CECIL AND IDA GREEN INSTITUTE OF GEOPHYSICS AND PLANETARY PHYSICS

2022 ANNUAL REPORT

SCRIPPS INSTITUTION OF OCEANOGRAPHY UNIVERSITY OF CALIFORNIA, SAN DIEGO

DIRECTOR'S WELCOME
FROM PETER SHEARER

IGPP enters 2023 with renewed strength as we return to in-person events and our halls are once again enlivened by the buzz of activity. Our faculty ranks have been strengthened by amazing recent hires and our students and postdocs remain among the best in the world.

IGPP research spans a huge range of topics within a variety of disciplines. We are pioneers in instrument design and data collection with a long tradition of theoretical rigor and innovative techniques. Our research extends from seafloor hydrothermal fields to the Tibetan Plateau, from atmospheric rivers to Antarctic ice shelves, and from the southern California crust to Earth's mantle and core. We are developing new approaches to analyze vast streams of geophysical data from satellites and ground-based networks, as well as our own land- and sea-based instruments. Science always benefits from unselfish cooperation in research, a vision we uphold, both within IGPP/SIO and in building collaborations with national and international communities.

The heart of IGPP is the quality of our science and our common goal to understand how our planet works, both for the joy of discovery and for its societal benefits. This was Walter and Judith Munk's original vision for IGPP and one that continues today.

CONTENTS

** no report in 2022*

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:

Senior Scholar Prof: *Heiner Igel, Ludwig Maximilians University Munich*

Senior Scholar Prof: *Christopher Davies, Univ Leeds*

Green Scholar: *Tyler Pelle, postdoc*

Green Scholar: *Zhe Jia, postdoc*

Green Scholar: *Diandian Peng, postdoc*

Miles Fellow: *William Davis, 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, the collection of novel datasets, and development of cutting edge analysis methods.

Graduate Students who successfully defended in 2022

Roslynn King - JDP (Steven Constable, Jillian Maloney, SDSU): *Groundwater under the ocean floor, working from the known to the unknown*

Teyang Yeh - *JDP* (Kim Olsen, SDSU): *Applications of high-frequency deterministic numerical simulations: Moving forward*

Julie Gevorgian - *MS* (David Sandwell): *Global Distribution and Morphology of Small Seamounts*

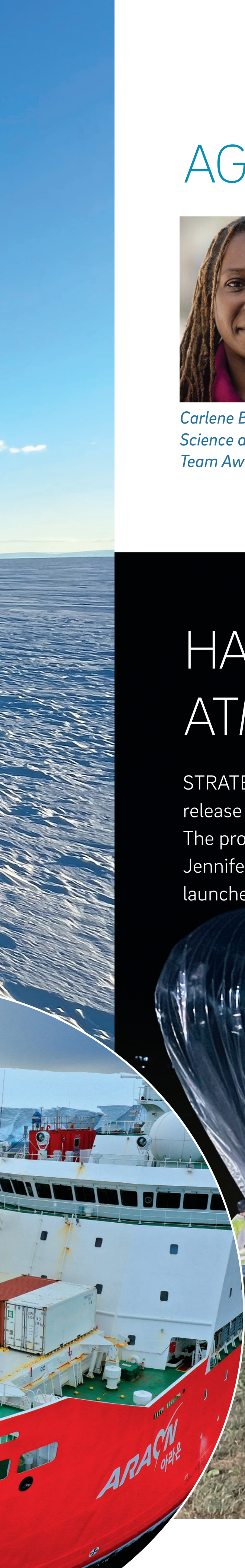
Xinyu Luo - *MS* (Wenyuan Fan): *A Joint Seismic and Space Geodetic Investigation of the 2016 Lamplugh Glacier and 2017 Wrangell Mountains (Alaska) Landslides*

Guilherme Sampiao del Melo - *MS* (David Sandwell): *Variations in Pn seismic velocities and lithospheric thermal structure across Mendocino fracture zone, eastern Pacific ocean*

Amy Whetter - *MS* (Adrian Borsa): *Comparing GNSS and InSAR Velocities in Preparation for NISAR*

GREENBAUM ACQUIRES WORLD FIRST OCEAN PROFILES NEAR THWAITES GLACIER

There is growing evidence that Thwaites Glacier is melting faster than computer models have been able to predict; the explanation will be found in well-hidden interactions between the ocean and Thwaites' dynamic floating ice tongue. Greenbaum and an international coalition of Antarctic researchers are conducting surveys of the glacier with a variety of platforms and approaches to find answers. With support from the Korea Polar Research Institute, National Science Foundation, NASA, the UCSD Academic Senate, Seequent Inc., and an Explorers Club Discovery Expedition Grant, Greenbaum is using helicopters to lower sensors into areas of the ocean that are otherwise impossible to access. The world first ocean profiles are illuminating ice-ocean interactions that have never been observed before. The groundbreaking work was featured by the *New Yorker Magazine* in **"Letter from Antarctica, Journey to the Doomsday Glacier"** printed on Nov 21, 2022, which describes the international collaboration and the challenges IGPP's Greenbaum overcame to survey Thwaites ("Doomsday Glacier"), one of Earth's most challenging environments to access.



AGU HONOREES

Carlene Burton, Science and Society Team Award

Cathy Constable, Edward Bullard Lecture in the Geomagnetism, Paleomagnetism and EM Section

Wenyuan Fan, Aki Early Career Award in Seismology

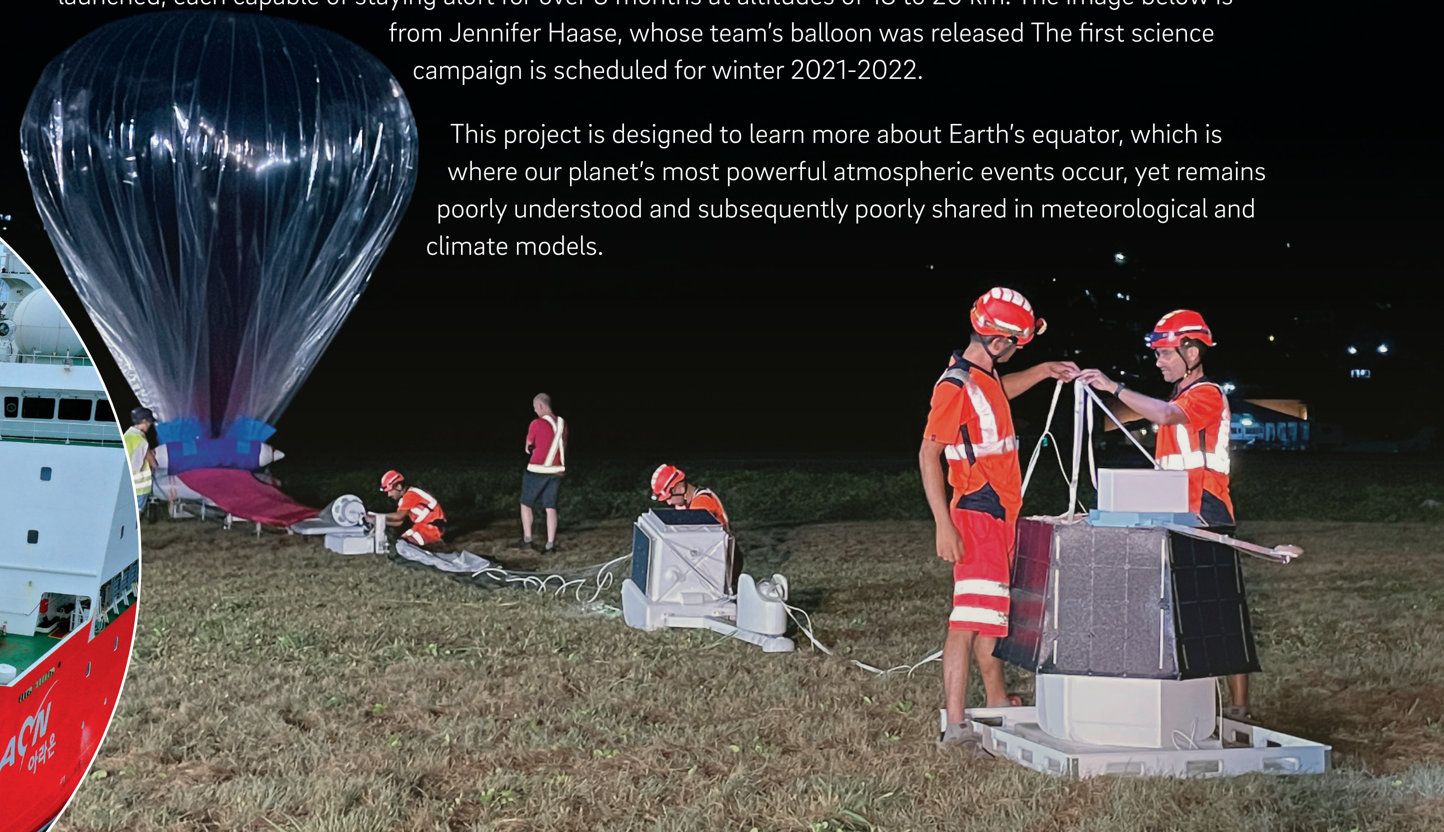
Gabi Laske, 2022 AGU Fellow

Vashan Wright, Science and Society Team Award

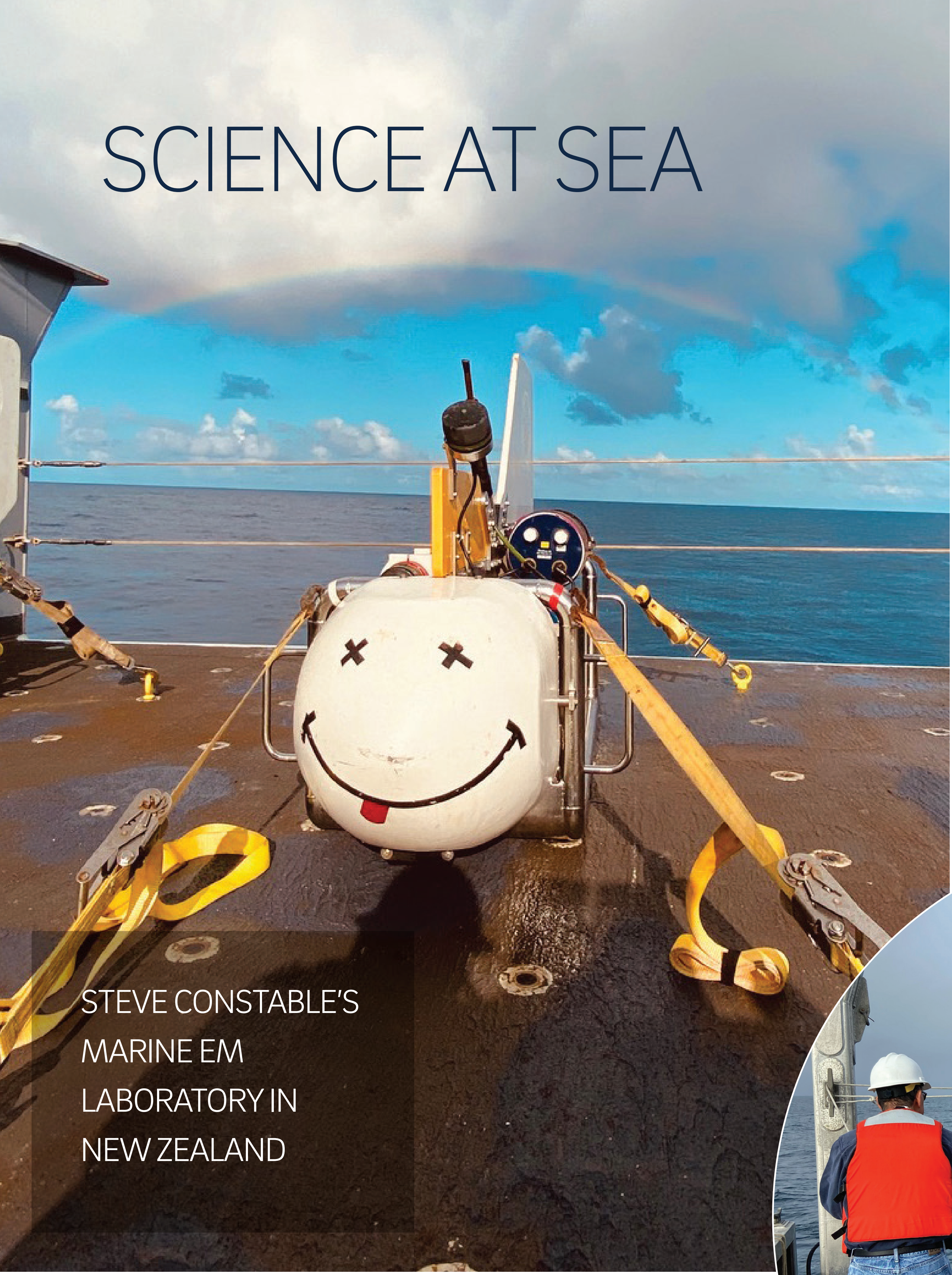
HAASE, TEAM STUDY EQUATOR'S ATMOPHERE VIA STRATÉOLE-2

STRATÉOLE-2, a French-US project to study climate processes in the Tropical Tropopause Layer equator, will release a total of nearly 50 long-duration balloons in three separate campaigns between 2019 and 2024. The project is led by Centre National d'Etudes Spatiales and LMD in France and US researchers, including Jennifer Haase, are funded by the National Science Foundation. Dozens of super pressure balloons will be launched, each capable of staying aloft for over 3 months at altitudes of 18 to 20 km. The image below is from Jennifer Haase, whose team's balloon was released The first science campaign is scheduled for winter 2021-2022.

This project is designed to learn more about Earth's equator, which is where our planet's most powerful atmospheric events occur, yet remains poorly understood and subsequently poorly shared in meteorological and climate models.



SCIENCE AT SEA



STEVE CONSTABLE'S MARINE EM LABORATORY IN NEW ZEALAND

ROSS PARNELL-TURNER, GRAD STUDENTS AND TECHNICIANS ABOARD R/V LANGSETH DEPLOYING IGPP-DESIGNED AND BUILT OCEAN BOTTOM SEISMOMETERS.

GLENN SASAGAWA TESTING THE WAVE GLIDER BEFORE DEPLOYMENT

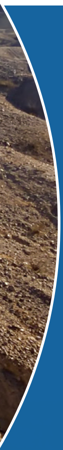
DAVID SANDWELL SHARES SCENES FROM THE PAINTED CANYON SAN ANDREAS FAULT FIELD TRIP WITH SDSU SCIENTISTS

GEOPHYSICS CURIOUS?

Students in the IGPP graduate program study Earth and other planets to advance our fundamental understanding of 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.



DUNCAN CARR AGNEW
Professor

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Research Interests: *Crustal deformation measurement and interpretation, Earth tides, Southern California seismicity, history of science.*

The eruption of Hunga volcano in Tonga on January 15, 2022, produced global air-pressure waves and tsunami of a magnitude not seen since the eruption of Krakatau on August 27, 1883. The wealth of data available has allowed detailed studies to be made of a number of aspects of these waves, and their interaction. It would be desirable to apply this new information to the (much sparser) dataset from 1883, to see how differently the waves behaved and perhaps extract more information on that eruption. A barrier to this is that there is no accessible digital version of either the air waves or the tsunami. The main source of information for most studies of the Krakatau eruption is the 1888 report produced by the Krakatoa Committee of the Royal Society of London; but the air waves (Strachey 1888) were not shown in any useful way (plots without scales). While large-scale plots of the tsunami data (Wharton 1888) are included in the report, no information is provided on the sources used.

It therefore seemed like a worthwhile project to digitize the data, starting with the original records or immediate copies whenever possible. The records of the Krakatoa Committee are archived at the Royal Society, but these do not contain any of the barograph or tide-gauge data. So this "data rescue" has involved contacting possible sources worldwide–after first working out what these source might be, something that has involved reading or skimming a vast number of 19th-century meteorological publications. Fortunately a great deal of this material is available online. Much is from Google Books (as curated by Hathitrust); as it turns out, a large fraction of these publications were collected by the UC library at the time they were published, and this is one collection Google scanned.

Some original records are still preserved, but in most cases what is available is a foldout plate showing (ideally) a photolithograph of the original (or of a drawing of it). Examples include Assmann (1884), Blandford (1884), Schiaparelli (1884), and Verbeek (1885). At this time the aneroid barograph in the form now common was just coming into use, so these records often come from mercury barographs of extremely varying design (Middleton 1964).

I have located about half of the barograms listed by Strachey (1888) in one form or another; Figure 1 shows where they are. I have also found one previously unknown barogram, and two new tide-gauge records. I am still pursuing a few leads, but the stage of searching for records is now basically complete. The next step will be imaging at high resolution and paying attention to making the scans planimetrically correct. After this comes processing images to extract as much information as possible (Figure 2), creating digital time series from the images, and examining possible dynamic magnification effects in the mercury barographs.

For the tide gauge data (digitized by Pelinovsky *et al.* 2005, but no longer available), one additional step will be to compute, retrospectively, the tides at each site, using either more recent data or modern satellite-based tidal models. Fitting these to the tide-gauge records should not only remove the tidal signals in an optimal manner, but provide a check on the timing–something not to be taken for granted with data of this vintage.

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Botley, F. V. (1951). A new use for the plate carree projection, *Geograph. Rev.*, **41,** 640-644, doi:10.2307/210710

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Schiaparelli, E. G. (1884). Osservazioni fatte a Milano sopra il passaggio delle onde atmosferiche prodotte dall'eruzione del vulcano Krakatoa nello stretto della Sonda, *Rend. R. Inst. Lombardo, Serie II*, **17**, 226-238.

Strachey, R. (1888). On the air waves and sounds caused by the eruption of Krakatoa in August, 1883, pp. 57-88 in T*he Eruption of Krakatoa, and Subsequent Phenomena*, (London: Trubner & Co.)

Verbeek, R. D. M. (1884). Sur la determination du temps de la plus forte explosion du Krakatau, le 27 Aout 1883, *Arch. Neerland. Sci. Exact. Naturel.*, **20**, 1-13.

Wharton,W. J. L. (1888). On the seismic sea waves caused by the eruption of Krakatoa, August 26th and 27th, 1883, pp. 89-148 in *The Eruption of Krakatoa, and Subsequent Phenomena*, (London: Trubner & Co.)

