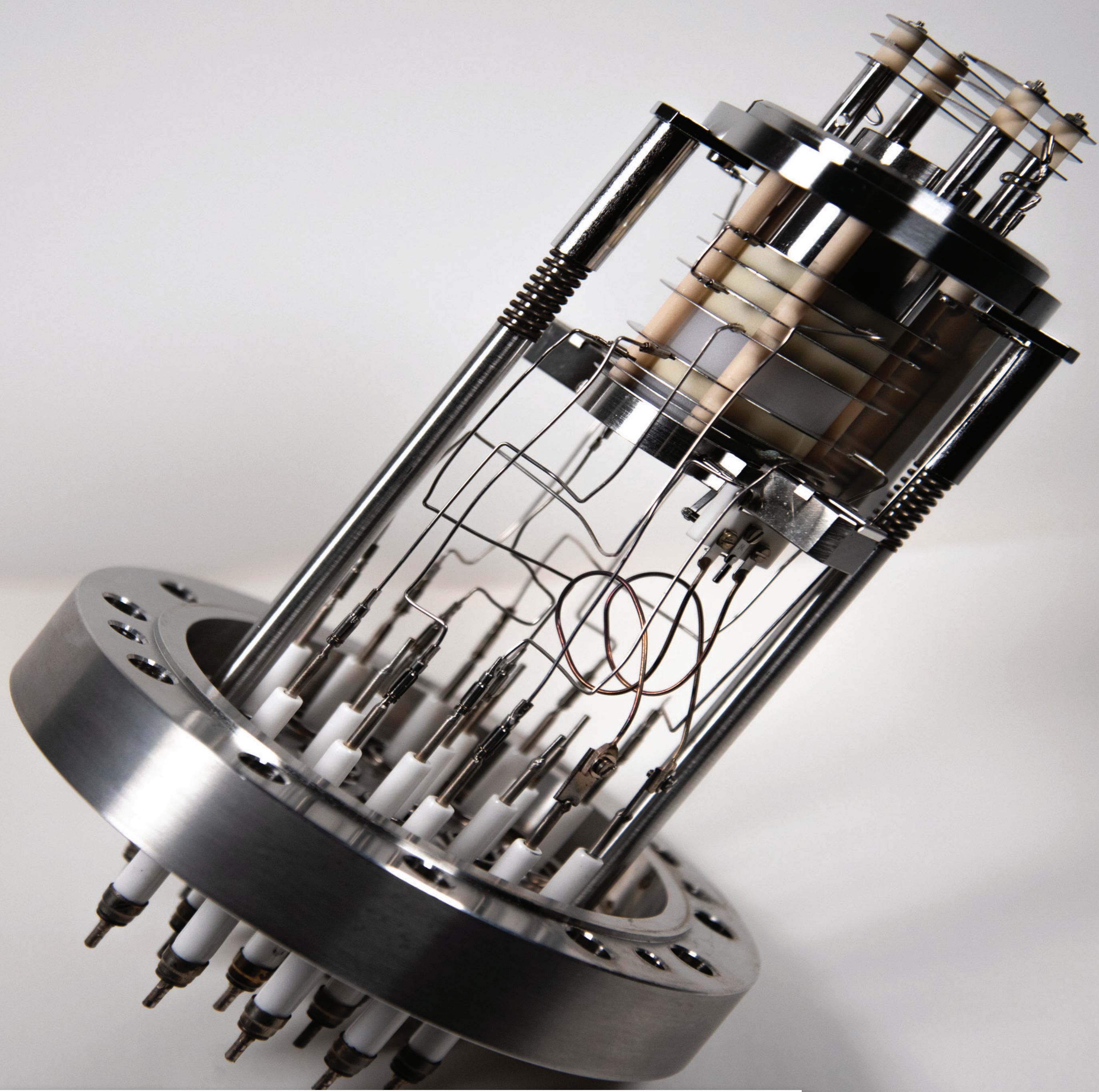
EARTH

DIVERSITY IN RESEARCH

AN OVERVIEW OF RESEARCH IN THE DEPARTMENT OF EARTH AND ENVIRONMENTAL SCIENCES



IMAGINATION CREATES NEW DISCOVERIES

DIVERSITY IN RESEARCH

Photmircograph of chalchedony (quartz) with calcite late emplacement of calcite cement. Photo Kacey Lohmann

DIVERSITY IN RESEARCH
A SPECTRUM OF INNOVATIVE SCIENCE

The research activity amongst the Department's faculty and students refects the integration of our expertise in both the Geological and Environmental Sciences. We are blessed by the strength of our faculty and the range of specialties that are applied to studies of deep time through application to contemporary problems with significant societal impact. These range from research in the physical processes of mountain building, earthquake propagation, and life's evolutionary patterns to studies of the impacts of melting permafrost and global recycling of mercury throughout the environment. While departing from the many classic studies in Earth History and Process, some of our research has evolved to focus on issues of impending climate change and human interactons with the environment. All continue to expand our fundamental knowledge of the Earth, its past, its present and all of which portends its future. In this issue we highlight the diversity of the Department's research and the people who guide it.

SEISMOLOGY

Research in the seismology group includes both observation- and computation-based studies. Our work relies on a spectrum of existing data streams, mainly seismic and geodetic data from the EarthScope Consortium, as well as collecting our own data using broadband seismometers and fiber-optic cables. We complement our observational work with theoretical studies, with an aim to determine the sensitivities of data, in addition to building computational simulations relying on high-performance computing. A theme across our group is imaging — imaging the interior of Earth, imaging the uppermost crust in volcanic or geothermal regions, or imaging earthquake processes — using earthquake generated seismic wavefields, the ambient vibrations of Earth (i.e., the seismic noise field), and static ground offsets. A large part of our research focuses on earthquake activity, from inferring properties of earthquakes, such as the stresses involved in earthquakes, to modeling earthquake rupture dynamics and the slow build-up of stress between the earthquakes. We also have research projects focussed on tsunamis, geothermal and volcanic systems, waterlevels in the Great Lakes, and even meteors. Most of our work is conducted within the geophysics lab by our graduate students, postdocs, and undergraduate researchers. The geophysics lab has plenty of room for impromptu chalkboard discussions, group meetings, and smaller discussions.

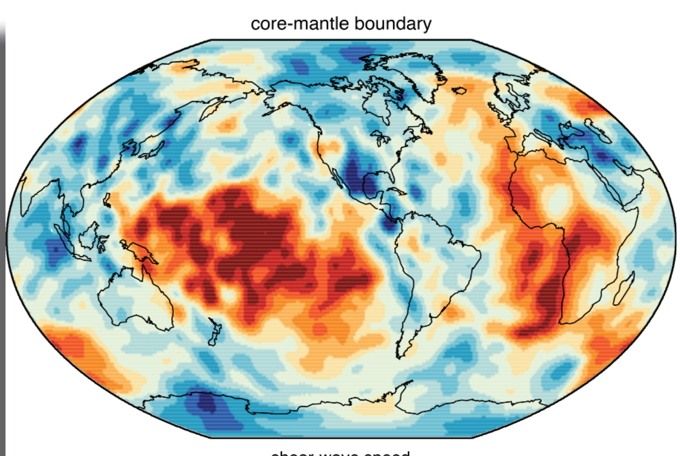
GEOPHYSICAL RESEARCH GROUP: Faculty and students that comprise the diverse Geophysical family (missing Eric Hetand)

EARTHQUAKE MECHANISMS
ASSISTANT PROFESSOR YIHE HUANG

Students in the Geophysical Research Laboratory utilize the excellent computational facilities available to this group of reseachers.

Our group studies the physical mechanisms of earthquakes and faulting processes using both observational methods (e.g., seismic data analysis) and numerical tools (e.g., earthquake rupture simulation). We're particularly interested in how fluid, fault zone structure and fault geometry can affect the nucleation, propagation and arrest of earthquakes and how earthquakes contribute to the strain budget and structural evolution of fault zones and plate boundaries. The ongoing research includes novel simulations of earthquake cycles in fault damage zones (graduate student Prithvi Thakur), stress drop measurement of the 2019 Ridgecrest earthquake sequence (graduate student Meichen Liu), imaging earthquake rupture using seismic data at frequencies below the bandwidth (graduate student Jing Ci Neo), relative magnitude calculation of small induced earthquakes (graduate student Sydney Gable), and physics-based simulations of tsunamis in the back-arc basin (postdoc Amir Salaree). We recently went out to the field and removed 8 seismic stations we deployed about 3 years ago. We're using the data to analyze small earthquakes around Lake Erie and understand their relationship with lake water levels.

SEISMIC IMAGING AND GLOBAL GEOPHYSICS
PROFESSOR JEROEN RITSEMA



eismic CAT scan of the lowermost mantle (2850 km depth) showing "large low shear velocity provinces" (LLSVPs) beneath Africa and the Pacific that may signify piles of relatively dense crustal fragments

My students and postdocs use seismic waves to study the structure and dynamics of Earth's mantle. In the past five years we pursued three directions of research. (1) We have applied seismic reflection techniques to seismograms from the USArray to measure the temperature of the mantle transition zone (400–800 km depth) beneath North America from estimated depths of mineral-phase transitions. We have mapped weak reflections off structures in the mantle transition zone that may have been oceanic plateaus on the Farallon plate. (2) Using seismograms from the Global Seismic Network we have studied wave scattering to trace fragments of relatively dense oceanic crust that are sinking in the lower mantle and stirred by global-scale flow. These fragments accumulate at the base of the mantle and currently form two piles beneath Africa and the Pacific that are thousands of kilometers wide and hundreds of kilometers high. (3) We have interrogated the quality of seismic tomography, including our own, using simulations and observations of wave focusing and diffraction. In detail, we have determined how well seismic waves can detect and resolve the geometry of conduits of thermal plumes rising from the deep mantle.

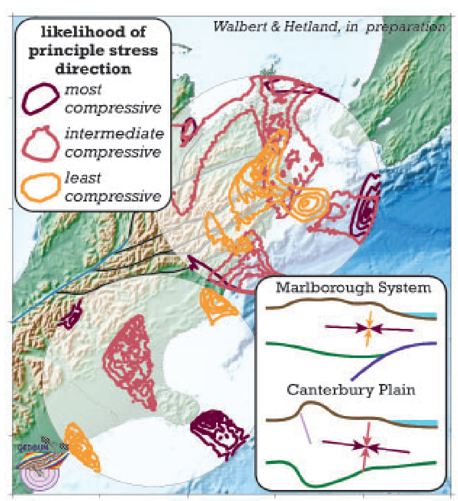
MAGMATISM-VOLCANISM AND SEISMOLOGY ASSISTANT PROFESSOR ZACH SPICA

Fiber Optic Cables become the new seismometer. Changes in backscattered light reflects how the fiber stretches and compresses in response to seismic waves.

Assistant Professor Zack Spica's research aims to gain a better understanding of the Earth via a combination of observational and interpretational work on seismic data. His research group is interested in imaging the Earth at every scale i.e., from the shallow subsurface to the deepest Earth interfaces such as the core mantle boundary, understanding volcanic and hydrothermal systems and predicting ground motion caused by earthquakes. His group is highly involved in a newborn seismological method called Distributed Acoustic Sensing (DAS) that turns fiber-optic cables into thousands of seismic sensors. The current research includes testing DAS technology for ocean-bottom exploration (graduate student Yaolin Miao), assessing non-linear seismic wave behavior on sedimentary basins (postdoc Loïc Viens), developing tools for urban seismic imaging using existing telecommunication infrastructures (graduate student Yang Li), monitoring and modeling environmental changes in mega-cities (postdoc Evgeniia Martuganova) and developing machine-learning algorithms for volcano monitoring (graduate student Leonardo van der Laat). His group is currently gathering DAS data with telecom ocean-bottom fiber-optic cable on the coast of Oregon, and plan to lead a large-scale experiment in Mexico City during winter 2022.

