Guyot Science
The Department of Geosciences
at Princeton University
Cover: Schoene research group field work in southwestern Colorado, summer 2014. Photo courtesy of C. Brenhin Keller.
Guyot Science

A Summary of the Research Progress and Accomplishments made by the Faculty Members of the Department of Geosciences

Climate, biogeochemical cycles and planetary tectonics are the three basic processes that shape the Earth system. Geoscientists face a unique challenge in seeking to understand the complexity of the Earth’s physical and biogeochemical systems. The surface environment of the Earth is controlled by interactions between the deep Earth, the atmosphere, the hydrosphere and the biosphere. These interactions occur on timescales ranging from picoseconds for chemical reactions on particle surfaces to the billions of years over which plate tectonic processes and biological evolution have radically altered the composition of the atmosphere, and in space from nanometer to planetary scales. Princeton’s Department of Geosciences is at the forefront of scientific discovery in the solid earth, the environmental geosciences and oceanography/climate science. Our faculty and students address critical societal issues, such as climate change and geologic hazards, through research and education at all levels. Our mission is to understand Earth’s history and its future, the energy and resources required to support an increasing global population, and the challenge of sustainability in a changing climate.

Geosciences Faculty (Left to Right): Lincoln Hollister (emeritus), Jessica Irving, George Philander, Stephan Fueglistaler, David Medvigy, Daniel Sigman, Adam Maloof, Jorge Sarmiento, Bess Ward (chair), Jeroen Tromp, Thomas Duffy, Satish Myneni, Gerta Keller, Blair Schoene, François Morel, Frederik Simons, Michael Bender (emeritus) and Allan Rubin. (Insets) John Higgins, Tullis Onstott and Michael Oppenheimer.
Our research program focuses on understanding the deep interiors of the Earth and other planets through experimental study of geological materials at high pressures and temperatures. We are also broadly interested in the physical and chemical behavior of all types of materials under extreme conditions. We use both static and dynamic compression techniques to achieve these states.

Laser-based dynamic compression provides new opportunities to achieve ultrahigh pressure conditions in the laboratory. In this technique, high-powered laser beams are used to ablate a sample surface and by reaction a compression wave propagates through the material under study. By controlling the shape and duration of the laser pulse, either shock or ramp (shockless) compression can be produced. Molybdenum (Mo) is a technologically important transition metal that is used as a standard in static and dynamic compression experiments. However, significant unanswered questions and unresolved discrepancies remain about the high pressure-temperature phase diagram of this fundamental material. We have carried laser-compression experiments on Mo to as high as 1000 GPa using x-ray diffraction as a diagnostic. Our results provide the first direct experimental determination of the crystal structure of Mo at these extreme conditions. We find that the body centered cubic (BCC) structure remains stable until shock melting occurs at about 400 GPa and under ramp loading the BCC structure is stable until 1000 GPa. Our results enable us to constrain the phase stability, melting curve, and equation of state of Mo to unprecedented levels of compression.

Our dynamic compression studies also have applications towards understanding the interior structures of extrasolar planets. Magnesium oxide (MgO) is likely to be a major constituent in the mantle of super-Earth planets. Ramp compression has been used to study MgO to 900 GPa and we have obtained the first direct evidence from x-ray diffraction for the rocksalt to cesium chloride phase transition near 600 GPa. In other experiments, we have measured the equation of state of diamond to record-breaking pressures up to 5000 GPa. These experiments have achieved pressures of Jupiter’s core for the first time, and have implications for the interior structure of large planets, both within and outside our solar system. We also carry out a program of static high-pressure research using the diamond anvil cells. The perovskite to post-perovskite phase transition in (Mg,Fe)SiO3 near the base of Earth’s mantle is a key for understanding the overall dynamics and evolution of the deep Earth. We have used the laser-heated diamond anvil cell to study the equations of state and phase relations of perovskites and post-perovskites over a range of iron- and aluminum-rich compositions at deep lower mantle conditions. For these results we are able to place new quantitative constraints on the amount of chemical heterogeneity required to explain seismic data for the deep Earth. This project is being extended in on-going work to systematically examine the properties of the perovskite to post-perovskite transition in magnesium iron germanates which can serve as close analogs for the silicates of the deep mantle.