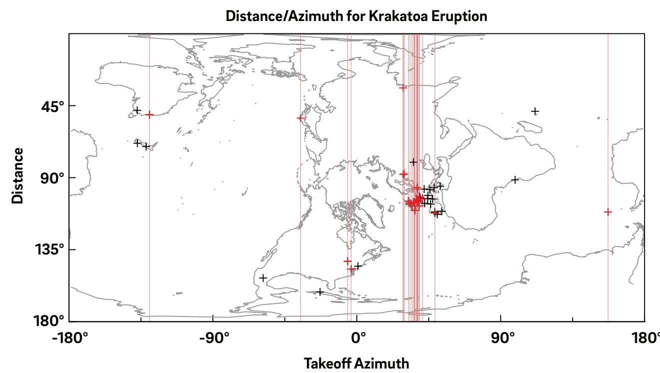

Figure 1: Map showing locations of barograph records, red when recoverable, black if not. The projection used (Botley 1951) makes wavefronts into horizontal lines and raypaths (shown in red) into vertical ones. Azimuthal coverage is fairly good, especially if backarc paths (the ones shown here with 180° added) are included.

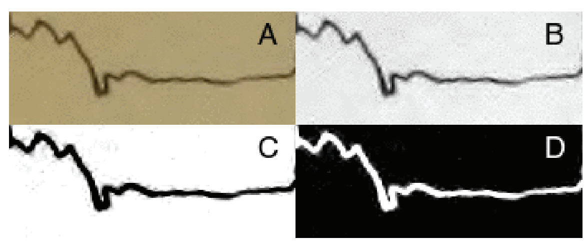

Figure 2: Figure 2: Processing workflow for images. A is raw image, of part of the plate for Blandford (1884), recorded by the Internet Archive. B is the image after applying a principal component analysis to convert from the original RGB colors to a grayscale; C is the same grayscale image after applying a nonlinear transform to convert the lighter pixels to white. D is the inverse of C; this can be regarded as noisy data, with x – y locations being the pixel numbers, and weights proportional to the brightness, so that a final digitized line can be created by a smoothing procedure (either smoothing splines or the loess local regression).

Background: The eruption of Hunga volcano January 15 launched material as high as 40 kilometers in altitude, blanketing nearby islands with ash and triggering destructive tsunami waves. Image courtesy of NASA

YEHUDA BOCK

Distinguished Researcher and Senior Lecturer
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Research Interests: *GNSS, crustal deformation and transients, geodetic reference frames, early warning systems for earthquakes and tsunamis, seismogeodesy, GNSS meteorology, structural health monitoring, data science, MEMS sensors*

The SOPAC group's current focus is the combined use of seismic and geodetic methods for natural hazards mitigation for communities affected by earthquakes, tsunamis, volcanoes, and severe weather (Bock & Wdowinski, 2021). To this end, we have now analyzed and archived high-rate (100 Hz) seismogeodetic displacements and velocities for 20+ historical earthquakes (Golriz et al., 2022; 2023) and 30+ years of daily GNSS displacements from thousands of stations (Bock et al., 2022). In 2022, our group included Peng Fang, Katherine Guns, Dorian Golriz, Alistair Knox, Anne Sullivan, Songnian Jiang, Allen Nance, Maria Turingan & Roland Hohensinn with laboratory & field assistance from Matt Norenberg, Glen Offield & Jennifer Matthews.

EARTH SCIENCE DATA PRODUCTS

Through a series of five-year NASA MEaSUREs projects Extended Solid Earth Science ESDR System (ES^3), we have collaborated with the Jet Propulsion Laboratory on the production of multi-level Earth System Data Records (ESDRs)

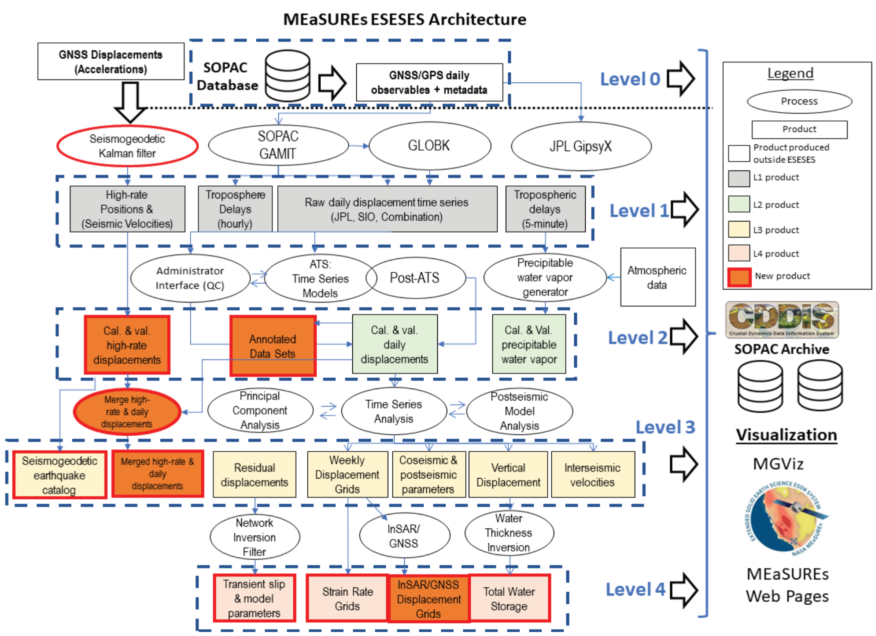

Figure 3. Hierarchy of ESDR product generation for the NASA MEaSUREs ES^3 project. Bold-red-outlined boxes indicate new ESDRs.

archived at SOPAC and NASA's geodetic archive CDDIS. The daily displacement time series form the underlying framework for higher-level products, including displacement and strain rate grids, transients in the crustal deformation cycle (slow slip, creep) and total water storage (Figure 3). Our products also include high-rate seismogeodetic observations of coseismic and early postseismic deformation (Jiang et al., 2021; Golriz et al. 2022), and tropospheric delay for InSAR calibration and precipitable water vapor as indicators of extreme weather events and climate change. We have developed the interactive MGViz time series visualizer (http://mgviz.ucsd,edu) and a MEaSUREs web site (http://sopac-csrc.ucsd.edu/index.php/measures-2/) to improve accessibility and expand our user community through improved outreach, and instructional videos, described in an on-line Algorithm Theoretical Basis Document (Bock et al., 2022) for better documentation and instruction. One of the advantages of our ESDRs is that they have gone through a rigorous calibration and validation process, including independent processing by two distinct GNSS analysis packages (GAMIT & GIPSY) in an effort to best represent physical phenomena of interest with minimal artifacts. Our combination solutions have been demonstrated to improve precision, quality and robustness (Ward et al., 2022). Common-mode removal from daily displacement time series through principal component analysis is particularly advantageous, resulting in rms values of 0.5-1.5 mm in the horizontal and 2-3 mm in the vertical for 20- to 30-year time series (Hohensinn et al., 2023). Currently, we are working with David Sandwell's InSAR group to integrate GNSS and InSAR displacements (Xu et al., 2021; Guns et al., 2022), and to merge high-rate and daily GNSS displacements (Jiang et al., 2021). We also archive and analyze GNSS data for the International GNSS Service and the California Spatial Reference Center (http://sopac-csrc.ucsd.edu/index.php/csrc/).

RECENT PUBLICATIONS

Golriz, D., B. Hirshorn, Y. Bock, S. Weinstein & J. Weiss (2023), Real-time Seismogeodetic Earthquake Magnitude Estimates for Local Tsunami Warnings. *J. Geophys. Res. Solid Earth.* DOI:10.1029/2022JB025555.

Hohensinn, R., P. Ruttner and Y. Bock (2023), Sensitivity of GNSS to Vertical Land Motion over Europe: Effects of Geophysical Loadings and Common-Mode Errors, *J. Geodesy,* in press.

Bock, Y., A. W. Moore, D. Argus, P. Fang, D. Golriz, K. Guns, S. Jiang, S. Kedar, S. A. Knox, Z. Liu & A. Sullivan (2022), Extended Solid Earth Science ESDR System (ES^3): Algorithm Theoretical Basis Document, Sept. 19, http://garner.ucsd.edu/pub/measuresESESES_products/ATBD/ESESES-ATBD.pdf

Bock, Y. et al., (2022), Geodetic Data, Data Products and GNSS Displacement Time Series Data Portal, https://www.youtube.com/watch?v=mMHSXCUU3Ms

Guns, K., X. Xu, Y. Bock, & D. Sandwell, (2022), GNSS-corrected InSAR displacement time-series spanning the 2019 Ridgecrest, CA earthquakes. *Geophys. J. Int.,* **230**(2), 1358-1373.

Ward, L.A., K. A. Guns, B. R. Smith-Konter, X. Xu, Y. Bock, D. T. Sandwell (2022), Vertical Postseismic Deformation of the 2019 Ridgecrest Earthquake Sequence, *J. Geophys. Res.: Solid Earth*, **127**(6), e2021JB023331.

Bock, Y. & 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

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

Xu, X., D. T. Sandwell, E. Klein, Y. Bock (2021), Integrated Sentinel-1 InSAR and GNSS time-series along the San Andreas fault system, *J. Geophys. Res. Solid Earth,* e2021JB022579. Video: https://www.youtube.com/watch?v=SxNLQKmHWpY

CDDIS ESDR archive: https://cddis.nasa.gov/Data_and_Derived_Products/GNSS/MEaSUREs_products.html (Need to get a NASA Earthdata account)

SOPAC ESDR archive: http://garner.ucsd.edu/pub/measuresESESES_products/ (Username: anonymous; Password: your e-mail address

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Associate Professor

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Research Interests: *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 4). 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.

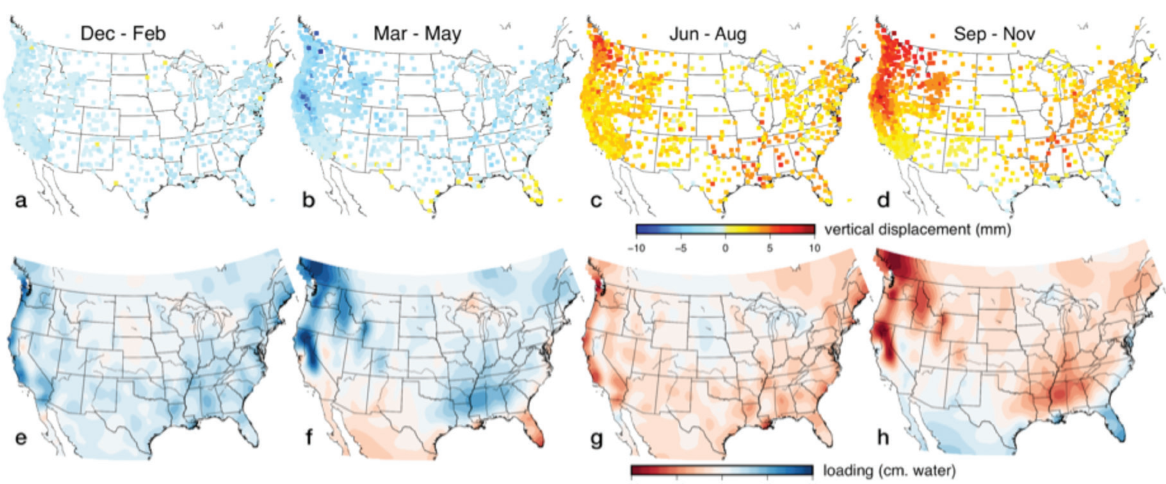


Figure 4. (a-d) Seasonal vertical displacements from GPS across the continental United States (CONUS), showing overall subsidence (cool colors) in the winter and spring, and uplift (warm colors) in the summer and fall. (e-h) Estimated terrestrial water storage anomalies (TWSA) corresponding to panels 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.

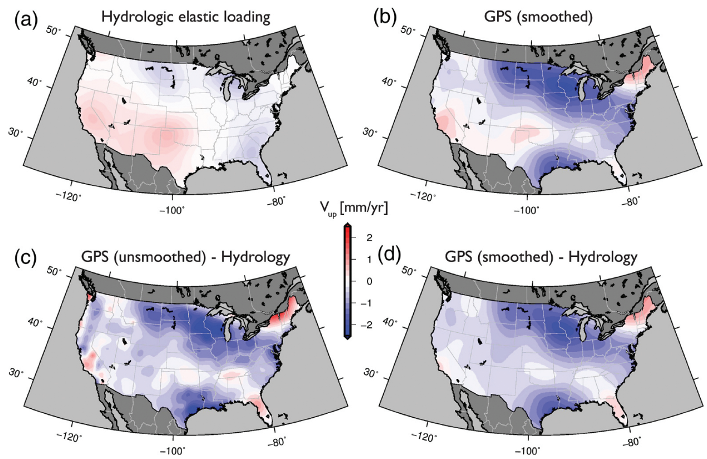


Figure 5. (a) Vertical rates due to elastic hydrologic loading, modeled using GRACE-derived terrestrial water storage estimates as input loads. (b) 300km Gaussian smoothed GNSS vertical velocity field. (c) Residual velocities after removing hydrologic loading rates from unsmoothed GNSS vertical velocities. (d) Residual velocities after removing hydrologic loading rates from the smoothed GNSS velocity field.

Our group has also been working to improve interpretations of GNSS-observed 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 5). 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.

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)

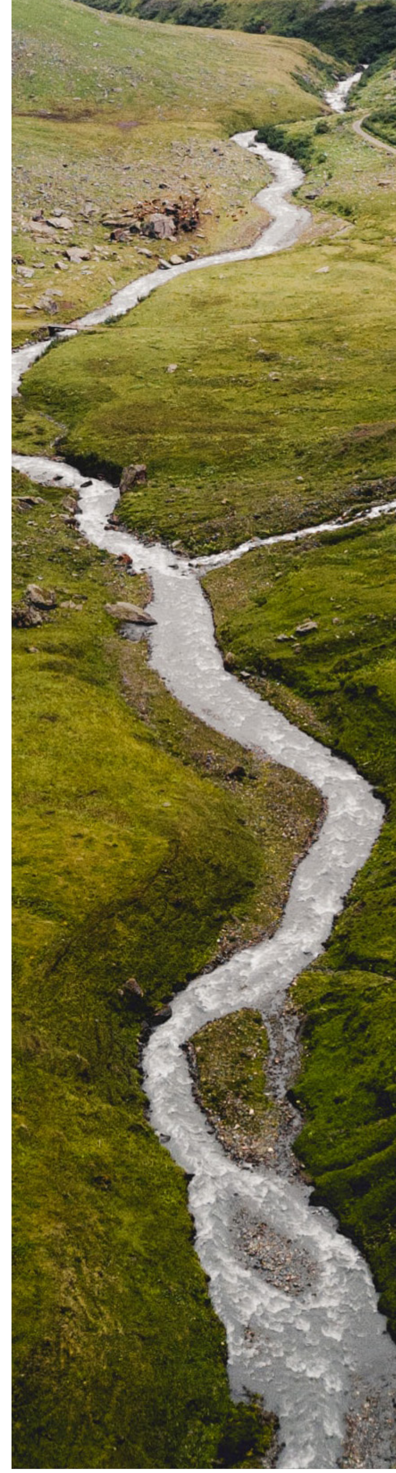
Levy, M.C., W.R. **Neely,** A.A. Borsa, & J.A. Burney (2020). "Fine-scale spatiotemporal variation in subsidence across California's San Joaquin Valley explained by groundwater demand." *Environmental Research Letters,* **15**(10)

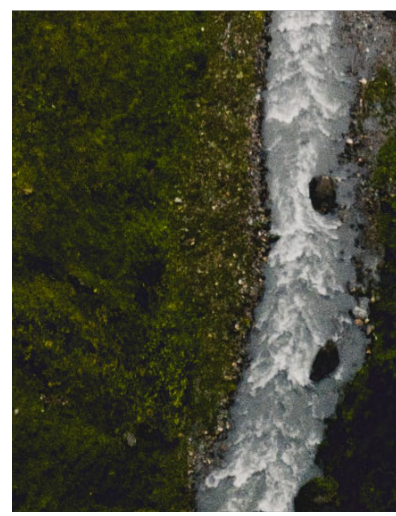
Silverii, F., E.K. Montgomery-Brown, A.A. Borsa, & A.J. Barbour (2020). Hydrologically induced deformation in Long Valley Caldera and adjacent Sierra Nevada. *Journal of Geophysical Research-Solid Earth,* **125**(5)

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

Distinguished Professor of Geophysics

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Research Interests: *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.*

Teaching Interests: *Geoelectromagnetism, Data analysis, Geophysical inverse theory*

Diversity Interests: *Geopaths from Community Colleges, Equity in Graduate Education*

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.

Recent progress has included the development of a new estimate for the geomagnetic power of variations in axial dipole moment (Figure 5), based on a suite of time varying field models at a broad range of resolutions. The power ranges across many orders of magnitude as the spectrum spans periods from 50 million years to less than a day. Sadhasivan & Constable (2022) used the spectrum to produce a stochastic model for geomagnetic variations, that provides a basis for new statistical comparisons with direct numerical simulations of the geodynamo.

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 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. Graduate students Nicole Clizzie and Trinity Carrasco have been focused on understanding both average geomagnetic field structure and variations on 100 ky to 5 My periods.

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 during excursions has been assessed using the more complete coverage accessible in numerical dynamo simulations in Korte et al. (2022), confirming that the commonly hoped for "preferred VGP path" signature would require coverage of many more excursional events than are currently available. A systematic study of regions of low field strength over all time intervals seems more promising.

The shortest period variations (less than 11 years) are being used in a new study of the deepest mantle conductivity in collaboration with Steven Constable.