GEOPHYSICAL DYNAMICS OF NATURAL HAZARDS ASSOCIATE PROFESSOR ERIC HETLAND

Research in the Quantitative Earthquake and hazard Dynamics (QED@UM) group is rooted in the union of geodetic methods and computation, with a focus on earthquakes and volcanoes. Geodetic data measures offsets of Earth's surface, mainly with GPS and satellite-based radar measurements that are complemented seismological observations. We use these geodetic data to image the patterns of earthquake slip on faults and to probe the processes of strain accumulation on seismogenic faults. Three of the current projects we are most excited about include: (1) the development of a novel method to form a higher-level geodetic data product, (2) the inference of the stresses that have caused recent large earthquakes, and (3) building a computational method to investigate the conditions under which supervolcanic eruptions are possible. Former graduate student Trever Hines applied a machine learning technique called Gaussian process regression (GPR) to GPS data, and current graduate student Eric Szymanski (a DOD/NDSEG fellow) is extending the GPR analysis to fuse GPS and InSAR data into an estimation of time-varying surface strain-rates. Graduate student Olivia Walbert's efforts have been focussed on determining the seismogenic stresses in South Island, New Zealand and the Afar triple junction in East Africa. Former graduate student, and current postdoc, Meredith Calogero, has undertaken the challenging project of working with two advisors (me and Prof. Rebecca Lange) and developing a new computational tool, TIRAMISU (TRansient hIgh-Resolution pArtial MeltIng Simulation of the crUst). TIRAMISU is capable of capturing meter-scale transient melting over weeks to months, while still modeling a 30-50 km thick crust over several millions of years, all in a simulation that runs on a common desktop in hours. Meredith will be moving onto a new postdoc at Bayreuth University. In addition to these projects, numerous undergrads have contributed to an ongoing project to build mathematical models of loss in natural disasters, using a variety of data streams and a variety of natural hazard types.



Inferred orientation of seismogenic stresses in central and northern South Island, New Zealand, from recent large earthquakes.

ENVIRONMENTAL AND WATER SCIENCES

The isotopic and elemental chemisties of water are integrated proxies of earth surface processes, recording the interactions between the hydrosphere, atmosphere, and lithosphere. Research at Michigan encompasses all of these interactions with a focus on time frames of both deep -time as well as anthropogenically-induced changes. For example, the isotopic composition of Hg illuminates the pathways for cycling through the atmosphere and hydrosphere as well identifying the source of such contamination. Application of noble gas contents and isotopic composition elucidate sources of subsurface fluids and their interactions with the lithosphere. The role of photochemical reactions with dissolve organic constituents highlights the magnitude of greenhouse gas emissions that are produced today and will be in future times. All enlighten our understanding of real-time processes impacting Earth's present and future.

ENVIRONMENTAL BIOGEOCHEMISTRY
PROFESSOR JOEL BLUM

Joel Blum's research has contributed to knowledge of the geochemistry and environmental chemistry of metals, nutrients and climate change. Most recently he has focused on understanding the biogeochemistry of the elements mercury, lead and arsenic in atmospheric, aquatic and terrestrial systems utilizing new methods developed in his laboratory. Most notably, Blum and co-workers developed a technique for high precision measurement of mercury stable isotope ratios using inductively coupled plasma mass spectrometry. In addition to mass dependent isotope fractionation, they documented several unprecedented patterns of mass independent isotope fractionation caused by the magnetic isotope effect and the nuclear volume effect. His research group experimentally calibrated the isotope fractionation due to a wide range of biotic and abiotic oxidation-reduction reactions and used these isotopic patterns to explore mercury chemistry at the isotopic level. This has led to advances in understanding of mercury biogeochemistry in the atmosphere, oceans, lakes, rivers, forests, soils, rocks, ore deposits and meteorites.

Joel Blum in the Sierra Nevada Mountains where he studies mercury contamination from history mining activities.

As an example, one recent study published in The Proceedings of the National Academy of Sciences applied the mercury isotope technique to explore the oxygenation of the Earth's atmosphere. The atmosphere became oxygenated around 2.4 billion years ago, and this event was preceded by at least one short-lived "whiff" of free O2 gas nearly one hundred million years earlier. The cause of this "whiff" has so far been difficult to identify. Blum and his collaborators measured mercury concentrations and isotope ratios across the "whiff" interval and found evidence for significant subaerial volcanism immediately preceding oxygenation. They proposed that subaerial weathering of fresh volcanic rocks acted as a fertilizer that stimulated biological productivity and O2 production in the surface ocean. This research result points to a strong linkage between planetary magmatic processes and the evolution of Earth's atmosphere.

GEOHYDROLOGY: NOBLE GAS GEOCHEMISTRY
PROFESSOR CLARA CASTRO

Clara Castro's research group and her collaborators have been using noble gases to tackle a diversity of issues concerning freshwater and geothermal reservoir management as well as paleoclimate reconstructions. They have also been using noble gases to clarify aspects related to the magmatic and tectonic evolution of regions holding major hydrocarbon reservoirs as well as reconstructing the migration history of natural gas in these systems.

Noble gases have been used for decades in sedimentary systems to identify freshwater sources, groundwater flow paths and to take advantage of their temperature dependence to reconstruct the evolution of past climate. However, their behavior remains poorly understood in fast infiltration systems, e.g., plutonic or volcanic fractured rocks as well as karst. As a result, she and Dr. Chris Hall, together with USGS collaborators have been studying the behavior of noble gases in the volcanic freshwater systems in Maui, Hawaii. To understand the behavior of noble gases in these systems, they have been studying the composition of noble gases in different forms of precipitation, including rainwater and snowfall. To complement these studies, they began looking at the composition of noble gases in liquid cloud water, which is the fog-like component within clouds. Currently, they are studying the noble gas composition of samples collected from Pico del Este, a coastal tropical rainforest in Puerto Rico, and samples from a humid temperate forest in the Shenandoah National Park, Virginia. Fog and cloud water commonly account for a significant portion of recharge occurring in these groundwater systems. This study is showing that noble gas patterns observed in small water droplets are similar to those found in some rapid infiltration groundwater systems, which significantly diverge from patterns commonly observed in sedimentary systems. This, in turn, has major implications for paleoclimate reconstructions based on groundwater noble gas temperatures.

Automated system for the extraction of noble gases from waters and natural gases was developed in in the Noble Gas Laboratory at the Universiity of Michigan.

Through a collaboration with colleagues at the University of Quebec at Montreal, Canada and the University of Morelia, Mexico, Clara's research group has also been studying all the major Mexican geothermal reservoirs. Currently, they are looking at the noble gas signatures at the Los Humeros reservoir, located in the Central Mexican Volcanic Belt to identify the different sources of fluids present as well as the impact of recharge water for sustainable, long-term exploitation. Los Humeros is the most recent geothermal field in Mexico undergoing significant development. It is also the hottest field in the country, with reservoir temperatures reaching 380-400˚C.

Finally, they have also been studying major unconventional and conventional hydrocarbon production systems in the United States. In particular, the Eagle Ford Shale system in Texas through a collaboration with colleagues at the Bureau of Economic Geology (BEG) and the giant Texas Panhandle gas field in collaboration with Texas Tech University. In these studies, they are using noble gases to reconstruct both the tectonic history of the region within the context of continental scale evolution and the maturation and migration history of these systems, which remain poorly understood.

AQUEOUS BIOGEOCHEMISTRY
ASSOCIATE PROFESSOR ROSE CORY

We study how sunlight influences freshwater greenhouse gas emissions and freshwater quality. Our work has shown that sunlight-driven (photochemical) processes account for a substantial amount of the greenhouse gases emitted from arctic rivers and lakes. That's important to know because current estimates are that 5–15% of the tremendous pool of carbon stored in permafrost soils could be emitted as greenhouse gases by 2100 given the current trajectory of climate change, resulting in an additional one third degree Celsius of global warming everywhere on Earth, not just in the Arctic. My recently graduated Ph.D. student Jenny Bowen (PhD '21) showed for her thesis work that climate model predictions of future greenhouse gas emissions from the rapidly warming Arctic may be too low by at least 14% because they do not include the greenhouse gases produced from photochemical processes in arctic lakes.

To make this discovery, Jenny worked with one of my former students (Dr. Collin Ward, now a scientist at WHOI), using a new system of LED he invented to identify and mimic specific wavelengths of sunlight responsible for the greenhouse gas production. Sunlight initiates a rainbow of reactions in natural waters. Knowing which wavelengths (colors) of ultraviolet or visible sunlight are responsible for greenhouse gas production is critical for quantifying this process on a landscape scale (i.e., from all arctic lakes during the ice-free summers). Jenny found that even relatively low energy (longer wavelengths) of visible sunlight can convert permafrost organic carbon into carbon dioxide (a greenhouse gas), in arctic freshwaters. This discovery included the first ever measurements of the radiocarbon age of the carbon dioxide produced from photochemical (sunlight-driven) processes, and it settled a debate on whether sunlight can convert ancient organic carbon into carbon dioxide.

My group also studies how sunlight influences water quality in the Great Lakes. Thanks to sunlight, all surface waters on earth are awash in reactive radicals and oxidants like hydrogen peroxide (at much lower concentrations than in the average medicine cabinet). We are testing the idea that toxin-forming harmful algal blooms may be due in part to radicals like hydrogen peroxide. So far, the results are mixed. Field data collected from Lake Erie support the idea that hydrogen peroxide may influence the abundance of toxin-forming algal blooms, but our lab data suggests other factors are at play (e.g., nutrient chemistry, etc).

***Jenny Bowen (PhD '21)** completing sample extractions in the lab to extract CO_2 for radiocarbon analysis*

EARTH MATERIALS AND THE SOLID EARTH

We combine field and laboratory work to understand the origin and evolution of Earth's crust, mantle and core and the chemical differentiation within and among each of those reservoirs. Ongoing projects include the evolution of volcanic systems in subduction zone environments and hot spots, the chemical connections between the mantle and the volcanic arc in subduction zones, mantle mineralogy, the dynamics of core-mantle interaction, the volatile history of Earth's moon, the formation of mineral deposits, and the evolution of the Martian mantle. From the building blocks of rocks, the minerals, to evolution of planetary bodies such as the Earth, Moon and Mars, our research ranges from the structure of crystals, the emplacement of ore bodies and magmas, to the formation of planets -- from the finest to largest scales.

ECONOMIC GEOLOGY: MINERALS AND MINING
PROFESSOR ADAM SIMON

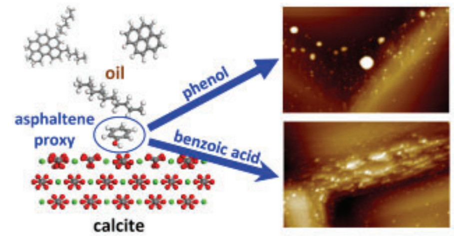
Adam Simon (Professor) and his lab family continue to investigate the origin of mineral systems by combining analytical, field, and experimental studies. We are working on natural systems in Australia, Canada, Chile, China, Namibia, Peru, Sweden, and the United States, in collaboration with academic and industry partners. The focus of our work is to understand the origin of two spatially and temporally related mineral systems: iron oxide - copper - gold deposits and iron oxide - apatite deposits. These deposits are important sources of their namesake metals as well as many others that form the backbone of our built environment. There is no consensus on how these deposits form, despite more than one hundred years of study. Our group, in collaboration with academic partners at the Universidad de Chile led by EARTH alumnus Martin Reich, developed a novel genetic model that explains the formation of these mineral systems and explains their spatial and temporal relationship. We have published twenty-three papers on these systems in the past six years and are now writing invited review papers that summarize our work.

Adam Simon *doing field work in Puerto Rico with* ***Laura Bilenker*** *(PhD '15, Asst. Prof. Auburn University) and* ***Tom Hudgins*** *(PhD '15, Assoc. Prof. Univ. Puerto Rico).*

We began a new collaboration with scientists at the German Research Centre for Geosciences to conduct experiments designed to equilibrate the mineral apatite with hydrothermal fluids over a range of redox conditions where the element sulfur transitions from sulfide to sulfite, including intermediate redox conditions where both species co-exist. This work is a continuation of our research that developed a sulfur-in-apatite oxybarometer applicable for magmatic systems, which we extended this year to included evolved dacitic silicate melt.

Adam continues to do research in the social sciences, working with colleagues from the UM School of Education and School for Environment and Sustainability to study pedagogical approaches and their impact on learning outcomes for courses taught by two faculty from different disciplines. This research demonstrates that having faculty from different disciplines, e.g., earth science and public policy, with fully integrated course content improves the student experience and measured learning outcomes. Adam started a new research project with collaborators in Morocco that involves UM undergraduate students who will work with Adam to assess sustainability initiatives and capacity building through the lens of multicultural, interfaith coexistence, particularly surrounding the historically Jewish mellahs of Fes, Marrakech, Essaouira, and Tangier, as well as the Benedictine Monastery at Toumliline, Azrou with the people who call(ed) these places home. Adam joined EARTH alumni Laura Bilenker and Tom Hudgins for field work in Puerto Rico and began a collaboration with new faculty member Robert Holder and lab family members Maria Alejandra and Daniel Blakemore to develop a micro-beam analytical method for quantitatively determining the age of magnetite crystallization.

