CECIL AND IDA GREEN INSTITUTE OF GEOPHYSICS AND PLANETARY PHYSICS

ANNUAL REPORT

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2021 DIRECTOR'S WELCOME

This past year witnessed fundamental change in the pursuit of science and scholarship. The loss of human connection, and our community's determined efforts to replace what we could with imperfect tools, has an upside in hugely expanded opportunities for scientific collaboration and participation. The downside is that our shared spaces are less populated, and we have to work harder to create incentives for our colleagues to come together in person. At IGPP, that is a work in progress.

At the same time, IGPP's deep connection to the physical world remains unbroken. We are still going to sea and into the field, we continue to make observations that change our understanding of our planet, and we are drawing scholars and students from every direction. New academic and research faculty have reinvigorated all aspects of IGPP's work, and this year's cohort of new students is IGPP's largest ever.

Our newly restored Judith and Walter Munk Laboratory was added to the National Register of Historic Places last year, not only because of the function and grace of the building, but also in recognition of the significance of the scientific research it has enabled. I can think of no more fitting a tribute to IGPP's storied past, and I can only imagine what IGPP's next 60 years has in store. Judging from the pages of this report, we will continue to make a difference.

Field trip to Cecil and Ida Green, Pinon Flat Observatory on November 20, 2021 (during a short break in COVID restrictions). First and second year graduate students and IGPP faculty/staff toured several of the seismic and geodetic facilities. Visitors from Stanford brought drones for flight testing in this remote facility. Participants included: David Sandwell, Anupam Patel, Jeena Yun, Jeremy Wong, Natalia Guerrero, John Rekoske, Guilherme de Melo, Jamin Greenbaum, Julie Gevorgian, Nicolas DeSalvio, Rebecca Gjini, Madeleine Kerr, Shangqin Hao, Ke Xu, Chih-Chieh Chien, Xinyu Luo, Zel Hurewitz, Xiaoyu Zou, Gabrielle Hobson, Raymond Thicklin, Matthew Brandin, Rob Mellors

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* Individual report not available this year





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 Biemiller, postdoc Green Scholar: Ellen Knappe, postdoc Green Scholar: Tyler Pelle, postdoc Miles Fellow: Daniel Blatter, postdoc

UC San Diego membership in Southern California Earthquake Center www.scec.org

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.

Graduate Student who successfully defended in 2021 Kyle Gwirtz, Ph.D. (Advisor: Matthias Morzfeld)

SCIENCE AT SEA

RSI

Ross Parnell-Turner's group has been monitoring volcanic and hydrothermal systems on the East Pacific Rise. In April 2021, his team traveled on R/V *Roger Revelle* to East Pacific Rise 9°50'N where the deployment of ROV Jason to 2.5 km below sea level captured a significant off-axis vent field. Steven Constable's Marine EM laboratory explores the crust and mantle underneath the oceans using marine electromagnetism. Key research areas include marine controlled-source electromagnetic sounding and the marine magnetotelluric method.



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WALTER MUNK GUYOT

The International Hydrographic Office annouced the naming of the Walter Munk Guyot to honor IGPP's founding director, the Einstein of the Oceans, for his contributions to science which "were measured not only in terms of the new knowledge his research yielded, but in the quality and diversity of the questions he considered."

Mapped from the RV *Sally Ride*, on a transit between Hawaii and Guam, the Walter Munk Guyot lies 1000 miles WSW of Honolulu. The newly named guyot is very large with a broad, level top that sits 1397m below sea level and descends to 5200m (the guyot's height is 3803m or 12500 feet). Once an island above sea level for ~20 million years, the guyot was initially formed by volcanic activity; wave erosion over time destroyed the top of the seamount resulting in a flattened shape. There are only 187 named guyots in the GEBCO database and at least 10 have been named in honor of Scripps Institution of Oceanography research or researchers:

Issacs Guyot - John Issacs Capricorn Guyot - 1952-53 SIO expedition Jacqueline Guyot - Jacqueline Mammerickx Menard Guyot - Bill Menard Revelle Guyot - Roger Revelle Scripps Guyot Shepard Guyot - Francis Shepard Valerie Guyot - Valerie Craig (wife of Harmon Craig) Winterer Guyot - Jerry Winterer Walter Munk Guyot - Walter Munk

DISTRIBUTED SENSING

Sia Sinter

Debi Kilb, Rob Mellors, and Lawrence Berkeley Lab's Veronica Rodríguez Tribaldos are using fiber-optic seismometers to gather earthquake data. Data gathering via distributed acoustic sensing is revolutionizing how seismologists gather and process earthquake data. Learn more about the process in their Union Tribune editorial here: https://tinyurl.com/app.

MUNK LAB LEGACY

Designed by acclaimed San Diego architect Lloyd Ruocco, "Munk Lab has been an incubator of scientific and geophysical exploration and advancement since its original construction in 1963." The building, named for IGPP's founding director, was designed by Ruocco with "functional attributes encouraging collaboration at all levels."

In 2020 efforts began to restore Munk Lab to its former glory and undo decades of deferred exterior maintenance by "repairing, reconnecting, selectively replacing, and refinishing severely deteriorated redwood and Douglas fir features including structural beams, posts, siding, sliding glass doors, and windows."

The restoration's success did not go unappreciated by The California Preservation Foundation, which awarded IGPP with the 2021 Preservation Design Award. Then in July of 2021, the San Diego Historical Resources Board lent its support for the Munk Lab to receive status on National Register of Historic Places. In October, the National Park Service announced the lab's official presence on the National Register of Historical Places!

GEOPHYSICS CURIOUS?

Students in the IGPP graduate program study Earth and other planets to advance our fundamental understanding their origin, composition, and evolution, and explore the implications for life, for the environment, and for society. The graduate program provides a broad education in the fundamentals of geophysics, alongside research and coursework spanning multiple specializations.

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

Is this graduate program for you? Read about some ongoing research in the following pages and learn more about the program online: igpp.ucsd.edu/program-study.

YEHUDA BOCK

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

GPS/GNSS, crustal deformation and transients, geodetic reference frames, 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 seismic and geodetic methods to support natural hazard mitigation for communities affected by earthquakes, tsunamis, volcanoes, and severe weather. Using 30 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. We archive and analyze GNSS data for the International GNSS Service and the California Spatial Reference Center. In 2021, our group included Peng Fang, Katherine Guns, Dorian Golriz, Alistair Knox, Anne Sullivan, Songnian Jiang, Allen Nance, Maria Turingan, Fernando Vazquez, with laboratory and field assistance from Matt Norenberg, Glen Offield and Jennifer Matthews.

RAPID MAGNITUDE ESTIMATION FOR LOCAL TSUNAMI WARNINGS

Tsunamis are a devastating natural, high fatality hazard. Because earthquakes generate most tsunamis, the first indication of a potentially life threating tsunami is the earthquake itself. Effective tsunami warning must therefore detect, locate and estimate the magnitude of the causative earthquake to infer tsunamigenic potential, and warn coastal populations as soon as possible after initiation of fault rupture. Current warning systems are well-developed for ocean-basin-wide tsunamis. They rely mainly on measurements of teleseismic waves by broadband seismometers. However, for large tsunamigenic events, broadband data may go off-scale ("clip"), if observed too close to the seismic rupture. Therefore, early warning for "local tsunamis," those that cause devastating affects to coastal communities closest to the earthquake's rupture, may not be sufficiently timely. Methods have been developed to improve timeliness, in particular the inversion of the W-phase to obtain the W-phase Centroid Moment Tensor, but is not sufficient in many cases. Another issue is magnitude saturation for earthquakes greater than M~8 that can result in significant underestimates of magnitude. Seismic networks also deploy strong-motion accelerometers to avoid clipping. However, acceleration data must be doubly integrated, causing drifts in displacement as a result of baseline errors; they also experience magnitude saturation. Real-time (GNSS) networks directly measure precise (~1 cm) high-rate displacements (typically, 1-10 Hz), including dynamic and permanent coseismic offsets, while not experiencing clipping in the near field or magnitude saturation, thereby, reducing the time required for precise magnitude estimation. Empirical scaling relationships using peak ground displacements (PGD), first developed at SIO, have been successfully used to rapidly estimate magnitude. However, GNSS displacements are not as precise as displacements integrated from seismic data cannot detect P waves. Therefore, GNSS networks require a seismic trigger for detection.



Figure 1. Rapid site-by-site magnitude estimation. The start of the coseismic window is based on P wave arrivals; the end time on the total release of energy derived from seismic velocities (Golriz et al., 2021). Using vertical seismogeodetic displacements, we take the absolute value of integrated displacements within the coseismic window for each station. The resulting moment magnitude is based on the far-field P-wave displacement term (Aki and Richards, 2002). Moment magnitude evolution over time (sec) is shown for the 8 largest events. Grey curves denote individual station estimates, red scatter points are event medians with 1-sigma deviation. "True" magnitude from Global Centroid Moment Tensor (dashed black line). Source: Golriz et al. (2022).

Combining GNSS with collocated strong-motion data with a Kalman filter yields unclipped broadband velocity and displacement ("seismogeodetic") waveforms that are sensitive to the entire spectrum of ground motions from the Nyquist frequency of the accelerometer data (typically 50 Hz) to the static offset, while minimizing baseline errors. We've developed a method to use seismogeodetic velocities to detect P waves and estimate the coseismic window over a network of near- to far-field collocated GNSS and accelerometer stations (Golriz et al., 2021). Using the vertical component of seismogeodetic displacement as an approximate source time function, we can then rapidly estimate moment magnitude (Golriz et al., 2022). Unlike empirical magnitude scaling relationships, our method is based on theory using the far-field P-wave displacement term in a spherically symmetric medium (Aki, K. and Richards, P.G., 2002, Quantitative Seismology). Using the seismogeodetic data from 11 earthquakes in the 7.2 < Mw < 9.1 range, we estimate Mw and rupture duration within 2-3 minutes of earthquake origin time with an accuracy of 0.1 to 0.2 magnitude units (Figure 1).