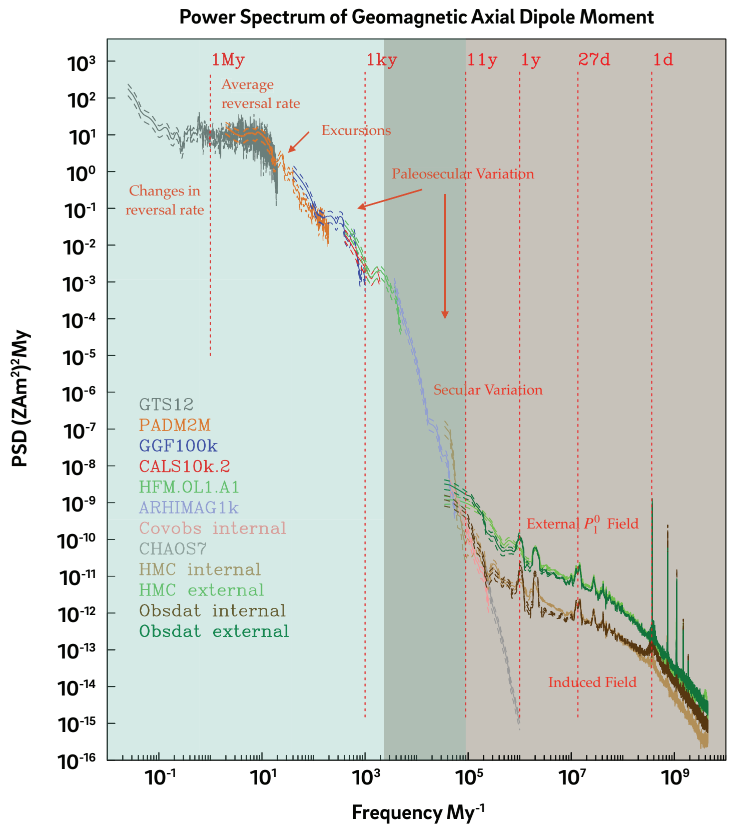

Figure 6: Power spectral density (PSD) estimates of the geomagnetic dipole moment from 0-160 Ma reversal record (GTS12), 0-2 Ma, PADM2M, GGF100k field model over the past 100 ka, Holocene models HFM.OL1.A1 and CALS10k.2, historical field model Covobs, followed by CHAOS7 largely based on satellite observations for the past 20 years. At the shortest periods hourly geomagnetic observatory data since 1900 are used to recover spectra of external field observations and their induced counterparts.

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STEVEN CONSTABLE
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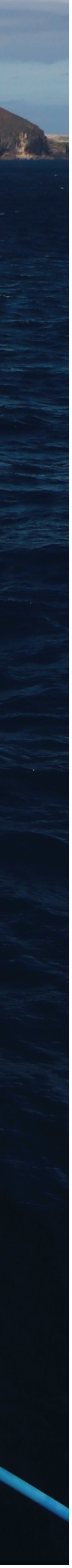
Research Interests: *Marine EM methods*

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.

Way back in 2004, Kerry Key and I collected both magnetotelluric (MT) and controlled-source EM (CSEM) data over the East Pacific Rise at 9° N. Inversions of the MT data showed a nice image of upwelling molten mantle, starting at a depth of about 90 km with a triangular shape consistent with passive upwelling focused towards the mid-ocean ridge. This result was published in 2013 but we are still working on the CSEM data. Recent inversions (Figure 7) show a conductive axial magma chamber centered beneath the ridge axis and deepening away from the ridge, a geometry that would focus eruptions at the ridge axis. Our data also image a wider magma chamber in the lower crust extending to both sides of the ridge axis, with a proximity that suggests intermittent recharge of the axial chamber. This combination of shallow and deep magma chambers support a hybrid model of crustal generation that incorporates gabbro formation from crystallization in the axial magma chamber (the "gabbro glacier") and sill formation fed by melt in the lower crust ("stacked sills"). We converted resistivity to melt fraction and estimate total melt volume to be about 140 cubic kilometers of melt per kilometer along strike, or about 250 ky of crustal formation, from which we can infer a residency time. The upper edges of the axial magma chamber and the deep crustal conductors imaged by the EM data follow the 1200°C isotherm computed for conductive cooling and migration of melt through a spreading center mush zone, which implies that the upper extent of melting is determined by a freezing horizon caused by thermal cooling. The interpretation of melt migration and conductive cooling is supported by a lack of evidence in the conductivity images for deep hydrothermal cooling near the ridge axis.

In other work this past year we collected CSEM data over the US Navy's test range offshore Florida, Interpretation carried out by postdoc Peter Kannberg provided an electrical conductivity model that illuminates the limestone stratigraphy under the range. Student Roslynn King continued to collect CSEM data offshore Southern California to investigate paleochannels buried in the offshore sediments and expand her offshore groundwater studies. Postdoc Daniel Blatter headed up the development of a method ("randomize then optimize") to quantify uncertainty in regularized two-dimensional models, something that is computationally difficult using standard Markov chain Monte Carlo methods.



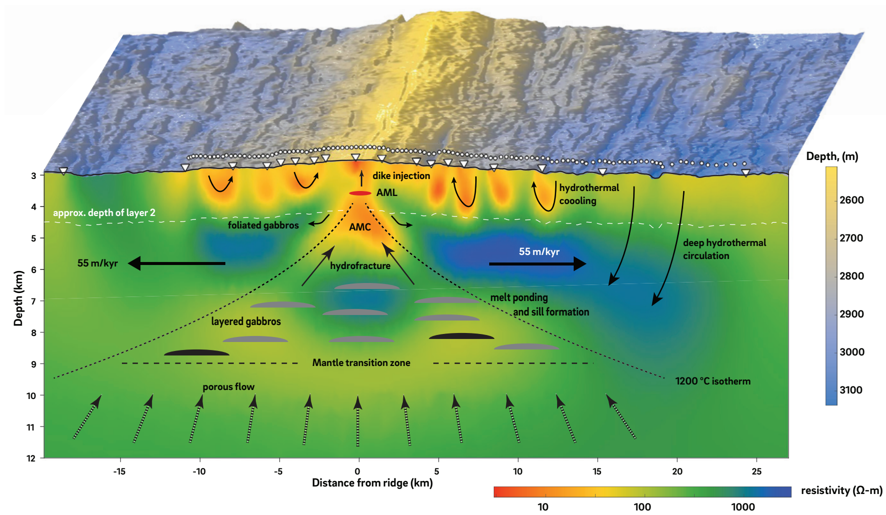


Figure 7: Seafloor electrical conductivity model inverted from controlled-source EM data collected across the East Pacific Rise. The feature marked "AMC" is the axial magma chamber. The axial magma lens ("AML") marked in red as shown in the figure is not imaged by our EM data, but is ubiquitous in seismic reflection data collected in this area.

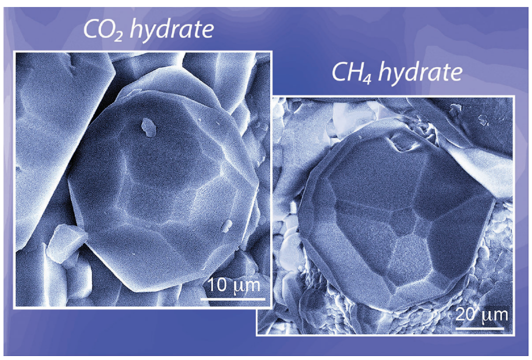


Figure 8: In a recent study, Laura Stern of the USGS and I made the case for CSEM monitoring of offshore CO_2 sequestration. If injected in deep-water sediments, CO_2 is dense enough to be gravitationally stable, but any leakage will form gas hydrate, a mixture of frozen water and gas. Laura and I had previously shown that CO_2 hydrate was an order of magnitude more electrically conductive than the methane hydrate commonly found in offshore sediments.

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Research Interests: *My research aims to improve understanding of seismic source processes, including earthquakes, slow earthquakes, transient environmental processes, and their interactions and triggering.*

We have imaged complex earthquake ruptures at subduction zone, at an oblique plate boundary, and at a transform system. In New Zealand, we identified that the moment magnitude (Mw) 7.3 2021 East Cape earthquake involved four slip episodes comprising a mixture of reverse, strike-slip, and normal faulting, and was driven by a combination of shallow trench-normal extension and unexpectedly, deep trench-parallel compression. Integrating multiple seismological and space geodetic analyses, we found that the devastating 2021 Mw 7.2 Haiti earthquake first broke a blind thrust fault and then jumped to a disconnected strike-slip fault (Figure 9). The complex rupture propagation was likely a major cause of the severe damage. In the Gulf of California, we found that the 2009 Mw 6.9 Canal de Ballenas earthquake likely ruptured at a super-shear speed, which generated large ground motions at teleseismic distances, dynamically triggering seismicity at multiple sites.

Fault architecture and slip mode partition are imprinted in microearthquakes and seismotectonic crustal structures. Ultra-fast spreading at the East Pacific Rise (EPR) has produced many closely spaced, multi-strand ridge transform faults, such as the Quebrada system. Although common along the EPR, the inter-relations between these faults and plate spreading dynamics have been enigmatic because of limited observations. We used seven months of ocean bottom seismograph data to investigate the Quebrada fault network and found abundant earthquakes unevenly distributed in the fault network, including two diffuse seismicity clouds penetrating into the upper mantle and one seismically active fracture zone. The observations suggest a complex regional plate-motion pattern, including possible heterogeneous rotations within the Quebrada system, which may have caused strong 3D local thermal and fluid effects, controlling the evolution of the fault system.

The Cascadia subduction zone poses serious earthquake and tsunami hazards to some of the most populous regions of the United States and Canada. However, as an exceptionally seismically quiet subduction zone, large megathrust

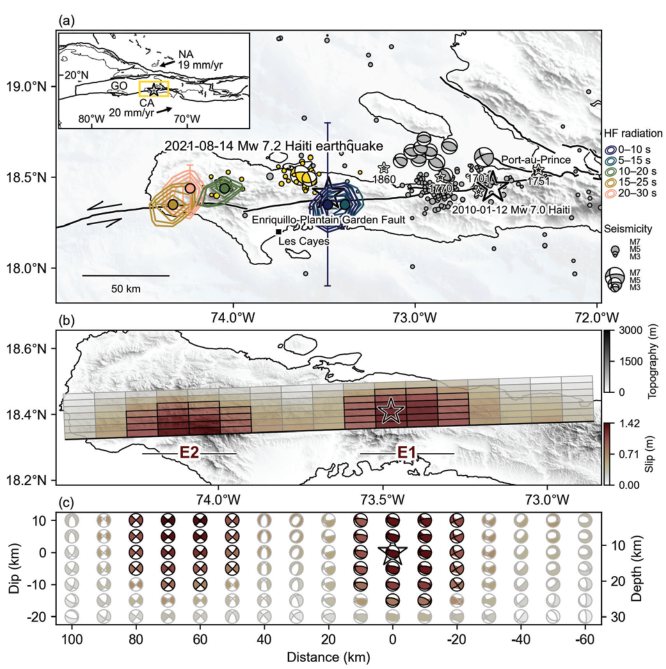

Figure 9. Finite-fault and back-projection models of the 2021 Haiti earthquake and seismo-tectonic summary of the Tiburon Peninsula, Southern Haiti. (a) The colored contours show the back-projection results. The location uncertainties (one standard deviation of latitude or longitude) are from Jackknife re-sampling. The black stars show the epicenters of the 2021 and 2010 Haiti earthquakes. The white stars show historical earthquakes in the region. The gray dots are the background seismicity, and the yellow dots are the 1-month aftershocks of the 2021 Haiti earthquake. The gray and yellow beach balls show available GCMT solutions of the events before and after the 2021 Haiti earthquake. (b) The colored cells show the finite-fault solution. Large slip patches are empathized by black cell boarders. The topography is from Shuttle Radar Topography Mission. (c) The cross-section of the moment-tensor distribution extracted from the resultant potency-density tensors. All the beach balls of the moment-tensor solution are represented as a lower-hemisphere stereographic projection (far-side focal sphere).

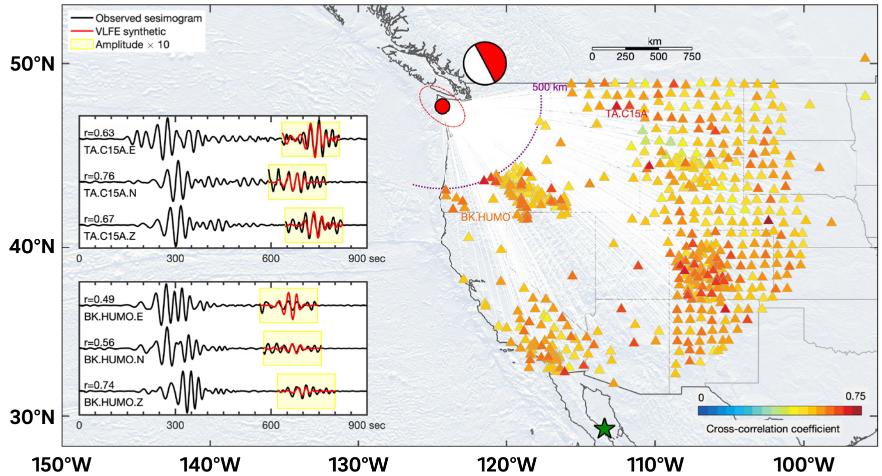

Figure 10. Seismic observations of the Cascadia very low frequency earthquake showing the average cross-correlation coefficients of the synthetic and observed waveforms of the Mw 5.7 event. The green star shows the 2009 M6.9 Canal de Ballenas earthquake. The red circle is VLFE. The beachball focal mechanism shows the preferred solution for VLFE. Triangles show seismic stations with their colors corresponding to the average cross-correlation coefficients. Waveforms of two annotated stations, TA.C15A and BK.HUMO, are shown in the insets. Insets: example three-component waveforms of the mainshock and the VLFE, overlain with synthetic waveforms of the VLFE. The two stations are at the eastward and the southward directions of the VLFE, respectively. The yellow shaded regions show records amplified by ten times.

earthquakes in Cascadia have never been recorded by modern instrumentation. In contrast, slow earthquakes in the region occur quasi-periodically, contouring seismogenic fault patches. Investigating these slow earthquakes would provide a new window into monitoring the physical conditions of the megathrust. We used large-scale seismic and geodetic arrays and identified three previously unknown very low frequency earthquakes (VLFEs) in Cascadia with one event located in between the seismogenic and tremor zones, a critical gap zone. Whether the gap zone can slip during future megathrust earthquakes has direct seismic hazard implications for coastal communities and perhaps further inland. This gap-zone VLFE has a moment magnitude of 5.7, the largest VLFE that has been identified across all subduction zones (Figure 10), and it is also the first, geodetically recorded VLFE, confirming the existence of the class of slip events. Our results suggest that some patches of the gap zone are capable of hosting large, fast slip events, indicating possible deep ruptures at sporadic spots in Cascadia. Our findings also show that the Cascadia megathrust is weak and is sensitive to transient stress perturbations. Moreover, the identified VLFEs challenge the current understanding of slow earthquake physics, and suggest that slow and regular earthquakes are likely regulated by the same rupture physics. The observation is exciting as it demonstrates that fast slip may occur in a variety of faulting conditions from the low stress, shallow crustal faults to the high-temperature, high-pressure downdip edge of the megathrust, such as the case we observed in Cascadia.

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YURI FIALKO
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***Research Interests:** My research aims to improve understanding of seismic source processes, including earthquakes, slow earthquakes, transient environmental processes, and their interactions and triggering.*

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.

Among the long-term research interests of Prof. Fialko are studies of co- and post-seismic deformation due to large earthquakes. By measuring surface displacements that result from earthquake ruptures and subsequent transient deformation, we can gain important insights into the rupture processes, and the mechanisms of stress relaxation at depth. Rheological properties of the lower crust and upper mantle are of considerable interest, in particular in actively deforming continental settings such as Tibet. Outstanding tectonic and geodynamic questions include the relative importance of brittle vs ductile deformation mechanisms responsible for the uplift and lateral extrusion of the Tibetan Plateau. The two end-member views on the deformation styles are: (i) fault-bounded blocks that experience little internal deformation, and (ii) essentially diffuse (fluid-like) deformation of much of the continental lithosphere.

In a recent project, Prof. Fialko and graduate student Zeyu Jin used space geodetic observations (Interferometric Synthetic Aperture Radar and Global Navigational Satellite System) to investigate surface deformation during and after two major strike-slip earthquakes, the 2015 M7.2 Sarez, and the 2021 M7.4 Maduo earthquakes that occurred near the north-west and north-east boundaries of the Tibetan plateau. They derived kinematic slip models for each event by inverting the observed surface displacements for sub-surface rupture geometry and slip distribution. Figure 11 shows an example of line-of-sight displacements due to the 2015 Sarez earthquake observed by the ALOS-2 satellite of the Japanese Space Agency. Coseismic slip models were then used to investigate mechanisms of time-dependent relaxation, stress transfer and possible triggering relationships between the mainshock and regional moderate-to-strong events. In case of the Sarez earthquake, the near-field postseismic displacements are best explained by shallow afterslip driven

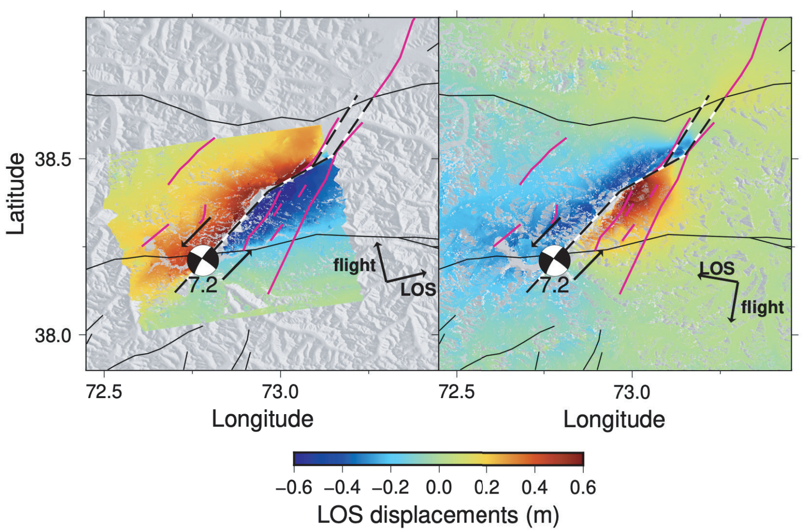

Figure 11. Coseismic surface displacements due to the 2015 M7.2 Sarez (Pamir, Tadjikistan) earthquake. Data were acquired by the ALOS-2 SAR satellite. Motion toward the satellite is deemed positive. The black-and-white dashed lines denote the modeled trace of the 2015 M7.2 earthquake. The magenta and thin black lines denote other active faults. Black arrows show the satellite heading and the line of sight direction. From Jin et al. (2022).

by the coseismic stress changes. The data also allow some contribution from poroelastic rebound, but do not show a clear signature of viscoelastic relaxation in the lower crust and upper mantle during the observation period, suggesting a lower bound on the effective viscosity of ~10^{19} Pa s. These findings point out to a relatively strong lower crust in the northwest corner of the Tibetan Plateau. A pair of M6+ events that occurred within 100 km and several months of the 2015 mainshock have experienced near-zero and in some cases negative static Coulomb stress changes, suggesting either delayed dynamic triggering, or no relation to the mainshock.

