inside fluid temperature and vessel external surface temperature. The clear dome is used to minimize condensation during low temperature operations.

ROSS PARNELL-TURNER
Assistant Professor

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Research Interests: Melting and deformation on mid-ocean ridges, mantle dynamics.

I'm a marine geophysicist, and joined IGPP from Woods Hole Oceanographic Institution in July 2018. My research uses geophysical observations to learn about how oceanic crust is created and deformed, with a focus on slow-spreading ridges, and on plume-ridge dynamics.

Seafloor spreading at slow rates is often taken up by extension on large-offset faults called detachments, which exhume lower crustal and mantle rocks. The exposed footwall may reveal a pattern of spreading-parallel corrugations, whose nature and origins remain controversial. One common hypothesis suggests that corrugations arise due to molding of a plastic footwall in contact with a strong, brittle hanging wall, in a process termed continuous casting. Thermal and mechanical arguments, however, indicate that this idea is implausible at mid-ocean ridges. With colleagues from France, Germany and the USA, we tackled this problem using near-bottom bathymetric surveys acquired with autonomous underwater vehicles (AUVs) over five corrugated detachments along the Mid-Atlantic Ridge (Figure 26; Parnell-Turner et al., 2018a). With a resolution of 2 m, these data allowed us to compare the geometry and spectral content of corrugations on oceanic detachments with differing fault zone lithologies, and accommodate varying amounts of slip. We found that the geometry of corrugations at the five sites is remarkably consistent, despite having different lithologies and slip histories. We also found that corrugations have well-defined ends, and do not extend across the entire exposed fault surface. Spectral analysis shows that fault roughness does not vary with slip, implying that the process of fault nucleation and growth is uniform during extension. We concluded that a strain localization hypothesis, where a network of small rupture patches coalesces into an uneven fault surface within a narrow subsurface depth window, best explains presence and geometry of corrugated fault surfaces on oceanic detachments.

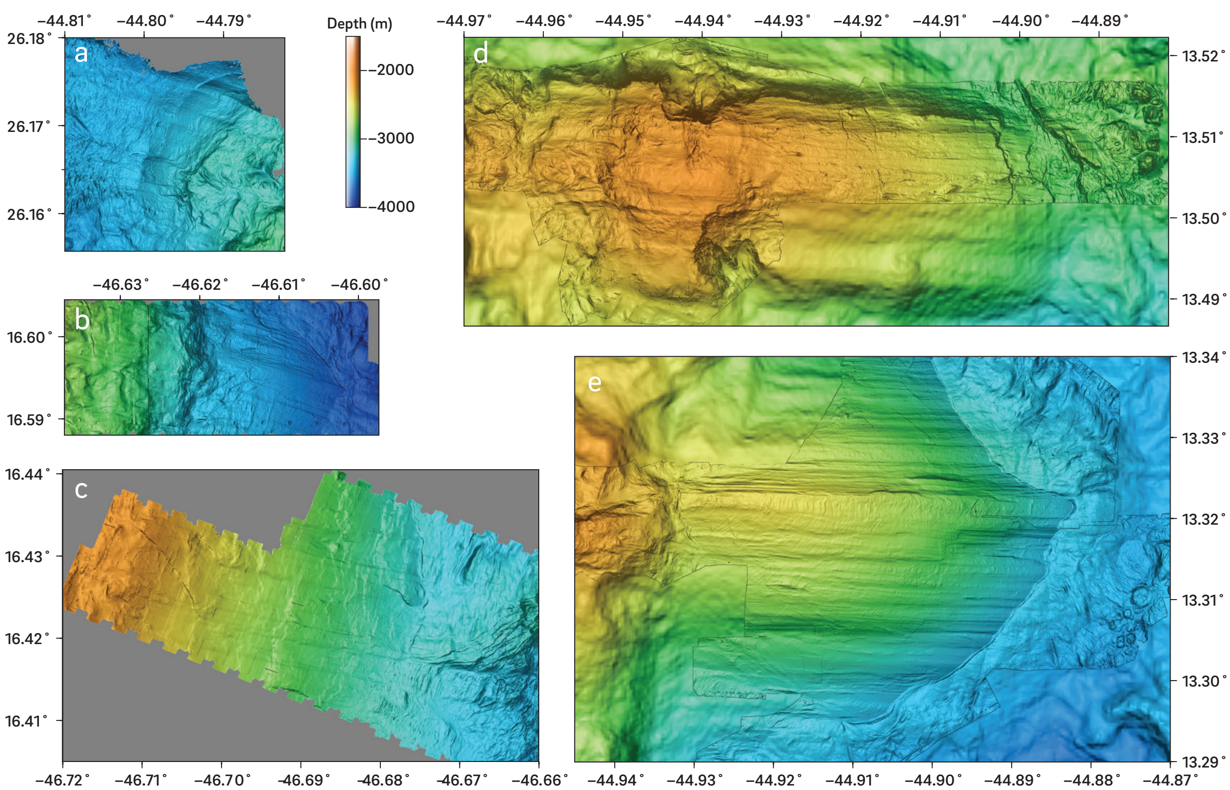

Figure 26. Bathymetric data collected at ~60 m above seafloor over corrugated detachment fault surfaces, using AUVs on the Mid-Atlantic Ridge. a) Trans-Atlantic Geotraverse. b) and c) Near 16°N. d) and e) Near 13°30'N and 13°20'N. Arrows show inferred slip direction. Modified from Parnell-Turner et al. (2018a).