COMPUTATIONAL AND ENVIRONMENTAL MINERALOGY
PROFESSOR UDO BECKER



Almost all environmentally relevant reactions in nature or in technical applications that involve minerals are surface or interface reactions. Be it crystal growth, adsorption reactions, mineral dissolution, redox reactions, or even the growth of crystallites from the melt, the actual reactions take always place at mineral surfaces. This is one reason why I got started to analyze the atomic and electronic structure, the chemistry and reactivity of mineral surfaces. In addition, over the last 20 years, a number of surface-sensitive techniques has been developed to image and analyze surfaces with up to atomic resolution. Thus, it is possible now to resolve reaction mechanisms step by step without relying too much on hypotheses. Furthermore, we can calculate some of these reactions at a quantum mechanical level. This way, it has become much more satisfying to understand environmental reactions, predicting these, or optimize certain reaction types for technological applications or remediation purposes. Among the projects that we are working on right now are: 1) the oxidation of sulfide surfaces that plays a role in acid mine drainage and the release of heavy-metal ions; 2) the adsorption and reduction of noble metal atoms on sulfide surfaces and the role that dopant ions (e.g., arsenic) and surface diffusion play to form nanoparticulates of these metals; 3) the role of the atomic and electronic structure of oxide surfaces (e.g., hematite) in redox reactions such as the adsorption of manganese which may play a role in the purification of drinking water; 4) the structure and stability of TiO_2 nanoparticules; 5) the adsorption of pesticides on clay particulates; 6) the role of jarosites as a secondary mineral for the storage of heavy-metal ions in open mine pits; 7) biomineralization processes as they occur in the growth of bones, teeth, and organisms such as coccolithopores; 8) the calculation of the thermodynamics and ordering processes in solid solutions such as sulfates (for example barite-celestite or barite hashemite) and carbonates oscillatory zoning in garnets; and 9) magnetic ordering in iron and iron-titanium oxides. Lately, we are reolving changes in oil vs. water weeting of carbonate minerals using comptations methods and atomic force microscopy (see attached image).

Photomicrograph of high-SiO_2 rhyolite from the Benton Range dike swarm in California. Photo by Juliana Mesa

EXPERIMENTAL PETROLOGY, MAGMATISM AND VOLCANISM
PROFESSOR BECKY LANGE

Becky Lange's research interests address how magmatism and volcanism have shaped the evolution of the solid Earth. This includes an interest in the rate and mechanism by which continental crust forms at subduction zones, which has taken her research group to the Mexican Volcanic Arc, where they have documented eruption rates, the proportions of different erupted magma types and the role of water in creating the unique compositional character and stratification of continental crust. Most recently, she and her students, in collaboration with geophysics faculty colleague, Prof. Eric Hetland, have been addressing the origin of high-SiO2 rhyolites (≥76 wt% SiO2), the most differentiated silicate magmas on Earth. An outstanding question is why they are so scarce at subduction zones (both as a plutonic and volcanic whole-rock composition) and yet erupt in super-volcano quantities (~100-1000's km3) in regions of continental extension. For example, in the last 1 Myr, two caldera-forming eruptions have occurred in the Basin & Range province of the western United Sates (~600 km3 Long Valley, CA; ~1000 km3, Yellowstone, WY).

In our collaborative work funded by NSF, recent Ph.D. graduate Meredith Calogero (headed to Bayreuth, Germany for a postdoc) is quantitatively modeling the mechanisms and timescales for the transfer of heat and volatiles from basalts injected into granitoid crust over high-resolution spatial (≥1 m) and temporal scales (≥ 1 day). We are paying particular attention to the role of pre-existing aplite dikes (only occurrence of high-SiO2 rhyolite in granitoid batholiths) in facilitating the rapid segregation and transport of interstitial melts from host granitoid and newly emplaced basaltic sills and dikes. Another recent Ph.D. graduate, Juliana Mesa, has documented the only known occurrence of a high-SiO2 rhyolite dike swarm (where average dike widths are ~2-3 m and thus meet critical-width criteria) that records crustal-scale transport (~10 km) of these viscous magmas (similar to creamy peanut butter) within a week or less.

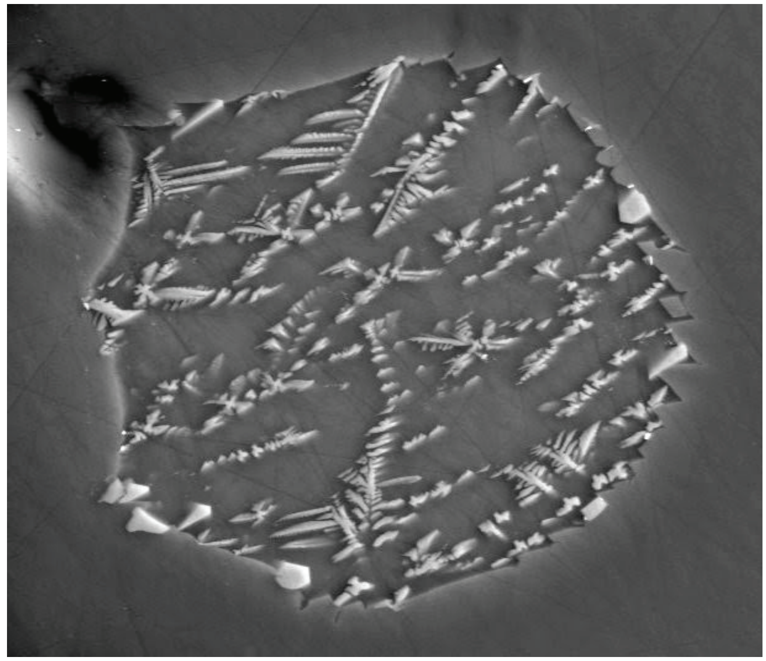
Other recent and current Ph.D. graduate students (James Jolles, Sarah Brehm, Bryanne Gordon, Maddie Frank) have been/are applying high-resolution thermometry and hygrometry to the Long Valley rhyolites (Bishop Tuff, Glass Mountain obsidians, etc.) as well as to basalts from across the entire western United States and Hawaii. Recent Ph.D. graduate Xiaofei Pu (now Research Scientist at Idaho National Laboratory) experimentally calibrated a brand-new olivine-melt thermometer/hygrometer, which enables both the temperature and melt water content at the onset of phenocryst growth (during rapid ascent along fractures) to be determined. Our group also makes extensive use of Laura Waters' (past Ph.D. student; now Assistant Professor at New Mexico Tech) updated plagioclase-melt thermometer/hygrometer.

Becky's research group is also actively involved in measuring the density and compressibility (via sound speed measurements) of multi-component silicate and carbonate liquids. Most recently, she has been collaborating with Dr. Aaron Wolf and Prof. Jackie Li on a co-funded NSF project to determine the thermodynamic properties of multi-component carbonate liquids at high pressure, which is needed to fully constrain the role of carbon cycling in the deep Earth. Recent Ph.D. graduate Sean Hurt (now Assistant Professor at Del Mar College, TX) worked with Aaron Wolf on computational models of carbonate melt structure and with Becky on density and sound speed (compressibility) measurements.

Becky Lange with undergraduate students on field trip to Long Valley caldera and Yosemite National Park.

EXPERIMENTAL PETROLOGY, TERRESTRIAL AND EXTRA TERRESTRIAL GEOCHEMISTRY PROFESSOR YOUXUE ZHANG

Professor Youxue Zhang's current research focuses on two directions: one is on multicomponent and isotope diffusion in silicate melts, and the other is related to volatile abundances in the Moon and degassing of lunar volcanic rocks.



Backscattered Electron image of a melt inclusion in Olivine..

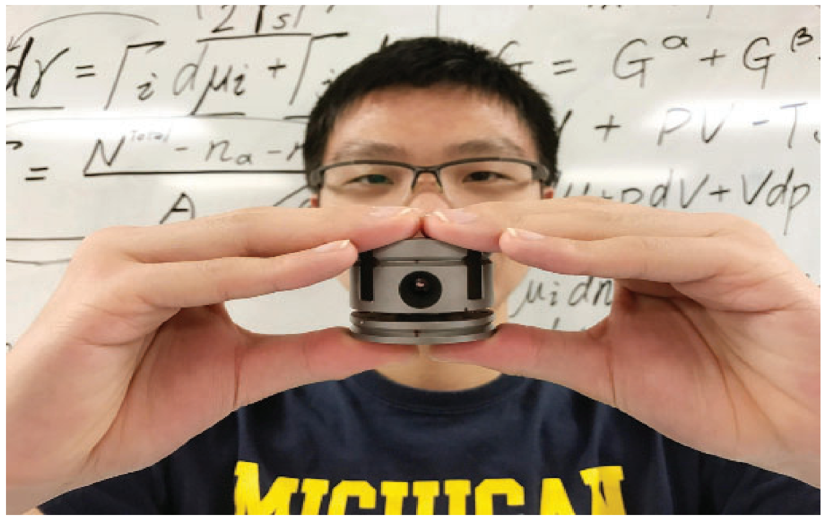
Magmas are complicated multicomponent systems, and diffusion in them is not well understood or quantified. Previous studies mostly focused on effective binary diffusion, meaning the consideration of the diffusion of one component relative to other combined components, without trying to understand how the diffusion of this component would affect other components, or how the diffusion of other components would affect this component. The effective binary diffusion treatment ignores the many oxides that display complicated diffusion behavior. Our study aims to understand and quantify the chemical diffusion of all major components together. We have overcome difficulties and developed new concepts along the way. We are now able to roughly predict the diffusion of all components in a basaltic melt. In addition, we are pushing for the use of Secondary Ion Mass Spectrometry to measure nontraditional stable isotope ratios in our diffusion samples. The data and modeling allow us to predict diffusive isotope fractionation in nature. Such fractionation has various applications. For example, potassium isotope fractionation may affect K-Ar ages slightly, important in high-precision dating. The isotope diffusion data also provide a new dimension to look at diffusion, and hence may reveal new insights on diffusion in silicate melts.

In the pursuit to determine abundances of volatile elements (such as H, F, Na, S, Cl, K, etc) in the Moon, water is one of the main targets. Even though there is no liquid water on the Moon, recent studies have led to a paradigm shift from a bone-dry Moon to a fairly wet Moon. Some mantle-derived lunar rocks have been shown to contain significant amount of water, up to 0.14 wt% at the time of eruption. Because lunar surface is essentially a vacuum, lunar volcanic rocks lost most of the volatiles after erupting to the lunar surface. Hence, the trick is to estimate the pre-eruptive concentrations of volatiles. The method we employ to investigate water and other volatiles in the Moon is to measure their concentration in mineral-hosted melt inclusions. A melt inclusion is a small pocket f melt (the ones we investigated are 0.011 to 0.10 mm in diameter) captured by a growing crystal. The host crystal provides some protection against loss of volatiles from the melt inclusions, meaning that the measured concentrations more closely represent preeruption levels. Naturally glassy melt inclusions are the best samples for the study because they quenched rapidly and hence preserve pre-eruptive concentrations of volatiles the best. Our study has allowed us to infer that the extent of water loss from the Moon is much smaller than previously thought, which prompted new classes of the giant impact hypothesis. In addition, our studies also show that the Moon is depleted in different volatiles (such as water and potassium) relative to the Earth by a similar factor, regardless of their condensation temperature. A late veneer that contributed less to the Moon than to the Earth might be able to explain the observation.

MINERAL PHYSICS AND THE DEEP EARTH
PROFESSOR JACKIE LI

Jie Li's research group specializes in investigating the behavior of planetary materials under extreme conditions and exploring the influence of material properties on the thermal and chemical evolution of Earth-like planets. Their current work seeks to understand planetary differentiation through melting and freezing, the origin and evolution of core dynamos in Earth-like planets and moons, and the role of volatile elements in planetary evolution and habitability.

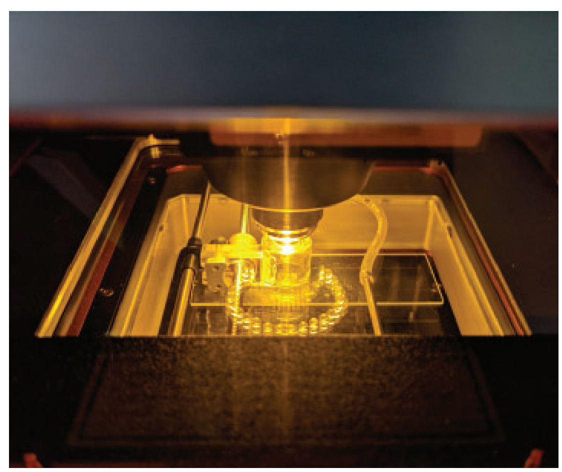
The group studies Earth and planetary materials under high pressures and high temperatures using multi-anvil apparatus, diamond-anvil cells, micro-analytical instruments, and synchrotron radiation facilities. To infer the nature and dynamics of the most inaccessible parts of our planet, they combine results in experimental geochemistry and mineral physics with seismic observations, cosmochemical constraints, and dynamic models. Their overarching scientific goal is to understand the origin and evolution of terrestrial planets, terrestrial-like moons and asteroids in the solar system.