Another project is aimed at evaluating 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. 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 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.

Other currently active projects include a joint seismic-geodetic study of the sub-surface structure of the Southern San Andreas fault, and mechanisms of earthquake triggering.

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HELEN AMANDA FRICKER
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Research Interests: *Cryosphere, Antarctic ice sheet, subglacial lakes, ice shelves, satellite remote sensing.'*

Our group is 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, an Honorary Professor at University of Swansea (1 February 2020 to present), and a member of the Australian Centre of Excellence for Antarctic Research.

Our research focuses on understanding the processes driving changes on the Antarctic ice sheet. One of the main unknowns is Antarctica's current contribution to global sea level rise, and predicting how that will change in the future. Because Antarctica is so large, and the time scales on which it changes are so long (decades to centuries), the only viable way to monitor it is with satellites. The main 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 and (ii) active subglacial lakes.**

(I) 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. Two decades ago, we made a strategic decision to focus on ice shelves rather than grounded ice, as it was becoming clear that these were the most vulnerable parts of the Antarctic Ice Sheet, and changes in their extent and thickness were triggering changes in grounded ice. Since most of the changes are linked to oceanic or atmospheric processes, this requires an interdisciplinary approach, which fits in with the research program at SIO. Our group is known for monitoring Antarctic ice shelves with satellite altimetry. We also perform fieldwork on ice shelves.

Satellite radar altimetry: Funded by NASA, we generate estimates of ice-shelf surface height data acquired by ESA satellites continuously since the early 1990s, and use these to understand the mass loss processes from ice shelves. Our 2015 paper revealed accelerated losses in total Antarctic ice-shelf volume from 1994 to 2012, and showed that ice-shelf thinning in these regions was substantial (some ice shelves thinned 18% in 18 years), raising concerns about future loss of grounded ice and resulting sea level. GP student (now postdoc) Susheel Adusumilli generated updated time series for 1994 to 2018 using CryoSat data, and generated a high-resolution map of time-averaged (2010-2018) basal melt rates, and time series (1994-2018) of meltwater fluxes for most ice shelves. This was important step in ice/ocean research because existing continent-wide melt rate datasets are averages for a 5-year period (2003-2008) and have no temporal variability, introducing uncertainties in sea level and climate projections. We also partitioned meltwater fluxes into deep and shallow sources to reveal signatures of temporal variability, providing insights into climate forcing of basal melting and the impact of this melting on the Southern Ocean.

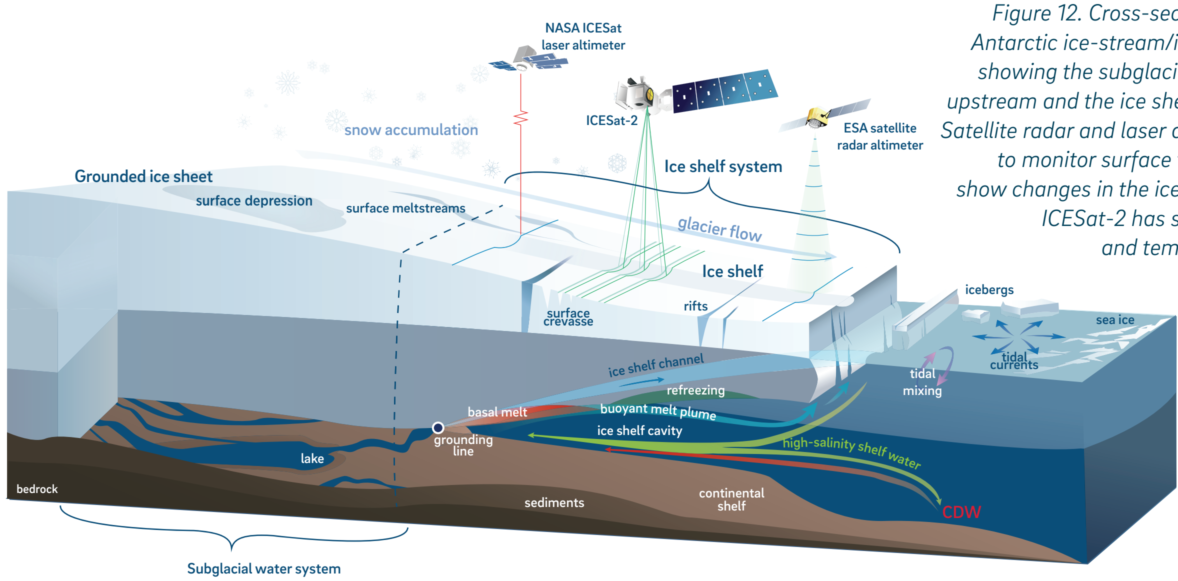

Figure 12. Cross-section of a typical Antarctic ice-stream/ice-shelf system showing the subglacial water system upstream and the ice shelf downstream. Satellite radar and laser altimetry is used to monitor surface topography and show changes in the ice sheets. NASA's ICESat-2 has sufficient spatial and temporal resolution to monitor features associated with processes driving changes.

Satellite laser altimetry (ICESat and ICESat-2): ICESat-2 was launched in September 2018 and extended the elevation record started by ICESat, and comparison between data from the two missions after just a year in orbit allowed for an estimate of mass loss of all the ice sheets from 2003 to 2019. This was the first comprehensive analysis performed simultaneously over all the ice sheets (both grounded and floating ice), and showed ongoing loss from both ice sheets, but also confirmed the link between loss of floating ice and loss of grounded ice through loss of buttressing, and showed that the variability is related to ocean and atmosphere processes.

Our group uses ICESat laser altimetry to look at small-scale features with ICESat-2. Many of the key mass loss and gain processes act on small spatial scales, and ICESat-2 data are sufficiently high resolution that to show details of the these processes for the ice sheets such as: iceberg rifting and calving3, ice fronts6, subglacial lakes9, and doline formation on ice shelves8. ICESat-2 also brought a new capability to surface melt detection on ice sheets: the 532 nm photons penetrate 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 (Fricker et al., 2020). 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. 5th year student Philipp Arndt has a NASA FINESST award to continue the surface melt work; 2nd year student Chance Roberts works on rifts and mélange thickness.

ICESat-2's top-of-snow measurement has enabled new insights into snow accumulation; Susheel Adusumilli used monthly height changes over WAIS to show that large height increases occurred in winter 20195. Using a computational model of the atmosphere and snow, they attributed a large number (41%) of these to short-duration extreme precipitation events, with 63% associated with landfalling atmospheric rivers (ARs) only 5.1% of the time.

II. 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 lakes3,9. We continue to monitor active lakes and have found 124 in total throughout Antarctica3,9. 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 student/postdoc Chloe Gustafson (for EM measurements) in 2018, and 3rd year student Philipp Arndt in 2019. The EM work led to discovery of large volumes of groundwater1.

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ALICE GABRIEL
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Research Interests: *Earthquake Physics, Computational Seismology, Tsunami, High-performance computing*

Diversity Interests: *I am advocating for Open Science in all aspects of research. This entails ensuring full reproducibility and FAIR data standards, developing Open Access Community Software for earthquake physics applications, such as SeisSol (www.seissol.org). I am also a founding member of the Seismica Initiative (www.seismica.org) which is a community-led effort to establish a Diamond Open Access (free to read and free to publish) journal for seismology.*

I am a seismologist combining physics-based computer simulations, routinely utilizing the largest supercomputers worldwide, with data-driven techniques and theoretical analysis to tackle one of the grand challenges of seismology: uncovering the physical mechanisms relevant to understanding earthquakes and related hazards such as tsunami. In summer 2022, I moved from Munich (Germany) to beautiful San Diego and joined IGPP as an Associate Professor.

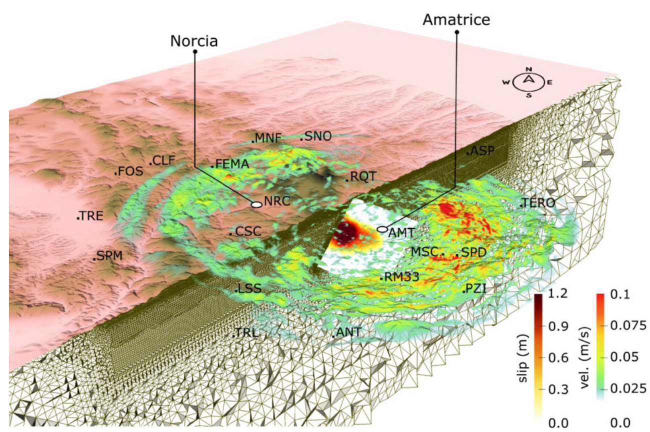

Figure 13. Broadband dynamic rupture modeling with fractal fault roughness, frictional heterogeneity, viscoelasticity and topography of the 2016 Mw 6.2 Amatrice, Italy earthquake (Taufiqurrahman et al., 2022)

Figure 14. *"Field work" at the Stampede2 supercomputer.*

My research this year bridged space-time scales as well as disciplines within Geophysics and with Computer Science and Applied Mathematics. I aim to harness the full breadth of Earth observations integrated with novel modeling approaches. This entails studying a range of geophysical problems with multi-physics character using high-performance computing.

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Research Interests: *Cryosphere, ice-ocean interactions, ice shelves, airborne remote sensing*

SUMMARY

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. I am also a trained Bystander Intervention facilitator and have begun offering field-focused training workshops to multidisciplinary teams.

ICE-OCEAN INTERACTIONS

The PGL is currently managing multiple projects supported by NSF and NASA to understand what is driving coastal glacier thinning in East and West Antarctica (Fig. 15). 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

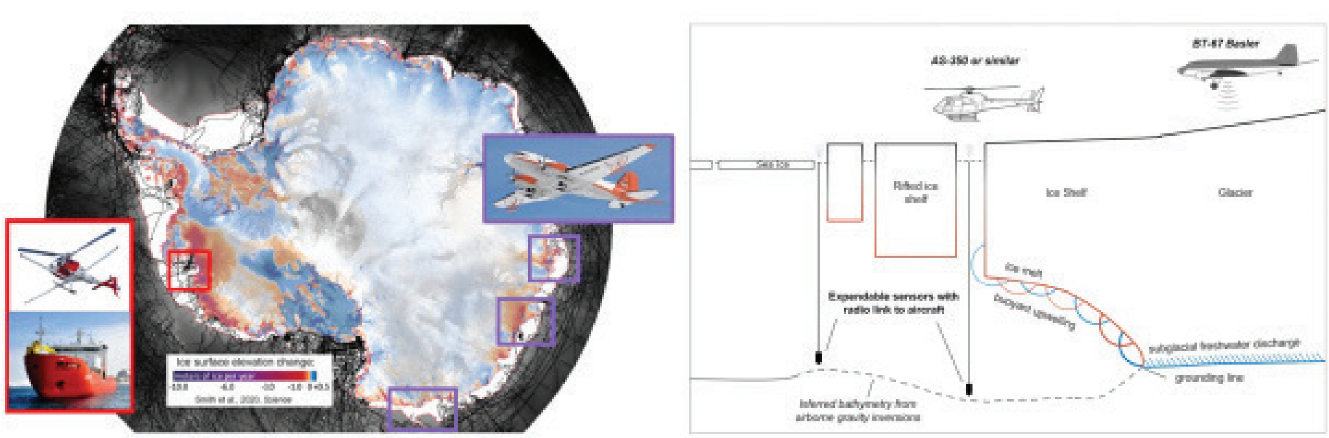

Figure 15. ***Focus areas and concept of operations:*** *Left: Map of ice surface elevation change in Antarctica (Smith et al., 2020, Science) with boxes indicating current PGL focus areas and observational platforms. Right: Conceptual profile of a rifted ice shelf similar to the Thwaites Glacier Tongue 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 led by the PGL seek to use fixed-wing and helicopter 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 marine platforms to access.*

reach (boxes in Fig. 14). 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 and in rifted ice shelves where no prior data have been acquired.

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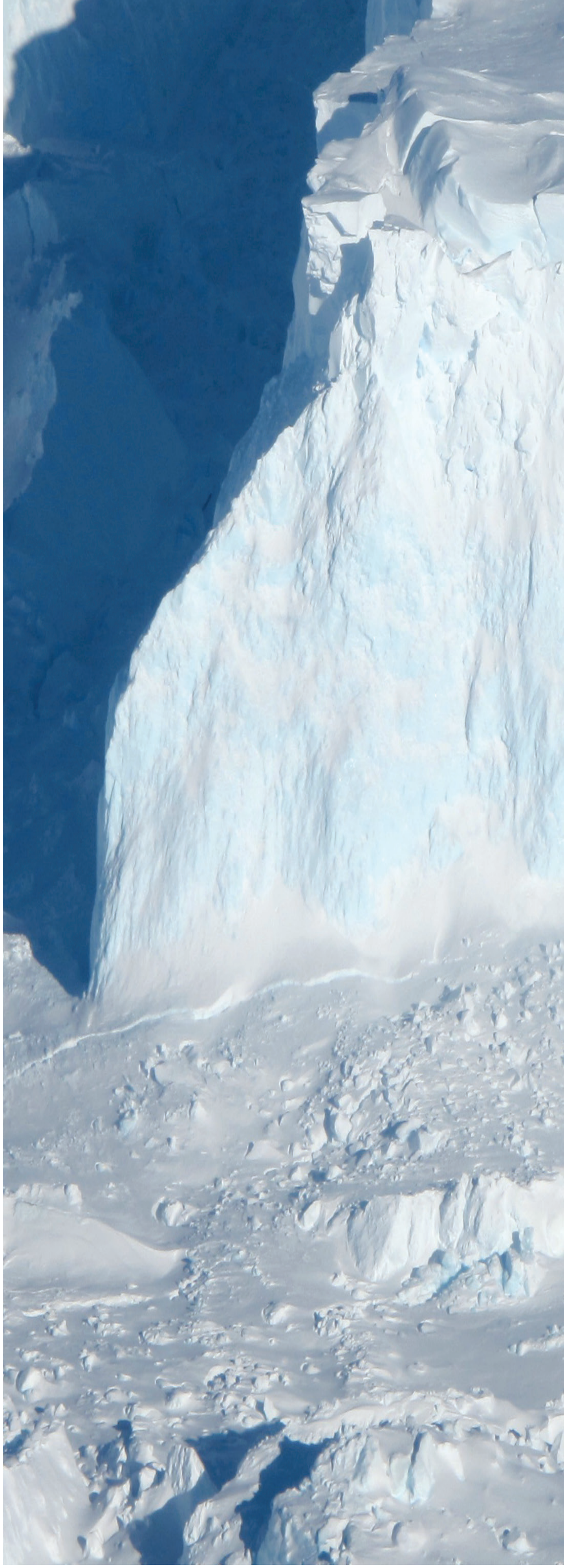

JENNIFER S. HAASE
Professor

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Research Interests: *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.

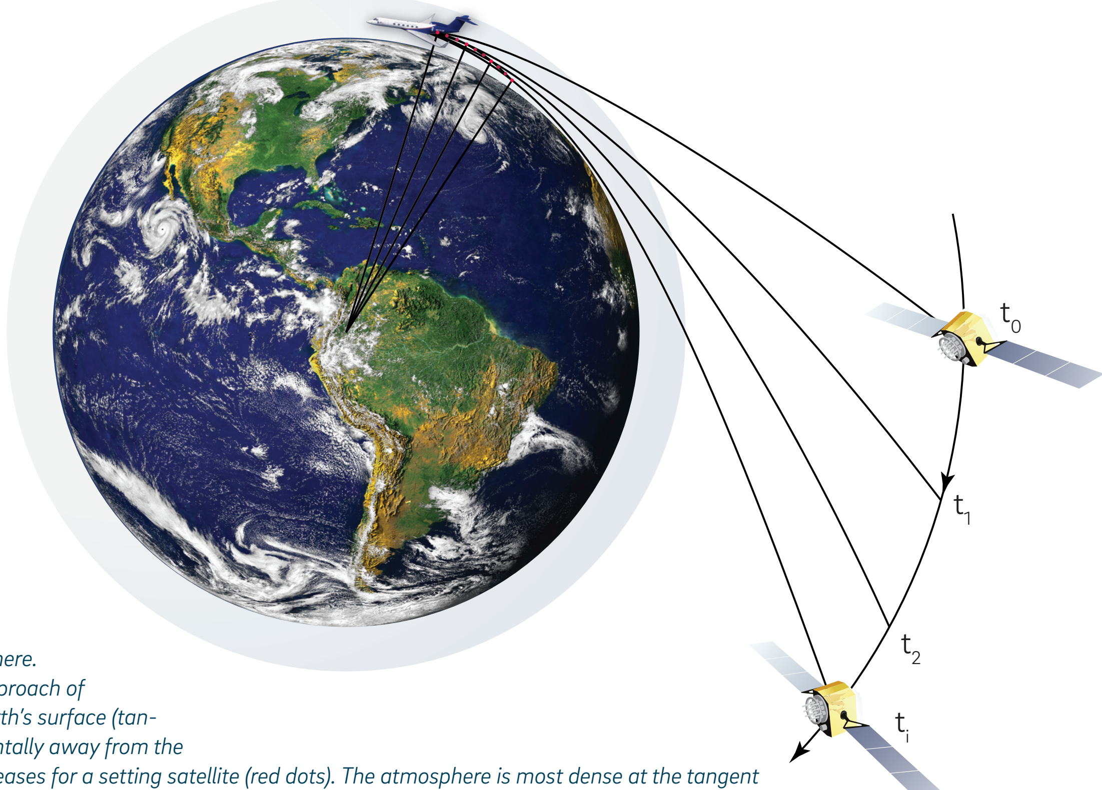

Figure 16. Airborne radio occultation geometry. GNSS signals are recorded as a satellite sets (or rises), with ray paths successively sampling deeper into the atmosphere. The points of closest approach of each ray path to the Earth's surface (tangent points) drift horizontally away from the aircraft 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.