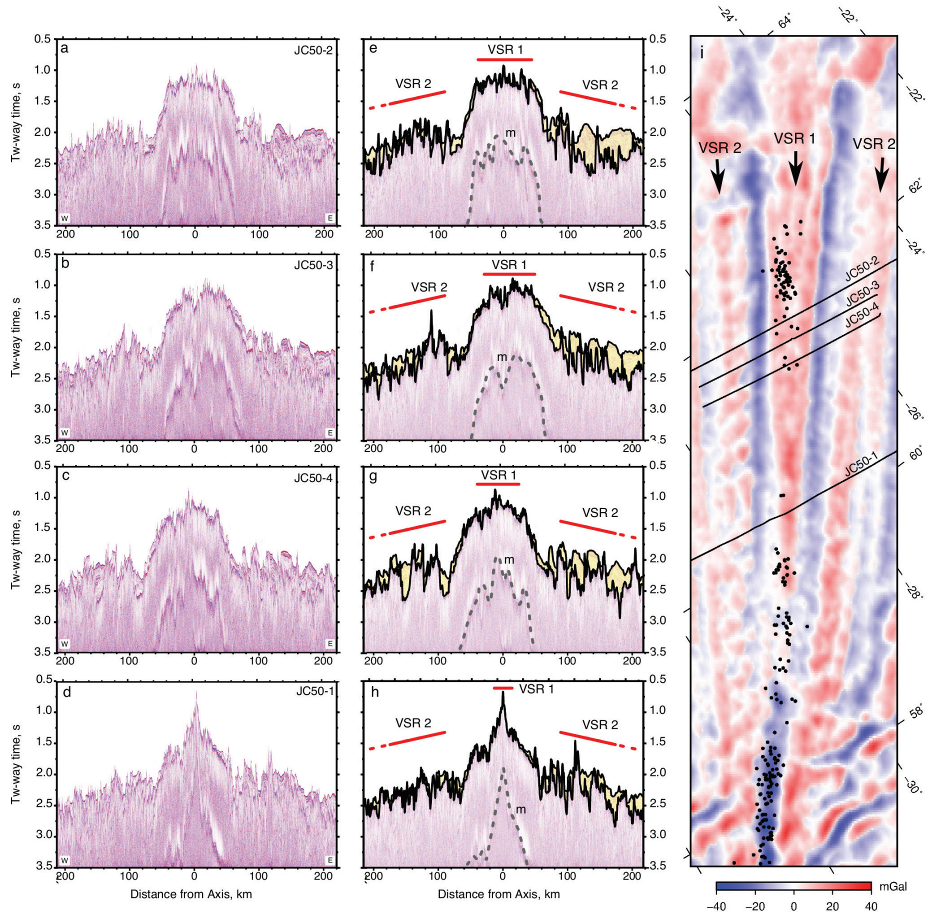

Figure 27. Portions of seismic reflection profiles crossing Reykjanes Ridge. (a–d) Profiles JC50-2, JC50-3, JC50-4, and JC50-1, respectively. (e–h) Interpretation: yellow shading = sedimentary cover, solid black lines = seabed and sediment-basement interface; labeled red lines = VSRs, m = seabed multiple. (i) Satellite free-air gravity anomaly map high-pass filtered to remove wavelengths >250 km. Labeled black lines = seismic profiles, black dots = relocated earthquakes between 1960 and 2009 (Mw >4;); labeled arrows = VSRs. From Parnell-Turner et al. (2017a).

In the North Atlantic Ocean, hot material rises up within the Iceland plume from deep within Earth's mantle, forming a regional-scale pancake-shaped upwelling. A pattern of distinctive V-shaped ridges (VSRs) and troughs that are hundreds of kilometers long and tens of kilometers wide can be observed either side of the Reykjanes Ridge to the south of Iceland. These VSRs are thought to be generated by waxing and waning of the plume, but their precise origin is hotly debated. Using seismic reflection data collected with colleagues from the UK, we assessed competing hypotheses for their formation and found that they are indeed an indirect record of plume activity through time (Parnell-Turner et al., 2017a). Pulses of hot material appear to be generated every 3 to 8 Ma. As they spread beneath adjacent tectonic plates, these pulses cause an increase in melting, which leads to the accretion of crust that is up to 2 km thicker than normal.

RECENT PUBLICATIONS

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Parnell-Turner, R., Mittelstaedt, E., Kurz, M.D., Jones, M., Soule, S.A., Klein, F., Wanless, V.D., Fornari, D.J., 2018b. The Final Stages of Slip and Volcanism on an Oceanic Detachment Fault at 13°48′N, Mid-Atlantic Ridge. *Geochem., Geophys., Geosyst.* doi:10.1029/2018GC007536

Parnell-Turner, R., White, N.J., Henstock, T.J., Jones, S.M., Murton, B.J., 2017a. Causes and Consequences of Diachronous V-Shaped Ridges in the North Atlantic Ocean. *J. Geophys. Res.* **122**, doi:10.1002/2017JB014225

Parnell-Turner, R., Sohn, R.A., Peirce, C., Reston, T.J., Macleod, C.J., Searle, R.C., Simão, N., 2017b. Oceanic Detachment Faults Generate Compression in Extension. *Geology* **45**, 923–926. doi:10.1130/G39232.1