Junjie Dong, *a senior student, holds a diamond anvil cell, which enables researchers to simulate Earth's extreme ranges of pressure and temperature in the laboratory. He is now pursuing his PhD at Harvard University.*

GEOCHRONOLOGY OF EARTH SYSTEMS
ASSISTANT PROFESSOR ROBERT HOLDER

Professor Holder's research combines innovative analytical approaches to geochronology (particularly LA-ICP-MS) with petrology, mineralogy, high-temperature geochemistry, field work, and numerical modeling. This research strives to understand the evolution of Earth's continents by constraining the time scales, length scales, and magnitudes of heat and mass transfer in the crust. Driving questions of my research include: What are the timescales and drivers of metamorphism—particularly at extreme temperatures and pressures—and what do they reveal about plate tectonics and the evolution of orogenic belts? When and how did modern plate tectonics develop? How did tectonism change over Earth's history? What processes are recorded by geo- and petrochronometers, including the U–Pb system in zircon, monazite, titanite, and carbonate rocks and minerals? Previous field seasons have been carried out in Norway, Madagascar, Austria+Czech Republic, southwestern USA, upper Midwest USA, Southern Victorialand (Transantarctic Mountains), Scotland+Shetland, and Maryland USA. This research effort is facilitiated by the recently establishment of the Geochronology Laboratory developed in 2020.



Laser ablation chamber that is couple to a ICP-MS utilized for geochrological determinations.

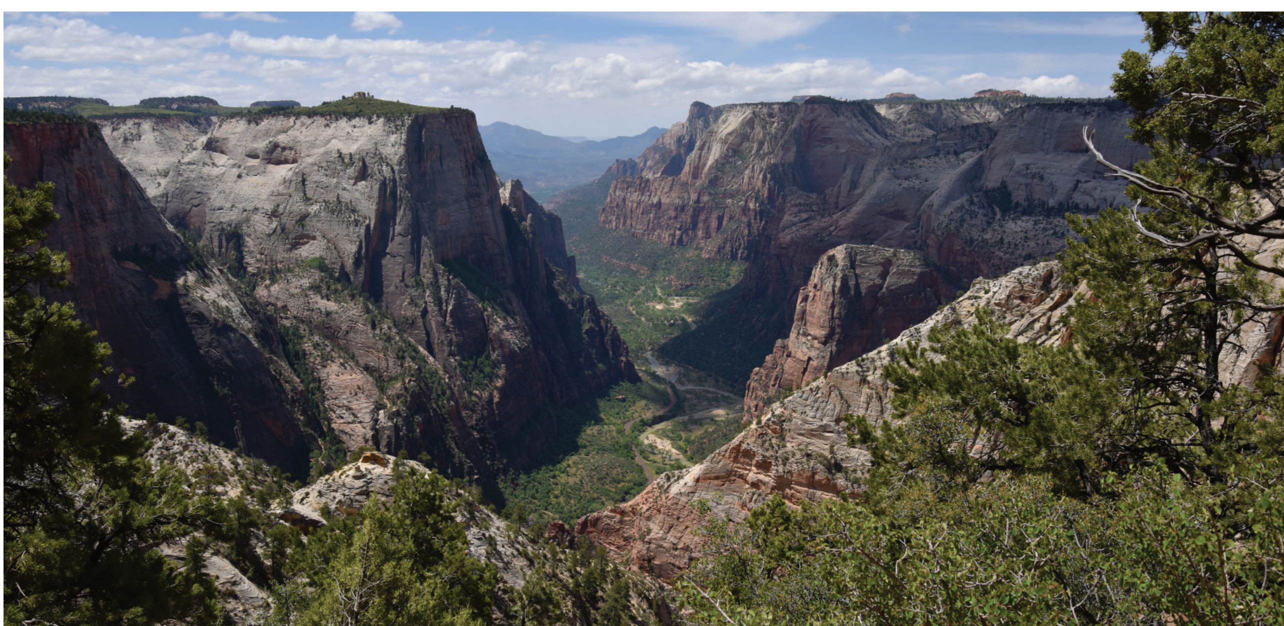
TECTONICS, STRUCTURE AND EARTH HAZARDS

Structural geology and tectonics focus on the manifestation of plate tectonic motions in the deformation of Earth's crust and lithosphere, from the scale of mountain ranges to individual faults and folds, and on timescales from deep Earth history to present-day tectonism and associated natural hazards. Active research projects at the University of Michigan circle the globe and include Canada, the western United States, the Middle East, Nepal, Tibet, and New Zealand.

CRUSTAL DEFORMATION AND SOCIETAL RESILIENCE
PROFESSOR BEN VAN DER PLUIJM

Battle Mountain near U-M's Camp Davis field station is an example of the last (Eocene) orogenic pulse of the US and Canadian Rocky Mountains, exposing Mesozoic sandy shales of the hangingwall of the Prospect Thrust.

Ben van der Pluijm works in the areas of structural geology and societal resilience. With graduate students, postdocs and colleagues, he has worked on Appalachian paleogeography and Grenville orogenic architecture, and, in more recent years, his group has increasingly focused their attention on fault zone geometry, fault rock dating and the fluid history of crustal fault systems. For example, work on fault gouges in the US and Canadian Rockies shows discrete orogenic pulses of fault activity, separated by longer periods of relative tectonic quiescence. Other studies combine clay dating with orogenic fluid fingerprinting through a combination of chronology and geochemistry of clays. These studies show the surprisingly large dominance of surface fluids over deep-sourced fluids in upper crustal faults. These research projects are typically field-oriented, with laboratory tools that include microscopy, rock magnetism, geochronology and geochemistry. A parallel interest area is US-oriented data science of societal resilience to environmental change and geohazards. These one-year topical studies are carried out with undergraduate students; example projects are Great Lakes water levels, anthropogenic earthquakes and landfall of hurricanes.



Zion National Park, Utah. Photo by Kacey Lohmann

TECTONICS AND CONTINENTAL DEFORMATION
PROFESSOR NATHAN NIEMI

Our research group studies continental deformation over timescales ranging from decades to tens of million years, with a particular interest in intracontiental deformation, including how such deformation is governed over geologic timescales by geodynamic driving forces, as well as the hazards posed by the complex, diffuse, and relatively "slow" fault systems that characterize such deformation. We rely heavily on field observations in our research, including geologic mapping, stratigraphy, and structural observations, as well as low-temperature thermochronometric data collected in the Michigan Helium Thermochronometry Laboratory (HeliUM) that reveal shallow crustal processes associated with faulting and land surface processes.

Nikolas Midttun (Ph.D. student) *mapping Eocene sedimentary strata of the Titus Canyon Formation in Titus Canyon, Death Valley National Park. These strata record the earliest phase of Basin and Range extension in the western United States and provide insight into the geodynamic drivers of intracontinental deformation.*

We collaborate with researchers within the department and around the world to bridge our work in tectonics with other fields, including co-seismic landsliding and hazards (**Marin Clark**), geochronology of fault gouge (**Ben van der Pluijm**), isotopic proxies for paleoclimate and paleotopography (**Kacey Lohmann, Sierra Petersen, Ben Passey, Naomi Levin, and Nathan Sheldon**), remote sensing analyses of co-seismic deformation (**Eric Hetland**) and tectonic drivers of biological diversification and evolution (**Catherine Badgely**). We also work with collarborators around the United States, and in places as diverse as New Zealand, China, and Azerbaijan.

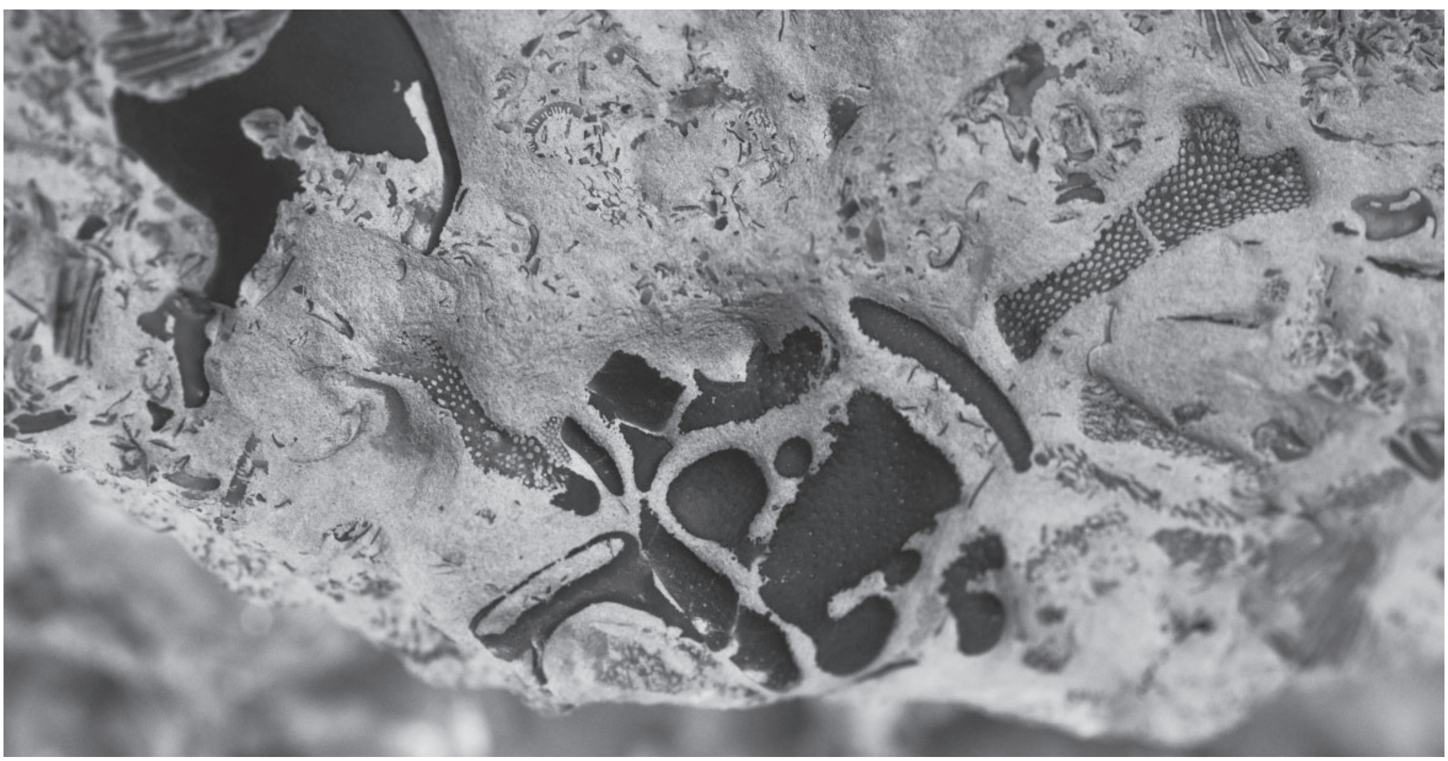
Two ongoing projects that we are particularly engaged in are in the Basin and Range of the western United States, and in the Greater Caucasus Mountains, spanning Azerbaijan, Georgia, Armenia and southern Russia. In the western U.S., we are undertaking detailed mapping, stratigraphic, and geochronologic studies to delineate the tectonic evolution of Eocene sedimentary basins that record the earliest phases of Basin and Range extension. We are interested in understanding the spatial and temporal patterns to the onset of this extension to discriminate potential geodynamic driving forces, understand the evolution of paleotopography, and relate this to biological diversification in the the Intermountain West.

Alex Tye (Ph.D. '19) *on the slopes of Babadağ in the eastern Greater Caucasus of Azerbaijan. These deformed marine strata record deformation of a subaerial accretionary prism above an active subduction zone between the Black and Caspian seas.*

In the Greater Caucasus, we believe we have identified a unique opportunity to study the transition from active oceanic plate subduction to nascent continental collision along-strike in a single mountain range. This geologically fleeting phase of tectonism must occur in all collisional orogens, but we understand little about how changes in plate boundary forces during this transition impact fault system dynamics, sedimentary basin development and landscape evolution. Studies of an active plate boundary transitioning from subduction to suturing will shed light on the evolution of orogens globally.

