DEPARTMENT OF
EARTH & PLANETARY SCIENCE

DEPARTMENT UPDATE

2018-2019

Berkeley
UNIVERSITY OF CALIFORNIA

FROM THE CHAIR

Welcome to our annual update. This is an opportunity to reflect on the past year and to showcase the exciting science within EPS. Fundamental research is being done at all levels. Our newest faculty member, Harriet Lau (page 3), arrived this summer and continues a long tradition of innovation in global geophysics. We advance research opportunities for undergraduates, such as department citationist Dakota Churchill (page 15). Our faculty, students, staff and alumni continue to make our department one of the world's best.

Accolades continue to pour in, and I highlight a few. Barbara Romanowicz was awarded the Bowie medal, the highest honor of our largest scientific society, the American Geophysical Union (AGU). The medal, recognizing both scholarship and service to the scientific community, is awarded for "outstanding contributions to fundamental Earth and space science and for unselfish cooperation in research." This was just one of the many awards Barbara received during the past year, including the American Geological Institute's (AGI) Legendary Geoscientist Medal. Daniel Stolper received AGU's Kuno award for outstanding contributions to the fields of volcanology, geochemistry and petrology. Eugene Chiang was elected to the American Academy of Arts and Sciences. Inez Fung was elected to the Royal Society. Don DePaolo was awarded the Goldschmidt Award by the Geochemical Society. Our alumni are being recognized across all the fields covered by the department: geology, geophysics, atmospheric science, marine science, environmental science, and planetary science. On page 18 we hear from one alumnus, Amanda Thomas who received this year's Richter award from the Seismological Society of America.

These can be challenging times for the Earth Sciences as we face rollbacks of environmental protections and the denial of scientific data and facts we uncover through our research. Yet the geosciences remain as important as ever, from identifying new resources to mitigating natural hazards (page 9). And the new fundamental discoveries enabled by space exploration (page 12), big data (page 9), the ability to model climate systems (page 10), and making new and precise geochemical measurements (page 6 and 7) highlight how much more there is for us in EPS to learn and contribute.


Michael Manga

A new growing challenge to our education and research missions is the rise of nationalism, which is creating new barriers to supporting international students and collaborations. We embrace open and equitable access to opportunities for learning and development as our obligation and goal. It is thus timely and with the deepest gratitude that EPS thanks the Houtzager family for their generous gift to create an endowment to support field research in developing nations by our graduate students. The first Houtzager awards will be granted over the coming year.

CONNECT WITH US

Please keep us updated and share a sentence or two for next year's annual update at eps.berkeley.edu. Our department's legacy is the success of our alumni. Feel encouraged to share your suggestions and recommendations. Alumni can request to join our LinkedIn group; please find the group here: https://www.linkedin.com/groups/6927573.
The costs of field experiences remain a barrier to providing an inclusive education. We remain committed to providing the best field education we can to all students. Our collective achievements are not possible without your continued involvement and help.

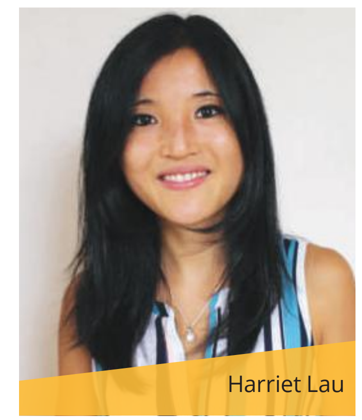
Photo: Graduate Student Nate Lindsey installing a seismometer in Azerbaijan to study mud volcanoes, September 2019.

Cover Photo: Professor Bethanie Edwards observes as graduate student Tatiana Gaméz passages phytoplankton cultures. Photo credit: Ben Ailes

WELCOME

GET TO KNOW OUR FACULTY

HARRIET LAU


Harriet Lau

The Earth is subject to forces with timescales that range from milliseconds to billions of years, and its deformational response (or, more formally, its rheological response) to these processes varies dramatically across this range. For example, seismic waves triggered by the sudden, brittle failure of rocks along faults are largely an elastic phenomenon akin to the ringing of a bell. In contrast, temperature differences of ~3000 degrees across the interior—from the boundary between the iron core and the rocky mantle to the outer surface of the crust—have existed since the formation of Earth 4.5 billion years ago, resulting in a slow fluid-like convection that provides the driving force for plate tectonics. At intermediate timescales of thousands to tens of thousands of years, the growth and disappearance of giant ice sheets during the last ice age warp the shape of the Earth and perturb both its gravitational field and rotation axis involving both a rapid, elastic response and a much slower, viscous response that persists to the present day. That the Earth can respond in such disparate ways to different geophysical forces is well known and the ultimate cause of this variation is due to energy dissipation: seismic wave energy in the mantle is slightly dissipative, while convective flow is almost entirely dissipative. The intermediate behavior is far less understood and a generalized model of Earth rheology covering these broad behaviors is still to be developed.

In my research, I aim to bring together a variety of geophysical observations that span spatial scales from the micro-scale to the global-scale and temporal scales from sub-seconds to billions of years—coupled with a consistently developed mathematical framework— to understand Earth rheology in a more holistic way.

To meet this end, many challenges arise: for example, the fields of seismology, ice age dynamics and mantle convection focus on data sets that reflect the narrow frequency bands appropriate to these processes. However, while modeling of each of these processes in isolation has had some success in reconciling observations, a broader inspection across these disciplines reveals enigmatic inconsistencies and misfits. As one example, inferences of mantle viscosity based on GPS measurements of crustal deformation after large earthquakes (post-seismic relaxation) are orders of magnitude lower than inferences derived from analyses of sea-level variations driven by ice age (ice plus ocean) loading. Perhaps this inconsistency indicates that the two processes are sampling fundamentally different regimes of viscous flow or that they reflect the different thermo-dynamical state in which the deformation occurs. Disentangling the many

continued on next page

Explaining Earth rotation with another love of mine, soccer (or more specifically, Manchester United).

effects—frequency-related, physical, and chemical—remains as the first step towards building a consistent rheological model of Earth's flow.

ON THE MICRO-SCALE

Small strain experiments subject cm-scale rocks or analogue materials to cyclic deformation at pressure and temperature ranges equivalent to that of the uppermost mantle. The oscillations are applied at a frequency range across the sub-seismic to seismic band and record the lag angle between the forced oscillations and the response of the rock sample, a direct measure of the intrinsic attenuation of the material. Macroscopic dissipation emerges from a range of processes from the grain scale down to the atomic scale. However, many open questions remain about exactly how such micro-scale processes can be incorporated into macroscopic theories that can then be applied to global-scale problems. Working together with experimentalists Ulrich Faul (MIT) and rock mechanicists like Ben Holtzman (Columbia University), I am assessing just how these micro-scale processes might manifest themselves in global-scale observations of geophysical processes while simultaneously developing a theoretical framework that allows these micro-scale processes to be incorporated into the modeling of global-scale geophysical processes.

ACROSS THE GLOBAL-SCALE

My work focusses on several observations that provide valuable insights into the interior of the Earth. These observations span a large range in frequency, while offering hints of the spatially varying thermodynamic state of the mantle.

In Space: Free Oscillation and Tidal Tomography
Together with Barbara Romanowicz, here at the Berkeley Seismology Laboratory, we are using the latest theory to bring several types of seismic and geodetic observations together in order to better understand the density distribution of the mantle—a key, though enigmatic, physical parameter required to understand how the mantle has evolved over Earth history. Free oscillations (whole-Earth vibrations triggered by deep and large earthquakes) and solid Earth tides (the deformation of the crust and mantle due to gravitational forces from the Sun and Moon) offer a so-far unrivalled glimpse of density in the deepest part of the mantle. In particular, we will focus on a special class of free oscillations known as Stoneley modes which are vibrations that are trapped along the core-mantle boundary and on semi-diurnal Earth tides caused by the very same forces that give rise to the twice-daily ocean tides we are so familiar with. This effort represents the first study of its kind, bringing together sophisticated inversion methods and unique geophysical observables.