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ANNE POMMIER
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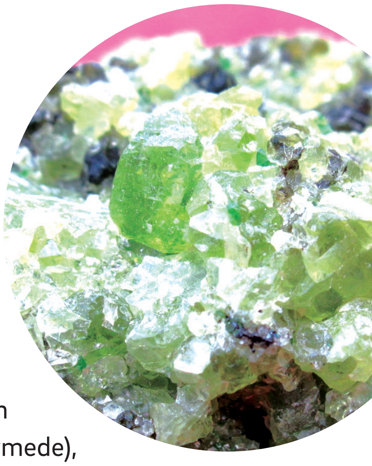

Research Interests: Physics and chemistry of silicate melts and metal alloys; role of magma in planetary interiors, from the scale of volcanic magma reservoirs to planetary-scale magma oceans; evolution of planetary interiors from "deep time" (e.g., planet evolution) to the present.

Research projects over the past 12 months have mainly focused on (i) the experimental investigation of the core of terrestrial planets (in particular, Ganymede), (ii) the development of electrical cell assemblies for the high-pressure community, (iii) the development of SIGMELTS 2.0, an improved tool to understand electrical anomalies in the Earth's crust and mantle. (i) and (ii) were funded by NSF grant, (iii) benefitted from support from the Green Foundation.

(i) Core crystallization is a crucial ingredient in the evolution of terrestrial bodies and is controlled primarily by chemistry and temperature. Transport properties, such as electrical resistivity, are a relevant probe of core crystallization processes, as variations in mass and heat transport in the cooling fluid likely impact the convective and diffusive mechanisms that govern the structure and dynamics of the core and might contribute to generate a magnetic field. I conducted electrical experiments on core analogues in the Fe–S, Fe-S-Si, and Fe-Si systems from 3.2 to 8 GPa and up to 1850°C using the multi-anvil apparatus (Pommier, 2018). Electrical resistivity was measured using the four-electrode method in the Planetary and Experimental Petrology Lab in IGPP. For all samples, resistivity increases with increasing temperature. In the Fe-S system, the higher the S content, the higher the resistivity and the resistivity increase upon melting. The resistivity of FeS and FeSi2 at 4.5 GPa is comparable at temperature below the melting temperature, whereas FeS becomes more resistive than FeSi2 by a factor of two upon melting, suggesting a stronger influence of S than Si on liquid resistivity. Electrical results are used to develop crystallization-resistivity paths. For instance, at 4.5 GPa, equilibrium crystallization, as expected locally in thin snow zones during top-down core crystallization, presents electrical resistivity variations from about 300 to 190 microhm-cm for a core analogue made of Fe-5 wt.%S, depending on temperature. Fractional crystallization, which is relevant to core-scale cooling, leads to more important electrical resistivity variations in the Fe-S system, depending on S distribution across the core, temperature, and pressure. Estimates of the lower bound of thermal resistivity are calculated using the Wiedemann–Franz law. Comparison with previous works indicates that the thermal conductivity of a metallic core in small terrestrial bodies is more sensitive to the abundance of alloying agents than that of the Earth's core. Application to Ganymede

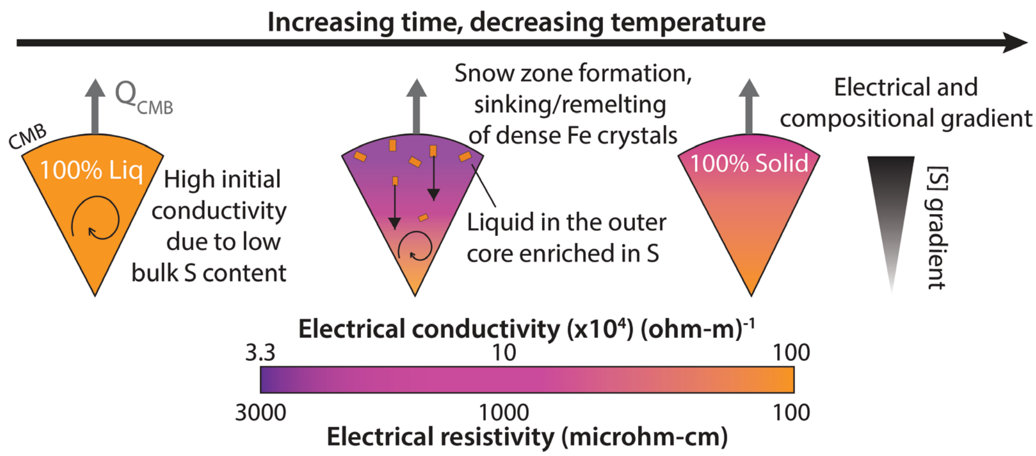

Figure 28. Example of top-down core crystallization and the evolution of the electrical response as chemistry and temperature change. Electrical resistivity values come from electrical experiments. In this example, pressure ranges from about 5 to 8 GPa, which is relevant to Ganymede's core (Pommier, 2018).

(Figure 28) using core adiabat estimates from previous studies suggests important thermal resistivity variations with depth during cooling, with a lower bound value at the top of the core that can be as low as 3 W/mK. It is speculated that the generation and sustainability of a magnetic field in small terrestrial bodies might be favored in light element-depleted cores.