GEOBIOLOGY AND PALEONTOLOGY THE ROLE OF LIFE IN EARTH PROCESSES AND HISTORY

Geobiology is the study of how life and Earth interact and co-evolve, both in the present-day and throughout Earth history. Thus, this research includes investigations of the rock record and modern ecosystems, including analogues of past environments. Geobiology and paleontology involve field work, computer analysis and modeling, and laboratory-based experiments to examine mechanisms through which organisms interact with their environment. Examples of active geobiology research at Michigan include examining the development of global biogeochemical cycles, exploring how Banded Iron Formations and other chemical sediments record evidence of Precambrian microbial metabolisms, reconstructing the composition of the atmosphere during key periods of biologic innovation, studying the ecological and environmental causes of toxic cyanobacterial blooms, interrogating the bioavailability of geologically-derived heavy metals in the environment, and investigating the microbiology, biogeochemistry, and sedimentology of microbial mats that are analogues of Precambrian 'mat world'. The fossil record documents interactions between life and planet over geological timescales. Paleontological research in EARTH is closely linked to the U-M Museum of Paleontology, an internationally significant collection of over 3 million fossil specimens and associated support personnel and facilities. U-M paleontologists conduct field-, lab-, and collection-based research to investigate the relationships and environmental implications of fossil plants, evolutionary radiation in aquatic vertebrates, the systematics of Mesozoic reptiles, links between topographic relief and diversification, and paleobiology and extinction of Pleistocene megafauna.



Fossiliferous Upper Ordovician limestone from Ohio contianing trilobites, bryozoa crinoids and fragmented brachiopods. Photo by kacey Lohmann

GEOMICROBIOLOGY: GENOMICS AND BEYOND
PROFESSOR GREG DICK

Microorganisms have dominated the history of Earth, playing an intimate role in shaping its chemical and physical properties. They continue their role as agents of biogeochemistry today as microbes drive a wide range of processes, including the cycling of elements and responses to global change that impact water quality and sustainability. My research interests are focused on this interplay between the biosphere and the geosphere, examining how microbes drive geochemistry and how geochemistry in turn shapes microbial diversity, metabolism, and evolution. Many biogeochemical cycles are actively driven by genetically encoded molecules that are often carefully regulated to be produced only under certain environmental or physiological conditions. Thus, dynamics that take place on molecular scales can help us to understand global biogeochemical cycles. As such, my research relies heavily on molecular-biological approaches that are closely coupled with geochemical approaches to achieve an integrated view of geomicrobiology.

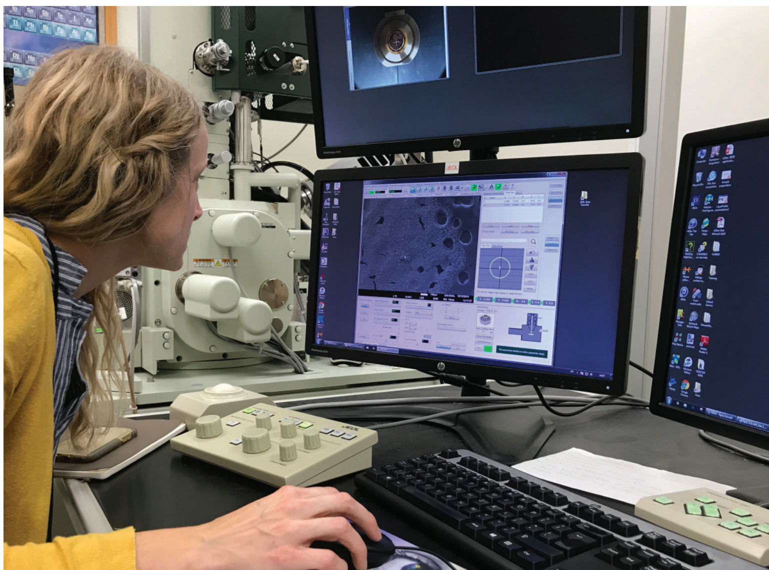
Collection of Lake Eire waters as part of Great Lakes cyanobacterial toxic bloom project.

Current and past research projects include: 1) Field and laboratory studies of toxic cyanobacterial blooms in the Great Lakes; how do the environmental and ecological interactions shape the development and toxicity of cyanobacterial blooms? 2) Biogeochemistry and microbial ecology of modern cyanobacterial mats as analogues of Precambrian "mat worlds"; how do microbial metabolisms and interactions influence ecosystem outcomes such as oxygen production? 3) Diversity and function of microbial communities in deep-sea hydrothermal plumes; how do microorganisms gain energy from deep-sea hydrothermal systems, and how do their metabolisms affect vent and ocean geochemistry?

Diver installing collection cylinders to cyanobacterial mats in Lake Huron. Recent work suggests that changes in day length may have contributed to the early oxygenation of the Earth's atmosphere. (Klatt, J.M., A. Chennu, B.K. Arbic, B.A. Biddanda, D. deBeer, and G.J. Dick (2021), Role of planetary rotation rate in benthic O2 export and Earth's oxygenation, Nat. Geosci. 14, 564–570).

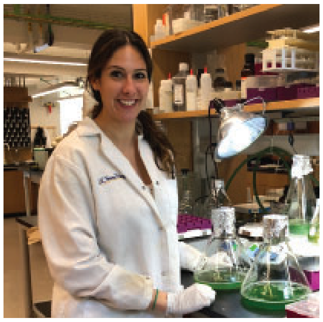
MINERAL SIGNALS OF EARLY LIFE
ASSISTANT PROFESSOR JENA JOHNSON

The Microbe Mineral Lab (MML), led by Jena Johnson, seeks to constrain how ancient life and our planet's surface geochemistry co-evolved over the first half of Earth history. Evidence suggests that life was present on early Earth, but these microscopic organisms are rarely preserved. Instead, we find signals of life through the chemical processes that organisms mediate, such as in their metabolisms. Our lab identifies early minerals from the Precambrian sedimentary rock record and ascertains whether these phases document specific biogeochemical processes through experiments simulating Precambrian environments and potential metabolisms. We apply micro-to-nanometer scale imaging (scanning and transmission electron microscopy) and cutting-edge spectroscopic (primarily Raman and X-ray) analyses to experimental products and rock samples to discover the relationships between microbial activities, precipitate chemistry, and primary minerals in the rock record. Our work ultimately aims to translate minerals into metabolic indicators to produce a novel record of biological development and metabolic evolution.



Chemical precipitates accumulated from the oceanic water column are the best prospect for discovering evidence of ancient marine life. The most prominent of these chemical sedimentary rocks in the early ocean are the quintessential iron- and silica-rich rocks of the Precambrian Era: Banded Iron Formations (BIFs). Geologists have been perplexed for centuries by how these peculiar rocks once formed since our modern oxygenated Earth does not host any environment that forms BIF-like mineral assemblages. Long interpreted as indicating a lack of atmospheric oxygen, the widespread and prolonged deposition of BIFs for the first two billion years of Earth's history may also signal that iron fueled the principal metabolisms of life before oxygen. To determine if iron-based metabolisms flourished in the early ocean, we need to ascertain the original iron minerals in BIFs and establish what (bio)geochemical processes can mediate their formation. Recent discoveries of early--potentially even primary--iron silicates in BIFs has prompted our MML group to actively test multiple hypotheses about how BIF iron silicates could have formed.

Over the past year, all of us in the Microbe-Mineral Lab have really enjoyed getting back into the lab and working alongside each other again. Chrissie Nims (MS'21) successfully completed her Master's thesis investigating the mineral products of iron-respiring microbes to test whether we can find signs of this metabolism in the minerals preserved in Banded Iron Formations. In September, she began a new job at Western Digital in California. Isaac Hinz (current MS student) published his first paper as first-author in Geology (Aug 2021 issue), reporting our discovery that ferric iron can trigger the formation of iron-rich silicate minerals in the environmental conditions predicted for the Archean ocean. Chrissie and undergrad alum Samantha Theuer (BS'19) were coauthors on this publication. Isaac's current MS thesis project is aging iron silicates with varying timescales and high temperatures to investigate how simulated diagenesis alters the mineral assemblage. Alice Zhou (current PhD student) is running experiments to understand how microbially mediated iron oxidation and reduction can transform iron-bearing minerals in Archean ocean analogs, assisted by Ben Klein (BS'23). Kaitlin Koshurba (new MS student) is beginning research on the mechanisms underlying early Earth and Martian clay formation, assisted by Trinity Pryor (BS'23). Dan Zammit (BS'21) is also working in the lab, keeping the lab running smoothly and helping Jena with research projects ranging from BIFs to metal-rich carbonates to dating terrestrial iron oxidation horizons.



MICROBIAL BIOGEOCHEMISTRY
ASSISTANT PROFESSOR JENAN KHARBUSH

Microbes in oceans and lakes play critical roles in carbon and nutrient cycling that are closely connected with water quality and climate change. Microbes are especially important in the cycling of nitrogen (N), an important nutrient for all living organisms. N is abundant in the atmosphere as N2 gas, but is often a scarce resource, because it is only usable by most organisms after it has been transformed into ammonium through the microbial process of nitrogen fixation. This biologically usable or "fixed N" is then converted into many different forms by microbes as they use it for growth and energy. Along with phosphorus (P), N is one of the nutrients that limits growth of the single-celled photosynthetic organisms known as phytoplankton. However, not all forms of N can be used by phytoplankton, and some phytoplankton "prefer" particular N forms over others. The size and composition of the fixed N inventory is therefore important in determining how much phytoplankton growth can occur, as well as which species are present in the community. This matters because the phytoplankton species that dominate an ecosystem can affect carbon and nutrient budgets, water quality, and food webs. Anthropogenic disruption of the N cycle has already resulted in adverse outcomes like harmful algal blooms that threaten water quality and security in the future.

Research in our lab is focused on understanding how different microorganisms, especially algae or phytoplankton, acquire and use N. This is needed to understand their responses to ongoing changes in N cycling and availability that will likely worsen with climate change. This work requires a combination of analytical chemistry, isotope geochemistry, and molecular biology approaches, as well as developing new methods to widen the "analytical window" of what we can measure.
Current research directions in the lab include: 1) Identifying and explaining isotope patterns produced during the biosynthesis of N-containing biomarkers, 2) Determining the role of N in the presence, persistence, and toxicity of the cyanobacterial harmful algal bloom in western Lake Erie, 3) Quantifying the production and cycling of dissolved organic nitrogen (DON) in freshwater ecosystems, and 4) Using molecular biomarkers to study carbon and nitrogen cycling in the Middle Island Sinkhole of Lake Huron.

PALEOBOTANY AND THE ENVIRONMENT
ASSOCIATE PROFESSOR SELENA SMITH

Dr. Selena Smith's lab group focuses on understanding plant diversity and plant-environment interactions, especially during the Cretaceous and Paleogene. Current geographic regions of focus are Western North America, India, and Antarctica. We also investigate living plants to develop a strong comparative framework for interpreting the fossils. Grad students in the lab are Zachary Quirk, who is studying fossil ginger evolution; Jerónimo Morales Toledo, who is examining fruit structure to better understand monocot flowering plant evolution; Kate Brooks, focusing on the diversity of Cretaceous angiosperms; and Mike Machesky, who is investigating environmental controls on stable carbon isotope composition of palms. Two undergraduates are continuing work in the lab: Malinda Barberio and Sarah Sturtz, studying leaf traits of different plant groups.

Kelly Matsunaga (Phd 20219) operating the CT scanner in the Computed Tomography Lab which is run by Drs. Selena Smith and Matt Friedman.

The PEPPR (Plant Evolution, Paleobotany, and Paleoecology Research) lab is run by Dr. Smith. It hosts four growth chambers, a wet chemistry area, workstations for analysis of 3D datasets, micro- and macro-photography setups, and compound/fluorescence and dissecting microscopes to support our work.