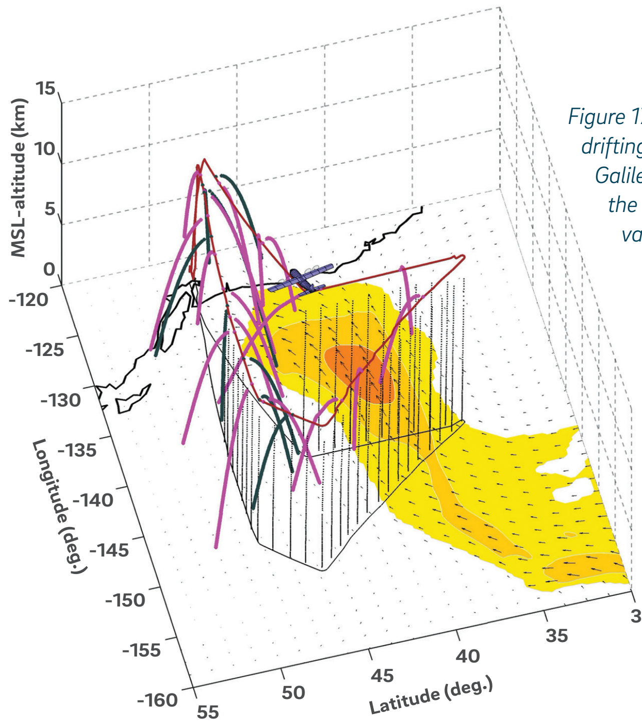

Figure 17. Three-dimensional view of sampling by airborne radio occultation drifting tangent points and dropsondes. Dark grey and magenta curves are Galileo and GPS occultations, vertical black lines are dropsondes released from the aircraft, whose trajectory is denoted by the brown line. Integrated water vapor transport is shown in color contours on the lower surface.

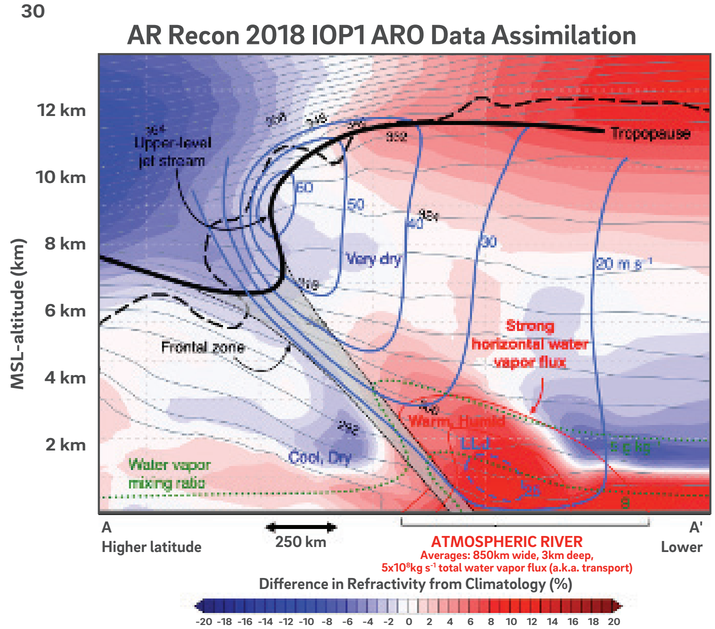

Figure 18. Refractivity anomaly cross-section through the meso-scale weather model that incorporated the aircraft observations, perpendicular to the atmospheric river transport direction. Refractivity anomaly (%) is the difference from a climatological model. The 2 PVU contour is represented by the thick 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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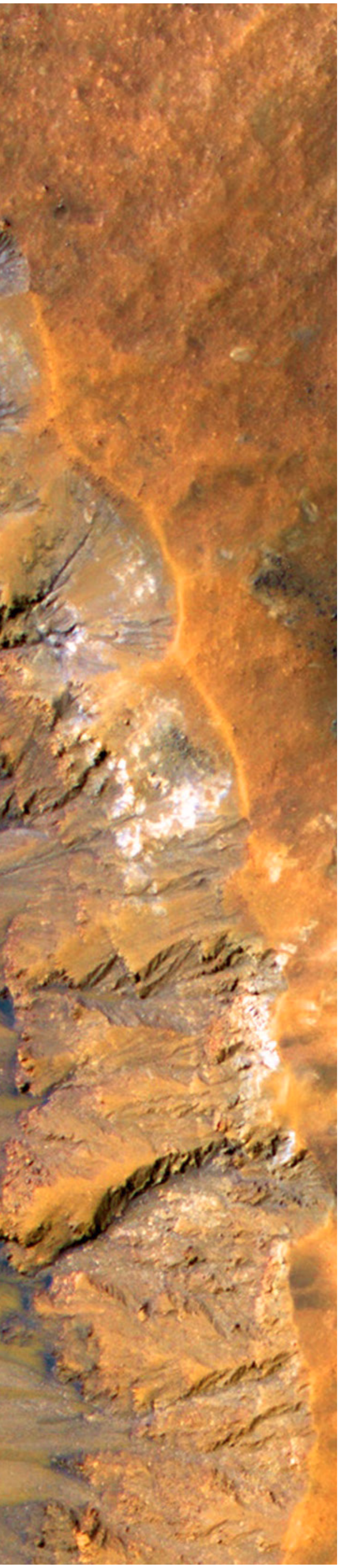

DEBORAH LYMAN KILB

Project Scientist

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Research Interests: *Crustal seismology, earthquake early warning and earthquake triggering.*

Equity, Diversity, and Inclusion (EDI) Interests: *Improving how science is communicated. Promoting jobs requiring skills within the intersection of science and art. Cultivating diversity, and acceptance of diversity, within our communities.*

EARTHQUAKE EARLY WARNING [Bose et al., 2022]. We test the behavior of the US West Coast ShakeAlert earthquake early warning (EEW) system during temporally close earthquake pairs to understand current performance and limitations. We consider performance metrics based on source parameter and ground-motion forecast accuracy, as well as alerting timeliness. We generate ground-motion times series for synthesized earthquake sequences from real data by combining the signals from pairs of well-recorded earthquakes (4.4 ≤ M ≤ 7.1) using time shifts ranging from –60 to +180 s. We examine fore- and aftershock sequences, near-simultaneous events in different source regions, and simulated out-of-network and off-shore earthquakes (Figure 19).

We find that the operational ShakeAlert algorithms Earthquake Point-source Integrated Code (EPIC), Finite-Fault Rupture Detector (FinDer), and the Propagation of Local Undamped Motion (PLUM) method perform largely as expected. EPIC provides the best source location estimates and is often fastest but can under-estimate magnitudes or, in extreme cases, miss large earthquakes. FinDer provides real-time line-source models and unsaturated magnitude estimates for large earthquakes but currently cannot process concurrent events and may mislocate offshore earthquakes. PLUM's strength is identifying pockets of strong ground motion. PLUM can overestimate alert areas, but this behavior depends on how the PLUM alert regional extents are defined. There is a trade-off between detection speed and the spatial extent of the alerting region, which is controlled by the radial distance that ground motions are extrapolated (here set to 30 km) from the observing station. Implications for system performance are: (1) spatially and temporally close events are difficult to identify separately; (2) challenging scenarios with foreshocks

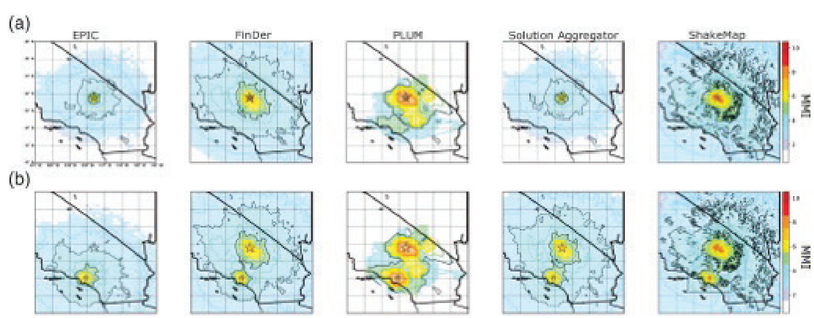

Figure 19. Modified Mercalli Intensity (MMI) maps predicted by four different methods (from left to right) EPIC, FinDer, PLUM, Solution Aggregator (EPIC+FinDer, operational ShakeAlert method) and the reference ShakeMap. (a) M7.1 Ridgecrest earthquake with M5.4 foreshock (dt=-10 s); (b) M6.0 El Monte (Los Angeles) earthquake with M7.1 Ridgecrest aftershock (dt=60 s). Ideally, the mapped MMI colors produced by each method should mimic the ShakeMap results and the outer (MMI=3.5) and inner contours (MMI=4.5) align too. PLUM does not have an outer contour as it only tracks MMI=4+ energy.

that are close in space and time can lead to missed alerts for large earthquakes; and (3) in these situations the algorithms can often estimate ground motion better than source parameters. To improve EEW, our work suggests continuing development that focuses on using ground-motion data to aggregate alerts from multiple algorithms, and to investigate methods to optimally leverage algorithm ground-motion estimates.

EDUCATION & OUTREACH – FLASH MOB SCIENCE [Carter and Kilb, 2022]. There is a little seismologist in everyone. One secret to unlocking a student's science potential at the undergraduate level is to offer laboratory exercises that leverage the inspiration, team spirit, and creativity already present in the current generation of college students. In this lab exercise we do that by using smartphones to cause a bit of scientific mischief. In these Flash Mob Science seismology experiments, several groups of 5–15 students download a mobile app that can record time-series data from their phones using the phone's vibrational sensors. This allows each device to record acceleration in the X, Y, and Z directions (Figure 20).

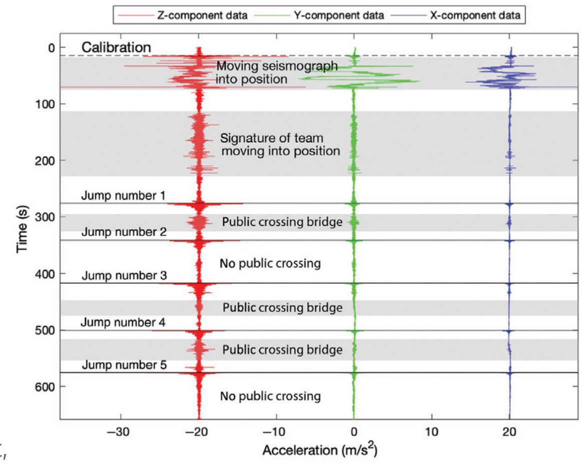

Figure 20. Sample Flash Mob data recorded by a student on a single phone on 15 March 2019 during the Spruce Street Bridge experiment that included five jump experiments (labeled). The X-component and Z-component data are shifted to make all data visible. The strong initial energy is the calibration jumps (labeled), following that the students moved into position. The signature of the team moving into position and the public walking across the bridge between jump experiments are visible in these data (labeled). The duration of these recordings is 700s (11.7 min).

We conduct quantitative experiments using student-created linear seismic arrays and deploy these arrays at prominent local landmarks (Hillcrest's Spruce Street suspension footbridge and the top floor of a parking garage) that are known to vibrate in response to relatively small forces. Our research team of students tested how these landmarks responded to different energy sources (people jumping, rocks dropping, and rubber mallet impacts). To model strike-slip fault motion, we also used a washing machine drip pan loaded with 150 pounds of sand that we attached to a car bumper using four ~48-inch bungee cords. For the experiment, the instructor drove forward at speeds of ~5 mph, and the students recorded the "strike-slip" motions. Students studied individual event recordings and the collective suite of data presented as record sections. Concepts such as wave speeds, wave types, noise, move out, and reverberations were all discussed. These data exhibit several distinct sets of waves with different frequency characteristics that the students analyze. We found that when students record the data they study, they become more engaged in analyzing the results and postulating what the data impart.

RECENT PUBLICATIONS

Böse, M, J Andrews, C O'Rourke, D Kilb, A Lux, J Bunn, and J McGuire (2022). "Testing the ShakeAlert Earthquake Early Warning System Using Synthesized Earthquake Sequences." *Seismological Res. Letters* 2022; doi: https://doi.org/10.1785/0220220088

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*Post-doc

GABI LASKE

Professor

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

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

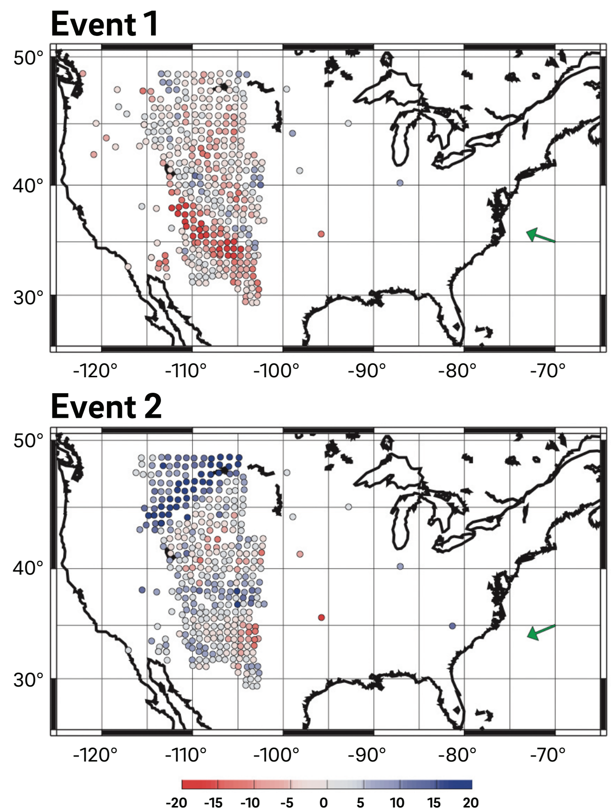

Figure 21. Arrival angles at 15 mHz for the 3 January 2009 Irian Jaya (Event 1) and the 15 January 2009 Loyalty Islands (Event 2) earthquakes. Green arrows mark the back azimuth from a station near San Diego to the source (displaced for unobstructed view). The overall patters are different between different events and reflect wavefront deformations as a result of wave propagation in the heterogenous Earth.

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 high-quality 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 21).

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 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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Ringler, A.T., Mason, D.B., Laske, G., Storm, T. and Templeton, M., Why do my squiggles look Funny? A gallery of compromised seismic signals. *Seismol. Res. Lett.,* **92**(6), 3873{3886, doi:1o.1785/0220210094, 2021.

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COMPUTATIONAL AND THEORETICAL SOLID EARTH GEOPHYSICS

My research focuses on the development of novel computational methods and software to enable new avenues of quantitative Earth science to be explored. To push the boundaries of what is computable, I develop scalable, efficient algorithms and software that exploit current and next-generation massively parallel **high-performance computing** (HPC) facilities. The software developed in my group are currently utilized (but not limited to) the following applications: long-time scale dynamics of continental rifting, subduction zones, melt migration in the mantle, regional seismology and geomorphology.

DISCONTINUOUS GALERKIN METHODS FOR MODELING THE SEISMIC CYCLE

Numerical simulations of sequences of earthquakes and aseismic slip (SEAS) aim to capture the complete seismic cycle in a single, self-consistent model. In these models, faults are predefined surfaces along which frictional sliding is governed by a rate- and state-dependent friction law embedded within an elastic medium. A single cycling simulation is computationally challenging as temporal scales vary from milliseconds to years, as a fault may be "locked" for decades, centuries, or millennia, and then rupture within seconds, and spatially one needs to resolve hundreds of kilometre-scale tectonic structures and metre-scale features on-fault. To simultaneously these challenges, in Uphoff *et al.* (2023) we developed a new Discontinuous Galerkin (DG) discretization for unstructured tetrahedral meshes that fully exploits HPC architectures. Our new DG method overcomes many modeling requirements which are not possible in most existing SEAS methods, specifically it allows for: curved faults, intersecting and branching faults and off-fault material heterogeneities. The new DG method has been implemented in a software package named Tandem (see software).

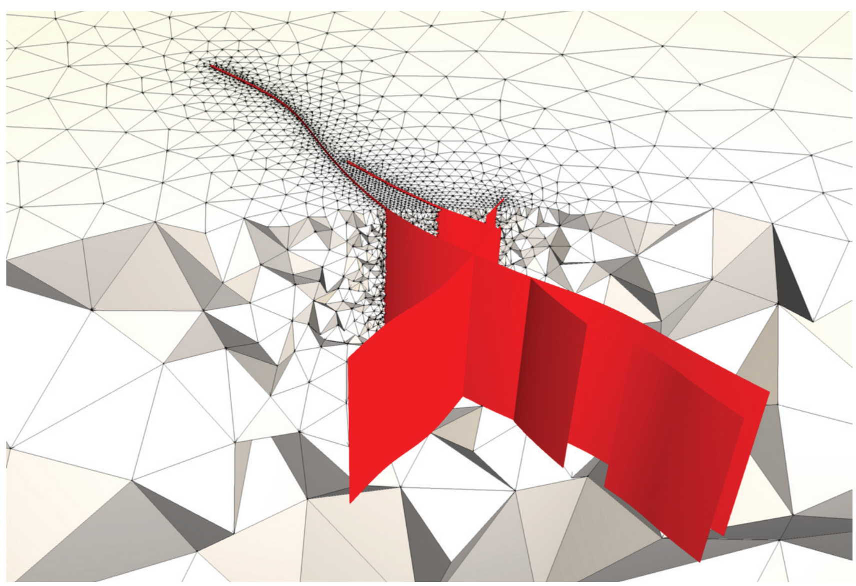

Figure 22. Zoom and cut-away view of the unstructured tet. mesh and curvilinear faults (red) used to simulate displacement from the Ridgecrest earthquake. The local spatial refinement near the fault results in a spatial resolution of ~250 m, compared with ~20 km at the domain boundaries. From Uphoff et al. (2023).

REDUCED ORDER MODELING

The computational cost of performing physics based forward models of time-dependent processes (e.g. seismic cycling, deformation of the lithosphere) in three-spatial dimensions is computationally expensive. For example, simulating the evolution of 500^3 km^3 of the lithosphere over a 30 million time span with a 1 km spatial resolution may require upwards of 1000 CPUs running continuously for two weeks. Due to the intrinsic cost of such simulations, few model realizations can practically be performed.

In our group we develop and exploit data-driven, non-intrusive reduced order models (ROMs) in order to build surrogate models of very expensive forward models. This research area has a strongly connection with **physics-based**

machine learning. Reduced order models enable rapid prediction, inversion, design and **uncertainty quantification** of large-scale nonlinear systems. We are currently deploying non-intrusive ROMs for a range of uncertainty quantification experiments within solid Earth geophysics. Specifically, we are using ROMs to quantify the variability of the thermal structure within subduction zones (with graduate student Gabrielle Hobson) and to enable real-time physics-based ground shaking predictions (with graduate student John Rekoske, see Rekoske *et al.* (2022)).