(ii) Electrical conductivity experiments under pressure and temperature conditions relevant to planetary interiors are a powerful tool to probe the transport properties of Earth and planetary materials as well as to interpret field-based electrical data. To promote repeatability and reproducibility of electrical experiments among multi-anvil facilities that use this technique, my collaborator K. Leinenweber (ASU) and I designed and developed an electrical conductivity cell for multi-anvil experiments based on the 14/8 assembly that was developed to allow access to high temperatures. Our electrical cell is available via the Consortium for Material Properties Research in Earth Sciences (COMPRES) and all the details of the design are accessible in Pommier and Leinenweber (2018). The electrical cell has been tested up to 10 GPa and about 2000 °C on different materials (silicates and metals, both in the solid and liquid state).

(iii) SIGMELTS (***sigmelts.ucsd.edu***) is a free web-application that aims to quantify electrically conductive or resistive features detected at depth using electromagnetic observations. The objective is to facilitate the modeling of the electrical properties of crust and mantle materials in order to improve the interpretation of field electromagnetic observations. It is designed for geophysicists and petrologists who want to compute the electrical conductivity of rocks using laboratory experiments conducted on melts (silicate and carbonate, dry and hydrous), aqueous fluids and minerals. The considered parameters entered by the user are temperature, pressure (depth), chemistry (such as water content or redox conditions), amount and geometry of each phase as well as deformation. Together with IGPP IT Jeff Roberts, we updated and improved the design and tools of SIGMELTS (Pommier and Roberts, 2018, accepted). The new SIGMELTS 2.0 features significantly expand the capabilities compared to SIGMELTS 1.0 (Pommier and LeTrong, 2011). The previous version of SIGMELTS lacked important features, including the capability to plot and export the computed data. In addition to a new, more user-friendly layout and an updated and expanded electrical database, SIGMELTS 2.0 now offers the user the option to visualize the computed data on a graph and to export calculations (in csv format) for use outside the app.

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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 2017-18 academic year was focused on understanding the geodynamics of the crust and lithosphere. Our group comprises four graduate students John DeSanto, Hugh Harper, Yao Yu, Sandra Slead and a lab assistant Ben Tea. Eric Xu received his PhD from SIO in November of 2017 and is working as a postdoc in our lab. Brook Tozer joined our group as a postdoc in early 2018. Our research on improvement the marine gravity field is co-funded by the National Science Foundation (NSF), NASA, and the Office of Naval Research (ONR). The NASA Earth Surface and Interior Program as well as the Southern California Earthquake Center provides funding for our research on the strain rate and moment accumulation rate along the San Andreas Fault System from InSAR and GPS. We also received 3 years of funding from NSF to improve the GMTSAR InSAR processing code and documentation.

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, AltiKa and Jason-2). This is resulting in a factor of 2-4 improvement in the global marine gravity field. Most of the improvement is in the 12 to 40 km wavelength band, which is of interest for investigation of seafloor structures as small as 6 km. The improved marine gravity is important for exploring unknown tectonics in the deep oceans as well as revealing thousands of uncharted seamounts (Matthews et al., 2016; Zhang and Sandwell, 2016; topex.ucsd.edu/grav_outreach).