MAMMOTHS AND MASTODONS: PALEOBIOLOGY AND EXTINCTION
PROFESSOR DAN FISHER

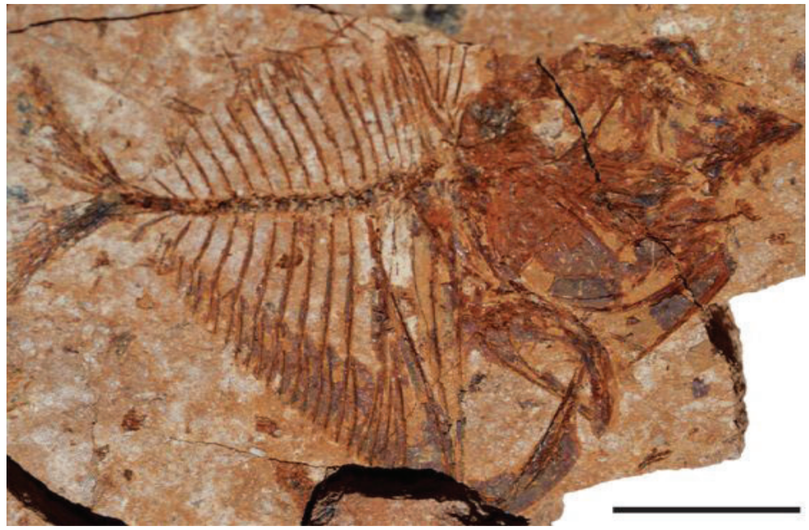
Fisher contributed to the study of this baby mammoth, found in Siberia, whose remains date back 42,000 years. James St. John/Flickr

Professor Fisher's current research focuses on the paleobiology and extinction of mastodons and mammoths, elucidated by studies of growth increments and compositional (mainly isotopic) time series sampled from their tusks. Fieldwork associated with these projects involves many Pleistocene proboscidean sites in North America (especially the Great Lakes region) and in Siberia. Siberian occurrences include permafrost-derived carcasses with extensive soft-tissue preservation, such as seen in the image of the baby woolly mammoth at right. North American occurrences include well-preserved mastodon and mammoth skeletons, some showing evidence of human association (including carcass processing, and in some cases, evidence of hunting). An example of one of these sites is seen in the group photo below, showing some of the work at the Fowler Center mastodon site. This was located near Mayville, at the base of the Michigan "Thumb." It was excavated by a team of U-M students and staff, joined by a dozen trainees, all of whom were teachers in the local public school system, with plans to use their experience to enhance their ability to communicate scientific concepts to their students. We recovered a significant portion of this animal's skeleton, along with compelling evidence of an ancient practice of underwater storage of carcass parts for later retrieval and use. This practice was first recognized at another Michigan mastodon site (Heisler) excavated by Fisher and his students, but the evidence was strikingly replicated at the Fowler Center site.

When our recent/current pandemic shut campus facilities down, and field work as well, Fisher focused on projects that required concentrated writing time, rather than field or lab work. These included an updated account (now available in a volume published by the University of Tübingen) of his experiments on carcass preservation by fermentation, induced by colonization of meat and fat by lactic acid-producing bacteria. He also completed several other projects now in review. Most recently, in the 8th International Conference on Mammoths and their Relatives, organized by colleagues in Bangalore, India, and presented by live-streaming, Fisher described recent advances (partly based on Jordan Hood's M.S. thesis work) in compiling whole-tusk life histories of mammoths by using microCT to correlate records from successive tusk cores (each normal to the tusk axis). Postdoc Mike Cherney represented another aspect of work being done in our lab by reporting on new evidence for the season of birth of American mastodons, and Ph.D. candidate Ethan Shirley capped off our contributions to the conference by presenting life history data from an adult female woolly mammoth. This entire tusk was CT-scanned in a large-format scanner at Ford Motor Company, after which Ethan segmented annual increments of tusk growth, which appear in the illustration as color bands outcropping on the surface of the tusk. Work like this contributes insights critical to unraveling likely mechanisms of late Pleistocene extinction of mammoths and mastodons.

Tuscola County natural sciences teachers helping to expose bones of the Fowler Center mastodon near Mayville, Michigan. Photo by Cindy Darling-Fisher.

EVOLUTIONARY BIOLOGY OF VERTEBRATES
ASSOCIATE PROFESSOR MATT FRIEDMAN



The moonfish Mene from an Egyptian locality dating to the Paleocene-Eocene Thermal Maximum. From a 2021 study in Geology led by PhD student Sanaa El-Sayed.

The Friedman lab seeks to understand the evolution of diversity in modern backboned animals by integrating data from fossil and living species. Members draw on techniques ranging from molecular systematics to computed tomography scanning to classic anatomical description. Current research projects include: investigation of new fish faunas from the ancient Indo-Pacific bearing on the origin of modern biodiversity hotspots; quantitative comparison of rates of change in living fossils; testing models of functional diversification in lobe-finned fishes; examination of soft-tissue preservation in Paleozoic vertebrates and its evolutionary consequences; the response of fish groups to mass extinctions; and field-based efforts to fill gaps in understanding of marine diversity at tropical latitudes during "hothouse" intervals of Earth history. Current research draws on fossil material from all continents, with many research projects involving international colleagues.

DINOSAURS AND BIOMECHANICS
PROFESSOR JEFF WILSON MANTILLA

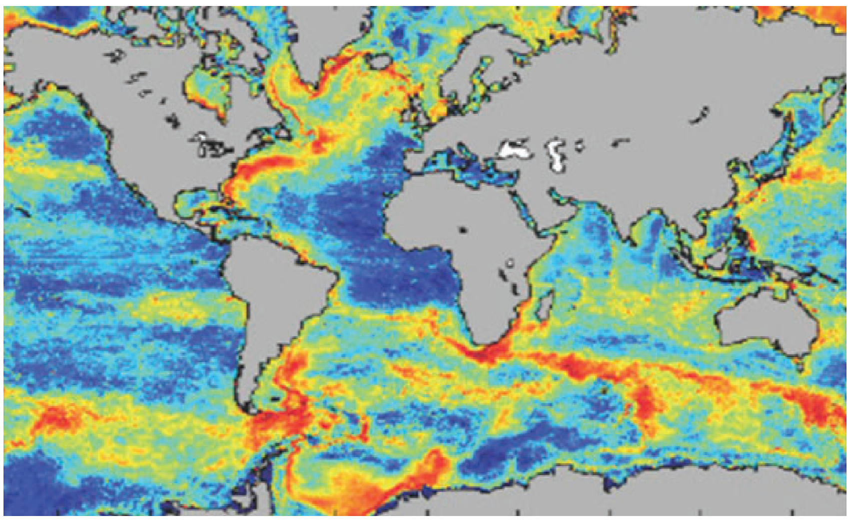
The Wilson lab investigates Mesozoic continental tetrapods, especially those from Jurassic and Cretaceous periods on southern landmasses. Questions include the effects of tectonics on tetrapod evolution and diversity, the evolution of body size and its osteological underpinnings, and the evolutionary relationships of sauropod dinosaurs. Ongoing field research efforts with collaborators in India aim to better understand how geological and geographic changes during the latest Cretaceous and earliest Cenozoic affected terrestrial vertebrates; newly developed projects in the Early-Middle Jurassic of Colombia and Argentina seek to better understand early evolution of sauropod dinosaurs.

*U-M Earth graduate student **Kierstin Rosenbach** transporting sediment samples in Rangapur, central India. These samples are from intertrappean deposits, which formed during hiatuses between outpouring of the Deccan Traps. They contain small bones of backboned animals that lived on island India during the latest Cretaceous, some 66 million years ago.*

EARTH SURFACE: OCEANOGRAPHY

The evolution of the Oceanography research program at the University of Michigan reflects the changing needs of society and the science. Through the years, it has transformed from a research endeavor focussed largely on the reconstruction of past patterns of biotic diversity, marine mineral formation and ocean tectonics to one striving the document and understand contemporary aspects of ocean circulation and and shifts in the organic structure of the ocean. This includes global scale modeling of the physical processes of tides, ocean atmosphere interactions and energy budgets of ocean circulation. Empirical reconstruction of the hydroclimate, the interaction of continental water runoff in response to climate forcing, provides a picture of the marine response in episodes of increases and decreases in coastal runoff.

OCEAN MODELING GROUP
PROFESSOR BRIAN ARBIC



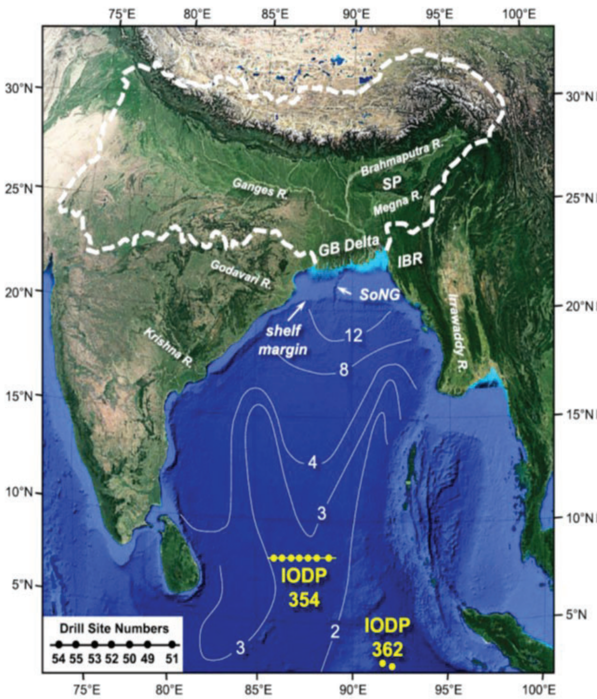
The OMG, led by Professor Brian Arbic, uses numerical models to simulate patterns of ocean tides and circulation. These in turn are frequently compared to both in-situ and satellite observations as an empirical test of their validity. Our main research interests are in global modeling of internal tides and the internal gravity wave continuum, the dynamics and energy budgets of the oceanic general circulation and mesoscale eddies (the oceanic equivalent of weather systems), and the variability of the coupled atmosphere-ocean system. We also have a growing interest in the application of ocean models to deep-time Earth system science problems. For instance, we have modeled the Chicxulub impact tsunami, and the evolution of tides and the Earth-Moon system over 4.5 Ga.

The OMG currently consists of University Corporation for Atmospheric Research (UCAR) research scientist He Wang, postdoctoral scientists Joseph Skitka and Ritabrata Thakur, PhD students Kristin Barton (Physics), Avik Mondal (Physics), and Lisa Nguyen (Applied Physics), and computer science undergraduates Daniel Garcia and Lingxiao Guan. Our group has funding support from NOAA, Office of Naval Research, NASA, NSF, and DOE. The group published seven papers in 2020 and has published eight thus far in 2021. Five papers led by former group undergraduates are in press/in review/in preparation. Our 2021 publication record includes co-authorship on a high-profile interdisciplinary paper led by departmental colleague Greg Dick's former post-doc, Judith Klatt.

Along with many dedicated colleagues from the US, Africa, and elsewhere, Professor Arbic continues his engagement in African STEM capacity development, with projects including the Coastal Ocean Environment Summer School in Ghana, Global Ocean Corps, EquiSea, and others. Global Ocean Corps was recently endorsed by the International Oceanographic Commission of UNESCO as a global capacity development programme of the UN Decade of Ocean Science for Sustainable Development. A Jamaica co-lead of Ocean Corps will present the programme at the UN COP26 conference in Glasgow.

GEOCHRONOLOGY OF MARINE SEDIMENTS
ASSOCIATE RESEARCH SCIENTIST: JAMIE GLEASON

In collaboration with PI's from the Universities of Kansas and Arizona, Montana State University, and Lancaster University (U.K.), Jamie Gleason (EES Research Faculty) won a grant from the National Science Foundation (NSF-NERC) to continue studies of ODP cores obtained aboard the JOIDES Resolution in 2015 (Bengal Fan Transect Exp. 354). This generous collaborative research grant is split between the U.S. and U.K. ($950K over 4 years), and will spur ongoing research into the depositional history of the world's largest sedimentary system. Using part of a record spanning 25 million years of sample resolution and 1.7 km of total drill core, Gleason and co-workers proposed to decipher the 'source to sink' Plio-Pleistocene history of Himalayan erosional processes from geochronological studies of detrital minerals in deep sea turbidites of the Himalayan-Bengal Fan, integrating data from modern rivers and shelf sands of the Bengal Basin. Preliminary results were published in 2018, implicating a complex interplay of climate and river dynamics in the provenance signal delivered to the Bengal Submarine Fan since the Miocene. These ongoing studies will have implications for econstructing Late Cenozoic records of Himalayan glaciation, monsoon dynamics, tectonic uplift and erosional rates in a changing climate.