In Frequency: The case of Iceland
Iceland represents a unique locality: not only is the island undergoing a large variety of geophysical processes, many of these processes have been captured in the geological record or measured by geophysical techniques and thus presents us with an exceptional wealth of data. The range in frequency of available data is unprecedented: from seismic attenuation measurements (~10 Hz, or ~10^{-8} years in period) to geological processes related to mantle convection acting on a time-scale spanning millions to billions of years; representing a combined 16 orders of magnitude. In between, ocean tides lap on and off the coast on hourly to monthly periods. The shifting around of ocean mass causes the crust and subsurface to deform. Crustal uplift due to the melting of Iceland's ice caps acts on several timescales: timescales due to modern climate change, the Little Ice Age (~500 years ago), and the 100,000-year ice age timescale, geologically recorded by ancient shorelines. At the extreme end of mantle-convection timescales, Iceland's peculiar "V"-shaped bathymetric ridges are thought to be driven by plume-related dynamic topography.

By singling out one geographical region, we focus on one thermodynamic setting and, taken together, these observations will provide a glimpse as to how the Earth behaves across a large band in frequency.

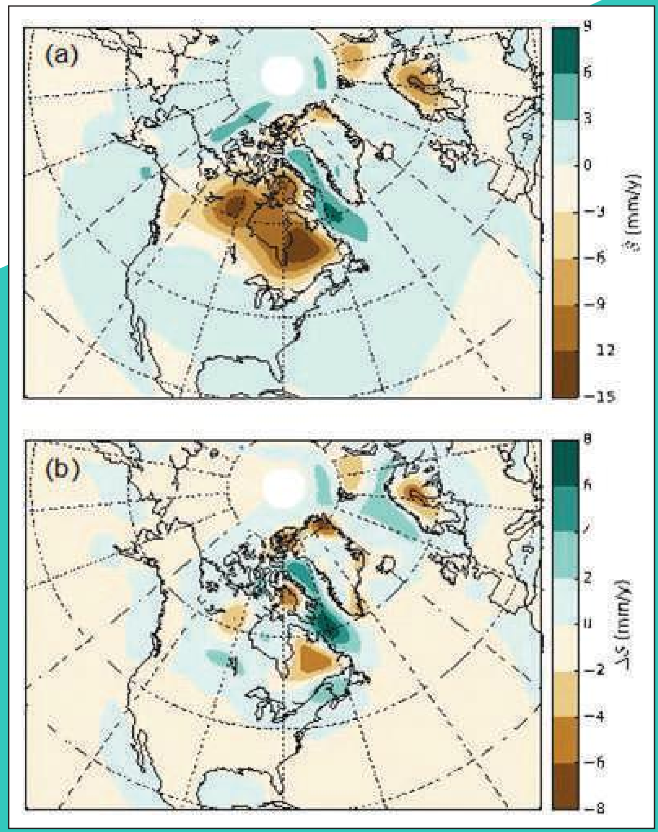
BRINGING IT ALL TOGETHER

Building a more accurate model of how Earth deforms will ultimately play a role towards a deeper understanding of the nature of Earth's rich history. The Earth system consists of several components: the biosphere, the atmosphere and oceans, the crustal surface, and the rocky and metallic interior. These subsystems dynamically interact, influencing each other in complicated and, oftentimes, unexpected ways. Such complexity demands an interdisciplinary approach that geoscientists must adopt to address Earth's story. Several intriguing mysteries have puzzled Earth scientists to this day: How has Earth's length of day changed through time? What drives dramatic ice age cycles that have persisted over the last two to three million years and why are these cycles changing (in frequency and magnitude)? To address these issues, with collaborators, we aim to bring together our ever-growing knowledge of both the solid Earth and insights of Earth's climate system.

Sunrise to sunset through history: The time it takes for the sun to rise and set is a fundamental parameter of the planet Earth and important to how we, as human beings, experience it. As ocean tides lap on and off the coast, energy is lost from the Earth-Moon orbital system, causing the Moon to recede from the Earth and, in response to this, Earth's rotation rate slows down. The geometry of the ocean basins dictates how much energy is lost and due to the dynamics of the solid Earth, this geometry always changes, whether driven by plate tectonics or modern, anthropogenically-related climate change. With collaborators, I explore these changes on daily to millions-billions of years time-scales in order to build a history of how quickly or slowly sunset-to—sunrise occurs.

The Mid-Pleistocene Transition: For the last three million years one dominant characteristic of Earth's surface climate has been the growth and decline of major ice sheets that reach several (~3-5) kilometers in depth. This growth-and-decline cycle is thought to be intimately linked with Earth's slight orbital changes which display distinct changes every 20-, 40-, and 100-thousand years resulting in small changes to the solar radiation that reaches Earth at the very same frequency. These changes have remained constant over these last 3 million years and yet the nature of the ice ages have changed dramatically. In particular, the magnitude of the growth-and-decline and the periods at which they occur—moving from a phase dominated by the 40,000-year cycle to the present phase dominated by the 100,000-year cycle— is an unexplained conundrum known as the Mid-Pleistocene Transition. If solar radiation patterns have remained relatively fixed, what, then, is driving these dramatic changes in ice age cycles? Together with rock mechanicists and climate scientists, we explore the possibility of how damage and memory in Earth's rocks – or more generally, non-linear rheology—might play a role in this transition. As an example of the solid Earth response, the figures below show the prediction of present day rate of change of sea level across the northernmost parts of North America in response to the melting of the Laurentide ice sheet.

These topics represent a small selection of basic questions in Earth's history that require a deeper understanding of the solid Earth coupled with an approach that must span many disciplines across Earth science. In collaboration with students and colleagues here in the Earth and Planetary Science department, I look forward to my journey here as both a learner and a teacher.



The ongoing rate of change of sea level across North America due to the melting of the ancient Laurentide ice sheet ~ 7,000 years ago. This can also be thought of as the negative of the rate of change in uplift.

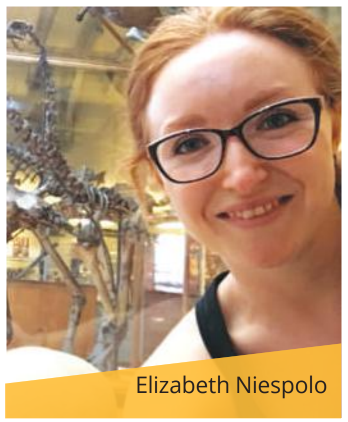
GEOPHYSICS

RESEARCH SPOTLIGHTS

BGC TURNS 25

The Berkeley Geochronology Center (BGC) was founded twenty-five years ago as an independent non-profit research institution on May 6, 1994. BGC has been a partner with EPS in research and student mentorship over the years. With laboratories for $^{40}Ar/^{39}Ar$, U-Pb, U-series, (U-Th)/He, and cosmogenic nuclide dating, as well as paleomagnetism, BGC complements facilities in EPS, extending and broadening the disciplinary reach of EPS faculty and students. Articles in this issue by PhD students Elizabeth Niespolo and Chelsea Willet exemplify the synergistic relationship between BGC and EPS.