- Bock, Y. and S. Wdowinski (2021), GNSS Geodesy in Geophysics, Natural Hazards, Climate, and the Environment, in Position, Navigation, and Timing Technologies in the 21st Century: Integrated Satellite Navigation, Sensor Systems, and Civil Applications, *IEEE*, 2021, 741-820, doi: 10.1002/9781119458449.ch28.
- Golriz, D, Y. Bock & X. Xu (2021), Defining the Coseismic Phase of the Crustal Deformation Cycle with Seismogeodesy, J. Geophys. Res.: Solid Earth, **126**, e2021JB022002. https://doi.org/10.1029/2021JB022002
- Golriz, D., B. Hirshorn, Y. Bock & S. Weinstein (2022), Real-time Magnitude Estimate for Local Tsunami Warnings, in preparation.
- Guns, K., X. Xu, D. Sandwell, Y. Bock (2021), GNSS-corrected InSAR Displacement Time Series Spanning the 2019 Ridgecrest, CA Earthquakes, *J. Geophys. Int.*, in review.
- Jiang, J., Y. Bock and E. Klein (2021), Coevolving early afterslip and aftershock signatures of a San Andreas fault rupture, *Sci. Adv.*, **7**: eabc1606, https://advances.sciencemag.org/content/7/15/eabc1606
- Klein, K., Y. Bock, X. Xu, D. Sandwell, D. Golriz, P. Fang, L. Su (2019), Transient deformation in California from two decades of GPS displacements: Implications for a three-dimensional kinematic reference frame, *J. Geophys. Res.*, DOI:10.1029/2018JB017201.
- Murray, J. R. et al. (2019), Regional Global Navigation Satellite System Networks for Crustal Deformation Monitoring, *Seismo. Res. Lett.* https://doi.org/10.1785/0220190113
- Wang M., J. Wang, Y. Bock, H. Liang, D. Dong, P. Fang (2019), Dynamic Mapping of the Movement of Landfalling Atmospheric Rivers over Southern California with GPS Data, *Geophys. Res. Lett*, **46**. https://doi.org/10.1029/2018GL081318.





ADRIAN BORSA

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Associate Professor, Director IGPP

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, permafrost, and groundwater) which are critical to closing Earth's water budget, but which are sparsely observed and poorly constrained. My group combines satellite gravity measurements of water mass change (from the GRACE mission) with GNSS (Global Navigation Satellite System) observations of crustal deformation associated with these water mass changes to recover the evolution of water storage across the continental USA and beyond (e.g. Figure 2). 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 spatiotemporal 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.

Our group has also been working to improve interpretations of GNSSobserved vertical crustal motion for North America. These collaborative efforts (with the University of Texas at Austin and the Jet Propulsion Laboratory) have focused on estimating and removing the contribution of elastic displacements from long-term changes in terrestrial water storage, which can obscure signals from tectonics and mantle dynamics (e.g. Figure 3). Most recently, we have begun to investigate differences between Glacial Isostatic Adjustment models for North America and the possibility that these models have missed long-wavelength GIA-related crustal motion that is apparent in GNSS-derived velocity fields.



Figure 2. (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 3. (a) Vertical rates due to elastic hydrologic loading, modeled using GRACE-derived terrestrial water storage estimates as input loads. (b) 300km Gaussian smoothed GNSS vertical velocity field. (c) Residual velocities after removing hydrologic loading rates from unsmoothed GNSS vertical velocities. (d) Residual velocities after removing hydrologic loading rates from the smoothed GNSS velocity field.

RECENT PUBLICATIONS (student and postdoc authors in bold)

- Michaelides, R.J., M.B. Bryant, M.R. Siegfried, A.A. Borsa (2021). "Quantifying Surface-Height Change Over a Periglacial Environment with ICESat-2 Laser Altimetry." *Earth and Space Science*, 8(8)
- Neely, W.R., A.A. Borsa, J. Burney, M.C. Levy, F. Silverii, M. Sneed (2021). "Characterization of groundwater recharge and flow in California's San Joaquin Valley from InSAR-observed surface deformation." Water Resources Research, 57(4)
- Lau, N, A.A. Borsa, and T.W. Becker (2020). "Present-Day Crustal Vertical Velocity Field for the Contiguous United States." Journal of Geophysical Research: Solid Earth, 125(10)
- Levy, M.C., W.R. Neely, A.A. Borsa, & J.A. Burney (2020). "Fine-scale spatiotemporal variation in subsidence across California's San Joaquin Valley explained by groundwater demand." *Environmental Research Letters*, **15**(10)
- Silverii, F., E.K. Montgomery-Brown, A.A. Borsa, & A.J. Barbour (2020). Hydrologically induced deformation in Long Valley Caldera and adjacent Sierra Nevada. Journal of Geophysical Research-Solid Earth, **125**(5)
- Adusumilli, S., A.A. Borsa, M.A. Fish, H.K. McMillan, and F. Silverii (2019). "A Decade of Water Storage Changes Across the Contiguous United States from GPS and satellite gravity." *Geophysical Research Letters*, **46**(22)
- Borsa, A., H.A. Fricker, K. Brunt (2019). "A terrestrial validation of ICESat elevation measurements." *IEEE Transactions on Geoscience and Remote Sensing*, **57**(9)
- **Enzminger**, T.L., E.E. Small, A.A. Borsa (2019). "Subsurface water dominates Sierra Nevada seasonal hydrologic storage." *Geophysical Research Letters*, **46**(21)

CATHERINE CONSTABLE

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Distinguished Professor of Geophysics

Earth's magnetic field and electromagnetic environment; Paleo and geomagnetic secular variation; Linking paleomagnetic 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 and is dominated by low frequency changes, associated with the predominantly dipolar internal field produced by the geodynamo in Earth's liquid outer core. Fluid flow and diffusive processes in the electrically conductive core produce secular variation in the magnetic field. The dipole part of the field exhibits the largest 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.

Work has continued on improving understanding the evolution of the geomagnetic field over 0–100 ka, a time interval



Figure 4. Concentration of Virtual Geomagnetic Poles (VGPs) during the Laschamp excursion as modeled by GGF100k and LS-MOD.2. Links have been proposed between Large Low Seismic Velocity Provinces, VGP paths, and areas of low field strength.

which is long enough to represent paleosecular variation and several geomagnetic excursions, during which the geomagnetic dipole strength drops and global or regional field direction show large departures from their more usual stable polarity configurations. Syntheses of paleomagnetic data were used to produce the time varying field model GGF100k, and over the past year there has been a focus on analyzing what can be learned from studying this model, and two others covering the intervals 50-30 ka (LSMOD.2) and 15-70 ka. In work together with Sanja Panovska and Monika Korte (of GeoForschungs Zentrum, Helmholtz Center, Potsdam), we have conducted a study of field structure during the Laschamp excursion which occurred around 40 ka and of other regional excursional events (see Panovska et al., 2019, 2020 for more details and animations). The ability to robustly recover preferred field structures as seen in Figure 4 is testable by assessing reliability of the analysis using numerical dynamo simuations.

Work with Christopher Davies (Leeds University, U.K.) has continued, linking numerical geodynamo simulations with paleomagnetic results, especially in the analysis of rapid changes in the magnetic field. Broad similarities between behavior in the paleofield and numerical simulations allow us to link potential physical processes in the simulations with actual



Figure 5. Axial dipole moment and the globally averaged PSV index of the GGF100k model for 0-100 ka.

field behavior, something that is not easily resolvable from paleomagnetic data and models. We continue to explore the distribution of rapid changes in magnetic field directions in GGF100k, other paleofield models, and numerical dynamo simulations to explore how to define unusually rapid geomagnetic events or URGEs.

In collaboration Professor Matthias Morzfeld of SIO, I have begun an investigation of the extent to which it might be possible to predict geomagnetic excursions or reversals from variations in dipole strength and direction. We initially focused on using recently developed paleosecular variation (PSV) index (see, e.g. Figure 5) which provides a means for evaluating the level of departure from a stable dipolar field configuration: our results to date highlight the need for continuing improvements in the temporal and spatial resolution of existing paleofield models so that more detailed information can be used.

Two PhD students have joined in my group in 2020 and 2021, Nicole Clizzie and Chancelor Roberts. Nicole's work is focused on understanding how to appropriately extend Giant Gaussian Process (GGP of the kind discussed in Brandt et al., 2020, 2021) models for the paleosecular variation based on time varying models like GGF100k to accommodate physically appropriate temporal and spatial correlations. This will make them more useful for determining which numerical dynamo simulations are statistically representative of the geomagnetic field. Chancelor is beginning to develop new methods for detailed regional geomagnetic modeling to accommodate rapid geomagnetic field changes such as occur during the Levantine Iron Age Anomaly and the Laschamp excursion.