EVOLUTION OF RIFT ARCHITECTURE AND FAULT LINKAGE DURING CONTINENTAL RIFTING

Continental rifts grow via the propagation, overlap and linkage of fault segments. These three processes are strongly influenced by the evolution of the surface and its response to processes such as erosion and sedimentation. In Wolf *et al.*, (2022), 3D thermo-mechanical models of lithospheric deformation (performed using pTatin3D—see software) were coupled to a landscape evolution model in order to investigate the coupling between erosion and tectonics, fault interaction and rift linkage. From this study, it was found that the strength of the crust can limit the interactions between individual rift segments and that inherited structures can place a first order control on fault overlap and linkage. It was also found that the efficiency of the surface processes can promote long lived fault activation, increase the accommodated offset and thus limit fault segment propagation.

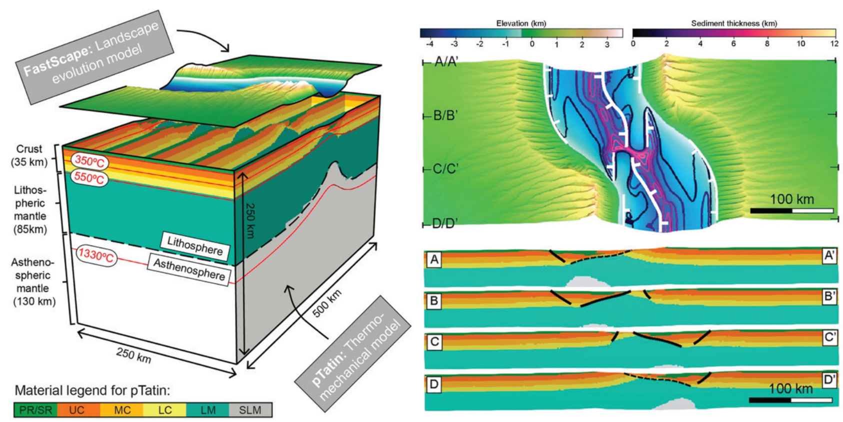

Figure 23. Left panel: Overview of the coupled model between pTatin3D (thermo-mechanical model) and FastScape (landscape evolution model). Right panel: Topography and lithology at 5 Ma when using a with high crustal strength, small heterogeneity offset and low surface process efficiency. From Wolf et al., (2022).

SOFTWARE

My group develops **open-source software** (OSS) which is publicly available. Open-source software promotes: reproducibility of scientific results; transparency in the methods and techniques being used; and community building and collaborations across the wider scientific community. Below I list software packages we actively deploy and develop.

Tandem (https://github.com/TEAR-ERC/tandem) A highly efficient HPC enabled seismic cycling package for 2D and 3D.

pTatin3D (https://bitbucket.org/ptatin/ptatin3d) A massively parallel HPC enabled package for simulating long the time-scale deformation of the mantle, lithosphere and crust.

PETSc (https://petsc.org) A suite of data structures and methods for the scalable (parallel) solution of scientific applications modeled by partial differential equations. It supports MPI and GPUs as well as hybrid MPI-GPU parallelism.

RECENT PUBLICATIONS

Uphoff, C., May, D.A. and Gabriel, A.-A. (2023). A discontinuous Galerkin method for sequences of earthquakes and aseismic slip on multiple faults using unstructured curvilinear grids. *Geophysical Journal International,* **233**(1). DOI: 10.1093/gji/ggac467

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Research Interests: *Seismic sensors, global seismic monitoring, optical fiber-based sensing, subsurface imaging of geothermal reservoirs, interferometric synthetic aperture radar.*

Global seismology. The 40 station IDA continues to operate well and replacement of the primary sensors from aged STS1 and KS54000 with newer sensors is on track. This has led to improved resolution of low frequencies across the network (Ringler et al., 2020). The recent Hunga eruption, which generated global atmospheric pressure waves and associated seismo-acoustic waves (Figure 24) (Matoza et al., 2022), was well-recorded by both seismic and infrasound sensors of the IDA network and IDA station MSVF, which was the closest global station to the eruption, has played a key role in the analysis.

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. 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 for seismology research (Chien et al., 2022; Ichinose et al., 2022; Ajo-Franklin et al., 2022). Enhancing capabilities of these sensors using quantum sensing techniques such as entangled photons is an interest (Krueper et al., 2022) (Figure 25).

Geothermal exploration. Research continued using 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. An ongoing project uses existing unused telecom cable 'dark fiber' to characterize geothermal resources in the Imperial Valley, CA (Ajo-Franklin et al., 2022; Nayak et al., 2021).

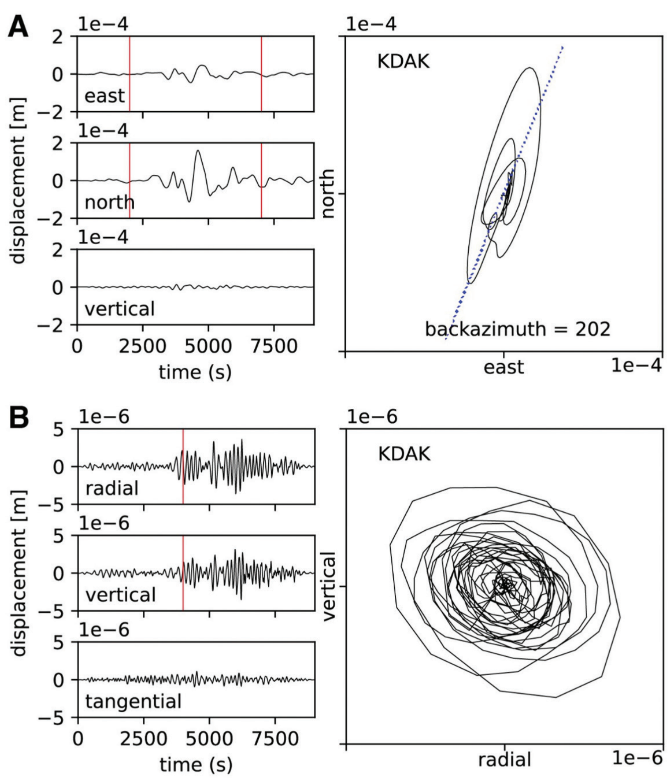

Figure 24. Example of data recorded by IDA network station KDAK showing Rayleigh waves generated by the acoustic wave. (left) Displacement waveforms for station KDAK at Kodiak, Alaska (USA) located approximately 8900 km from the eruption. The red lines denote the window used for the horizontal particle motion plot (right). The dotted blue represents the expected back azimuth from station to source. Data have been detrended and filtered from 0.0005 to 0.005 Hz. (B) (left) Displacement waveforms for station KDAK at Kodiak, Alaska located approximately 8900 km from the eruption. The red lines denote the window used for the radial/vertical particle motion plot (right). Data have been detrended and filtered from 0.005 to 0.05 Hz. The particle motion is elliptical, indicating Rayleigh waves. From Matoza et al. (2022).

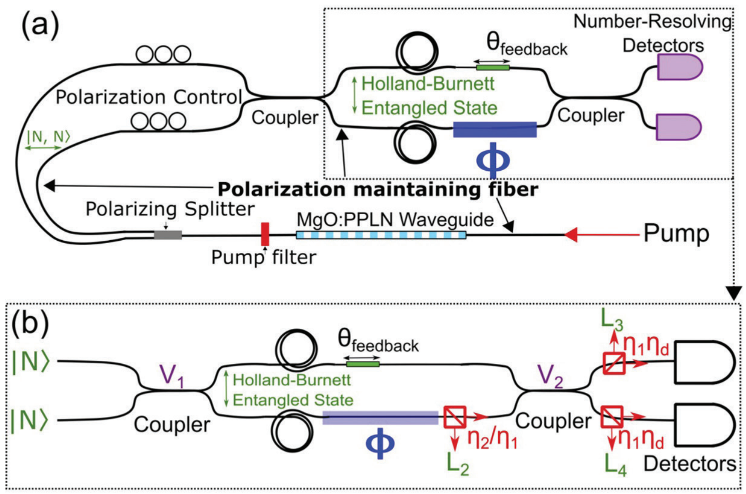

Figure 25. Example of a quantum sensing enhanced fiber sensors. a) Schematic of an entanglement-enhanced Mach-Zehnder Interferometer, with equal photon number inputs |n› in each port creating a Holland-Burnett state inside the interferometer. The bottom branch accumulates an unknown phase ϕ while the top branch includes a controllable element $\theta_{feedback}$ that can ensure an optimal measurement. (b) Simplified schematic for modeling. The state experiences loss (red) both inside the interferometer ($\eta 1$ and $\eta 2$) and in the number-resolving detectors (ηd). The internal loss mode L1 with loss $1 - \eta 1$ is grouped into other losses for simplified analysis. From Krueper et al., (2022).

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Nayak, A., J. Ajo-Franklin, and the Imperial Valley Dark Fiber Team, 2021, Distributed Acoustic Sensing Using Dark Fiber for Array Detection of Regional Earthquakes, *Seis. Res. Lett.*, **92**, 4, https://doi.org/10.1785/0220200416

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Research Interests: *Computational & mathematical geophysics—inverse problems, Markov chain Monte Carlo, stochastic and 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. The process 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 and, more broadly, in Earth science.

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 makes 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 choose.

My research group continuously works an all three of these core issues and brings new algorithms for Bayesian inference into geophysical action.

UNCERTAINTY QUANTIFICATION OF REGULARIZED GEOPHYSICAL INVERSION

The RTO-TKO. Regularized inversion remains the workhorse algorithm for learning geophysical models from data. It becomes increasingly important, however to supplement the inferred models with measures of "uncertainty", i.e., to not only learn a model, but to also be able to talk quantitatively about how accurate we expect the model to be. Mathematically and computationally, computing uncertainty is a difficult task.

Over the past year, we created a new algorithm, which we call the RTO-TKO, that quantifies uncertainty in regularized inverse problems (Refs. 2-3). The algorithm is designed to make use of existing optimization technology, to leverage massively parallel computer architectures and to estimate relevant regularization parameters on the fly. We applied the RTO-TKO to invert magnetotelluric data to image a resistive salt body in the Gulf of Mexico, surrounded by conductive, seawater-saturated sediments. Compared to existing uncertainty quantification technology, the RTO-TKO reduced the computation time from ten days (on a large computer) to two days (less if needed).

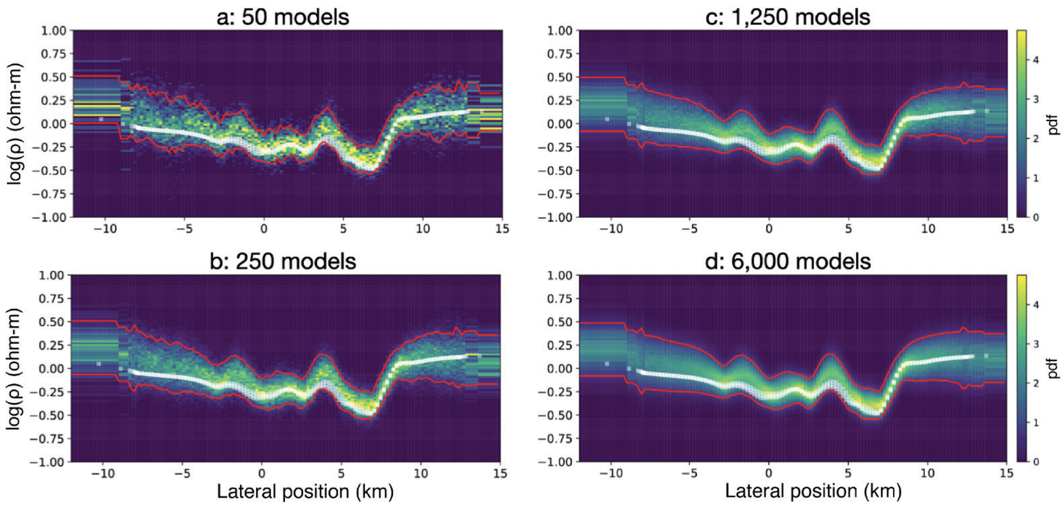

Figure 26. Illustration of the fast convergence of the RTO-TKO method (figure taken from Ref. 3). Shown are slices through a resistivity model obtained by inverting the Gemini MT data. When only the first 50 RTO-TKO samples are used to make the estimate, the distribution looks ragged but the location and width of the 90% credible interval is already fairly accurately estimated. The distribution has fully converged by the time 1,250 samples have been drawn.

COVARIANCE ESTIMATION AT EXTREME SCALES

The estimation of covariances is a fundamental ingredient in many problems in Earth science, and appears naturally at a vast scale in Numerical Weather Prediction (NWP). All standard NWP techniques require estimating the covariance matrix for the near-term weather forecasts, but the dimensionality of the covariance estimation problem in NWP is immense. A typical global weather model has billions of unknowns, which are updated by tens of millions of observations. The large cost of running the weather model necessitates that the ensemble size (number of weather simulations) is small compared to the number of unknown weather variables. A typical ensemble size is 100, and, therefore six orders of magnitude smaller than the number of unknowns. It is a mathematical/statistical fact that covariances computed with 100 ensemble members in a space of dimension 10^8 are polluted with numerical error and, therefore, pretty much useless.

Together with collaborators at the Navy Research Laboratory (NRL) and with support from the Office of Naval Research (ONR), I could derive a universal law that translates (estimated) correlation into "localization." The localization boosts the accuracy of covariance estimates far beyond of what one would expect given the small ensemble size (Ref. 1). Our universal law is applicable in a wide range of scenarios that possibly go beyond NWP and we are aiming to use our results in the near future on estimation and inverse problems in space weather.

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 render 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 true in geophysics. There are no vast amounts of data—every measurement and observation is the result of a long, costly effort. For example, collecting geophysical data (in a marine environment) often involves throwing expensive equipment of of a research vessel, then coming back months later to retrieve the data collecting devices and downloading the data from the devices that have been exposed to the ocean for months (hoping that the devices are robust enough to withstand the forces of the open, deep ocean). To make things more complicated, 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" prediction can have disastrous consequences, e.g., when predicting the path of a hurricane.

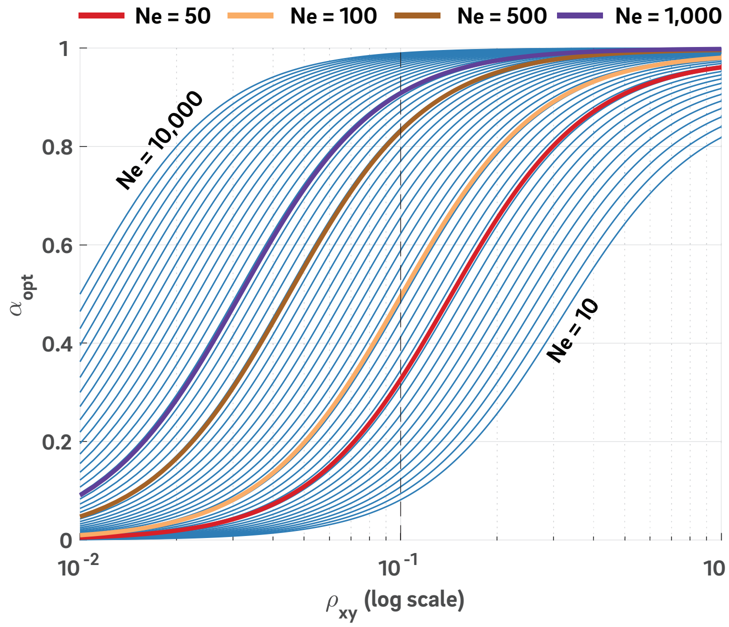

Figure 27 Illustration of the universal law that translates correlation into effective localization of covariance estimates (figure is taken from Ref. 1).

Nonetheless, there are many ingenious and careful efforts to port the success of ML and AI into Earth science, keeping the above mentioned problems in mind. My students, collaborators and I follow this path as well. A recent example is to use a machine learning method called "support vector machines" to decipher the dynamics that lead to a reversal of the axial geomagnetic dipole field (Ref. 4). Indeed, it is well known that the magnetic field of our planet reverses polarity and during such a reversal, the magnetic north pole becomes the south pole and vice versa. It is not understood why and how these reversals occur and, for this reason, it is difficult to predict when the next reversal will occur.

Support vector machines (SVM) are typically used to classify photos, e.g., to distinguish photos of cats from photos of dogs. One needs to train a SVM by showing it many examples of dogs and cats. After training, the SVM is able to classify a new photo, as a cat or a dog. We ported this idea to Earth science and trained a SVM on dynamic, paleomagnetic data, spanning the past two million years of Earth. The SVM then classifies the dynamics as "reversal-precursor" or"normal dynamics"—we thus simply replaced "cats" and "dogs" with the dynamics of Earth's magnetic field. We found out that the few paleomagnetic data we have make it difficult for a ML algorithm to succeed, but by supplementing the paleomagnetic data with models of Earth magnetic field, we were able to clearly spell out the limitations of ML/AI for this problem and outline paths that could lead to success in the future. Thus, this story is "to be continued" in future installments of the IGPP annual report.

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2. D. Blatter, M. Morzfeld, K. Key, S. Constable, Uncertainty quantification for regularized inversion of electromagnetic geophysical data|Part I: motivation and theory, *Geophysical Journal International*, **231**(2), 1057{1074 (2022).
3. D. Blatter, M. Morzfeld, K. Key, S. Constable, Uncertainty quantication for regularized inversion of electromagnetic geophysical data—Part II: application in 1-D and 2-D problems, *Geophysical Journal International,* **231**(2), 1075{1095 (2022).
4. K. Gwirtz, T. Davis, M. Morzfeld, C. Constable, A. Fournier, G. Hulot, Can machine learning reveal precursors of reversals of the geomagnetic axial dipole field?, *Geophysical Journal International,* **231**(1), 520{535 (2022).

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

My research concerns how oceanic crust is created, deformed and altered, with a focus on mid-ocean ridges and mantle plume-ridge interactions. My group at IGPP aims to answer questions about magmatism, faulting and fluid circulation at mid-ocean ridges, and the processes of mantle convection and rifting. We use a broad range of geophysical observational methods from earthquake seismology and scientific ocean drilling to mapping and sampling using deep-submergence vehicles 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.