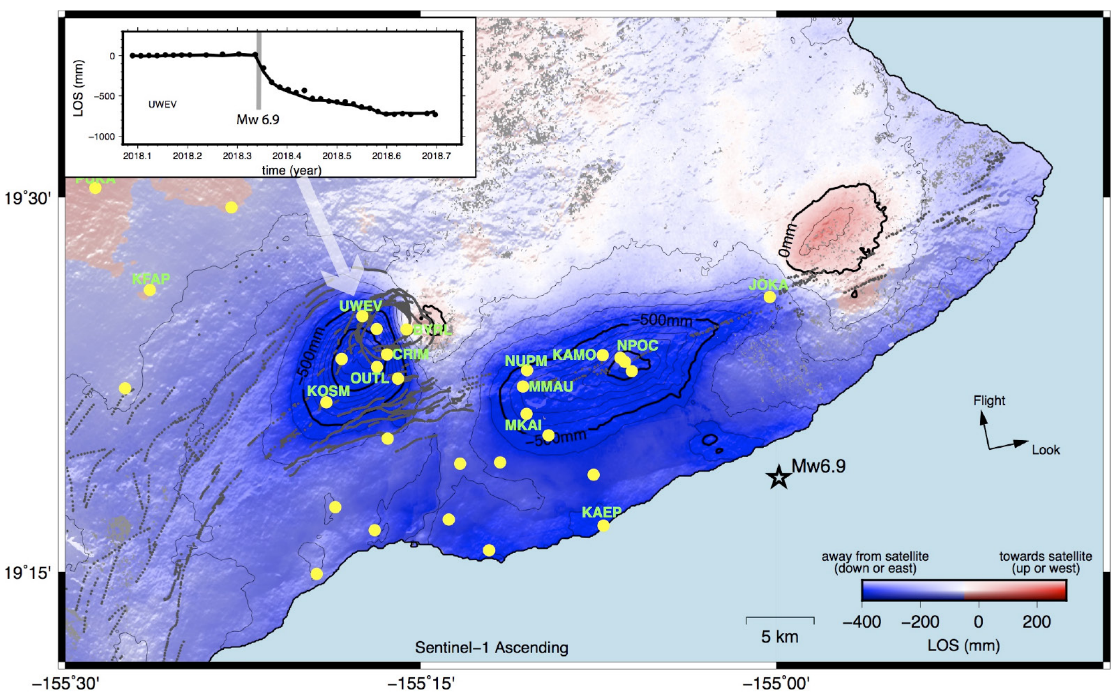

Figure 29. Line of sight (LOS) deformation associated with the 2018 Kilauea Hawaii event derived from Sentinel-1 InSAR and continuous cGPS (yellow dots). The event began on in late April as an eruption at the PuuOo crater which was followed by opening and dike injection on the East Rift Zone. This triggered a major earthquake (May 4, 2018, Mw6.9) on a shallowing dipping thrust fault (https://www.usgs.gov/news/k-lauea-volcano-erupts). Lava flows began along the lower East Rift zone and continued until late August 2018 destroying nearly 700 homes and displacing thousands of residents. We are working with colleagues at the University of Hawaii at Manoa to develop a complete deformation time series of this ongoing event (http://pgf.soest.hawaii.edu/Kilauea_insar/).

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 associated with earthquake hazard (Xu et al., 2017). Recently we used this method to develop a deformation time series of the 2018 volcanic and seismic event at Kilauea Hawaii (Figure 29). Over the past three 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 third new satellite is ALOS-2, launched by JAXA. **These satellites have the measurement cadence and spatial coverage needed to revolutionize our understanding of earthquake cycle processes both globally and along the San Andreas Fault System (Figure 29**). The InSAR processing was performed with new geometric alignment software (Xu et al., 2017) which is now part of GMTSAR developed at SIO (topex.ucsd.edu/gmtsar).

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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, 2016.

Sandwell, D. T., and P. Wessel, Interpolation of 2-D vector data using constraints from elasticity, *Geophys. Res. Lett.,* 43, 703-709, 2016.

Xu, X., D. T. Sandwell, E. Tymofyeyeva, A. Gonzalez-Ortega, and X. Tong, Tectonic and anthropogenic deformation at the Cerro Prieto geothermal step-over revealed by Sentinel-1 InSAR, IEEE Trans. *Geosciences and Remote Sensing,* 55, 5284-5292, 2017.

Xu, X., D. T. Sandwell, D. Bassett; A Spectral Expansion Approach for Geodetic Slip Inversion: Implications for the Down-dip Rupture Limits of Oceanic and Continental Megathrust Earthquakes, *Geophysical Journal International,* in press, https://doi.org/10.1093/gji/ggx408, 2017.

Zhang, S., D. T. Sandwell, Retracking of SARAL/AltiKa radar altimetry waveforms for optimal gravity field recovery, *Marine Geodesy,* 40, 40-56, 2017.

PETER SHEARER

Distinguished Professor

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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, Nevada, 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.

Graduate student Daniel Trugman applied an improved spectral decomposition approach to estimate stress drops for induced earthquakes in Kansas and found they have lower average stress drops than earthquakes in California with no clear relation to injection well locations (Trugman et al., 2017). He used a similar method to estimate stress drops for over 5000 earthquakes in the San Francisco Bay area and compared his results to peak-ground-acceleration (PGA) measurements (Trugman and Shearer, 2018). He developed a new ground-motion-prediction equation (GMPE) method using machine learning and found a strong correlation between dynamic stress drop and residual PGA (see Fig. 30), implying that GMPEs could be improved by accounting for spatial variations in median stress drop among small to moderate earthquakes.

On a more regional scale, postdoc Janine Buehler identified examples in USArray data of teleseismic S waves converting to Rayleigh waves at the western U.S. coastline (Buehler et al., 2018). These converted waves are an important source of signal-generated noise in continental seismology and can be explained used simple synthetic models of the coastline velocity structure. Using global seismic data, graduate student Wenyuan Fan applied back-projection methods to study several

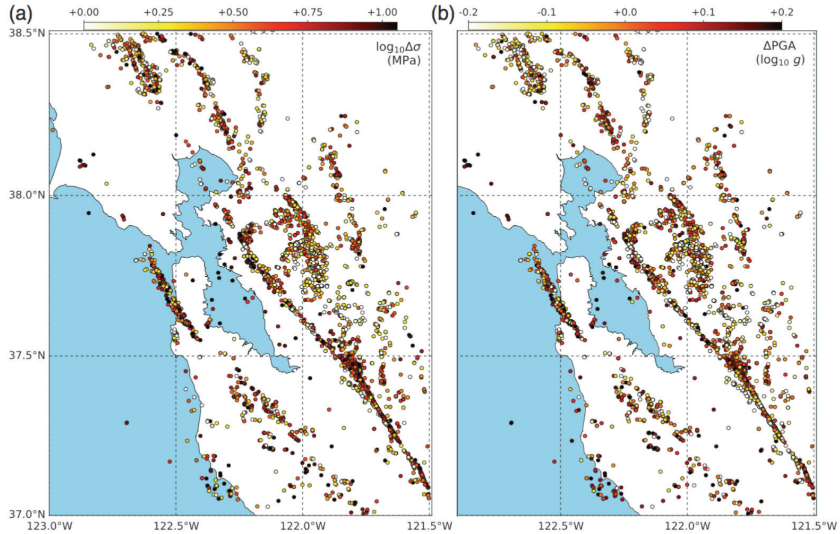

Figure 30. A comparison of spatial variations in: (a) estimated earthquake stress drops (Δσ), and (b) peak-ground-acceleration (PGA) residuals, for the San Francisco Bay region. Note the strong correlation between higher-than-average stress drops and higher-than-average PGA values, both plotted in red.

earthquakes. High-frequency back-projection of the 2006 Mw 7.8 Java earthquake suggests two distinct rupture stages and spatial correlation of the second stage with splay fault traces seen in residual gravity maps (see Fig. 231 and Fan et al., 2017). Analysis of 46 aftershocks of the 2011 M9 Tohoku earthquake shows that back-projection of the mainshock is relatively unbiased by timing errors due to 3D structure away from its epicenter (Fan and Shearer, 2017). In response to a study challenging some of our earlier results, Fan and Shearer (2018) showed that coherent arrivals in the P coda of the 2012 Mw 7.2 Sumatra earthquake are more likely from an early aftershock than delayed and displaced water reverberations from the mainshock.