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- Brandt, D., C. Constable, M. Ernesto, 2020. Giant Gaussian process models of geomagnetic paleosecular variation: a directional outlook, *Geophysical Journal Internaitonal*, **222**, 1526-1541, doi:10.1093/gjj/ggaa258.
- Davies, C., & C.G. Constable, 2020. Rapid geomagnetic changes inferred from Earth observations and numerical simulations, *Nature Communications*, **11**, 3371, doi:10.1038/s41467-020-16888-0.
- Panovska, S., M. Korte, and C. G. Constable, 2020. The global geomagnetic field of the past hundred thousand years, *Eos*, **101**, doi:10.1029/2020E0146890.
- Brandt, D., M. Ernesto, C. Constable, 2021 Consistent and contrasting aspects of the geomagnetic field across epochs with distinct reversal frequencies revealed by modeling the Kiaman Superchron Geochem. *Geophys. Geosyst.* doi:10.1029/2021GC009866.

STEVEN CONSTABLE

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Distinguished Professor

Marine EM methods

Steven Constable leads the SIO Marine EM (Electromagnetic) Laboratory at IGPP. EM methods can be used to probe the geology of the seafloor, and we have used them to study plate boundaries, marine gas hydrate, offshore geothermal prospects, permafrost, hydrothermal venting and associated massive sulfides, groundwater, and conventional oil and gas reservoirs.

Some time ago we developed a surface-towed EM system for mapping permafrost in shallow water, and this system has been used several times of groundwater studies. I reported last year on some work done off Hawai'i, which attracted a lot of press attention when it was published (Attias et al., 2021), including the New York Times. Roslynn King, a student in our Joint Doctoral Program with SDSU, has been using this instrument to image groundwater off San Diego, as well as paleochannels, tar seeps, and groundwater off Santa Barbara. Figure 6 shows our results offshore San Diego. Freshened water associated with the San Diego aquifer, which provides up to 5% of the water used by San Diego, is evident as increased resistivities near the seafloor, but the distribution of fresh water appears to be influenced by segments of the Silver Strand Fault.

In the 2019 IGPP report I introduced a magnetotelluric (MT) study we had done on the Mid-Atlantic Ridge along with seismology colleagues from the UK, highlighting the good agreement between the MT inversions and surface wave inversions. This year we published an interesting result (Harmon et al., 2021) where we predicted seismic velocities from the electrical resistivities of the MT model, and re-started the seismic inversions from this starting model. Previously, the seismic inversions were started from a one dimensional layered model of typical ocean crust. It is surprising how different the two surface wave inversions are, and the agreement with the MT model is now even better. Having both seismic velocity and electrical conductivity for each model cell allowed us to simultaneously predict temperature, melt fraction, and water content of the melt in the mantle.







Figure 7. Top: Surface wave velocity predicted from electrical conductivity, used as a starting model. Middle: Seismic model inverted from EM starting model. Bottom: Model inverted from 1D starting model. The two inversions fit the surface wave data identically well.

RECENT PUBLICATIONS

- Harmon, N., S. Wang, C.A. Rychert, S. Constable, and J.M. Kendall (2021): Shear velocity inversion guided by resistivity structure from the PI-LAB Experiment for integrated estimates of partial melt in the mantle. *Journal of Geophysical Research: Solid Earth*, **126**, 0.1029/2021JB022202
- Rychert, C.A., S. Tharimena, N. Harmon, S. Wang, S. Constable, J.M. Kendall, P. Bogiatzis, M.R. Agius, and D. Schlaphorst (2021): A dynamic lithosphere-asthenosphere boundary near the equatorial Mid-Atlantic Ridge. *Earth and Planetary Science Letters*, **566**, 10.1016/j. epsl.2021.116949
- Stern, L.A., S. Constable, R. Lu, W.L. Du Frane, J.J. Roberts (2021): Electrical properties of carbon dioxide hydrate: Implications for monitoring CO2 in the gas hydrate stability zone. *Geophysical Research Letters*, **48**, 10.1029/2021GL093475
- Attias, E., S. Constable, D. Sherman, K. Ismail, C. Shuler, and H. Dulai (2021): Marine electromagnetic imaging and volumetric estimation of freshwater plumes o shore Hawai'i. *Geophysical Research Letters*, **48**, 10.1029/2020GL091249
- Key, K., and S. Constable (2021): Inverted long-baseline acoustic navigation of deep-towed CSEM transmitters and receivers. *Marine Geophysical Research*, **42**:6, 10.1007/s11001-021-09427-z
- Attias, E., D. Thomas, D. Sherman, K. Ismail, and S. Constable (2020): Marine electrical imaging reveals novel freshwater transport mechanism in Hawai'i. *Science Advances*, 6, eabd-4866, 10.1126/sciadv.abd4866
- Wang, S., S. Constable, V. Reyes-Ortega, H. Jahandari, C. Farquharson, T. Avil e s-Esquivel (2020): Twodimensional determinant inversion of marine magnetotelluric data and a field example from the Gulf of California, Mexico. *Geophysics*, **86**, E37–E57, 10.1190/GE02019-0735.1

Figure 8 (background). IDA's Chris Sites and Don Elliott prepare to lower the new STS6A seismometer into the 100m deep borehole at Pinyon Flat Observatory. Sensors from deep boreholes like this one are particularly effective for recording horizontal earth motions. Photo: J. Conley



J. PETER DAVIS

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Specialist

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

GSN network maintenance has proven to be a particular challenge during the COVID pandemic. Normally IDA technicians would be traveling around the world to repair malfunctioning equipment or install new instruments to keep the network in optimal operating condition. Prior to the lockdown, IDA technicians installed new borehole instruments at two sites in Kazakhstan and one in Uganda. Figure 1 shows one of these sensors being lowered into a 100m deep borehole at Pinyon Flat Observatory, our local station and the only field trip we have conducted during the pandemic lockdown. Placing this seismometer in a borehole is a way to insure the quietest possible setting for recording distant earthquakes.

IDA staff members are constantly working to ensure the finest quality data are collected from each instrument including fine-tuning our models of each station's instrument responses and checking data timing 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 9 shows the results of one data quality test we performed at many stations this year. We exploited the fact that almost every station had more than one broadband seismometer deployed there to test the accuracy of the timing. Short data segments from co-located pairs of sensors were compared to

see if, within a common frequency band, the time series were synchronized properly. The results for station II.ALE shown in this figure indicate that the apparent time shift between the sensors was less than 5 milliseconds, an acceptable result and about as accurate as can be obtained with this method. This encourages confidence that these recordings may be used in studies of deep mantle and core structure that require accurate measurements of time shifts of this order.

RECENT PUBLICATIONS http://dx.doi.org/doi:10.7914/SN/II http://dx.doi.org/doi:10.1785/0220170280



Figure 9. Apparent time shift between the primary and secondary seismometers at II.ALE measured from the cross spectrum of 10min-long segments drawn daily. The low values and small scatter over this long time period provides evidence to support the highly accurate timing of these data. Accurate timing is essential for many studies of deep Earth seismic structure.

MATTHEW DZIECIUCH

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Research Geophysicist

Acoustical Oceanography, Ocean Acoustic Tomography, Signal Processing

My research focuses on the remote sensing of the ocean with long-range acoustic transmissions. This offers a unique capability for measuring ocean interior properties, such as horizontally averaged temperatures and currents. The travel-time of sound waves propagating through the depths is affected by both small-scale and large-scale ocean processes. Acoustical oceanography seeks to use sound propagation in the ocean to understand some of the dynamic processes that are present. Some of the processes that can be studied include climate change, ocean circulation, internal waves, and tides.

Recently, along with Peter Worcester, we have deployed moorings for a new experimental program in the Arctic that measures the heat content along a trans-Arctic path extending from near Svalbard to near the North Slope of Alaska. A map of the 2019 deployment is shown in Figure 10. The extreme environment of the Arctic is perhaps the most vulnerable to anthropogenic climate change. Part of the experimental 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.

The sound source operates near 35 Hz in order to avoid the rough ice-cover scattering losses associated with higher frequencies. The stratification of the Arctic is complicated and 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 affected. The experiment has been designed to learn the most possible from the acoustic traveltime, transmission loss, and scattering as the sound interacts with the stratification and with the rough ice-cover. Another important goal is to examine the feasibility of underwater acoustic navigation of autonomous instruments which are expected to be increasingly deployed in the under-

The field program collected data for one year and was recovered in the late fall of 2020. In addition to the logistics of loading people and gear onto an

sampled ice-covered Arctic ocean.

Figure 10. Deployed experimental layout of the CAA-TEX field program. The blue dots designate acoustic transceivers (sources and vertical line arrays.) While the orange dots designate acoustic receivers only.

icebreaker while keeping them COVID free, we were further hampered by a main propulsion motor failure on the one capable USGC vessel. Fortunately, we were able to reorganize with the help of the Norwegian Coast Guard vessel KV Svalbard and all the moorings were successfully recovered. This past year has been devoted to analyzing the data, the quality is excellent and we are expecting to publish our results soon.

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WENYUAN FAN

Assistant Professor

My research broadly concerns seismic source processes, including earthquakes, slow earthquakes, transient environmental processes, and their interactions and triggering. Understanding seismic source processes is one of the most fundamental goals of seismology. For example, earthquakes and landslides can cause catastrophic disasters, and understanding the physics behind these events is critical for hazard assessment and mitigation. Further, seismic sources are transient events during the long geological history, knowing their mechanisms can help to decipher the large-scale tectonic and landscape evolution processes. In particular, earthquakes and subduction zone process tightly couple with each other, and studying slip events can offer a unique window to reveal the dynamics of subduction zone at different spatial and temporal scales. My research seeks to unmask physical mechanisms regulating seismic source processes by developing new imaging techniques, using dense seismic arrays, and acquiring onshore and offshore geophysical observations.