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Recent relevant publications


temperature trends and their connection to sea surface and ozone and implications for climate, cirrus cloud contributions, interactions between stratospheric dynamics and equatorial Kelvin propagation, tropical cloud distributions, and highly detailed process-level analyses on the other hand. Topics we are currently working on include an interdisciplinary approach on the one hand, without implicit a-priori assumptions.

Our interest in the interactions of processes requires an interdisciplinary approach on the one hand, and highly detailed process-level analyses on the other hand. Topics we are currently working on include equatorial Kelvin propagation, tropical cloud distributions, interactions between stratospheric dynamics and ozone and implications for climate, cirrus cloud microphysics and dynamics, tropical tropospheric temperature trends and their connection to sea surface processes and assume that the water vapor entering the stratosphere is given by the minimum saturation mixing ratio encountered during ascent into the stratosphere. We refer to this as the Lagrangian Dry Point (LDP), and we interpret observed variations in stratospheric water vapor based on the LDP distributions. This simple model explains observations remarkably well, but progress from a diagnostic to a prognostic model remains a major challenge.

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My primary research interest is the evolution of the carbon cycle and the global climate system over Earth history. One focus has been on processes that control the chemical composition of seawater, and how those processes have changed on geologic timescales. Another is understanding how the chemistry of carbonate sediments is affected by processes that occur post-deposition. These include early diagenetic recrystallization, dolomitization and hydrothermal alteration. The tools I have employed to study these include numerical models of chemical and isotopic biogeochemical cycles, as well as analysis of traditional stable isotopes of oxygen and carbon, and new isotope systems such as magnesium, calcium, and potassium.

Over the past year my lab has gone from a set of blueprints and invoices to a fully-functioning laboratory making state-of-the-art high-precision stable and trace element analyses on a range of geologic samples. In February 2013, construction on the Higgins lab and the installation of the Thermo Neptune multi-collector inductively coupled plasma mass spectrometer (MC ICP-MS) was completed. Since that time, we have established protocols for a number of metal isotope systems—magnesium, calcium, and most recently, potassium. The development of measurements of stable potassium isotope ratios is significant as our achieved precision is a factor of 3-5 better than previously reported, allowing us to demonstrate stable K isotope variation in low temperature environments for the first time. This work may have a range of applications given the importance of potassium in many geological, environmental and biological systems. In the last year we have also pursued automation of sample processing for isotope analysis. In cooperation with Dionex Corporation we have developed a method for using an ion chromatography instrument connected to a fraction collector. This setup permits rapid (~30 minute) sample throughput and opens the possibility of collecting multiple cation fractions (e.g. Mg, Ca, and K) on a single injection. Using this system we are able to produce data sets that are roughly 10x larger than previous studies.

By leveraging the high-throughput capacity in ICP systems with rapid automated sample processing, we have been able to tackle a number of geological questions which
require large data sets. Projects currently in progress include a high-resolution study of Ca isotope variability in Wonoka Formation rocks of Ediacaran age—host of Earth history’s largest carbon isotope perturbation—as well as a systematic study of Mg isotope variability in Phanerozoic dolomites, a survey of Mg and Ca isotope variability in modern shallow-water carbonate depositional environments, and a reconstruction of seawater Ca/SO$_4$ ratios using measured Ca isotope values in marine sulfate evaporites. This latter study is in press in Geology and authored by postdoctoral fellow Dr. Clara Blatter. In the coming year I anticipate further progress on these and additional projects, with a greater focus on K isotopes and their utility in studying K cycling in both low temperature (i.e. Earth surface) and high temperature (i.e. subduction zones) environments.