RECENT PUBLICATIONS

Buehler, J. S., N. J. Mancinelli, and P. M. Shearer, S-to-Rayleigh wave scattering from the continental margin observed at USArray, *Geophys. Res. Lett.*, **45**, doi: 10.1029/2017GL076812, 2018.

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Fan, W., and P. M. Shearer, Coherent seismic arrivals in the P wave coda of the 2012 Mw 7.2 Sumatra earthquake: Water reverberations or an early aftershock?, *J. Geophys. Res.*, **123**, 3147-3159, doi: 10.1002/2018JB015573, 2018.

Trugman, D. T., S. L. Dougherty, E. S. Cochran, and P. M. Shearer, Source spectral properties of small to moderate earthquakes in southern Kansas, *J. Geophys. Res.*, **122**, 8021-8034, doi: 10.1002/2017JB014649, 2017.

Trugman, D. T., and P. M. Shearer, Strong correlation between stress drop and peak ground acceleration for recent M 1–4 earthquakes in the San Francisco Bay Area, *Bull. Seismol. Soc. Am.*, **108**, 929-945, doi: 10.1785/0120170245, 2018.

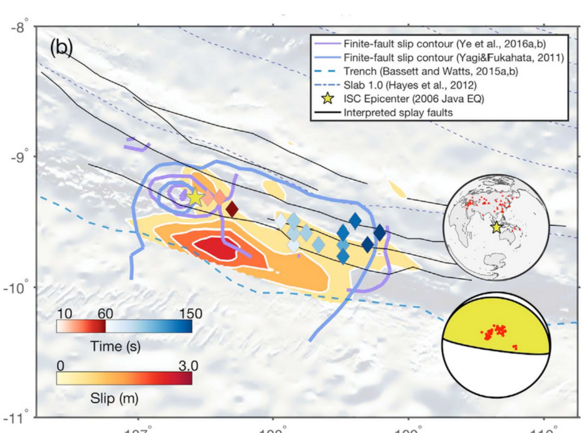

Figure 31. Seismic and tsunami back-propagation results and slip models of the 2006 Java earthquake (from Fan et al., 2017). Contours show two different finite-slip models. Diamonds show the peak-energy locations of high-frequency back-projection. Stations used for back-projection and their P-wave polarity with the GCMT focal-mechanism are shown as inserts. The subduction geometry is from Slab 1.0 with 20 km separation.

LEONARD J. SRNKA

Professor of Practice

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

Following up on the model research done at IGPP by Arnold Orange, Kerry Key and Steve Constable (Orange et al. 2009), I revisited the concept of using time-lapse (or "4D") marine controlled-source electromagnetic methods (CSEM) for monitoring fluid changes during production in offshore hydrocarbon reservoirs. That concept is technically attractive, since the bulk resistivity of a hydrocarbon-bearing porous rock which CSEM can measure is much more sensitive to fluid saturation changes (i.e. the hydrocarbon-to-water ratio) than is the bulk interval p-wave (acoustic) velocity that can be measured with reflection seismic methods. This is especially true of gas reservoirs, as well as those with high gas/oil ratios. Figure 32 illustrates this phenomenon. CSEM surveys are also less expensive and faster than seismic surveys, which are potentially attractive aspects for industry. Time-lapse CSEM may also be applicable to CO_2 sequestration, such as being done at the Sleipner East field offshore mid-Norway.