Landslide encompasses a wide range of processes. The dynamic geomorphic process can drastically reshape the landscape and redistribute the sediments. Seismic observations can aid in detecting and locating landslides. The innovative way of studying landslides has greatly improved our understanding of the dynamics. My previous visiting scholar Ryo Okuwaki led a study to apply a new method to continuous Japanese data and successfully identified small landslides that were triggered by Typhoon Talas in 2011 (Figure 10), including a landslide in the Tenryu Ward, Shizuoka prefecture, Japan, ~400 km east from the typhoon track. The Tenryu landslide displaced a total volume of 1.2-1.5 x 10⁶. The landslide was much smaller than those detected by using globally recorded surface waves, yet the event generated coherent seismic signals propagating up to 3000 km away. Our observations confirm that landslide attributes, including the mass, inertial force, and surface wave magnitude, empirically scale with each other and these scaling relationships are likely invariant for landslides of different sizes. The detection of landslides using this seismic means is very useful since they often occur in remote and mountainous areas and other ways of detection (e.g., field observations) tend to be slow.

Understanding earthquake foreshocks have both scientific and societal implications regarding earthquake physics and seismic hazards. Using dense arrays in the Ridgecrest region, my postdoc Haoran Meng found immediate foreshocks of 527 earthquakes that occurred within a month of the 2019 Mw 7.1 Ridgecrest earthquake (e.g., Figure 11). These immediate foreshocks are adjacent to their mainshocks and likely near-instantaneously trigger the following slip within 100 seconds. Attributes of the P waves of these immediate foreshocks do not seem to correlate with the mainshock magnitudes. The

Figure 10. Tenryu landslide that was triggered by Typhoon Talas, 2011. The left panel shows the digital elevation models (DEMs) of the Tenryu landslide. Our detection was within 5 km of the ground-truth location. Our failure model obtained with the seismic records also matches well with the DEM model. The panel on the right shows the before and after image of the topography.

Figure 11. Example earthquake P waves and their preceding signals from the immediate foreshocks recorded by the nodal stations. The preceding signals are highlighted by the gray boxes and amplified for visual comparisons. The amplification factors are listed in the boxes. The records are the vertical components of example nodal array stations and the waveforms are band-pass filtered at 1 to 20 Hz with a casual 2nd-order Butterworth filter.

current set of observations can be best interpreted as representations of the cascade model. In this cascade model, a slip event on a small fault patch that is adjacent or within the earthquake rupture area rapidly transfers stress to a surrounding fault patch and leads to an unsteady dynamic rupture. Our observations suggest that earthquake rupture may initiate in a universal fashion but evolves stochastically. This indicates that earthquake rupture development is likely controlled by fine-scale fault heterogeneities in the Ridgecrest fault system, and the final magnitude is the only difference between small and large earthquakes.

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YURI FIALKO

Professor

Earthquake physics, crustal deformation, space geodesy, volcanology

Professor Fialko's research is focused on understanding the mechanics of seismogenic faults and magma migration in the Earth's crust, through application of principles of continuum and fracture mechanics to earthquakes and volcanic phenomena. Prof. Fialko is using observations from space-borne radar and global navigation satellites to investigate how the Earth's crust responds to seismic, magmatic, and anthropogenic loading.

One of the long-term research interests of Prof. Fialko is the state of stress in the Earth's crust. There is a long-standing debate regarding the level of average shear stress resolved on seismogenic faults. Estimates of the earthquake stress drops place a lower bound on shear stress resolved on seismogenic faults on the order of 1-10 MPa. Laboratory measurements of

quasi-static rock friction, orientation of young faults with respect to the inferred principal stress axes, and measurements in deep boreholes in stable intraplate interiors suggest that the brittle upper crust should be able to support much higher shear stresses on the order of the lithostatic pressure (> 100 MPa for ~15 km thick seismogenic zone), provided that the pore fluid pressure is approximately hydrostatic. In contrast, unfavorable orientation of some mature faults with respect to the principal stress axes, the "heat flow paradox" of the San Andreas Fault, a possibility of fluid over-pressurization, low frictional strength of some parts of mature faults suggested by scientific drilling experiments, and strong dynamic weakening observed in laboratory friction experiments at slip rates in excess of ~0:1 m/s lend support to the "weak fault" theory according to which faults may operate at background shear stresses well below the failure envelope

predicted by the Byerlee's law.

Direct measurements of stresses acting at seismogenic depths are largely lacking. Seismic data (in particular, earthquake focal mechanisms) have been used to infer orientation of the principal stress axes. In a recent study, Prof. Fialko showed that the focal mechanism data can be combined with information from precise earthquake locations to place constraints not only on the orientation, but also on the magnitude of absolute stress at depth. The proposed method uses relative attitudes of conjugate faults to evaluate the amplitude and spatial heterogeneity of

Figure 12: Finite strain and rotation recorded by offset dikes near the 2019 Ridgecrest earthquake rupture. Satellite photo of a dike swarm offset by left-lateral faults (white dashed lines) that havefthe same attitude as the 2019 left-lateral rupture that produced the M6.4 foreshock (red line). α is the angle between the axes of the least compressive stress acting at present (dashed yellow line) and at the time of dike emplacement (solid yellow line). White cross marks the indicated coordinates. The inset shows the outcrop location (blue rectangle) with respect to the entire earthquake rupture (red lines). From Fialko and Jin (2021).

the deviatoric stress and frictional strength in the seismogenic zone. Relative fault orientations (dihedral angles) and the sense of slip are determined using quasi-planar clusters of seismicity and their composite focal mechanisms. The observed distribution of dihedral angles between active conjugate faults in the area of Ridgecrest (California, USA) that hosted a recent sequence of strong earthquakes suggests in situ coefficient of friction of 0.4-0.6, and depth-averaged shear stress on the order of 25-40 MPa, intermediate between predictions of the "strong" and "weak" fault theories. Another project was focused on understanding the nature of relative orientations of faults ruptured during the 2019 Ridgecrest earthquake sequence. Observations in tectonically active areas increasingly reveal sets of high-angle conjugate faults ("cross-faults") that apparently contradict theories of faulting based on experimental data. Possible explanations include low in situ coefficient of friction, dominant control of ductile shear zones in the lower crust, and tectonic rotation. Discrimination between these mechanisms has been hindered by uncertainties in the state of stress, deformation history, and fault geometry at seismogenic depths. Prof. Fialko and graduate student Zeyu Jin used a combination of seismic, geodetic, and geologic data to demonstrate that ubiquitous cross-faults in the Ridgecrest, California area, including those ruptured in the sequence of strong earthquakes in 2019, result from rotation from an initially optimal orientation consistent with experimental data. The inferred rotation pattern can be explained by the geodetically measured velocity field. The proposed model suggests that the observed asymmetric rotation of faults in the Eastern California Shear Zone can result from simple shear. The same mechanism can be responsible for high-angle conjugate faults observed in other tectonic settings. Other currently active projects include a joint seismic-geodetic study of the sub-surface structure of the Southern San Andreas fault, and postseismic transients due to large earthquakes on the edges of the Tibetan Plateau.

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HELEN AMANDA FRICKER

Professor, co-lead Scripps Polar Center

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. I am a member of NASA's ICESat-2 Science Team. I became an AGU Fellow in December 2017 and gave the John F. Nye Lecture at AGU in 2019. I am an Honorary Professor at University of Swansea (1 February 2020 to present).

My 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, & predicting how that will change in the future. Because Antarctica is so large, & 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 technique we use is **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 Sept 2018)); these multiple missions have provided ice sheet height data for ~25 years. 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.

Ice shelves: Antarctica's ice shelves 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 and retreat result in enhanced ice discharge across the grounding line (GL) to the ocean. Our group specializes in monitoring Antarctic ice shelves from satellite altimetry (radar and laser). We also perform fieldwork on ice shelves.

Satellite laser altimetry (ICESat and ICESat-2): ICESat-2 was launched in September 2018 and I also led the writing of the first paper that came out on ICESat-2 over the ice sheets, comparing with the previous NASA laser altimetry mission (ICESat) to make an estimate of mass loss of all the ice sheets from 2003 to 2019, including the ice shelves; his allowed us to make direct comparisons between loss of floating ice and subsequent loss of grounded ice (through loss of buttressing).

ICESat-2 brings a new capability to surface melt detection on ice sheets: the 532 nm photons penetrate through standing water and are reflected from both the water and the underlying ice; the difference between the two (corrected for refractive index) provides a depth estimate.

Surface melting has been difficult to quantify because depth estimates are challenging. We led a pilot project with several investigators who contributed depth estimates for four Amery melt features with depths ranging to 6 m, using seven different ICESat-2 algorithms and compared them with estimates from coincident Landsat MSS and Sentinel-2 images. This showed ICESat-2 water depth estimates can be used to tune image-based depth algorithms, enabling improved ice-sheet wide estimates of melt volumes across Antarctica and Greenland; 3rd year student Philipp Arndt just received a NASA FINESST award to continue the surface melt work.

Field-based studies: I was PI on an NSF project ROSETTA-Ice which investigated the Ross Ice Shelf using airborne geophysics (gravity, laser and radar) conducted over four Antarctic field seasons. GP student Maya Becker participated in the 2016/2017 and 2017/2018 field seasons. We also worked with GP postdoc Emilie Klein who used GPS data from Ross Ice Shelf (from an NSF project led by SIO's Peter Bromirski) to identify a seasonal cycle in ice velocities. Ice-sheet modeling by GP postdoc Cyrille Mosbeux demonstrated that the seasonal cycle in velocity was consistent with the seasonality of near-ice-front basal melting, and that this seasonality extended onto the surrounding grounded ice; i.e., short-term changes in basal melting had a significant effect on the ice shelf's buttressing of the grounded catchments. Cyrille Mosbeux also worked on modelling the Ross ice front, working with GP student Maya Becker.