ELIZABETH NIESPOLO, RECENT GRADUATE

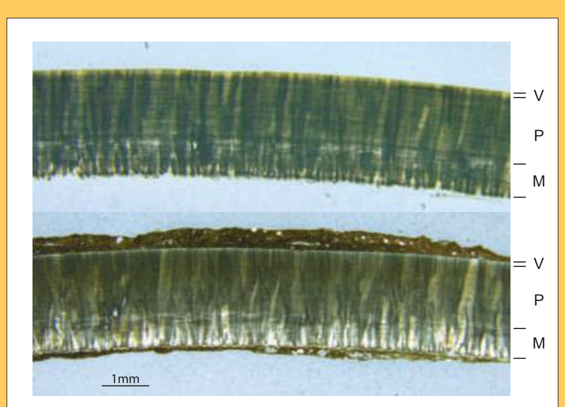


Elizabeth Niespolo

Evidence of human evolution spans a paltry ~0.1% of Earth's history, and yet, we humans have manipulated natural resources in ways no other animal on Earth has before us. When humans begin to adapt to more diverse environments around 300 thousand years ago (ka), and later successfully disperse out of Africa, researchers ask whether they modify their environments, and in their wake, drive ecosystem shifts, extirpations, and/or extinctions. The timing, tempo, and sequence of these events, and how they are geologically recorded, are crucial to test hypotheses on the covariance of human evolutionary and environmental change.

Under the advising of Paul Renne, I have worked in the Afar Triangle (Ethiopia) to refine the ages of intercalated hominid fossils and archaeology by dating volcanic ashes (called tephra) with $^{40}Ar/^{39}Ar$ geochronology. Because existing paleoanthropological records throughout Africa provide only disparate appearances and sparse representation of most hominid species with ~100s ka gaps in the record, field work is crucial to continue populating the human evolutionary tree with precise chronological control. Field work in Afar is adventurous and immersive: the landscapes are shrubby and sparsely inhabited badlands, and exotic wildlife surrounds us, including baboons, Nile crocodiles, hippopotamus, ostriches, and hyenas. Lions still roam the Afar, but I've only ever seen their footprints; their geographic range is shrinking from anthropogenic environmental pressures.

While $^{40}Ar/^{39}Ar$ dating of tephra has been a bulwark of building chronologies for eastern African paleoanthropological sites, many Pleistocene sites remain poorly constrained in time or undated entirely if they lack volcanic ashes. However, these sites commonly contain ostrich eggshell fragments, made of ~2-mm thick, low-Mg calcite that are geochemically suitable for $^{230}Th/U$ dating and resistant to diagenesis in deep time. With my co-advisor Warren Sharp, we have developed a novel application, called $^{230}Th/U$ burial dating of ostrich eggshell, which will open new doors for constraining the timing and tempo of human evolution, adaptation, and geographic range expansion in the Pleistocene. We are dating sites in southern and eastern Africa that have the potential to change our understanding of the development of modern human behaviors, such as coastal foraging, diversification of stone tool manufacture, and the earliest evidence of art. I will continue to develop other eggshell dating techniques in my postdoc, and I hope to continue advancing our understanding of the spatio-temporal variation of human evolution and the concomitant environmental conditions through time.



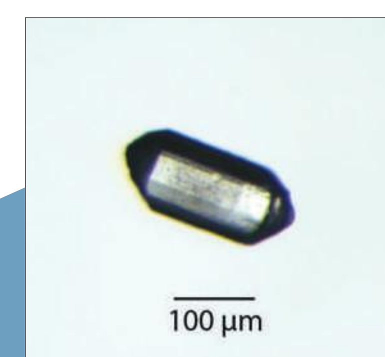
Photomicrographs of thin sections of (upper) modern ostrich eggshell and (lower) archaeological eggshell from Lukenya Hill, Kenya (^{14}C age: 39.0-36.1 kcal BP, $^{230}Th/U$ burial age: 37.9 ±1.6 ka, 95% C.I.) with adhering detritus-rich soil carbonate. Labels indicate: V. vertical crystal layer; P. palisade layer; M. mammillary cone layer. Calcite is stable in soils in semi-arid to arid climates, and ostrich eggshell biomineral calcite preserves primary crystal habits in deep time.
Figure from Sharp, W.D., Tryon, C.A., Niespolo, E.M., Fylstra, N., Tripathy-Lang, A., Faith, J.T., Peppe, D.J., 2019, $^{230}Th/U$ Burial Dating of Ostrich Eggshell, Quaternary Science Reviews v. 219, 263 – 276, doi: 10.1016/j.quascirev.2019.06.037

CHELSEA WILLETT, GRADUATE STUDENT

Chelsea Willett

As part of the Surface Process Geochemistry (SPG) group, I use the presence and diffusion of radiogenic ^{4}He in the mineral apatite (pictured) to quantify long-term rates of terrestrial erosion using a technique known as apatite U-Th/He (AHe) thermochronometry. Radioactive uranium and thorium, present at detectable levels in apatite, decay to stable isotopes of lead via a series of α- and β-decays. For each α-decay, a ^{4}He nucleus is formed. Above ~70°C, this ^{4}He diffuses out of the crystal, but below that temperature the ^{4}He is retained. By measuring the total amount of U, Th, and ^{4}He in an apatite crystal, one can determine the time elapsed since the crystal cooled and connect the result to processes that drive exhumation, such as fluvial or glacial erosion or tectonics.

Thanks to my work with SPG group leader Professor David Shuster, I have spent the past five years applying and improving AHe thermochronometry using noble gas mass spectrometry at the Berkeley Geochronology Center. Through a series of diffusion experiments aimed at understanding the relationship between the diffusion of ^{4}He and damage to the apatite crystal structure caused by radioactive decay, we have determined that apatite diffusion kinetics depend on a sample's past temperature, parent nuclide concentration, and apatite chemistry. That is, not all apatite is created equally when it comes to radiation damage. Furthermore, I have had the good fortune of applying AHe thermochronometry to two field sites in the Patagonian Andes. In one study, with collaborators from Yale and UC Santa Cruz, we determined that a transition from fluvial to glacial erosion in central Patagonia resulted in as much as a ten-fold increase in localized erosion rates. I am looking forward to discovering what the granite from Torres del Paine (pictured) will reveal about landscape evolution further to the south!

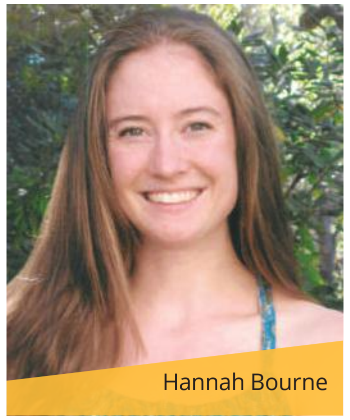


Apatite crystal photographed under an optical microscope. Concentrations of U, Th, and He in crystals such as this form the basis of AHe thermochronology. Image courtesy of N. Fylstra.

Checking out the granite laccolith in Torres del Paine (Chile) on a sample-collecting trip.

RESEARCH SPOTLIGHTS

HANNAH BOURNE, RECENT GRADUATE


Hannah Bourne

Ocean Phytoplankton live for a week before they are eaten, yet this process is the start of a globally important transport of sinking organic matter into the deep sea which fosters ocean uptake of atmospheric CO_2. So little is known about the fast process of this so-called Biological Carbon Pump (BCP) because all observations until recently have required ships. Consequently, we don't know how the BCP will respond to human induced changes to the ocean. Professor Bishop's group at Berkeley and Lawrence Berkeley National Laboratory (LBNL) has developed low cost deep diving autonomous robots called Carbon Flux Explorers which are designed to measure the hourly variations of the sinking rates of particulate organic matter to kilometer depths and to transmit data in real time to satellites for missions as long as one year. CFEs use transmitted light imaging to quantify the accumulation rate of particles; as part of its development, we needed to calibrate this optical proxy for particle flux.

This year, Dr. Hannah Bourne (EPS PhD, 2018) published the first study documenting the strongly correlated relationship of the CFE's optical particle flux proxy with measured carbon and nitrogen flux. In other words, Hannah's work has put the letters C and N into CarboN Flux Explorer. Dr. Bourne's study (published in Biogeosciences) with EPS Professor Bishop and coauthors, was facilitated by LBNL engineers Todd Wood and Tim Loew, and undergraduate students Yizhuang Liu, Xiao Fu, and Elizabeth Connors and was funded by the National Science Foundation. It required the design and integration of an entirely new particle sampling system with the CFE.