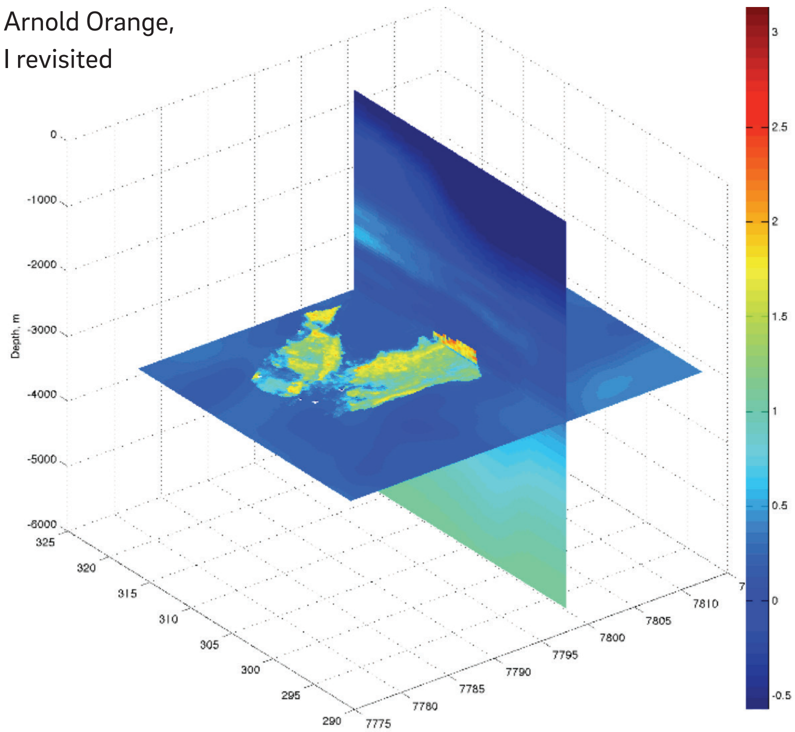

Figure 32. Sensitivity of bulk resistivity (log scale) and p-wave velocity (linear scale) to gas saturation changes in a high-porosity sandstone.

A stronger motivation to revisit 4D CSEM technology is the 2009 study by Steven Constable, Kerry Key, and Arnold Orange (all SIO) and Andrew Lockwood of Woodside Petroleum. Woodside provided reservoir resistivity volumes (174x252x120 pixels) for various preliminary production scenarios for the Pluto gas field, Northern Carnarvon Basin, offshore NW Australia, at times of [0, 1, 2, ...10] years from production start. These volumes were used in 2009 to estimate CSEM time-lapse signals for Pluto on a confidential basis. The study was fully released in October 2017. I included excerpts of the study in my workshop presentation at the 2017 SEG Annual meeting. Figure 33 shows the averaged bulk vertical resistivity of the Pluto reservoir at 3500m depth, prior to gas production, with a flat seafloor and a uniform background resistivity set at 1.0 Ohm-m. For computational efficiency, the Woodside model was sub-sampled to a 48x50x40 mesh, averaged over 3x5x3 nodes. The CSEM model survey set the sources and receivers at 50m above the seafloor. Calculations were done at 0.1 Hz using the 3D finite-difference frequency-domain isotropic modeling code obtained from Chester Weiss at Sandia National Laboratory.

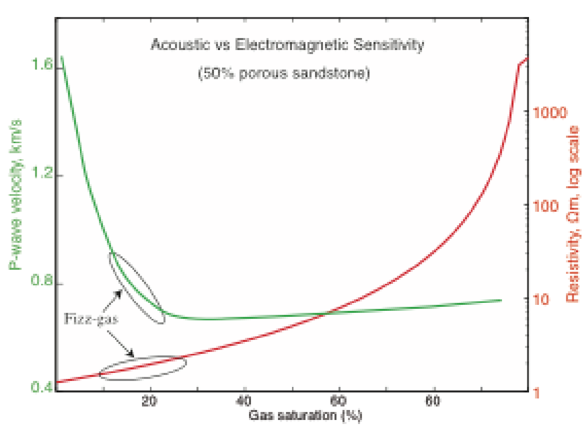

Figure 33. Pluto resistivity depth model.

Figure 34 shows the changes in that resistivity at reservoir depth at a time of three years from production start, as would be measured by the CSEM for two scenarios: "expected" reservoir behavior (EX), and "train wreck" behavior (TR) where some unexpected reservoir

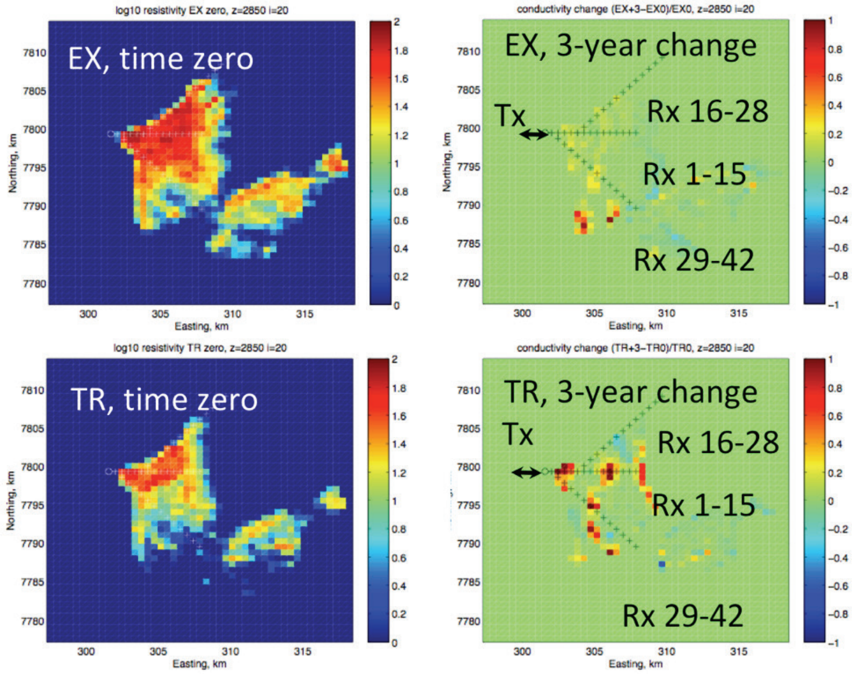

Figure 34. Sensitivity of bulk resistivity (log scale) and p-wave velocity (linear scale) to gas saturation changes in a high-porosity sandstone.

structure or porosity-permeability distribution has resulted in sub-optimal depletion. The source was an E-W pointed electric dipole Tx, and the receivers were placed over the areas of maximum changes.