Subglacial water system: In 2006, I discovered active subglacial water systems under the fast-flowing ice streams of Antarctica in repeat-track ICESat data. Height changes on the order of several meters corresponded to draining and filling of active subglacial lakes. We continue to monitor active lakes and have found 124 in total throughout Antarctica. I was PI on two large NSF projects that culminated in drilling of two subglacial lakes (Whillans in 2013 and Mercer in Jan 2018). Matt Siegfried (former GP student) led the geophysics team, which also included former IGPP Prof. Kerry Key and GSR Chloe Gustafson (for EM measurements) in 2018, and 3rd year student Philipp Arndt in 2019.

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Figure 14. (a) Map of ice surface elevation change in Antarctica (Smith et al., 2020, Science) with boxes indicating current PGL focus areas; (b) recent deployment of an Airborne eXpendable Bathy-Thermograph (AXBT) sensor in East Antarctica; (c) conceptual profile of an ice shelf from upstream of the grounding line (right) to the adjacent ocean and sea ice (left). We use ice-penetrating radar data to infer atmosphere- and ocean-driven melt processes, gravity and magnetics to constrain the depth and shape of the seafloor, and expendable ocean sensors to determine the state of the ocean and for seafloor depth constraints. Current NSF and NASA projects underway in the PGL seek to use fixed-wing and rotary-wing aircraft in East and West Antarctica, respectively, to acquire geophysical data and deploy expendable ocean probes in areas that are otherwise impossible or impractical for conventional icebreaker platforms to access.

JAMIN S. GREENBAUM

Assistant Research Geophysicist

Cryosphere, Ice-ocean interactions, Ice shelves, Airborne remote sensing

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My work is guided by a desire to understand the causes and impacts of ongoing and future sea level change. Recently I have been focused on understanding the processes controlling ice shelf melt and grounding line retreat in Antarctica, emphasizing the acquisition and analysis of airborne remote sensing data over ice shelf cavities and other under-observed areas along the Antarctic continental shelf. Beyond data analyses and interpretation, I also seek to develop novel techniques to access and observe difficult to reach environments. I am dedicated to inclusive global collaborative science and maintain close ties with scientists, pilots, and other experts from around the world.

Ice-ocean interactions: The PGL is currently managing multiple projects supported by NASA and the NSF to understand what is driving coastal glacier thinning in East and West Antarctica (Fig. 14a). We apply a variety of observational and numerical modeling approaches to constrain boundary conditions and identify processes related to Antarctic coastal ice sheet stability. Recently, this work has included analyses of radar data to detect subglacial water systems and grounding lines and to infer surface and basal melting of ice shelves. We also use gravity and magnetics data to infer the geology and geothermal heat flux beneath the Antarctic Ice Sheet, and the shape of the seafloor beneath sea ice and ice shelves where icebreakers struggle to sail. We are particularly interested in understanding the impact of discharged subglacial meltwater on ice shelf basal melt.

Airborne remote sensing for ice-ocean interactions: Airborne platforms can effectively and repeatedly access areas impossible or impractical for marine platforms to reach (Fig. 14 b and c). We use ice-penetrating radar data to characterize boundary conditions useful for numerical ice sheet and ocean circulation models (e.g. basal morphology and small scale roughness); we apply gravity and magnetics data to infer the depth and shape of the seafloor beneath floating ice; and we use airborne-deployed ocean sensors to sample the ocean state along ice shelf fronts where no prior data have been acquired.

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JENNIFER S. HAASE

Research Geophysicist

I work in two broad research areas: 1) Earthquakes, seismic hazard, and tsunami hazard and 2) hazards from severe weather using GPS signals as a remote sensing technique from aircraft and stratospheric balloons.

AIRCRAFT OBSERVATIONS OF MOISTURE IN ATMOSPHERIC RIVERS

Atmospheric rivers (ARs) are long narrow filaments of high moisture transport over the ocean usually associated with extreme and long duration rainfall when they impact the western coast of the US. The moisture distribution within atmospheric rivers when they arrive at the coastline is a major factor in determining the spatial distribution and intensity of precipitation. Aircraft reconnaissance missions with targeted dropsondes have been operationalized recently to provide high resolution observations and improve forecast model initial conditions of winds, moisture, and temperature in the region of extensive cloud cover and rain that is difficult to measure from satellites. We seek to increase the amount of data available from the reconnaissance missions with airborne GNSS (Global Navigation Satellite System) radio occultation (ARO) profiles that are collected continuously during flight without additional expendable costs. We derive the first refractivity profiles from the European Galileo system, and combine them with Global Positioning System profiles to demonstrate accuracy comparable to dropsonde observations. The combined dataset enhances the coverage at a scale relevant for mesoscale weather modeling. The refractivity anomaly from the mesoscale model reveals key features of the atmospheric river including the low-level jet and tropopause fold that illustrate the potential strength of the ARO method to directly

measure AR characteristics.

Figure 15. Figure 1. Airborne radio occultation geometry. GNSS signals are recorded as a satellite sets (or rises), with ray paths successively sampling deeper into the atmosphere. The points of closest approach of each ray path to the Earth's surface (tangent points) drift horizontally away from the aircraft as altitude decreases for a setting satellite (red dots). The atmosphere is most dense at the tangent point, so the measured refractive delays are most strongly influenced by the atmospheric properties at this location. Retrievals of atmospheric refractivity, moisture, and temperature are represented as values along these slanted tangent point profiles.

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Figure 16. Three-dimensional view of sampling by airborne radio occultation drifting tangent points and dropsondes. Dark grey and magenta curves are Galileo and GPS occultations, vertical black lines are dropsondes released from the aircraft, whose trajectory is denoted by the brown line. Integrated water vapor transport is shown in color contours on the lower surface.

Figure 17. Refractivity anomaly cross-section through the mesoscale weather model that incorporated the aircraft observations, perpendicular to the atmospheric river transport direction. Refractivity anomaly (%) is the difference from a climatological model. The 2 PVU contour is represented by the thick black dashed line. Potential temperature contours are shown in gray. The schematic representation of the vertical structure of the AR [Ralph et al., 2017] is superimposed on the refractivity anomaly, with no adjustments to the horizontal or vertical scale to illustrate how refractivity anomaly captures the key features of the atmospheric river structure and in particular the area at the top of the moist low level jet where convection occurs.

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DEBORAH LYMAN KILB

Project Scientist

Research Interests: Crustal seismology, earthquake early warning and earthquake triggering. Diversity Interests: Improving how science is communicated to students and the public. Promoting jobs requiring skills within the intersection of science and art. Cultivating diversity, and acceptance of diversity, within our communities.

Earthquake Early Warning [Kilb et al., 2021]. Earthquake early warning (EEW) detection schemes require (1) ample seismic information to identify where large ground motions are underway; (2) determining if these ground motions are significant enough to issue a detection; and (3) detecting large ground motions in a timely fashion. Some EEW methods estimate earthquake source parameters like magnitude and location and then input those parameters into a ground-motion prediction equation, while other methods use observations of the ground motions to directly forecast shaking. We explore the latter approach using the PLUM (Propagation of Local Undamped Motion) method to detect earthquakes that produce shaking above a target value. In this work, we test PLUM's ability to detect earthquakes using two data sets: 558 earthquakes magnitude 3.5 and above from California, Oregon, and Washington (2012–2017) and a test suite of historic and problematic signals (1999–2015) curated by ShakeAlert. We find a two-station detection method is preferred over a one-station method as two-stations can greatly minimize false detections. The PLUM method is also 100% successful at avoiding non-earthquake anomalous signals and can successfully differentiate ground shaking from local and distant earthquakes. We conclude that PLUM may be a promising candidate for integration into the U.S. EEW system.

Figure 18. Evolution of the PLUM alert area for the 2014 magnitude 5.1 La Habra earthquake (open circle). Triggered stations (red triangles) and those predicted to exceed the threshold (orange triangles) at 3, 8, and 13 s after the event origin time. The first alert is issued 3 seconds after the earthquake origin time, and the alert area grows as more stations exceed the thresholds. The final distribution of stations that exceeded the threshold (red) and those predicted to exceed the threshold (orange) are juxtaposed on the USGS ShakeMap (lower right). Note that all stations that PLUM predicted to exceed the MMI=4 threshold, but were not exceeded on the ShakeMap, are within 30 km of a station that did exceed the threshold. This zone of over-alerting (e.g., locations where ground motions are predicted to exceed the threshold but do not) is inherent to PLUM.

Semantics at the Salton Sea: When does a swarm become a sequence? [Kilb et al., 2021]. On June 5 at 1 a.m. local time, a series of small to medium earthquakes started shaking the southeast shore of the Salton Sea in Southern California. The largest event was a magnitude-5.3 strike-slip earthquake about 11 hours after the series started. Over the last few days, more than 1,000 quakes have occurred in this area. At first glance, this seemed like a fairly standard earthquake swarm — a common occurrence for the Salton Sea region (Figure 19). Upon a deeper dive into the earthquake data, however, the latest series of quakes may actually be a mainshock/aftershock sequence. What that means for the residents of this shaken region doesn't change: The chance of an earthquake exceeding magnitude-7 within the following month remains less than 1% (see the U.S. Geological Survey's Aftershock Forecast). For researchers, though, these events offer a new perspective on the source physics of these earthquakes.