The system shown in the photograph above—constructed mostly from 3D printed parts fabricated in Jacobs Hall—went from design to the ocean in less than one month. The study which took place in California coastal waters in August 2016 R/V Oceanus (photo by Jessica Kendall-Bar) and June 2017 aboard R/V Revelle.

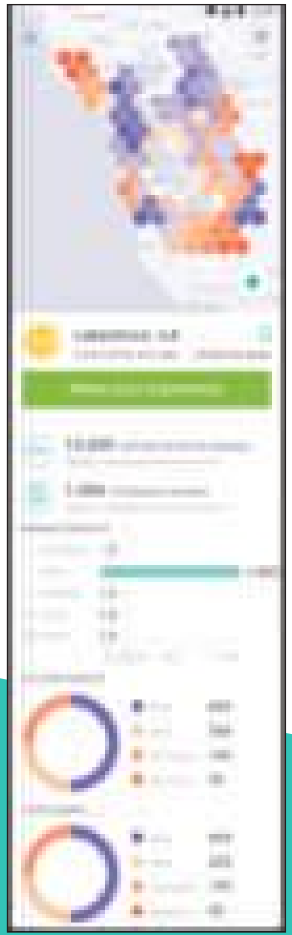
QINGKAI KONG, RESEARCHER

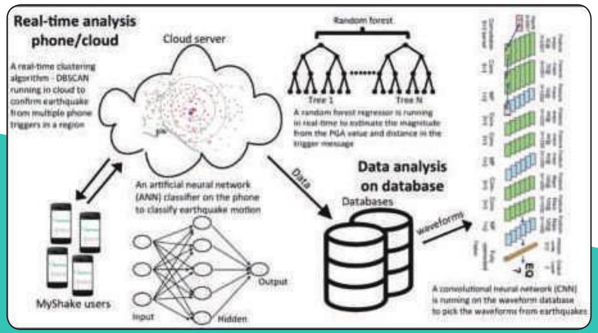

Qingkai Kong

Modern seismology has made many amazing contributions to our understanding of Earth's structure and the physics of earthquakes, such as plate tectonics and the mechanics of earthquakes. Many of these contributions are from the data recorded using seismic and geodetic instruments. Recent advancements in data science techniques and tools provide a new opportunity for seismologists to gain additional insights. Here at the Berkeley Seismology Lab, we are applying data science to various projects related to traditional seismological data as well as new types of data.

The MyShake project aims to build a global dense smartphone seismic network to monitor earthquakes and provide earthquake early warning using the power of crowdsourcing. The idea is to turn your smartphone into a portable seismometer to monitor earthquakes. To turn your smartphone into a seismometer, just simply download the application, which will start to monitor the accelerometer (a sensor that can sense the movement of the phone). Whenever it senses some earthquake-like motion, your phone will send a message to the cloud server where messages from multiple phones in a region can be aggregated to confirm an occurring earthquake. What really powers the MyShake system are a series of data science algorithms to distinguish earthquake-like motion, confirm earthquake occurrence and estimate the magnitude as shown in right panel. So far MyShake has been downloaded more than 300,000 times and recorded more than 900 earthquakes globally. The data recorded by MyShake users could potentially provide more information about the earthquakes and even the behavior of buildings in earthquakes, since there are more records close to earthquakes and within the buildings.

Not only is the sensor data useful, but users can also provide useful information after they felt an earthquake. In the new version of MyShake, users can fill in short surveys whether they felt the earthquake, and noticed any damage to buildings, bridges and roads. Left panel shows an example of the view of user-felt reports for a hypothetical earthquake. This data can be used for rapid assessment of the damage after the earthquake and give users a sense of hazards near them. In a future version of MyShake, there are plans to collect photos uploaded from users. Currently, the team is working on using a machine learning model to recognize images with damaged structures from any photos uploaded by users.





Left Panel: An example of user submitted felt reports, the polygons on the map show user reported damages.
Right Panel: The data science algorithms that power the MyShake system. There are algorithms used on the smartphones or the cloud servers.

RESEARCH SPOTLIGHTS

MICHAEL DIAZ, POSTDOCTORAL SCHOLAR

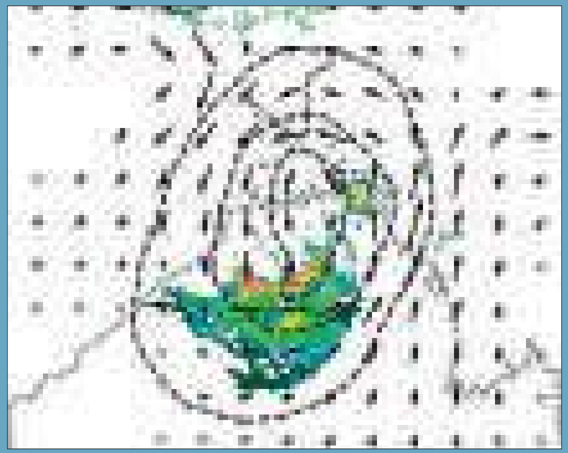
Michael Diaz

The Indian subcontinent, home to about a quarter of the world's population, is influenced by one of Earth's most prominent monsoon systems. The resulting climate is characterized by dramatic contrasts in seasonal rainfall. For example, the city of Kolkata receives about three quarters of its annual 1.8 meters of rain between June and September. Such large variations inevitably bring about both floods and droughts. With agriculture of central importance to this region's economy, understanding the monsoon and its variability is invaluable.

A large source of rainfall variability in this region is linked to storm systems known as monsoon depressions. They share many features with tropical depressions and tropical storms found in other low-latitude parts of the world, but tend to be larger in size and have weaker winds. The rainfall they produce has often been catastrophic, producing floods that have killed hundreds to thousands of people. Despite detailed records of individual monsoon depressions extending back to the 1800s, surprisingly little is known about what causes them. I am working as a postdoc with Professor William Boos to understand how these storms form and intensify.

To accomplish this goal, we developed an idealized, high-resolution numerical model of the atmosphere to simulate how monsoon depressions form and interact with the larger-scale monsoon system. Using this model, we found several features of the background environment to be essential for the development of these storms. One such feature is the strong wind shear (a technical term for a spatial change in wind speed or direction) in the north-to-south direction. It exists because of opposing currents of westward winds to the north and eastward winds to the south. Monsoon depressions can grow by gaining spin from this sheared flow. A second feature is the substantial wind shear in the vertical direction, which results from winds changing from strong and eastward near the surface to strong and westward aloft. Although this shear is detrimental to the formation of typhoons and hurricanes, it aids the development of monsoon depressions through a complex interaction with the depression's circulation that leads to rising air motion. This rising motion causes moisture to condense and form precipitation. The heating generated by this condensation is essential to the growth of monsoon depressions. Finally, with condensation being vital to their development, the ample moisture in this region is a third key factor favoring their development.

Since these results are based on idealized numerical simulations, we are working to apply these findings to observed monsoon depressions. Our group is actively collaborating with the government of India to enhance the observational tracking and prediction of monsoon depression rainfall. Further refinement of the theoretical ideas that emerge from our idealized model will hopefully contribute to improved rainfall forecasts in this densely populated and vulnerable region.



Simulated rain water mixing ratio, perturbation pressure, and perturbation winds of a monsoon depression

CLIMATE CHANGE WITH DAVID ROMPS, PROFESSOR

David Romps

Introduction to Climate Change (EPS 7), taught by Professor Romps, was added to the roster of course offerings in the fall of 2017. The course introduces students to the science of global warming, the looming climate crisis, and the Earth resources available to stop it.