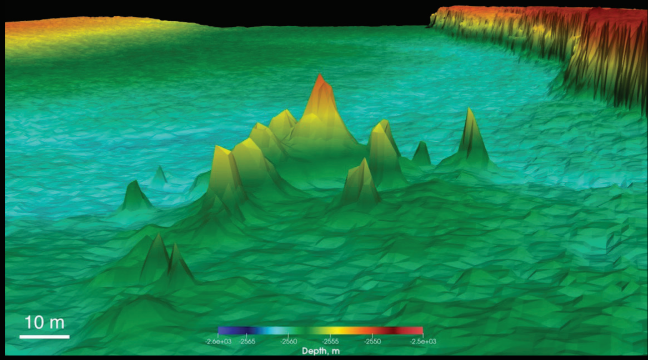

Figure 28. Perspective view of bathymetry around YBW-Sentry hydrothermal vent field, discovered in 2021 aboard Scripps vessel RV Roger Revelle. Data collected by autonomous underwater vehicle Sentry, at 1 x 1 m resolution. Active venting here releases fluids at ~360°C, with sulfide chimneys up to 10-m high covering an area equivalent to a football field.

Several key results from a multi-year NSF-sponsored sea-going effort to investigate an active submarine volcanic system at 9°50′N on the East Pacific Rise came to fruition this year. We used hydrothermal vent temperature time-series data, recorded by autonomous thermal probes installed over several years, to estimate subsurface rock permeability, a first order crustal parameter that is notoriously challenging to estimate. Combing the temperature time-series data with the natural forcing effects of ocean tides, we could explain changes in seismicity, stress, and permeability in the build-up and aftermath of the last major seafloor eruption event in 2005 (Barreyre et al., 2022). In parallel with this effort, we collected mapping data during 19 dives of autonomous underwater vehicle *Sentry* during three cruises beginning 2018. Led by IGPP graduate student Jyun-Nai Wu, we used these data to estimate the extent and volume of the 2005-2006 eruption at the study site, which provides insight into the frequency of the eruption cycle (Wu et al., 2022). During the third of these expeditions in 2021 aboard Scripps-operated vessel RV *Roger Revelle*, we discovered a new class of off-axis hydrothermal vent, whose position and fluid pathways are likely controlled by the presence of a nearby fault (Figure 29; McDermott et al., 2022). This discovery has significant implications for hydrothermal circulation at fast-spreading ridges, and how larval ecosystems repopulate after seafloor eruptions. Over the years, major breakthroughs in our understanding oceanic crustal structure and plate spreading have been made at this site by Scripps scientists, and it continues to deliver new surprises.

Partial support from the Green Foundation allowed us to upgrade and deploy four Ocean Bottom Seismographs (OBS) to the 9°50′N study site in January 2022 (Figure 30), to detect

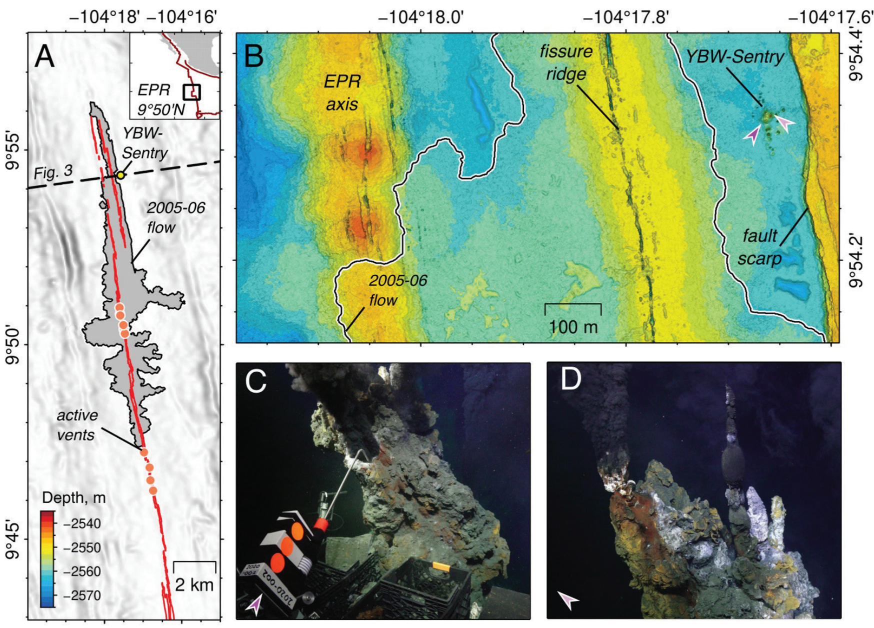

Figure 29. (A) YBW-Sentry hydrothermal vent field (yellow dot), located ~750 m east of EPR axial summit trough (red lines), ~5 to 7 km north of other known vents (orange dots). Gray polygon is 2005 to 2006 lava flow extent. (B) Near-bottom bathymetric data showing YBW-Sentry field, EPR axis, off-axis fissures, fault scarp, and 2005 to 2006 eruption extent (black line). (C and D) Photographs of actively venting sulfide chimneys at YBW-Sentry. Field of view is ~1 m wide and ~2 m wide at the center of frame for C and D, respectively; positions of images and look directions are indicated by arrows in B. From McDermott et al. (2022).

earthquakes triggered by the volcanic system as it builds to the next eruption. The OBS lab hosted at IGPP maintains one of the largest academic fleets of instruments in the United States, making it a critical player in delivering National Science Foundation-supported projects. However, the current OBS fleet is >20 years old, expensive to maintain and operate. Although robust hardware exists in current SIO OBS fleet, upgrades such as commercially-available dataloggers are now needed to meet the needs of the scientific community. The instruments are expected to be recovered in January 2023 during an expedition scheduled on RV *Atlantis* and will be used to locate microearthquakes and assess instrument performance, assuming they haven't already been buried in lava!

TEACHING INTERESTS: I currently teach two classes; SIO103 *Introduction to Geophysics*, which is an upper division undergraduate class that takes a quantitative approach to topics in whole-Earth geophysics ranging from seismology and InSAR, to heat flow and gravity. I also teach SIOG221 *Plate Tectonics in Practice*, which is a graduate class that builds upon classic concepts in plate tectonics such as rotations on a sphere and marine magnetics, with an emphasis on practical implementation of tools that are applicable to a wide range of Earth science problems.

DIVERSITY INTERESTS: Over the past year I have fostered an educational partnership with the San Diego County Office of Education and teacher-leader Camille Fowler of Garfield High (San Diego), a continuation school that serves students struggling on a conventional path. Aiming to bring geoscience topics to classrooms serving historically marginalized students, we delivered a two-day Phenomena Design Team workshop at SIO in spring 2022, where six teachers worked together to develop teaching resources centered around my research on mid-ocean ridges. Participants first identified phenomena

Figure 30. Ocean bottom seismographs ready to be deployed at the East Pacific Rise in January 2022, partially supported by the Green Foundation. Credit: Chris Armerding, IGPP

aligned with Next Generation Science Standards (e.g., volcanic and hydrothermal vent activity at mid-ocean ridges), and then worked together to assemble resources that support both teachers and students in their learning. The resources generated at this workshop were presented by IGPP graduate student Zoe Yin during a session at the California Science Education Conference in fall 2022, enabling them to be disseminated to classrooms across California and beyond.

RECENT PUBLICATIONS

Barreyre, T., Parnell-Turner, R.E., Wu, J. and Fornari, D.J. 2022. Tracking crustal permeability and hydrothermal response during seafloor eruptions at the East Pacific Rise, 9°50′N. *Geophysical Research Letters*, https://doi.org/10.1029/2021gl095459.

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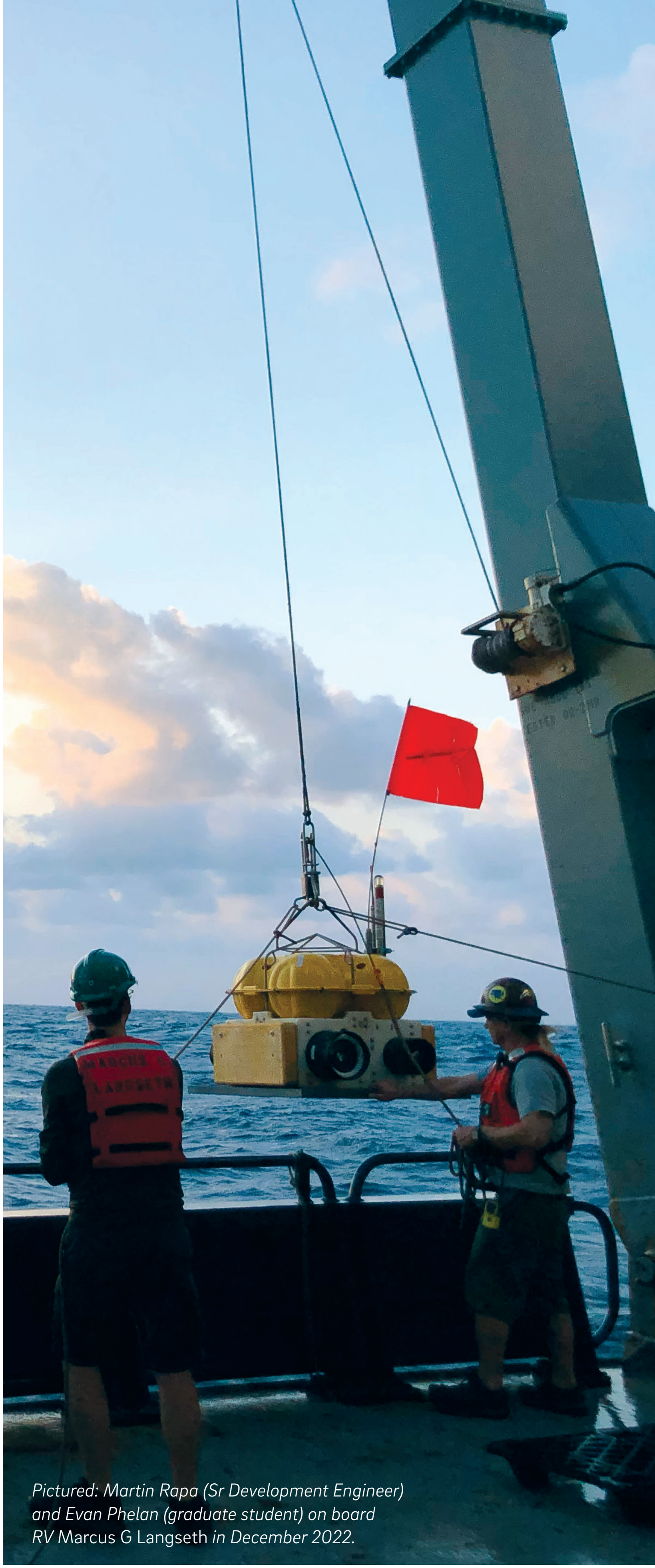

Pictured: Martin Rapa (Sr Development Engineer) and Evan Phelan (graduate student) on board RV Marcus G Langseth *in December 2022.*

DAVID T. SANDWELL

Professor

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

STUDENTS AND FUNDING: Research for the 2021-22 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, Julie Gevorgian and a postdoc 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 (topex.ucsd.edu/gmtsar).

GLOBAL GRAVITY AND BATHYMETRY: We are improving the accuracy and spatial resolution of the marine gravity field using data from 6 satellite radar altimeters (CryoSat-2, AltiKa, Jason-2, and Sentinel-3A/B, HY-2). 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 (Figure 31).

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 (https://www.youtube.com/watch?v=SxNLQKmHWpY). 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.

TEACHING INTERESTS: Geodynamics (SIO 234); Satellite Remote Sensing (SIO 135/236) and Physics of Surfing (Freshman Seminar). Sandwell published his Advanced Geodynamics book with Cambridge Univ. Press, 2022.

RECENT PUBLICATIONS

Gevorgian, J., Sandwell, D.T., Yu, Y., Kim, S.S. and Wessel, P., 2022. Global Distribution and Morphology of Small Seamounts. *Earth and Space Science*, in press.

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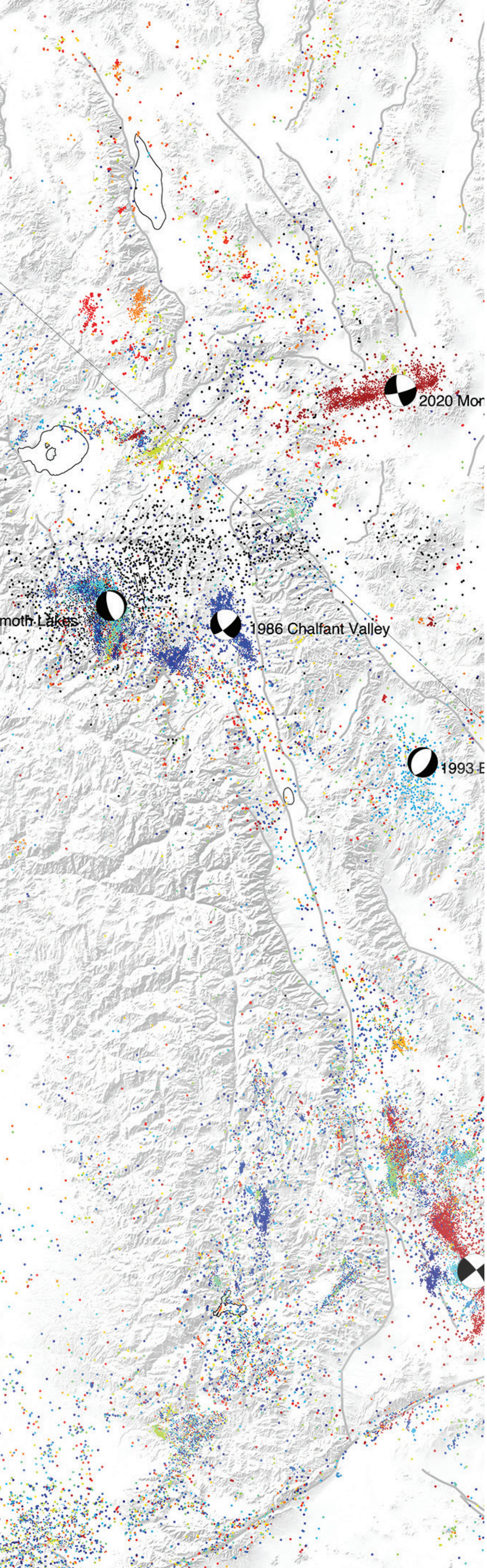

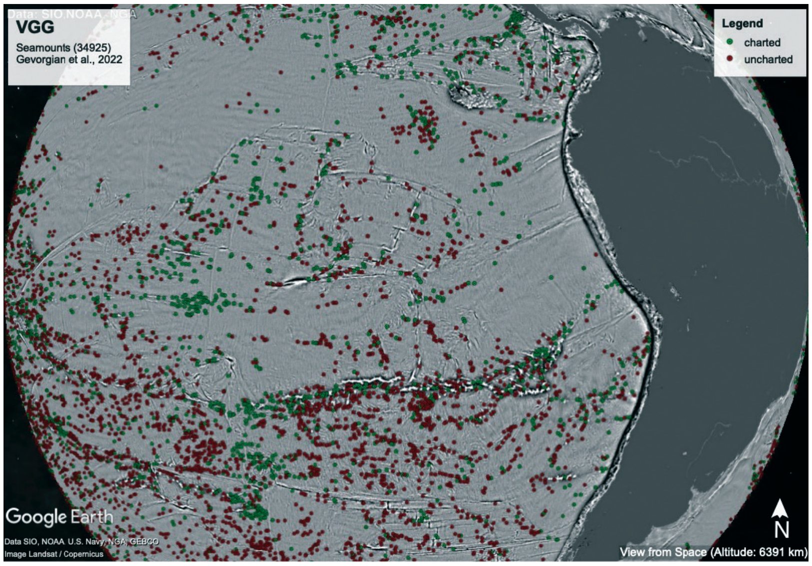

Figure 31. Vertical gravity gradient from satellite altimetry was used to increase the global seamount catalogue by 18,000 seamounts. More than 25,000 of these seamounts are uncharted. We are working with the National Geospatial Agency and Saildrone Inc. to survey ~500 of the seamounts having predicted depths < 400 m. Several have summit depths < 30 m having coral reefs that can be seen in satellite imagery.

Figure 32. Participants in the March 5-6, 2022 GNSS field campaign across the Cerro Prieto Fault, MX. Faculty and students from CICESE, Ensenada, MX and Scripps Oceanography, San Diego, USA worked in collaboration to survey 31 monuments in two days. We had similar field surveys once or twice every year between 2010 and 2020. The 2021 survey was canceled due to COVID19 restrictions.

Figure 33. Annual backpack trip to Sierra Nevada. Participants left to right: Tim Parker, Cassie Parker, Rick Aster, David Sandwell, Peter Shearer, Jeff Gee.

PETER SHEARER

Distinguished Professor of Geophysics, Director IGPP

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Research Interests: *Seismology, Earth structure, earthquake physics*

My research uses seismology to learn about Earth structure and earthquakes, using data from the global seismic networks and local networks in California, Nevada, Hawaii, and Japan. My work in crustal seismology has focused on improving earthquake locations using waveform cross-correlation, systematically estimating small-earthquake stress drops from P-wave spectra, and studying properties of earthquake clustering, especially swarms and foreshock sequences. At deeper depths, much of my research has involved resolving properties of the mantle transition-zone discontinuities and the lithosphere-asthenosphere boundary.

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

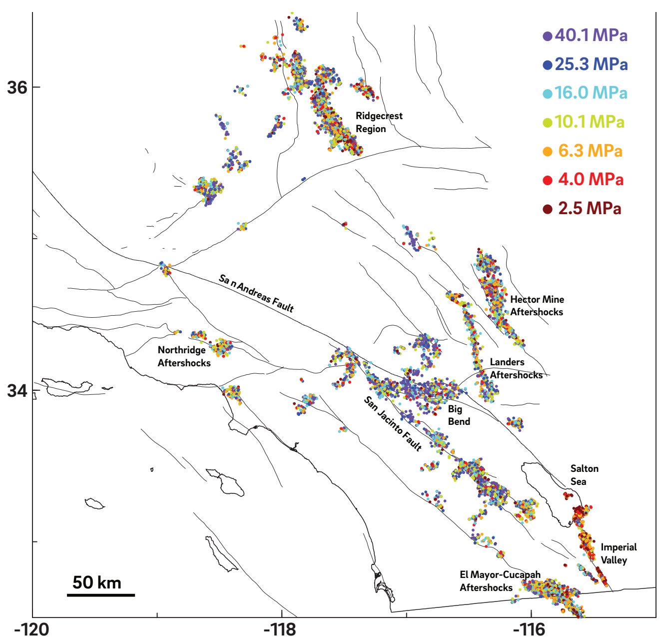

Figure 34. Stress-drop estimates for 28,012 M 2 to 4 earthquakes in southern California from 1996 to 2019. Each earthquake has at least 10 M < 1.6 nearby calibration events; thus results are only obtained in regions of relatively dense seismicity. Higher stress drops are plotted in blue, lower stress drops in red. Surface fault traces are plotted. From Shearer et al. (2022).