Drilling rig on Joides Resolution used for retrieving deep ocean cores.
Photo by Kacey Lohmann

EARTH'S SURFACE CLIMATE -- ITS HISTORY AND FUTURE

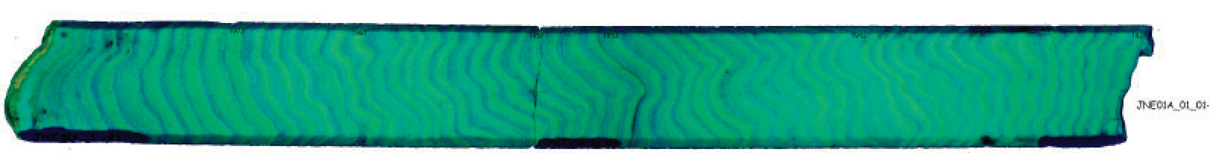
The overriding objective of this group's research focus is to provide reconstructions of the patterns and pulses of Earth's climate on both near- and deep-timescales and to illuminate the magnitudes and rates of change during times of climate transitions. For much of the researchers, this involves the development and application of climate proxies to provide empirical reconstruction of paleotemperature and environmental conditions ranging from terrestrial, to coastal and marine settings on both local and global scales. In addition, studies of the diagenetic alteration of the materials used for these reconstructions provides insight into the fidelity of records preserved in the material of study. These data, in turn, are complemented by numerical simulations of climate that evaluate the causative factors associated with climate change in the past, while providing predictive models for changes in the future.

FROM CAVES TO CORALS: RECONSTRUCTION OF PAST CLIMATES
PROFESSOR JULIA COLE

My group's research generates paleoclimate records relevant to climate change on human time scales. Our data extend the observational history of important climate systems, provide new information on the full range of natural variability, and improve our conceptual and physical understanding of climate change. We connect paleodata with climate models to improve understanding and evaluation of both.

A major focus of my group is developing climate reconstructions from long-livecd and fossil corals. Corals are uniquely valuable sources of information on tropical climate variability; in most of the tropical oceans, instrumental climate records don't predate the mid-20th century. Our coral work emphasizes understanding how the tropical oceans respond to current and past changes in climate forcing and background conditions. A major focus of our research is to determine the nature of the tropical Pacific's response to recent changes in anthropogenic forcing, using multiple geochemical tracers of past climate. We are also developing fossil coral records to extend this view beyond recent centuries. We are extending this perspective to the Atlantic and Indian oceans.

Our cave research emphasizes reconstruction of hydroclimate in the southwestern US, with a particular focus on changes in drought frequency and the monsoon. We use a combination of modern cave system monitoring and multivariate paleoclimate methods to produce high-resolution reconstructions of past climate. Our recent work highlights changes in the southwest (US) monsoon, along with multidecadal-multicentury variability, across the last 12,000 years. I also explore the use of isotope-enabled climate models to assess the sensitivity of paleorecords to hydroclimate changes, and to identify areas of disagreement among observations and models.



Fluorescence image of coral core sample delineating annual growth structure sampled for sub-monthly paleoclimate reconstruction through elemental and isotopic analysis.

STABLE CLUMPED ISOTOPE PALEOCLIMATE PROGRAM
ASSISTANT PROFESSOR SIERRA PETERSEN

Research in the SCIPP Lab focuses on reconstructing past climate using geochemical tools, in particular, stable and clumped isotopes of carbonate fossil shells. We have ongoing projects focusing on reconstructing climate in the Cretaceous, Miocene, Pleistocene and other time periods, looking at how climate has changed on million-year down to sub-annual timescales. Since the beginning of the academic year, the SCIPP group has gained four new undergraduate researchers through the UROP program and two new PhD students who will be working on calibrating the clumped isotope paleothermometer for use in marine gastropods (PhD student Alex Quizon) and reconstructing temperature and salinity of the shallow ocean of the Pliocene Florida platform (PhD student Lucas Gomes).

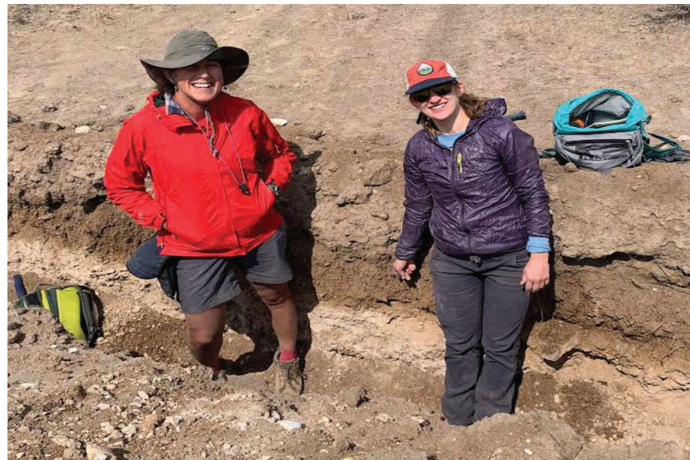
Despite COVID restrictions on lab density over the past year, and thanks to valiant efforts of our lab manager Ashling Neary, our mass spectrometers have been producing high quality clumped and stable isotopic data, which we are interpreting as fast as we can. PhD student Jade Zhang published her first paper on paleoceanography of Bermuda during the Last Interglacial. Other group members have papers in the pipeline on topics ranging from Eocene climate and tectonics in southern California (postdoc Julia Kelson) to vital effects in bivalve shell precipitation (PhD student Allison Curley) to Late Cretaceous paleoceanography in northern Europe (master's student Heidi O'Hora). The group said goodbye to postdoc Matt Jones, who leaves us for a prestigious postdoc at the Smithsonian Institute. While in the SCIPP group, Dr. Jones worked with senior thesis student Jon Hoffman to reconstruct mean and seasonal ocean temperature variation in the Cretaceous Western Interior Seaway. We will continue to collaborate with Dr. Jones on this project and beyond, using samples from IODP cruises he sailed on near Australia and the Smithsonian Institute where he is now a Peter Buck Postdoctoral Fellow.

Jade Zhang (PhD Candidate) *sampling Pleistocene outcrop in South Carolina as part of the 125K paleoclimate study.*

Sierra's group traveled to South Carolina to target marine invertebrate fossils from the Last Interglacial period (~125,000 years ago). This was a time of global warmth, with global average temperatures roughly 1-2C warmer, ice sheets smaller and, subsequently, sea level 5-9m higher than today. In some ways, this time period can serve as an analog for what future global climate could become as global temperatures increase into a similar range of 1-2C warmer than pre-industrial levels. Yet this warmth was achieved with atmospheric CO_2 levels of only 280 ppm. This means the Last Interglacial climate does not represent the end-game for global warming, but just a brief stepping stone we might quickly pass as higher CO_2 levels drive our planet even warmer.

PALEOCLIMATE: TROPICAL CLIMATE CHANGE, SOILS AND HUMAN EVOLUTION
ASSOCIATE PROFESSOR NAOMI LEVIN

Naomi's group has been bustling with a range of projects in the field and lab. PhD student Sarah Katz is reconstructing Pleistocene and Holocene climate from the Junín region of Peru using triple oxygen and clumped isotopes from lake carbonate. MS student Jada Langston is studying the paragenesis of carbonates in rift basin sediments from the Afar region of Ethiopia. Postdoc Julia Kelson is working on developing triple oxygen isotopes as a tool for understanding soil carbonate formation. Million Mengesha is visiting from Addis Ababa this Fall, through the UM African Presidential Scholars program, working on developing a triple oxygen isotope record of environmental change from Pliocene and Pleistocene soil carbonates from the Afar and Turkana Basins of Ethiopia and Kenya, which both hold key fossil archives for studies of human evolution.



Naomi Levin(Professor) and Juia Kelson (Postdoc) *in soil pit at Reynolds Creek, Idaho.*

Margaret Rudnick (Uundergraduate) and Juia Kelson (Postdoc) *checking soil monitoring instrumentation at the UM Edwin S.George Reserve in Pinkney, MI*

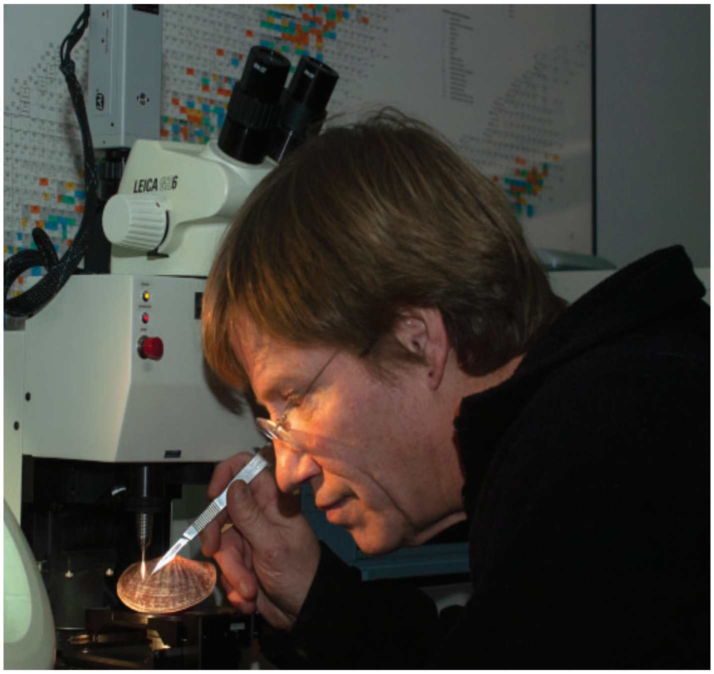
Four undergraduate majors (Kirsten Andrews, Margaret Rudnick, Miriam Bartelson and Matthew Salinas) are working on the lab helping operate the mass spectrometers, collecting rainfall, river and soil samples, and processing samples. We are particularly excited to welcome Matthew who is a freshman and an Earth Camp alumnus!

The Levin's Stratigraphy and Basin Analysis Class at Charleston Falls , OH (Left to Right): *Jada Langston, Tara Lonsdorf, Georgia Oppenheim, Daeun Lee, Jeronimo Morales Toledo, Naomi Levin, Mike Machesky, Cecilia Howard, Matt Chicoye, Rodrigo Tinoco Figueroa, Sally Keating*

CARBONATE GEOCHEMISTRY
PROFESSOR KYGER "KACEY" LOHMANN

Carbonate geochemistry, my principal area of specialization in the geological sciences, utilizes the chemistry and fabric of carbonate minerals to reconstruct the conditions present in ancient environments. For example, the isotopic and elemental chemistry of carbonate , whether formed as the shell of an organism or through abiotic chemical reactions, captures a record of the temperature and chemistry of fluid from which it was formed. As such, carbonate chemistry serves as a important proxy for deciphering Earth history.

Studies undertaken in my program have developed new analytical methodologies and interpretive approaches which have been applied to several areas of exciting research in the earth sciences. These include: evaluation of secular changes in ocean chemistry over the last billion years; reconstruction of latitudinal thermal gradients during times of global warming; and resolution of intra-annual temperature seasonality for continental, and marine settings. The objectives of such studies are significant for these provide constraints on the directions and magnitudes of change and the rates at which at these have occurred in the past.



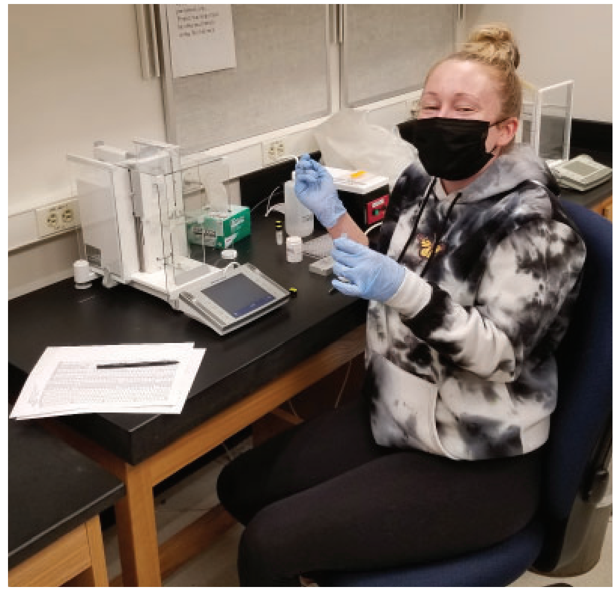
Kacey Lohmann (Professor) *removing powder carbonate sample to reconstruct seasonal-scaled isotopictemperatures for an Antarctic scallop using the Micromilll Microsampler. This device was developed in collaboration with Merchantek based on a prototype developed by Kacey and David Dettman (PhD '91).*

Current projects include: 1) a stable and clumped isotope analysis of 125Kyr mollusca from the western Atlantic to document changes in Gulf Stream circulation in response to northen latitude warming; 2) Paleoaltimetry of Miocene lacustrine carbonates in Gros Ventre and Teton mountain region; and 3) evaluation of the mid-Pliocene warming event through an analysis of high resolution isotope studies of molluscan carbonates.