After learning some basic physics of radiation, the students use their new skills to calculate the temperatures of Mercury and Mars. The temperatures of those planets are set by a simple balance: energy in the form of shortwave radiation (sunlight) is absorbed by the surface, and energy is lost to space at that same rate by the emission of invisible longwave radiation from the surface. The more sunlight that is absorbed, the hotter the planet must be in order to radiate away an equal amount of power in that invisible longwave radiation. Therefore, Mercury, being closer to the Sun, is hotter than Mars. The students discover, however, that these simple calculations fail miserably for Earth. If we apply the same techniques to our home planet, we would calculate that Berkeley should be colder the currently coldest inhabited place on Earth (Oymyakon in Siberia, for those who like trivia).

To make further progress, the students learn about ideal gases and the effect that depressurization has on rising air, leading to colder temperatures aloft. The fact that the air gets colder the higher we go in the atmosphere is key to Earth's greenhouse effect. Due to the presence of greenhouse gases like water vapor and carbon dioxide, the atmosphere radiates to space not from the ground, but from an effective surface five kilometers up in the atmosphere. But, because temperatures decrease as we move up in that atmosphere, that "surface" is colder than the actual surface of Earth, meaning that the greenhouse gases emit longwave radiation at a slower rate than the surface. To balance the flows of energy (sunlight absorbed by the surface and longwave emitted by the greenhouse gases), Earth must be warmer than it would be without an atmosphere.

As the students learn, the cause of global warming is the lifting of that effective emission height higher in the atmosphere due to the addition of greenhouse gases to the atmosphere (primarily the addition of carbon dioxide from burning coal, oil, and gas). As that "surface" moves upward to colder temperatures, the Earth must warm to keep that "surface" at the same temperature.

Fortunately, Earth provides a fix to this man-made crisis: solar power, if harnessed over 1% of the land surface, can power 10 billion people all living like Americans. But, the students also learn that global warming is permanent on timescales of tens of thousands of years. Whether or not we avert a planetary catastrophe is largely a question of what we choose to do over the coming decade.

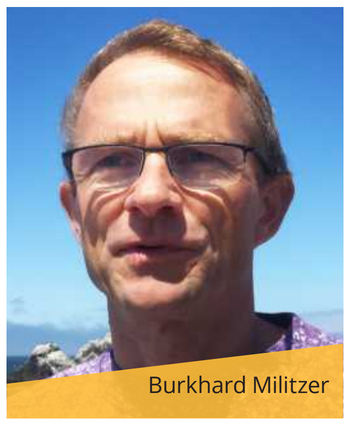
Image credit: NASA/JPL/Space Science Institute

RESEARCH SPOTLIGHTS

PLANETARY SCIENCE

WHEN SATURN BECAME THE LORD OF THE RINGS

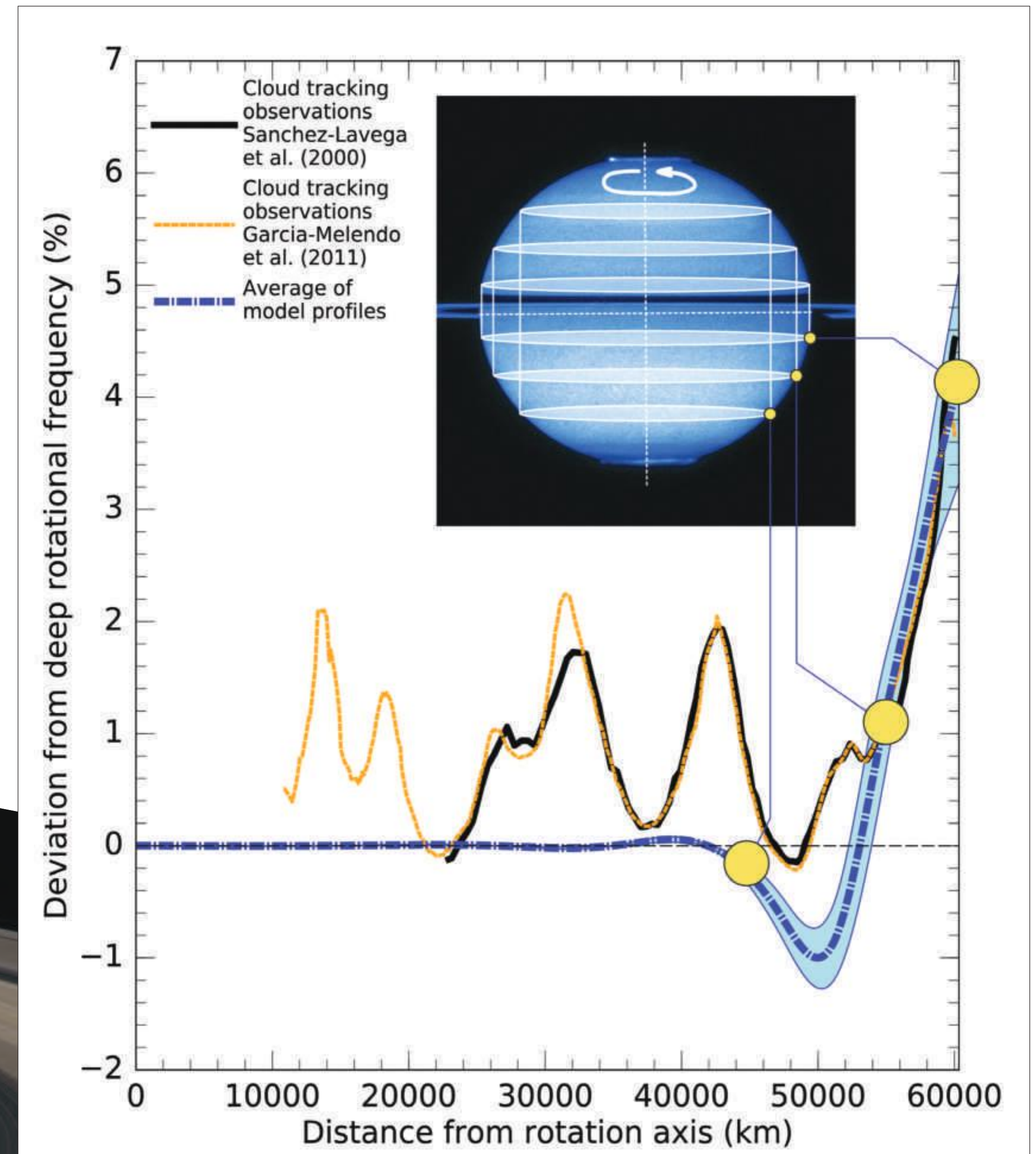
BURKHARD MILITZER, PROFESSOR



Burkhard Militzer

During its 13 years in orbit around Saturn, the *Cassini* spacecraft has made a number of remarkable discoveries that helped us better understand the planet and its satellites. It flew for example through the plumes of the icy moon Enceladus and measured its composition. The spacecraft dropped the Huygens probe into the atmosphere of the moon Titan and, for the first time, we learned about the lakes and river systems that are hidden underneath the dense haze. The probe also relayed back pictures from boulders in these rivers, except that these boulders were made of water ice and moved by flowing hydrocarbons due to Titan's low urface temperatures.