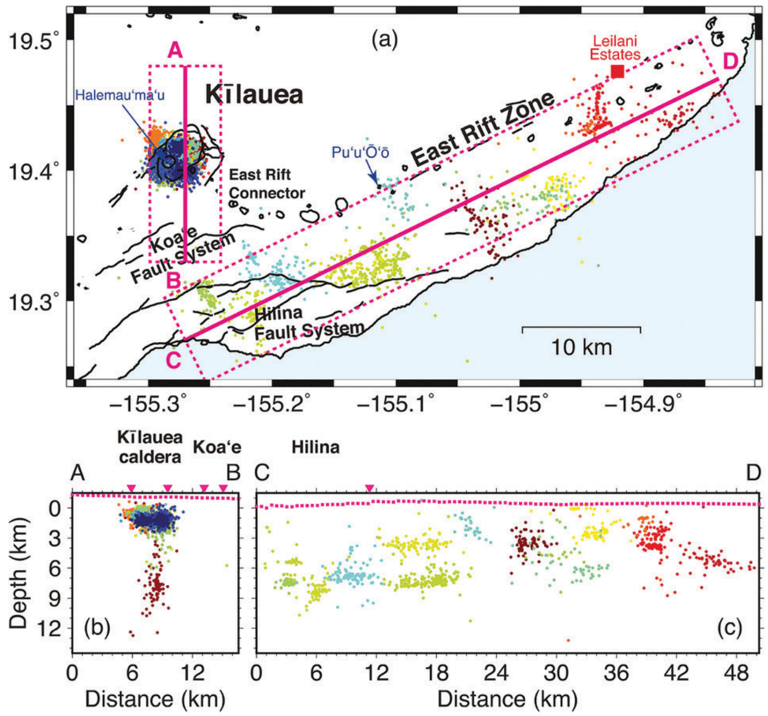

Figure 35. In situ Vp /Vs ratios for similar earthquake clusters in the 2018 eruption sequence. (a) Map view of the earthquakes in the clusters with robust Vp /Vs ratios colored by the corresponding Vp /Vs values. (b and c) Depth distributions along profiles A-B and C-D, respectively. Inverted triangles mark the locations of some major geological structures, including Kīlauea summit caldera and the Koa'e and Hilina fault systems. From Lin and Shearer (2021)

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. Recently we have applied a new method that fixes the properties of the smallest earthquakes. This removes any true coherent spatial variations in stress drops among these events but ensures that any spatial variations seen in larger-event stress drops are real and not an artifact of inaccurate path corrections. Applying this approach in southern California, we document spatial variations in stress drop that agree with previous work, such as lower-than-average stress drops in the Salton Trough, as well as small-scale stress-drop variations along many faults and aftershock sequences (see Fig. 34).

Using seismic data recorded on Hawaii, Guoqing Lin and I recently computed changes in source properties and seismic velocities during the 2018 Kīlauea eruption. We observe changes in focal mechanism type at the summit area during the eruption and temporal variations in estimated in situ Vp /Vs ratios corresponding to the eruption, with increases in the summit and decreases in the East Rift Zone. The sustained low Vp /Vs ratios below 4 km depth under the summit caldera suggest persistent ascent of volatiles from the mantle (see Fig. 35). The low Vp /Vs values in the East Rift Zone are probably associated with increased degassing.

RECENT PUBLICATIONS

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PETER WORCESTER
Researcher Emeritus, RTAD

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

My research is focused on the application of acoustic remote sensing techniques to the study of large-scale ocean structure and on improving our understanding of the propagation of sound in the ocean, including the effects of scattering from small-scale oceanographic variability. My recent research has been focused in the Arctic Ocean, which is undergoing dramatic changes in 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. 36). 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 six acoustic transceiver moorings and a Distributed Vertical Line Array (DVLA) receiver mooring that were deployed north of Alaska during August-September 2016 and recovered during September-October 2017 (Fig. 1). 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 extraordinarily stable. The peak-to-peak low-frequency travel-time variability of the early, resolved ray arrivals that turn deep in the ocean was only a few tens of milliseconds, roughly an order of magnitude smaller than observed in previous tomographic experiments at similar ranges, reflecting the small spatial scale and relative sparseness of mesoscale eddies in the Canada Basin. The high-frequency travel-time fluctuations were approximately 2 milliseconds

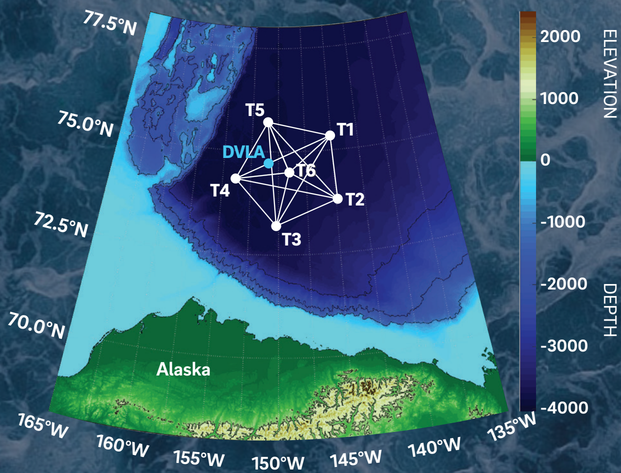

Figure 36. The 2016–2017 CANAPE experiment consisted of six Teledyne Webb Research acoustic transceivers (T1–T6) and a vertical line array receiver (DVLA). The array radius is 150 km.

rms, roughly comparable to the expected measurement uncertainty, reflecting the low internal-wave energy level. Even with the dramatic changes occurring in the Arctic, the Beaufort Sea provides a highly stable acoustic environment. The ice cover is still present throughout much of the year, albeit thin and with reduced areal extent, insulating the Arctic Ocean from wind and solar forcing. The implication is that long temporal processing and near-optimal pulse compression gains should be possible. The transmission loss increased significantly in winter, however, likely because of scattering when the signals reflect from the ice cover. Finally, ambient sound also varied over the year, with minimum levels in May-June 2017 when the ice was thickest.

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VASHAN WRIGHT
Assistant Professor

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Members of Scripps Tectonorockphysics Lab (STRPL) study tectonics, paleoseismicity, earthquake-triggered hazards, and geoscience diversity. We study geologic processes and hazards by examining sediments and rocks deposited beneath the surfaces of oceans, lakes, rivers, and beaches. We examine sediments and rocks using seismic reflection and refraction surveys, which are tools that estimate the properties of the Earth's subsurface from human-controlled sound waves. We also examine sediments and rocks using cores, aerial imagery, and x-rays. We combine data from these methods with numerical, experimental, and theoretical rock physics, fluid flow, and heat flow models to understand how sediments and rocks change or deform on macro- (meter- to kilometer-scale), microscale (size of grains), and meso- (between macro and microscale) after deposition. We then use established principles or laws of geology and physics to determine whether any observed post-depositional changes to sediments and rocks are related to tectonic forces, paleoclimatic changes, paleoseismicity, and/or past earthquake-triggered hazards. Alongside these studies, we also use quantitative and qualitative survey tools, alongside machine learning algorithms, to study how the cultural contexts of people influence geoscience diversity. Our studies aid in understanding how and why the earth and other planets may respond to future hazards while improving the culture of our discipline.

Soft Earth Geophysics employs concepts from statistical physics to study relatively easily deformable sediments within Earth's crust. There are numerous examples of statistical physics being useful in studying earth systems, prompting the need to expand the application of statistical physics in Earth and Planetary science. By doing so, we can solve, from first principles (in a more rigorous way), problems related to sediment deformation by (1) dropping the erroneous assumption of elastic deformation, (2) no longer treating sediments as continuum media exclusively, and (3) instead approximating sediments as the states of matter that they are -- solids, liquids, and gasses depending on the conditions they find themselves in and the nature of any applied forces.

A second noteworthy research area is our use of x-ray microtomography for studying the deformation of natural-deposited sediments. We pioneer sediment collection with microstructures preserved, then 3-D imaging with x-ray

Figure 37. Photo showing members of Scripps Tectonorockphysics Lab (STRPL). From left to right are Carlene Burton (research data analyst and lab manager), Richard Kilburn (graduate student), Vashan Wright (Principal Investigator), and Jhardel Dasent (graduate student).

Figure 38. Photo showing Jhardel Dasent and Richard Kilburn collecting sediment samples from the San Andreas fault zone. This study aims to determine whether records of past tectonic activity are preserved in near-surface fault zone grains.

microtomography, followed by digital analyses of the grains and pores. We are conducting these experiments in lab-reconstituted sands, in natural fault gouges, on beaches, and in submarine tectonic environments.

Diversity Interests: Our research on geoscience diversity is near and dear to our hearts. This research is about understanding the barriers to the full participation of Black, Brown, Indigenous, and Other People of Color in Geoscience. It is about understanding and dismantling inherently racist systems of power so that People of Color can find fulfillment in geoscience. Vashan Wright and Carlene Burton lead the Unlearning Racism in Geoscience (URGE) and Representation and Retention in Geoscience (R2GEO) programs.

At Scripps, PI-Wright and Carlene Burton focus on supporting Students of Color. We have check-in lunches with first-year Black and Brown students. We hosted a Black Men at Scripps cookout to discuss how these students should be and can be supporting each other. The lab hosts monthly meetings with Scripps Students of Color (up to 9 at a time), where they practice giving oral presentations, socialize, and learn from each other. Over the last year, we read and discussed Navigating an Academic Career book, discussed how to develop good research ideas, met with Geoscientists of Color outside Scripps, and discussed how to write a research bio, discussed how to give an elevator pitch.

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MARK ZUMBERGE

Research Geophysicist

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Research Interests: *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. Many individuals at Scripps are collaborators in these projects, including, Donald Elliott, William Hatfield, David Price, Dennis Rimington, Glenn Sasagawa, Joel White, and Frank Wyatt.*

Widespread deployments of GPS sensors in the past decade have helped identify Slow Slip Events (SSEs), especially near subduction zone faults in Cascadia, Costa Rica, Japan, and New Zealand. Understanding SSEs (also known as "slow earthquakes") presents an opportunity to gain new insights into the mechanism governing locking and unlocking of subduction zone and other faults, and may be important in assessing the hazard levels presented from potential great earthquakes and tsunami.

We installed two orthogonal optical fiber strainmeters on the seafloor to detect SSE. While GPS networks have sufficient sensitivity to map the location of aggregate SSEs when averaged over days or weeks, they do not cover that portion of the crust under the oceans, nor are they able to distinguish the timing of various sub-events because of the need for averaging. In contrast, optical fiber strainmeters have their best signal to noise ratio at shorter periods, complementing GPS. Because SSEs evolve in complex patterns indicative of propagating stress fronts, it is important to resolve, both in scale and time, the deformation signals in order to understand more fully the evolution of the rupture plane. In conjunction with GPS, the availability of highly sensitive and stable strainmeters offshore will enable such characterizations.

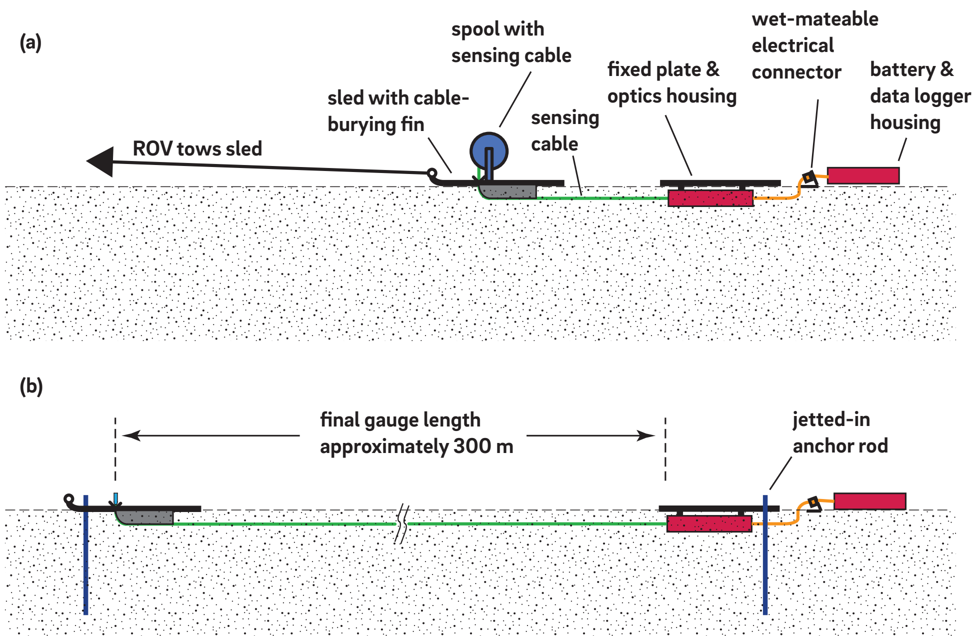

Figure 39. Cartoon depicting the deployment scenario. In (a), after positioning two end anchors on the seafloor next to each other, an ROV towed the sled-like anchor across the sediment while the optical fiber cable was spooled off and pushed down into the sediment, burying it. The drawing in (b) shows the final situation after the fully extended cable is in place and anchor rods were installed.

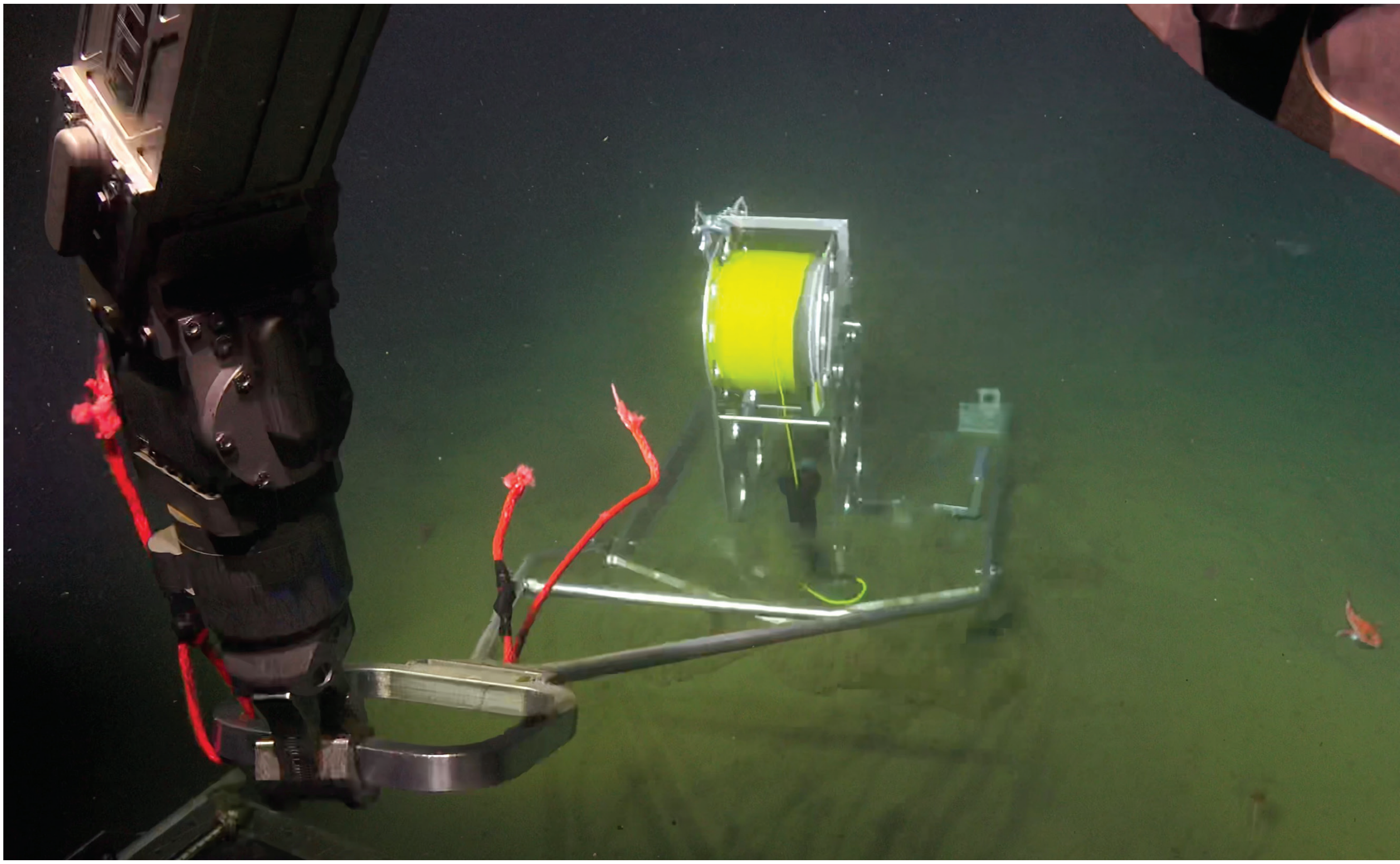

Figure 40. Photograph of the deployment sled being towed by the ROV Jason.

An optical fiber strainmeter records strain by interferometrically tracking the length of an optical fiber stretched between two attachment points in a trench, in a borehole, or on the seafloor. A laser illuminates a Michelson interferometer and a signal processor records changes in the optical path of the stretched optical fiber, yielding strain sensitivity of parts per billion.

From land-based GPS records in Oregon and Washington we hypothesized that shallow slip offshore is likely to accompany onshore SSE events. Our ongoing measurements are timed to capture this hypothesized offshore slip, testing this model and others that address the extent of an offshore locked zone. We will revisit the site to recover the data and replace batteries in July of 2023.

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