Accomplishments over the past year include the publication of a theoretical paper on the history of the carbon cycle as recorded in the carbon isotopic composition of carbonates in Science (Schrag*, Higgins* et al., 2013), and the submission of manuscripts reconstructing the Mg isotopic composition of seawater over the Cenozoic in pelagic carbonates (Higgins & Schrag, in review).

More papers and projects can be found by visiting: www.princeton.edu/geosciences/people/higgins/

Recent relevant publications


I arrived in the Department of Geosciences in February 2013. Since then my main focus has been on setting up both my research group and projects, as well as on teaching. I have been working on regional seismic studies of Earth’s inner core. Previous work I have carried out has shown that the inner core shows a degree one variation—that is, that the seismic properties of the eastern and western hemispheres of the inner core show variations in both isotropic velocity and in seismic anisotropy. The cause of these large-scale seismic differences has not yet been explained. The nature of the transition region between the eastern and western hemispheres may contain important information about the mechanism which can produce such variation in the inner core.

The main project I have been working on this year is therefore seismic imaging of the inner core region under Africa and Europe, which is where I have previously calculated that the boundary between the two hemispheres may be located. This year, I have collected and analyzed what I believe to be the biggest regionally focused dataset of PKPbc-PKPdifferential travel times. PKPd is a seismic wave generated by an earthquake which travels through all the layers of the Earth, reaching its deepest point in the inner core. PKPbc is a wave which travels along a similar path through the earth but reaches its deepest point in the outer core, allowing it to be used as a reference phase for PKPd. These travel times can be used to understand where the inner core velocity is anomalous with respect to a one dimensional Earth model; they are not affected by issues like the earthquake mis-location or by heterogeneous structure in the shallow Earth.

The seismograms I have gathered to produce my new dataset were recorded between 2000 and 2012 at both permanent seismic networks and temporary deployments across the world, including at the Earthscope project’s US Array. Many of the events analyzed did not produce sufficiently high quality seismograms in the study region to be used. At this time the dataset consists of 1770 measurements from 289 events and 58 seismic networks. My seismic data reveals an interesting and unexpected result—there is no discernible boundary between the eastern and western hemispheres under Africa and Europe. Instead, PKPbc-PKPdifferential travel times illuminate a laterally uniform inner core in this region using both polar paths (which are sensitive to anisotropic velocity variations) and equatorial paths (which are more sensitive to isotropic velocity variations and less strongly affected by the inner core’s anisotropy). I have imaged a region which has weaker anisotropy than in the western hemisphere, but stronger anisotropy than in the eastern hemisphere—an intermediate sector of the inner core.

I presented these preliminary results at the AGU meeting in San Francisco in December 2013. In order to strengthen these results I plan to make measurements on seismograms generated by events in additional regions including the Atlantic Ocean. These events will provide valuable extra coverage of my study region. In addition, I will gather data from events in 2013 to further extend my dataset.

This year, in addition to my main project, I have commenced work on a collaboration with E. Day (who was at MIT during 2013 and in 2014 will be working at the University of Cambridge) on probing the inner core using PKIKP PKKP, which is an exotic seismic phase which transits the entire Earth twice. I have also presented work at the Earthscope national meeting (North Carolina) and, the Gordon Research Conference on the Interior of the Earth (Massachusetts) and the joint IAHS-IAPSO-IASPEI meeting (Gothenburg, Sweden).

In addition to this work, I have been working with my new Ph.D. student, Wenbo Wu, who arrived in September 2013. Wenbo is making observations of PKiKP, a wave which reflects off the surface of the inner core, together with PKiKP coda which contains information about the scattering properties of the uppermost inner core. He is also making estimations of the magnitude of PKiKP coda which would be expected for different strengths of scattering material in the uppermost inner core using 2D SPECFEM. At the moment, data gathered from the US Array suggests that PKiKP and its coda are elusive but can sometimes be observed at high frequencies for well situated earthquakes.