Figure 19. Map of the Salton Sea region in Southern California. Earthquakes (magnitude-2.0 and greater) within the last two decades are depicted as gray x's and earthquakes that are assumed part of swarms are color-coded: 2000 olive; 2005 orange; 2012 green; 2016 yellow; 2020 red and 2021 blue (three days of data only).

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* Post-doc

GABI LASKE

Professor of Geophysics

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

Gabi Laske's main research area is the analysis of seismic surface waves and free oscillations, and the assembly of global and regional seismic models. She has gone to sea to collect seismic data on the ocean floor. Laske's global surface wave

database has provided key upper mantle information in the quest to define whole mantle structure. Graduate students Christine Houser and Zhitu Ma as well as students from other universities have used her data to assemble improved mantle models. Most recently, she demonstrated that free oscillation observations are possible on free-fall ocean bottom seismometers to frequencies around 1 mHz. Most recently, she collaborated with colleagues from Incorporated Research Institutions for Seismology (IRIS) to assemble a catalog of common data problems.

The USArray arrival angle project: Laske and her team assembled a dataset of surface wave arrival angles using both her hands-on traditional toolbox as well as the automated Python-based tool DLOPy that her graduate student Adrian Doran developed. The comparison was the basic for an IRIS summer internship project, and results were recently published. While DLOPy is a superior tool to collect highquality arrival angle data at frequencies 20 mHz and higher, the hands-on tool is still needed for the analysis of Love wave data. Ongoing research investigates how heterogeneous Earth structure causes marked changes in arrival angles that are observed across that USArray (Figure 20).

The PLUME and OHANA projects: For the past decade or so, Laske and her team have analyzed records from ocean bottom seismometers (OBSs). She led the Hawaiian PLUME project (Plume{Lithosphere{Undersea{Mantle Experiment) to study the plumbing system of the Hawaiian hotspot. PhD student Adrian Doran conducted a first ever joint analysis of seafloor compliance and ambient-noise Green's functions. The group's most recent paper describes a Monte-Carlo search for sediment and uppermost crustal structure. In 2021, Laske and

Figure 20. Arrival angles at 15 mHz for the 3 January 2009 Irian Jaya (Event 1) and the 15 January 2009 Loyalty Islands (Event 2) earthquakes. Green arrows mark the back azimuth from a station near San Diego to the source (displaced for unobstructed view). The overall patters are different between different events and reflect wavefront deformations as a result of wave propagation in the heterogenous Earth.

her team deployed OBSs halfway between Hawaii and North America for the OHANA project to investigate 40-50 Myr old northeast Pacific lithosphere. The OHANA project contributes to the international Pacific Array initiative.

The CABOOSE project: The CAlifornia BOrderland Ocean SEismicity project (CABOOSE) is a collection of small OBS deployments, past and on-going, to assess seismicity offshore Southern California. In 2014, a 3-month deployment about 300 km west of La Jolla revealed never-before seen seismic activity 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 inner Borderland seismicity. For a recent deployment, development engineer Martin Rapa designed an in-situ calibration frame for the pressure sensor to help better understand the still poorly known instrument response of that sensor. Doran and Laske modeled

the time series of three sensors. Benchmarking their results also against traditional post-processing techniques, they found significant, previously undocumented variance between the sensors.

The rich dataset of this deployment reveals numerous repeat events along the San Clemente Fault that have not been detected by the Southern California Seismic Network. The Laske team investigates a comprehensive event catalog. Related to this project, undergraduate cognitive sciences student Spencer Okamoto analyzed recent earthquake swarms in the greater Salton Sea area for his SIO199 independent studies project. Spencer's proficiency in Python programming and LaTex typesetting allowed effective mentoring via Zoom during a COVID-19-restricted, remote-working environment.

Global reference models: Laske continues to compile and distribute global crustal models. CRUST1.0, A 1-degree crustal model, was released in 2013. Applications relying on CRUST1.0 are found across multiple disciplines in academia and industry. Laske maintains the distribution website and provides guidance to users. Laske continues collaborations with Walter Mooney from the USGS and others to update databases and ultimately provide a refined crustal model.

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ROBERT J. MELLORS

Research Scientist

Seismic sensors, optical fiber-based sensing, subsurface imaging of geothermal reservoirs, interferometric synthetic aperture radar.

Photonic sensors. Recent technological advances in seismic sensors provide new capabilities for seismic monitoring and subsurface imaging. Photonic-based sensors, such as distributed acoustic sensing (DAS), offer exceptional potential for high-spatial density seismic measurements with a high dynamic range and wide frequency bandwidth. These sensors measure the strain (or strain-rate) at all points along a fiber and are capable of monitoring kilometers of fiber. The optical fiber sensors appear to be especially useful for boreholes, seafloor, ice sheets, and other challenging environments. The challenges lie in interpreting the response and of the photonic sensor, optimizing signalto-noise, and effectively working with the large datasets, which often are 10's of TB in size. My research is focused on how to effectively use these sensors and includes both signal analysis and forward modeling of the signals and to understand the strengths and weaknesses of these sensors (Figures 21 and 22).

Geothermal exploration. Research continued geophysical methods applied to geothermal exploration. Geothermal energy is an attractive source of low-carbon energy, but finding new geothermal reservoirs is a challenging problem. We conducted a wide-scale survey of Western Saudi Arabia using data from a regional seismic network in collaboration with King Saud University (Al-Amri et al., 2020). Another, ongoing project uses existing unused telecom cable 'dark fiber' to characterize geothermal resources in the Imperial Valley, CA (Nayak et al., 2021).

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Figure 22. Comparison of fiber-optic acoustic data (labeled DAS) and standard seismic sensors (broadband and strong motion) for an earthquake sequence that includes a magnitude 5 earthquake approximately 15 km from a dark fiber deployment. Some 'clipping', likely due to phase saturation/unwrapping artifacts, is apparent on the dark fiber data.

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MATTHIAS MORZFELD

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Associate Professo

Computational & stochastic modeling, sampling methods for inverse problems, numerical analysis, reduced order modeling

I am an applied mathematician who works on computational tools that are useful in Earth science. The common theme that ties my work together is merging computational models with data, often via a Bayesian approach. This is easy to explain with the example of a weather forecast. Suppose you use a mathematical model for the weather to make a forecast. If the model calls for rain but you wake up to sunshine, then you should calibrate your model to this observation before you make a forecast for the next day. This is an example of Bayesian inference. My research focuses on the design, analysis and application of numerical methods for Bayesian inference problems in geophysics.

Bayesian inference problems in geophysics are characterized by three important properties, which make finding a solution very difficult, both conceptually and computationally.

- (i) The problems are "high-dimensional," which means that the computational model has many components, typically millions or hundreds of millions. Each component of the model needs to be updated in view of the data, which make computations difficult and, without clever mathematics, impossible to perform.
- (ii) The models are "nonlinear," which means they are complicated and many standard tools and methods do not directly apply or lead to incomplete, sometimes misleading, results.
- (iii) There are often many models that fit the data equally well, and it is usually not clear which model one should ultimately choose.

My research group continuously works an all three of these issues and brings new algorithms for Bayesian inference to bear in important geophysical problems.

Recent results on high-dimensional and nonlinear problems. One recent innovation for addressing the high-dimensionality and nonlinearity is a new, multi-scale technique for localization in ensemble forecasting. The idea of ensemble forecasting is great: Rather than making one prediction, we make several and use the variation within the forecast ensemble to estimate the uncertainty in our forecast. This idea is indeed used in a large number of problems, ranging from weather forecasting, to climate science (ensembles of different climate models), to predicting the time evolution of the South Atlantic anomaly of Earth's magnetic field. But the ensemble predictions are only useful if they can accurately represent the variations in a very high-dimensional space (we have many parameters to estimate). This is difficult because an accurate, high-dimensional representation requires a large ensemble, which, in turn, requires an unrealistic computational burden.

One way out of this di culty is to impose an anticipated statistical structure (akin to sparsity in numerical linear algebra), and the process of doing so is termed

Figure 23. Illustration of how the multi-scale localization scheme improves the accuracy of ensemble estimates of covariance matrices.

"localization." Localization has been used for a decade or so in numerical weather prediction with great success, but it remains a largely empirical technique, that requires a huge amount of tuning (essentially a trial and error process). With models and observations transitioning into a more nonlinear regime, empirical methods for localization are no longer adequate. What is needed is a mathematical theory that can guide the design of new, nonlinear localization methods. My team and I, supported by the Office of Naval Research, have been working on this problem for quite some time and have recently created a new method for localization in multi-scale problems. Multi-scale here means that the underlying physical system is characterized by more than one spatial or temporal scale, and that the various scales interact in a complex manner. With collaborators at the National Center for Atmospheric Research (NCAR), we have combined computational linear algebra with multi-scale localization to discover a more accurate representation of uncertainty in ensemble forecast methods.

An illustration of the method is shown in Figure 23, where we show the "true" covariance matrix of a test problem, a naive ensemble estimate, and the estimate of the matrix after applying our multiscale scheme. The need for localization is evident from comparing the left and center panels: The naive ensemble approximation (center) is a very noisy version of the "truth" (left) and this noise pollutes forecasts down the line. The success of our multi-scale scheme is evident by comparing the left and right panels: After localization, the estimate (right) has a striking similarity with the truth (left). See Ref. 1 for more detail.