Only during its final 22 orbits, the spacecraft dove inside Saturn's rings and came closer than ever before to the planet's visible surface and measured its gravity fields with unprecedented precision. In anticipation of these gravity measurements, we had constructed a comprehensive suite of plausible interior models that consisted of a layer of molecular hydrogen, a helium rain region, a metallic hydrogen layer, and a dense rock-ice core. Since our models had worked fairly well for Jupiter, we were

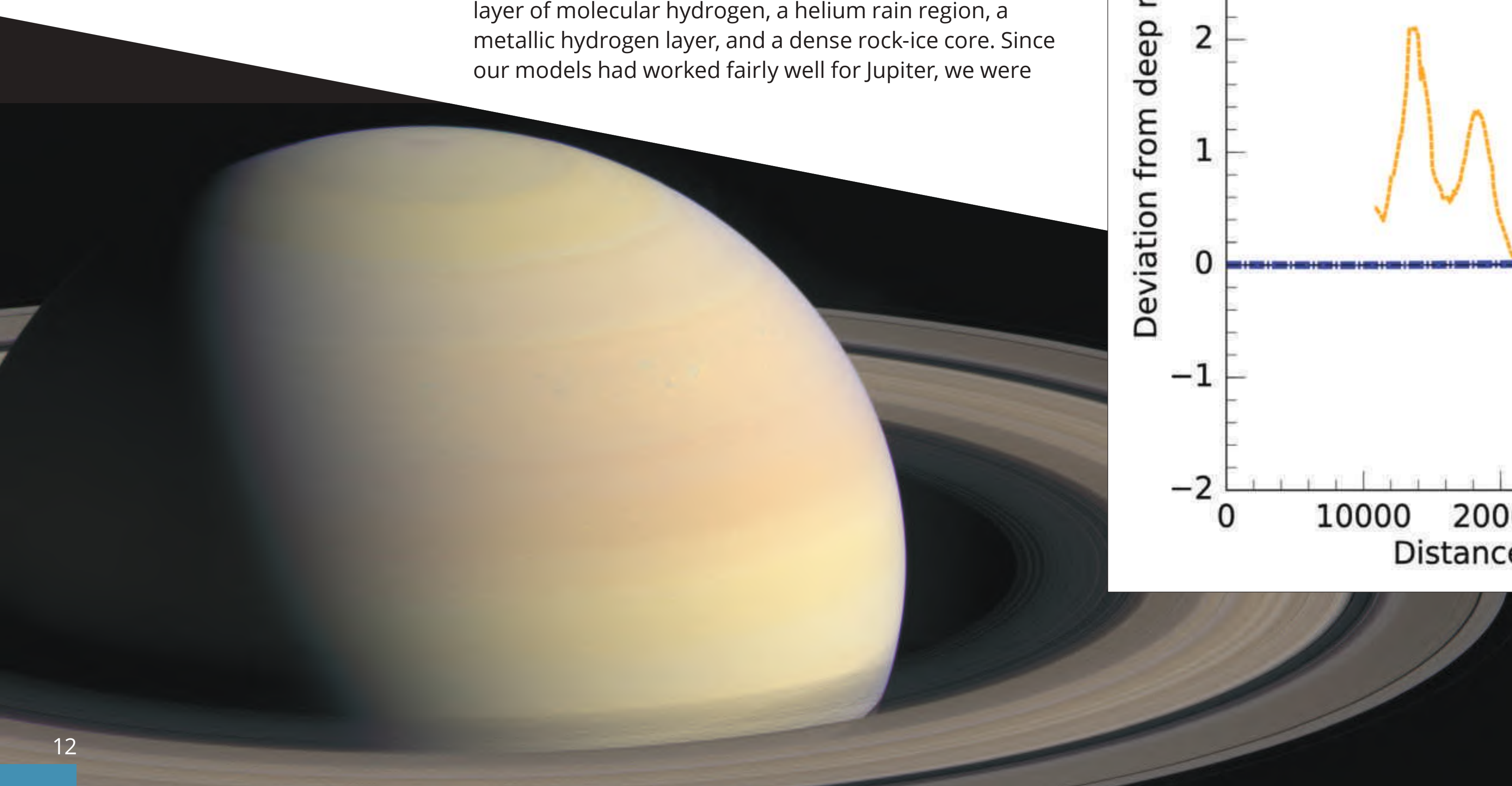


Saturn's unusual gravity field implies that the winds are at least 9000 km deep at the equator and flow 4% faster than the planet's deep interior.

confident that the gravity coefficient J_8 would soon be measured to be between -8.9 and -8.6 × 10^{-6}. However, when our collaborators told us that Saturn's J_8 was in fact -14.6 × 10^{-6}, we knew something was missing from all of our interior models and from those constructed previously. Solving this puzzle took almost my entire sabbatical that I mostly spent in a coffeeshop in Oxford, Ohio, where my wife is a professor. It soon became clear that the measurements could be explained if somehow there was extra mass distributed around Saturn's equator. Based on this hypothesis, we introduced *differential rotation* (or winds) into our models while we had previously assumed Saturn rotated uniformly like a solid body. If we introduce an equatorial jet that rotates about 4% faster than the deep interior (see figure), we can match the spacecraft data very well because the added centrifugal force mimics the effect of extra mass around the equator. The winds in our models turned out to be compatible with the motion of clouds in Saturn's atmosphere but no one had assumed the winds to be so massive and about 9000 km deep, which is the conclusion that has emerged from Saturn's unusual gravity field.

During those final orbits, the *Cassini* spacecraft also determined the mass of Saturn's rings. Their combined weight is 40% of the mass of the moon Mimas or 0.0002 lunar masses. This may not sound too remarkable until you translate this measurement into an age for Saturn's rings. I must admit that I had naively assumed that Saturn's rings were as old as the planet because every time I looked at Saturn, it had rings. However, we approximately know the flux of meteoritic material that darkens Saturn's icy rings over time. Using the color of the rings today, we determined the Saturn's rings are only between 10 and 100 million years old, which is a surprisingly young age. It tells us a dramatic event must have occurred near Saturn in our recent solar system history. 100 million years ago, the dinosaurs still roamed the Earth. They disappeared when a giant impact occurred near the Yucatan peninsula 65 million years ago as we have learned from W. Alvarez's seminal work. The *Cassini* data implies that a drastic event occurred around Saturn that produced the icy rubble that makes up the rings today.

When our results were published, they were shared many times on the internet. The funniest comment came from the Russian website rambler.ru, which posted an article titled Астрономы узнали, когда Сатурн стал «властелином колец». When translated into English, it becomes the title of this article.



PLANETARY SCIENCE

OCEAN SOCIETY

ABBY JACKSON-GAIN, OCEAN SOCIETY PRESIDENT

Abby Jackson-Gain

The Ocean Society of Berkeley had an eventful and successful year. We had many new members, as this year was the largest our club has ever been! We continued volunteering with BASIS (Bay Area Scientists in Schools) and teaching our 'Oceans are for Everyone' lesson to second-grade classrooms every month. We also teamed up with Surfrider of Berkeley to host some beach clean-ups throughout the year. We had many great speakers come to our meeting, including Sara Elshafie, a PhD student in the Integrative Biology department who presented a science communication through storytelling workshop.

Several times throughout the spring semester after our Thursday meetings, we went to the Exploratorium After Dark event where Bay Area scientists and artists come and share what they do in the interactive science museum in San Francisco. It was a great way for club members to bond and learn about the interesting things people are doing here in the Bay. We also had joint events with the Atmospheric Science Association and the Geologic Association of Berkeley, one of which was a graduate student panel where undergraduates could ask questions about grad school and talk to some of the graduate students in the department. This was a great event that helped foster community in the department among the undergrads and grad students and we hope to do it again! Another exciting crossover for Ocean Society was our joint trip to Hastings Natural Reserve with the Entomology Club of Berkeley. We were able to learn about and collect insects and in turn, we shared some of our ocean knowledge with Entomology folks when we hiked in Big Sur. We also went on many other incredible trips this past year including to Santa Cruz, Bodega Bay, and Point Lobos.

The second year of Summer Ocean Society during Summer 2018 was a success as well. It was a great way to maintain the EPS undergraduate community during the summer. We were even able to go to the Monterey Bay Aquarium, who hosted our club and took us on a complimentary tour behind the scenes! It's been an amazing year and I'm thrilled that Kai Crombie will be taking over the role as club president in the fall. I can't wait to meet new members and see what new endeavors our club will take on in the future.