Additional 2D forward modeling (not shown) using the Scripps MARE2DEM finite-element frequency-domain code confirmed these results. More 3D modeling work is planned to incorporate bathymetry and nonuniform resistivity above the Pluto reservoir.

It is unclear at this stage of the research if simple differencing of realistic forward modeling results would be sufficient to demonstrate feasibility that would lead to an actual survey. Recent feedback from members of the Scripps Seafloor Electromagnetic Methods Consortium (SEMC), where 4D CSEM was discussed at the March 2018 meeting, suggests that actual 3D imaging using nonlinear inverse methods may be required for industry tests and later applications. The current downturn in exploration CSEM use by industry is also a factor. However, at least one international oil and gas company has expressed interest in pursuing 4D CSEM.

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PETER WORCESTER
Researcher Emeritus

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

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

My recent research has been focused in the Arctic Ocean, which is undergoing dramatic changes in the ice cover and ocean structure. Changes in sea ice and the water column affect both acoustic propagation and ambient noise. This implies that what was learned about Arctic acoustics in the past is now obsolete. My group has conducted or participated in a series of experiments in the Arctic.

Thin-ice Arctic Acoustic Window (THAAW). A Distributed Vertical Line Array (DVLA) receiver mooring was deployed near the North Pole during April 2013. The mooring line parted above the anchor shortly after deployment, and the mooring drifted slowly south toward Fram Strait in the Transpolar Drift, providing a time series of ambient noise until it was recovered in September 2013 (Ozanich et al., 2017).

DAMOCLES, ACOBAR, and UNDER-ICE. My group participated in a series of ocean acoustic tomography experiments in Fram Strait that were led by our colleagues at the Nansen Environmental and Remote Sensing Center (NERSC) in Bergen, Norway (Geyer et al., 2016; Sagen et al., 2017).

Canada Basin Acoustic Propagation Experiment (CANAPE). CANAPE was designed to determine the

Figure 35 (background). A 250-Hz HLF-5 acoustic source being lowered from the R/V Sikuliaq during the 2015 CANAPE Pilot Study. (Photo: Alexis Denton) fundamental limits to the use of acoustic methods and signal processing imposed by ice and ocean processes in the new Arctic. To achieve this goal, the CANAPE project conducted two experiments: (1) the short term 2015 CANAPE Pilot Study and (2) the yearlong 2016–2017 CANAPE experiment. The hope is that these first steps will lead to a permanent acoustic monitoring, navigation, and communications network in the Arctic Ocean. The specific goals of the CANAPE project include (1) understanding the impacts of changing sea ice and oceanographic conditions on acoustic propagation and fluctuations; (2) characterizing the depth dependence and temporal variability of the ambient noise field; and (3) measuring the spatial and temporal variability in the upper ocean throughout the annual cycle by combining acoustic and other data with ocean models.

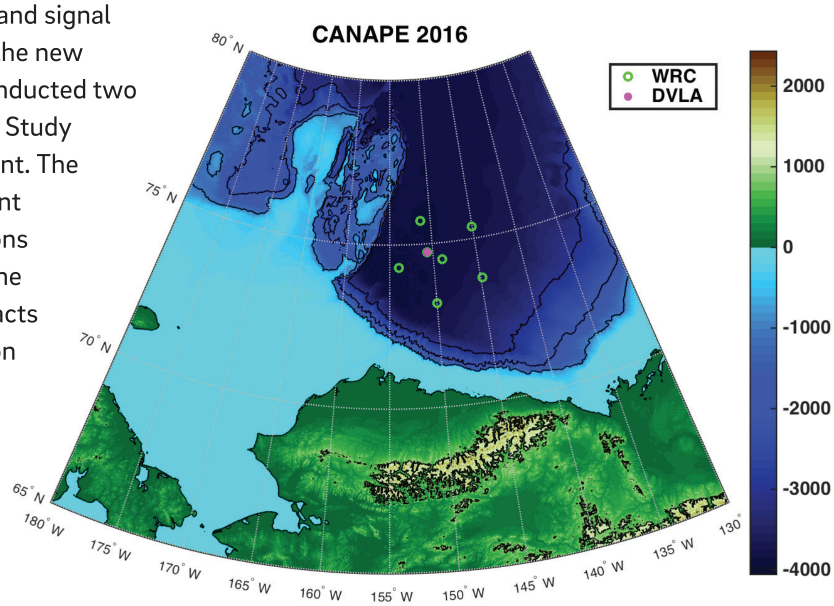

Figure 36. The 2016–2017 CANAPE experiment consisted of six Teledyne Webb Research acoustic transceivers (WRC, green) and a DVLA receiver (DVLA, red). The array radius is 150 km.

For the 2016–2017 CANAPE experiment, six acoustic transceiver moorings and a DVLA receiver mooring were deployed north of Alaska during August-September 2016 and recovered during September-October 2017 (Figure 36). The experiment combines measurements of acoustic propagation and ambient noise with the use of an ocean acoustic tomography array to help characterize the oceanographic variability throughout the year in the central Beaufort Sea. The one-year deployment in a fixed geometry provides measurements in open water during summer, in the marginal ice zone (MIZ) as it transitions across the array during the spring and autumn, and under complete ice cover during winter. Processing and analysis of the data acquired during the 2016–2017 CANAPE experiment has just begun.

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