Recent advances in geomagnetic data assimilation. In geomagnetic data assimilation (DA), one aims to calibrate models of Earth's dynamo to observations of Earth's magnetic field. This is important for decadal forecasts of Earth magnetic field (which we find on every smart phone), understanding the South Atlantic anomaly, and more broadly improves our understanding of the fluid flow in Earth's liquid outer core. DA is routinely used in numerical weather prediction (NWP) and in the modeling and forecasting of ocean flows, but application to the geomagnetic field has been difficult because the geodynamo—its models and its observations—is so different from the atmosphere or oceans.

Nonetheless, we learn lessons from atmospheric sciences, and therefore know that simplified "proxy" models, such as those pushed forward by Edward Lorenz, have been an invaluable tool for discovering new DA techinques in NWP. My student Kyle Gwirtz, together will collaborators at NASA Goddard Space Flight Center (GSFC), set out to create a new proxy model for use as a testbed in geomagnetic DA. The idea is to find a simplified model, that can be used in extensive numerical experiments to study difficulties in geomagnetic DA. The model is illustrated in Figure 24. We then further set out to study localization in geomagnetic DA with our new proxy model (see above for what localization is and why it is so important for DA and ensemble forecasting). Our results illustrate that current localization techniques may not be adequate in geomagnetic DA and we also offer new ideas for creating adequate localization methods for geomagnetic DA (see Ref. 2 for more detail). Indeed, Kyle, who graduated in Nov. 2021, will continue this work at NASA GSFC, funded via a prestigious NASA Postdoctoral Fellowship.

Proxy magnetic field

Proxy velocity field

Figure 24. Illustration of the magnetic and velocity fields of a two-dimensional proxy model.

Scientific uses of machine learning. Computers and hand-held devices have become a normal part of our daily lives and along with computers came the broad use of statistical algorithms, typically referred to as machine learning (ML) or artificial intelligence (AI). By now, ML and AI are encountered daily: the algorithms sort our email for spam, suggest the next video we want to watch, assist in completing our tax returns, and present us with advertisements that are of interest. The incredible success of ML/AI is in large part due to the availability of massive amounts of data: looking through vast amounts of emails makes it possible to identify features that renders an email suspicious. In addition, often very simple strategies can be very successful: it is likely that you will enjoy watching a video very similar to the one you just enjoyed watching. Simple strategies are easy to discover. Finally, if the ML/AI algorithm makes a mistake, the consequences are usually "minor"—the company makes less money because the advertisement strategy is sub-optimal, or you may need to delete a few additional emails.

None of the above is generally true in geophysics. There are no vast amounts of data—every measurement and observation is the result of a long, costly effort. Simple prediction strategies are useless—I may often turn out to be right when I predict that the weather tomorrow will be the same as the weather today, but such a prediction strategy misses the point of predicting *changes* in the current conditions. And finally, a "wrong" assessment or prediction can have disastrous consequences, e.g., when predicting the path of a hurricane.

Nonetheless, there are many ingenious and careful efforts to port the success of ML and Al into Earth science, keeping the above mentioned problems in mind and my students, collaborators and I follow this path as well. Specifically, we have recently adapted Global Bayesian Optimization (GBO) to tune localization and inflation in ensemble DA, to estimate uncertain or unknown parameters of numerical models, or doing both at the same time (estimate model parameters while simultaneously tuning localization/inflation). GBO is an ML technique, used in the tech-industry for advertisement placing. The reasons for why GBO is an adequate method for tuning localization or estimating model parameters are a bit intricate and mathematical, but, and to come to the point, we had great success with borrowing ideas from the tech industry to make progress in important geophysical and Earth science problems (see Ref. ~3 for more detail).

The computational methods and mathematics I work on often find use in—to me—unexpected ways. Examples include predictions of Earth's axial magnetic dipole field (Ref.~4), studying paleomagnetic data (Ref.~5), modeling the Argentine Basin in the Southern Ocean (Ref.~6), and even in image deblurring problems at the Nevada National Security Site (which is home to Area 51, see Refs.~7 and~8).

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ROSS PARNELL-TURNER

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Assistant Professor

Melting and deformation on mid-ocean ridges, mantle dynamics

My research is focused on discovering how oceanic crust is created and deformed, with a focus on mid-ocean ridges, and mantle plume-ridge dynamics. My group works to understand the thermal and tectonic structure of mid-ocean ridges, and the processes of mantle convection, hydrothermal circulation, and rifting. Our efforts are underpinned by a diverse range of observational methods from earthquake seismology and scientific ocean drilling to high-resolution near-bottom data and samples collected by submersibles and robots. We combine these observations with theoretical models to constrain the tectonic and fluid dynamical processes taking place in often remote and extreme deep-sea environments.

The intersection between the slow-spreading Mid-Atlantic Ridge and Iceland hotspot provides a natural laboratory where the composition and dynamics of Earth's upper mantle can be observed. Plume-ridge interaction drives variations in the melting regime, which result in a range of crustal types, including a series of V-shaped ridges and V-shaped troughs south of Iceland. Time-dependent mantle upwelling beneath Iceland dynamically supports regional bathymetry and leads to changes in the height of oceanic gateways, which in turn control the flow of deep water on geologic timescales. I am the Co-Chief Scientists of IODP Expedition 395, which aims to test these ideas by drilling 200 m deep into oceanic crust at five sites on the flank of the Reykjanes Ridge south of Iceland (Parnell-Turner et al., 2020). After being postponed in 2020, our plan was partially implemented during Expedition 395C over 60 days in the summer of 2021, although COVID-19 restrictions meant that no scientists were able to be on the vessel (Figures 25, 26 and 27). Despite this reduced shipboard staff and the usual weather challenges in the North Atlantic Ocean, we successfully recovered nearly 800 m of basaltic core, 1700 m of sedimentary core, and collected over 2 km of wireline logging data. These cores and data will allow us to test the hypothesis that thermal pulses in the mantle plume cause changes in crustal thickness, and also investigate the process of progressive crustal alteration and changes in deep-water circulation. We are scheduled to return to the Reykjanes Ridge in 2023 during Expedition 395 to complete our scientific objectives, hopefully with a full scientific complement on board.

Continuing my long-standing interest in the structure of slow-spreading ridges, we used an array of autonomous hydrophones in the equatorial Atlantic Ocean to detect Pn arrivals, which are routinely identified in the continents, but in the oceans, are more elusive (de Melo et al., 2021). We showed that

Pn rays from regional earthquakes, which travel just below the Moho, can provide insights into the thermal and compositional properties of the upper mantle. We found higher velocities associated with transform faults, and lower velocities for ray paths parallel to plate spreading.

This year saw the second of four planned expeditions to the 9°50'N segment of the East Pacific Rise, where we are mapping the pre-eruption seafloor, and monitoring the temperature and chemistry of vent fluids. Volcanic eruptions in the oceans account for a large fraction of the magmatism on Earth, yet their size and frequency remain poorly understood. Repeat eruptions at the 9°50'N segment have been well documented over the past 30 years, but the circumstances during the build-up to the next eruption remains uncertain. Sailing on RV *Revelle*, we successfully completed a 115 km2 multibeam survey during 19 missions with autonomous underwater vehicle Sentry, and installed autonomous high-temperature vent loggers at 12 vents. We also continued with our time-series sampling of vent fluids, by collecting 65 in-situ fluid samples, which provide insight into chemical exchanges in the shallow crust and above the magma chamber (Figure 28).

RECENT PUBLICATIONS

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Figures 25, 26, 27, 28 (left to right, below): 20: The sun shines on the moonpool of RV JOIDES Resolution during IODP Expedition 395C. Photo: Sarah Kachovic. 21: Derrick of the RV JOIDES Resolution during IODP Expedition 395C. Photo: Sarah Kachovic. 22: Basalt cores being curated during IODP Expedition 395C. 23: ROV Jason control van onboard RV Revelle during cruise RR2102 at the East Pacific Rise, April 2021. Photo: Zoe Yin.

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Professor of Geophysics

Geodynamics, global marine gravity, crustal motion modeling, space geodesy

Students and Funding: Research for the 2019-20 academic year was focused on understanding the geodynamics of the crust and lithosphere. Our group comprises four graduate students Hugh Harper, Yao Yu, Matt Brandin and Julie Gevorgian. We support two postdocs Eric Xu and Katherine Guns. Our research on improvement the marine gravity field is co-funded by NASA and the Office of Naval Research. Our research on strain rate and moment accumulation rate along the San Andreas Fault System from InSAR and GPS is funded by the NASA Earth Surface and Interior Program as well as the Southern California Earthquake Center. We also receive funding from the National Science Foundation to improve the GMTSAR InSAR processing code and documentation (http://topex.ucsd.edu/gmtsar).

Global Gravity and Bathymetry: We are improving the accuracy and spatial resolution of the marine gravity field using data from 5 satellite radar altimeters (CryoSat-2, AltiKa, Jason-2, and Sentinel-3A/B). This is resulting in steady improvements 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. The improved marine gravity is important for exploring unknown tectonics in the deep oceans as well as revealing thousands of uncharted seamounts including Walter Munk Guyot (Figure 29).