Marine Isotope Stage 7 (MIS 7) beach unconformably overlain by MIS 5e beach and eolian deposits on the coast of eastern Bermuda. This location is one of many assoicated with the joint research of ***Sierra Petersen (Asst. Professor), Kacey Lohmann (Professor) and Ian Winkelstern (PhD '16)*** *where mollusca are collected for isotope paleotemperature determination: Photo by Kacey Lohmann*

GEOBIOLOGY RESEARCH IN TERRESTRIAL SYSTEMS
PROFESSOR NATHAN SHELDON

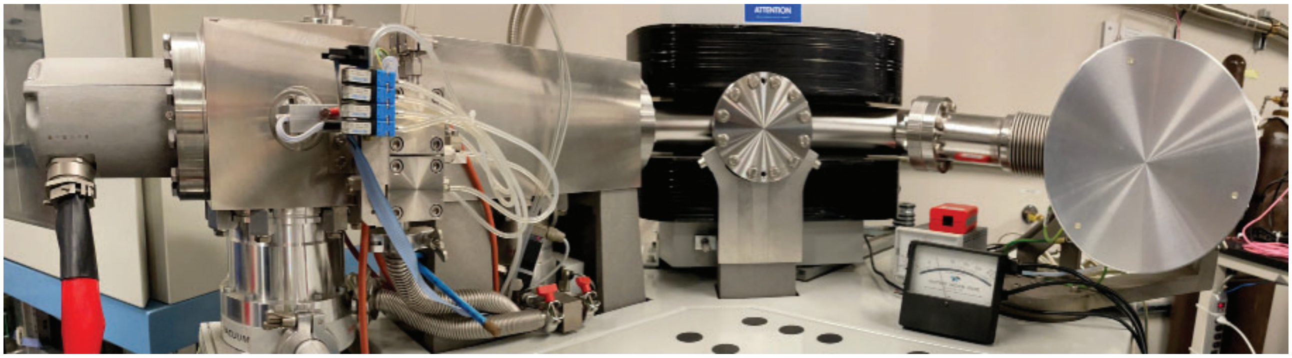
Nathan Sheldon runs the Geobiology Research in Terrestrial Systems (GRiTS) group. The group studies the interactions between environmental conditions and life ranging from modern process-based studies to early terrestrialization of the biosphere over three billion years ago. Current projects include paleoclimatic and paleoecological reconstruction of the Green River Basin during the early Eocene climatic optimum as part of a large research consortium, geobiological research in Thunder Bay National Marine Sanctuary (Lake Huron) using 'omics and elemental and organic geochemistry, and bioclimatic analysis of plant leaf morphology and chemistry.



Undergraduate researcher ***Kelsey Jones (BS ‘21)*** *is using the microbalance to weigh out sediment samples for elemental and isotopic analysis.*

The past year has been a whirlwind of comings and goings. Bekah Stein (PhD '20) and Becca Dzombak (PhD '21) defended their dissertations, Melanie Shadix (MSc '20) her Masters thesis, and Sonya Vogel (BSc '21) her honors thesis. Bekah started a post-doc at Berkeley in January 2021 and has subsequently received both an NSF Post-Doctoral Fellowship and an Agouron Institute Post-Doctoral Fellowship in support of her research. Becca is coming off of a year as GSA's Science Communication Fellow, followed by a similar fellowship at AGU, and now a permanent permission in science communication at AGU. Mel returned to active duty in the Air Force and redeployed shortly after completing her thesis. Sonya was accepted into a Masters program at the University of Vermont. In addition to returning PhD student Cecilia Howard and undergraduate researcher Amelia Jelic, the group welcomed new PhD student Diana Velazquez, new Masters student Mike Machesky, and new undergraduate researcher Kelsey Jones.

GRiTS PhD students Cecilia Howard and Diana Velazquez unload core samples collected by NOAA divers in Thunder Bay National Marine Sanctuary in October. The samples included microbial mats, sediments, and lake water from a submerged, anoxic part of Lake Huron to be analyzed by the Sheldon, Kharbush, and Dick labs at UM, as well as by former UM post-doc Judith Klatt at the Max Planck Institute.

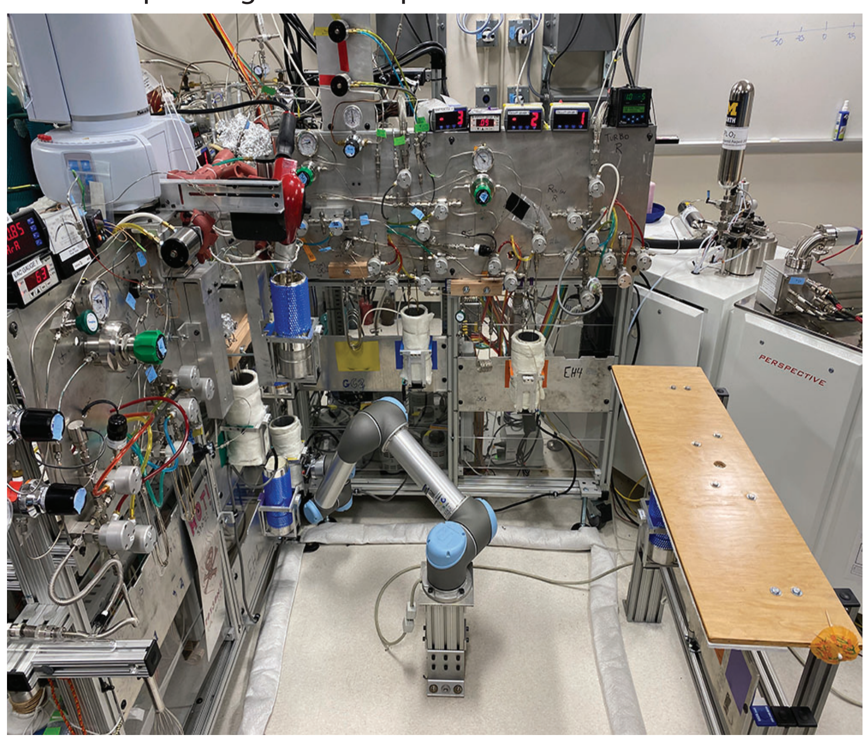


ISOTOPOLOGUES IN PALEOCLIMATE RESEARCH
ASSOCIATE PROFESSOR BEN PASSEY

Ben Passey's research group focuses on developing and applying new methods in stable isotope geochemistry to address questions about past climates and environments. The past year has seen many exciting developments. Graduate student Nick Ellis is a whiz with programming and robotics, and has completed the full automation of our extraction line for high-precision triple oxygen isotope analyses. The system features a 6-axis articulated robot arm (like a miniature version of robots seen in automotive factories) capable of moving liquid nitrogen vessels and heaters from trap to trap. Nick is using this system to study 52 million-year-old fossil mammals from the Bighorn Basin in Wyoming, hoping to reconstruct their climatic setting, ecological context, and prevailing atmospheric carbon dioxide levels.

Graduate student Natalie Packard is using triple oxygen and 'clumped' isotopes to study ancient lakes. Her projects include the late glacial to present climate and hydrology of Bear Lake (UT-ID), as well as that of the much older Lake Gosiute (early Eocene) and Green River Formation sediments it left behind in southwest Wyoming. Natalie's triple oxygen isotope data is revealing new information about the waxing and waning of this (at times) Great Lake-sized lake, with the data pointing to river capture and abandonment events as major drivers.

Postdoc Tyler Huth has been improving speleothem-based paleoclimatology by exploring the triple oxygen and dual clumped isotope systematics of these materials. Both approaches address the non-equilibrium isotope effects that have plagued efforts to reconstruct absolute growth temperatures. The results are looking promising, and we believe we are getting close to the realization of absolute temperature reconstruction. Because cave temperatures reflect the ground surface temperature above, this approach would allow us to tackle one of the holy grails of paleoclimate research, thermodynamically-based reconstruction of past land temperatures.



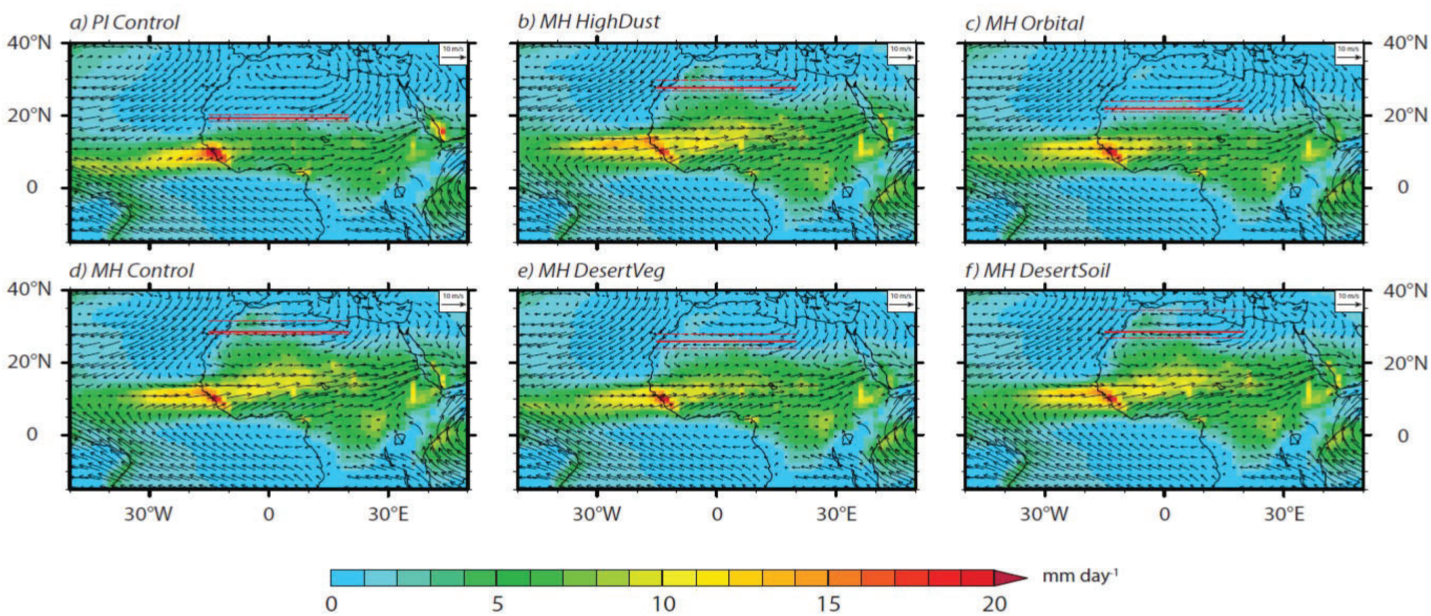
The Iso-Paleo-Lab's fully automated triple oxygen isotope extraction line, a.k.a. "RoboCap".

PALEO/CLIMATE DYNAMICS
PROFESSOR CHRIS POULSEN

Earth's climate has experienced tremendous variability through its history, from ice ages to greenhouse worlds, and is currently warming at an unprecedented rate due to human activities. Chris' research group investigates climate in the past, modern, and future using earth system models to understand the causes, feedbacks, and variability of climate change.

The lab has several active projects. PhD student Sophia Macarewich has been modifying an earth system model to incorporate and quantify the physiological effects of extinct plants on Late Paleozoic terrestrial climate and will soon be defending her dissertation. PhD student Jeremy Keeler and MS student Emily Do are continuing work in the lab to understand climate dynamics and to quantify climate sensitivity in the hot greenhouse worlds of the Eocene and mid-Cretaceous. PhD students Dauen Lee and Julia Campbell are working on a new collaborative project that seeks to link Miocene climate, tectonics, and mammalian diversification in the Turkana Basin of Kenya. And, postdoc Paul Acosta is investigating how the rifting of Atlantic and the widening of the South Atlantic altered circulation and hydrological regimes across South America and Africa.

In the last year, Dr. Alex Thompson completed a dissertation that investigates Holocene climate paradoxes and specifically the influence of dust and vegetation change on the mid-Holocene green Sahara and the Holocene thermal maximum. Alex is now a postdoc at Washington University in St. Louis. And, postdoc Dr. Phoebe Aron completed studies looking at the utility of oxygen-17 as an environmental proxy and the spatial variability of water isotopes in central South America. Phoebe is now a Principal Scientist at Hazen and Sawyer in Baltimore.



Climate simulations of monsoon season (JJAS) precipitation and low-level winds vectors for the a) the pre-industrial and b-f) under different mid-Holocene scenarios. Solid red line represents the median northernmost latitude reached by the West African Monsoon (WAM).