Left: Ocean Society visiting the Monterey Bay Aquarium; **Right:** Club members in Santa Cruz

DEPARTMENTAL CITATION
DAKOTA CHURCHILL

Dakota Churchill

Hello, my name is Dakota and I am among the most recent graduates from the Earth and Planetary Science Department at UC Berkeley. It is my honor to be asked to write this letter and share some of my research. As it does for all who join our community, the EPS department provided me with countless opportunities that greatly enriched my learning experience. I am especially grateful to have had the opportunity to complete my senior thesis in which I studied the sinter age and maturation at Castle and Giant Geyser in Yellowstone National Park.

As a part of my project, I joined a group of researchers from UC Berkeley, Montana State University, the United States Geological Survey, and Yellowstone's National Park Service. We collected samples of silica sinter deposited by geysers in the Upper Geyser Basin and determined their age and mineralogy. Our goal was to better constrain the age of the basin and the geysers, their deposition rate, and their change in mineralogy over time. My thesis looked specifically at Castle and Giant Geyser in detail because of their large size. To gain insight on their formation, we analyzed samples using Radiocarbon Dating, X-ray Powder Diffraction, X-ray Tomography, Scanning Electron Microscopy, and X-ray Fluorescence.

Our results showed that radiocarbon ages obtained from the sinter do not correlate with stratigraphic position. This result calls into question the accuracy of radiocarbon dating as a method for obtaining the age of geyserite deposition, and instead, indicates that radiocarbon dates should only be viewed as upper bounds. X-ray fluorescence revealed a negative correlation between water content, trace element concentrations, and stratigraphic location. This finding provides additional means for mapping the relative ages of sinter along a geyser cone in addition to that of maturing mineralogy from amorphous opal A to quartz.

Future researchers can use these results for hazard assessment, preserving Yellowstone's resources, and as interpretative information for the scientific community and the public. Additionally, this project has opened the door further for research that will aid our understanding of the formation of hydrothermal features through time. Remaining questions sparked by my research include, but are not limited to, the following: How long does it take for large geysers to grow? Can we obtain rates of geyser growth? Has hydrothermal activity been constant or intermittent since deglaciation in YNP? And was there any pre-glacial hydrothermal activity?

Without the guidance and support from Berkeley's Earth and Planetary Science Department, I would not have had the opportunity to tackle these questions. The department provided funding, sending me to UC Irvine to radiocarbon date my samples, and provided me with a lab at UC Berkeley where I could process, analyze, and create thin sections of my samples. I am immensely grateful to the EPS department for this invaluable research experience, and I am honored to have the opportunity to share that research here.

Dakota Churchill in Yellowstone

COMMENCEMENT 2019

THIS YEAR EPS AWARDED 29 BAs, 7 MAs, AND 10 PhDs

Faculty line up for processional, clockwise from twelve o'clock: Bill Boos, David Romps, Imke de Pater, Robin Bell (commencement speaker and AGU president from Columbia University), Jim Bishop, Bethanie Edwards, Inez Fung

Environmental Earth Science: Andrew Gunem, Dominique Lemanek, Danielle Satin, Spencer Steven Tagg, Thao Thi Phuong Tran, Ani Angel Matevosian

Geophysics: Ryan Carl Caspary, Matthew Thomas Abramo, Owen Nelson, Ellis Jay Vavra

Doctor of Philosophy (PhD): Joshua Tollefson, Kathryn Materna, Elizabeth Marie Niespolo, Olive Sierra Boyd, Robert Martin-Short, Noah G. Randolph-Flagg

Geology: Dakota Churchill, Julia Nancy Anderson, Victoria Isabel Jurado, Nicole Mizrahi, Owen Nelson, Robert J. Sherwood, Erika Karina Cota Solis

Master of Arts: Savannah Blake, Matthew Kirk, Rory French, Berenice Gonzalez, Irene Liou, Jacob Yung

Planetary Science: Carolina "Cee" Gould; **Atmospheric Science:** Katelyn Anna Yu

Atmospheric Science: Katelyn Anna Yu; **Marine Science:** Josue Anthony Torres, Costas Soler, Yayla Sezginer, Jesse Gil, Giselle Lopez Mendoza

Commencement 2019 photos courtesy of Mohabbat Ahmadi.

AWARDS

AMANDA THOMAS, PH.D. 2012

Amanda Thomas

Amanda M. Thomas was this year's recipient of the Charles F. Richter early career award from the Seismological Society of America. Amanda began her career in science as an Aerospace Engineering student at the Georgia Institute of Technology. After completing an IRIS summer internship, Amanda decided to attend graduate school in Earth Science. In the fall of 2007, she began graduate studies at Berkeley working with Roland Bürgmann on problems related to slow earthquakes and deep fault rheology. In 2012 she was awarded a National Science Foundation postdoctoral research fellowship to continue studying slow fault slip at Stanford University. Amanda began her appointment as an assistant professor at the University of Oregon in the fall of 2015.

Amanda's research focuses on problems in seismology and fault mechanics. She's interested in the state of stress and physical properties of faults, physics of the earthquake source, seismotectonics, and crustal deformation. Ongoing work in her group focuses on quantifying earthquake and tsunami hazards in the Pacific Northwest, relating the physical properties of faults to the type and character of seismicity they produce, and using observations of tiny earthquakes to constrain fault rheology. In her spare time Amanda enjoys hiking with her dog (and her husband), glamping, and mothering her two daughters.

A seismometer on top of Mt. Hood (Cascades in the background).

2018 AWARDEES OF THE CERTIFICATE FOR DISTINGUISHED TEACHING

- **Chris Moeckel** (EPS 50, Spring 2018)

OUTSTANDING GRADUATE STUDENT INSTRUCTOR AWARD

- **Hannah Bourne** (EPS 103, Spring 2018)
- **Robert Martin-Short** (EPS 102, Spring 2018. EPS 109, Fall 2018)
- **Thomas Smart** (EPS c12, Spring 2018)

ESPER LARSEN JR. RESEARCH FUND GRANTS FOR 2018-19

- **Don DePaolo,** U-series Comminution Age study: Responses of sediment transport to climate change
- **Michael Manga,** Age, chemistry, and diagenesis of silica sinters in the Upper Geyser Basin, Yellowstone,with implications for how the hydrothermal and magmatic systems responded to deglaciation
- **David Shuster,** Visualizing and quantifying alpha recoil damage density in apatite
- **Daniel Stolper,** The history of deep-ocean dissolved O2 and its link to the mineralogy and petrogenesis of oceanic and continental crust

CHARLES H. RAMSDEN ENDOWED FUND GRANTS FOR 2018-2019

- **Don DePaolo:** EPS 119 Field trip to Arizona, Spring 2019
- **Banfield, Renne, Wenk, Grimsich:** Maintenance of the Scanning Electron Microscope (SEM) and X-ray Diffractometer (XRD) used for undergraduate instruction and research
- **Nicole Mizrahi:** Analysis of oxygen isotope and sulfur isotope samples from the Hell Creek and Tullock formations in Montana to investigate climate change across the Cretaceous-Paleogene boundary
- **Thao Tran:** Research project investigating an extreme precipitation event that happened in California from 1861-62, which inundated many cities and is projected to repeat within 50 years
- **Abigail Jackson-Gain:** Fieldwork for senior honors thesis to collect fern and rock samples from sites in the Altiplano Central and Sierra Madre Occidental regions of Mexico for climate and geologic data on the evolution of hybrid ferns
- **Maryn Sanders:** Fieldwork at Antelope Valley site in Williams, CA on landslides by looking into the dependence of stability on soil type, water content, thickness and its hydraulic conductivity
- **Ellis Vavra:** Research for senior honors thesis in Geophysics on the relationships between deformation and seismicity during 2014-2019 unrest in Long Valley, CA
- **Robert Rhew and Catherine Halversen:** Communicating Ocean Sciences to Informal Audiences, to fund co-instructor for course EPS C100 which combines marine science concepts with instruction in effective ways of communicating scientific knowledge, including meaningful outreach experiences teaching marine science in informal science centers, such as science museums and aquariums

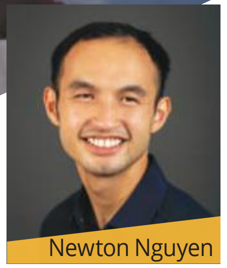
Marcel Houtzager

THANK YOU

EPS thanks the Houtzager family for establishing the Marcel Houtzager Fund for Graduate Student Fieldwork, to honor the memory of geologist Marcel Houtzager.