Integration of Radar Interferometry and GPS: We are developing methods to combine the high accuracy of point GPS time series with the high spatial resolution from radar interferometry to measure interseismic velocity along the San Andreas Fault system associated with earthquake hazard (http://topex.ucsd.edu/insargen). Over the past six 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. A Major earthquake (M7.1) struck Ridgecrest California in July 2019 and the surface deformation was extremely well imaged by these satellites (http://topex.ucsd.edu/SV_7.1/index.html). This research is described in a forthcoming publication in the journal Science [Xu et al., 2020]

RECENT PUBLICATIONS

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Figure 29. Mapping of Walter Munk Guyot. (upper) Predicted seafloor depth based on satellite-derived gravity anomaly and sparse ship soundings. (lower) This large guyot (flat-topped seamount) was surveyed by SIO Research Vessel Sally Ride during a transit from Honolulu to Guam. In October 2021 this guyot was named after Walter Munk who was an extraordinary scientist and the founder of our IGPP lab. Walter passed away in February 2019. (https://scripps.ucsd.edu/news/seamount-named-iconic-scripps-oceanographer-walter-munk)

Figure 30. Participants in the spring 2021 class on Seafloor Geodesy (https://topex. ucsd.edu/sg/) visit the SIO Marine Facility to see a wave glider that is used for GNSS acoustic experiments. Mark Zumberge, Glen Sasagawa, and Surui Xie operate the NSF-funded instrument pool for the US Seafloor Geodesy community (https://sites. google.com/view/seafloor-geodesy-community/)

PETER SHEARER

Distinguished Professor

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. At deeper depths, much of my research has involved resolving properties of the mantle transition-zone discontinuities.

I am currently collaborating with Rachel Abercrombie at Boston University to compare and test methods for spectral analysis of local earthquakes. We have investigated the origins of the large uncertainties and scatter in stress-drop estimates of small to moderate earthquakes in Southern California and found that the empirical correction factors estimated to correct for attenuation along the ray paths play a critical role. Unfortunately, these factors are difficult to determine with confidence using most local earthquake datasets, owing to tradeoffs between source and path effects. We recently showed how borehole seismic records, which are less affected by attenuation, can be used to calibrate spectral corrections and yield more reliable earthquake stress drop estimates, as illustrated in Figure 31 for aftershocks of the 1992 Big Bear earthquake. These results will inform our efforts to compute reliable stress drop estimates for small earthquakes across southern California and other regions.

Figure 31.Stress-drop estimates for over 1500 aftershocks of the 1992 Big Bear earthquake in southern California obtained using calibration data from Q-corrected spectra from the Cajon Pass borehole seismometer at 2.5 km depth. The median stress drop is 44 MPa, with events of higher stress drop plotted in blue and purple and events with lower stress drop plotted in red and brown. The star marks the location of the M 6.3 Big Bear mainshock. From Shearer et al. (2021).

In global seismology, I have long been interested in imaging upper-mantle discontinuities. Analyses of precursors to the seismic phase SS resulting from underside reflections off mantle discontinuities have proven particularly useful in mapping global properties of the 410- and 660-km discontinuities. Former IGPP Green Scholar Shawn Wei (now at Michigan State) has built a large database of SS precursor waveforms and recently documented a strong reflector at 810-km depth beneath the Kamchatka subduction zone, which is likely thickened crust associated with the 100-Myr-old oceanic plateau of the Hawaiian plume head, subducted to the uppermost lower mantle about 25 Myr ago (see Figure 32).

My research in southern California has continued to focus on improving earthquake locations (e.g., Ross et al., 2019), analyzing spectra to resolve corner frequency and estimate stress drop for small earthquakes (e.g., Shearer et al., 2019), and using coda waves to study scattering and intrinsic attenuation, as well as earthquake source properties (e.g., Wang and Shearer, 2019).

Figure 32. Cross-sections through the Kamchatka slab derived from different types of seismic data. (a) Stacked SS precursor waveforms, showing the well-known 410- and 660-km discontinuities and a regional reflector at 810 km depth. Red and blue indicate positive and negative signals above the 95% confidence levels, respectively, whereas gray shows the 2 σ stack uncertainty. (B) The position of the 810-km reflector with respect to a 3D tomographic model (TX2019slab) of P velocity variations. From Wei et al. (2020).

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PETER WORCESTER

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Researcher Emeritus, RTAD

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 both the ice cover and ocean structure. Changes in sea ice and the water column affect both acoustic propagation and ambient sound. This implies that what was learned about Arctic acoustics in the past is now largely obsolete. I have most recently been involved in the analysis of data collected during the 2015–2017 Canada Basin Acoustic Propagation Experiment (CANAPE) and the 2019–2020 U.S.-Norwegian Coordinated Arctic Acoustic Thermometry Experiment (CAATEX). Here I report on the CANAPE experiment. My colleague, Dr. Matthew Dzieciuch, reports on the status of the CAATEX experiment in his annual report.

CANAPE was designed to determine the 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 (Fig. 31). 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 sound 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.

The 2016–2017 CANAPE experiment included components in both the deep Canada Basin and on the continental shelf and slope north of Alaska. Dr. Dzieciuch and I had primary responsibility for the deep-water CANAPE experiment, for which six acoustic transceiver moorings and a Distributed Vertical Line Array (DVLA) receiver mooring were deployed north of Alaska during August-September 2016 and recovered during September-October 2017 (Fig. 33). The sources transmitted linear frequency-modulated signals with bandwidths of 100 Hz and center frequencies of approximately 250 Hz. The experiment combined measurements of acoustic propagation and ambient sound with the use of an ocean acoustic tomography array to help characterize the oceanographic variability throughout the year in the central Canada Basin. 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. All of the ice covering the array during 2016–2017 was first-year ice that reached a maximum thickness of about 1.5 m in late winter and early spring, even though the Canada Basin has historically been a region with extensive multi-year ice that survived over one or more summers.

The measured travel times were remarkably stable, with peak-to-peak variability of only about 20 milliseconds over the entire year. In comparison, travel times in mid-latitudes at similar ranges

4000

-2000

-4000

Figure 33. The 2016–2017 CANAPE experiment consisted of six Teledyne Webb Research acoustic transceivers (T1–T6) and a vertical line array receiver (DVLA). The array radius is 150 km. There was additional instrumentation on the continental shelf (PECOS).

vary by something like an order of magnitude more (~200 milliseconds peak-to-peak) due to the effects of ocean mesoscale variability with spatial scales of roughly 100 km and time scales of about one month. The high-frequency travel-time fluctuations at periods shorter than a day caused by small-scale oceanographic variability were also much smaller than in mid-latitudes. This was not unexpected, because the ocean internal wave field that scatters sound is much weaker in the Arctic Ocean than in mid-latitudes. In addition, the transmission loss increased significantly in winter, likely in part because of scattering when the signals reflect from the ice cover and in part due to changes in the ocean stratification. Finally, ambient sound also varied over the year, with minimum levels in May-June 2017 when the ice was thickest.

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MARK ZUMBERGE

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Research Geophysicist

Measurements of crustal deformation on land and on the seafloor. We use laser interferometry through optical fibers to measure strain in boreholes and trenches on land, and through optical fibers pressed into the sediment on the seafloor. We are using new cold-atom interferometry technology to make precise absolute measurements of gravity on land and planning to further the development for its application on the seafloor. We make continuous, calibrated pressure measurements on the seafloor to detect vertical deformation. We also are developing opto-mechanical borehole sensors for geodetic and seismic research on land. Finally, we are participating in a community effort to expand seafloor geodesy with the GPS-A method (described below). Many individuals are collaborators in these projects, including Jon Berger, Adrian Borsa, David Chadwell, Fanghui Deng, Donald Elliott, William Hatfield, David Price, Dennis Rimington, Glenn Sasagawa, Joel White, Frank Wyatt, and Surui Xie.

A long, ongoing, collaborative effort to expand our knowledge of crustal deformation occurring on the seafloor finally gained a foothold through a \$5M grant from the National Science Foundation to establish a pool of equipment for seafloor geodesy. A multi-institutional group of PIs (David Chadwell, Scripps; Noel Bartlow, Univ. of Kansas; Andrew Newman, Georgia Tech.; David Schmidt, Univ. of Washington; and Spahr Webb, Columbia Univ.) advocated through several proposal cycles that we cross the coastline boundary and establish offshore geodetic sites to enhance models of subduction zone

On the left is a Sonardyne seafloor transponder. It listens for coded acoustic pulses and replies with a unique pulse of its own. Measuring the round-trip time-of-flight of the pulses gives a measure of the distance between the transponder and the waveglider on the surface that initiated the connection. Below, are two Liquid Robotics SV3 wavegliders, the latest generation vehicle available. They have been fitted with additional GPS antennas, acoustic transducers, and inertial navigation sensors to equip them with GPS-A capability. Scripps has purchased 51 transponders, each with a 10-year battery pack, and three of the GPS-A wavegliders.

tectonics constrained so far mostly by onshore GPS stations. These efforts culminated in a grant to Scripps to purchase 51 Sonardyne seafloor transponders and three Liquid Robotics SV3 wavegliders enabling us to establish a network of 16 seafloor stations whose positions can be determined with cm resolution using a combination of GPS and acoustic ranging. Our current effort is to commission this equipment, readying it for a community-defined deployment in 2022.

In addition to gaining horizontal information from the sites, one third of the transponders contain a continuous pressure recorder whose measurements can reveal vertical movement of the seafloor. Because ambient sweater pressure is determined by depth (primarily), change in pressure accompanies change in depth—this is detectable at the cm level also. While oceanographic and gauge drift complicate the interpretation of the data, it has been shown that an interesting and important component of the subduction process known as slow-slip (sometimes called slow-earthquake or also episodic tremor and slip) is evident in pressure records, further illuminating the process under study.

A community workshop was held in the Spring of 2021 in which marine geodesists and other stakeholders collaborated to design an experiment to deploy the equipment in an as-yet-to-be-named region. The Cascadia subduction zone and the Aleutian Trench are front-running candidates.

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