The fellowship will support students from developing nations and fieldwork in developing nations. Recipients will use the support to develop new research skills and produce data that will contribute to their dissertations or theses.

ALUMNI UPDATES


Newton Nguyen

NEWTON NGUYEN (2016) is now a Graduate Student, Department of Environmental Science and Engineering, Caltech. You can connect with him on LinkedIn.

FRANK PABIAN (1971) is a Retired Los Alamos National Laboratory Fellow with a recently published article in the Seismological Research Letters NOV/DEC 2018. Volume 89, Number 6. "Although I never became a practicing 'Geologist' in my career, nearly everything that I learned while at Berkeley did prove to be useful to me later in life in one way or another (even as a United Nations Chief Nuclear Inspector in Iraq in the 1990s)... [sic]... so please do pay attention and remember as much as possible... [sic]... because you never know how what you might learn can be applied later in life. "


Frank Pabian

MARIANNE STAM (1980) is a Retired Los Alamos National Laboratory Fellow after 47 years in the field of satellite imagery analysis for nuclear nonproliferation. She currently volunteers at the Cal DOJ Riverside Crime Laboratory assisting with training and case review. She is also involved in national and international Forensic Geology scientific working groups which means traveling all over the world to meet with Forensic Geology colleagues. Her advice "learn about different cultures. Join professional organizations as soon as you can and network. Get to know your professors and don't be afraid to ask them questions - they just might become your mentors!"

CAROLINA LITHGOW-BERTELLONI (1994) is now a Professor at UCLA. Her advice: "It's okay to ask for help, don't need to know everything or do everything on your own."


Rebecca Smith

DAVID O'BRIEN (1995) is a data analyst for the Alaska Cancer Registry in the Alaska Department of Health and Social Services. "I will always remember things like being a TA under Lionel Weiss during my first year and doing x-ray mineralogy research under Rudy Wenk during my second year. It was under Rudy that I wrote a small grant proposal and our lab was the proud recipient of one of the first IBM XT and IBM AT personal computers! The XT didn't even have a hard drive. Rather, it had two 5 1/4 inch floppy drives and the entire operating system fit on one bootable floppy disk!" Advice: "pursue a summer internship at a company that [you] might want to eventually work with, even if it [doesn't] pay anything. Working in a real life situation while being a grad student is valuable experience and might result in a job after graduation."

IBRAHIM SULEIMAN was a Post-Doctoral Researcher with EPS. Now teaches Geology & Geophysics at the University of Tripoli Libya.


Richard Cheney

REBECCA SMITH (2010) is now a Postdoctoral researcher in planetary geology at SUNY Stony Brook. You can connect with her on LinkedIn.

RICHARD CHENEY (1972) completed his Masters in Public Administration degree at San Francisco State University in May 2019. This is his third Masters (International Relations, University of the Philippines, 1979; Geophysics, Texas Tech University, 1982). He says "Cal's biggest impact has more to do with how it shaped my world-view. I try to share my experiences with new Cal students when the opportunities arise. This term I participated in an open forum with junior college transfer students new to Cal; I always try to make at least one football game so I can tailgate with the CalVets. I was recently inducted into the Benjamin Ide Wheeler Society at Cal. Go Bears!"

Have an update you would like to share in next year's publication? Go to eps.berkeley.edu and click on Connect With Us, or email eps_alumni@berkeley.edu. Alumni can also request to join our LinkedIn group; please find the group here: www.linkedin.com/groups/6927573

EVENTS


Graduate student camping trip to Kings Canyon, Grant Grove August 15-19, 2019.


Students surrounded by snow and butterflies while on a camping trip with Geological Association at Berkeley (GAB) and Ocean Society, August 3, 2019.


Professor Burkhard Militzer leads a demonstration with liquid nitrogen on Cal Day, April 18, 2019.


Halloween party, October 31, 2018.


Robin Bell, AGU president from Columbia University, gives the Commencement Address for the 2019 EPS Graduation Ceremony, May 21, 2019.


Thanksgiving potluck, November 15, 2018.


Professor Walter Alvarez with a matching sock puppet made by staff for a skit presented at Santa Barbara's Day, December 4, 2018.


Professor Nick Swanson-Hysell adds detail to his contribution to the department's Pi Day drawing, March 14, 2019.


Professor Jim Bishop elucidates a matter to Professor Daniel Stolper at the Welcome BBQ, September 5, 2019.


Professor Inez Fung colors clouds on the pavement for large group chalk drawing on Pi Day, March 14, 2019

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Butler, Peggy D
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Lathon, Robert Bruce
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Lawrence Livermore National Laboratory
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Lin, Wu Nan
Link, Percy Anne
Lopez-Morillas PhD, Consuelo
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Louie, Susan C
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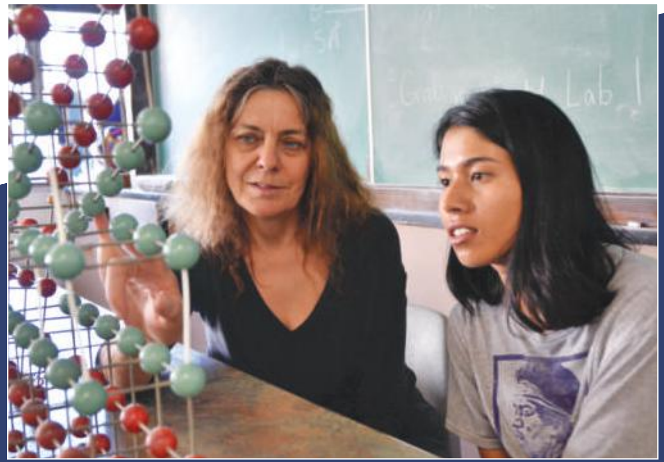

Professor Jill Banfield explains the structure of a dislocation in a mineral to a student. Photo credit: Ben Ailes

FACULTY & STAFF

FACULTY

Richard Allen
Walter Alvarez
Jill F. Banfield
James Bishop
Kristie Boering
William Boos
George Brimhall
Bruce Buffett
Mark Bukowinski
Roland Bürgmann
Eugene Chiang
Ronald Cohen
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Margie Winn

Faculty Retreat, August 2019: (back row) Burkhard Militzer, Raymond Jeanloz, Barbara Romanowicz, David Romps, Doug Dreger, Daniel Stolper, Bill Boos, Richard Allen, Stephen Self, Harriet Lau; (front row) Bethanie Edwards, Michael Manga, Bill Dietrich, Roland Bürgmann, Kristie Boering

Back Cover Photo: Canyon in the making: Under guidance from Don DePaolo we studied the local geology of Arizona; at Grand Falls specifically the interaction between volcanic activity and the environment. A few million years ago a lava flow had filled in a small canyon, causing the diverted river to carve out a new canyon. EPS 119, supported by Charles H. Ramsden Endowed Fund, Spring 2019, GSI Chris Moeckel.

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