Recent relevant publications


My primary research focuses on major catastrophes in Earth's history including the biological and environmental effects of catastrophes, such as meteorite impacts and major volcanic eruptions that lead to mass extinctions, rapid climate changes and ocean acidification. This research integrates paleontology, stratigraphy, sedimentology, geochronology and geochemistry in reconstructing past environmental changes associated with or leading up to mass extinctions. The main focus has been on two major catastrophes—the Chicxulub impact and Deccan volcanism—and their respective roles in the end-Cretaceous mass extinction. This research is largely the result of interdisciplinary collaborations and with an international team of scientists and students.

**Deccan Volcanism and the KTB mass extinction:** For the past three decades Deccan volcanism has been suspected of playing a major role in the end-Cretaceous mass extinction but proof remained elusive due to the lack of marine microfossils for dating in this continental flood basalt province. Our study of oil company deep wells in the Krishna-Godavari Basin documented the mass extinction in planktic foraminifera in intertrappean sediments between the world’s longest lava flows near the end of the Maastrichtian and ending with the KT boundary as having erupted over just 230,000 years ending with the mass extinction.

**Age of Chicxulub impact and relationship to the KTB mass extinction:** The Chicxulub impact is commonly believed to have crashed into Yucatan precisely at the KT boundary and caused the mass extinction. However, the stratigraphically oldest impact glass spherule ejecta documented from NE Mexico and Texas predate the mass extinction by 100-150 ky. Elsewhere in the North Atlantic, Caribbean, Belize, Guatemala and southern Mexico, there is a consistent pattern of impact spherules reworked in early Danian sediments and overlying a major KTB unconformity. This indicates that the Chicxulub impact predates the KT boundary and did not cause the mass extinction.

**Mass wasting in the North Atlantic not related to Chicxulub Impact:** Mass wasting and slumps, in the North Atlantic, some with Chicxulub impact spherules, have been interpreted as the result of Chicxulub impact-generated earthquakes. High-resolution faunal, stratigraphic, mineralogical and stable isotope studies reveal that this disturbance occurred in the early Danian well after the KT boundary mass extinction and was likely caused by Caribbean tectonic activity. This study is part of the Ph.D. project of Graduate Student Paula Mateo.

Recent relevant publications


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My interests center on the relationship between ancient life, climate and geography. The Neoproterozoic-Cambrian Era (900-490 million years ago) is a particularly important interval in Earth history because, at the same time that Earth endured unusually rapid drift of the continents and ice ages that advanced glaciers to sea level in tropical latitudes, animals first evolved and quickly became large and diverse. I choose precipitated sedimentary rocks such as limestone as my history books because a single outcrop of limestone may contain physical evidence for the energetics of winds, waves and currents, biological imprints of ecology and evolution, chemical records of the climate system, and magnetic evidence of latitude and geography. My group conducts extended field campaigns to map these physical and chemical records into a three-dimensional landscape of ancient environments. I also pair these studies of ancient systems with more recent analogues in order to understand how better-constrained Earth-system changes, such as bacterial iron, sulfur and carbon cycling in modern peritidal carbonate systems, Pleistocene sea level variability, and orbital forcing of climate, actually are recorded in sediments. The goal of my research is to better understand the origin of animals, the evolution of Earth’s climate, and the sensitivity of the Earth-system to physical, chemical, and biological perturbations.

Last year we built a new lab and installed the one of a kind automated serial grinder and imager that we call GIRI. The purpose of a destructive technique like serial grinding is to facilitate the discovery of embedded objects with weak density contrasts outside the sensitivity limits of X-ray CT-scanning devices (Feature segmentation and object reconstruction are based on color and textural contrasts in the stack of images rather than density). The device (GIRI) we have developed is a retrofit imaging station designed for a precision CNC surface. The instrument is capable of processing a sample 20x25x40 cm in size at 1 micron resolution in x, y and z axes. Directly coupled to the vertical axis of the grinder is an 80 megapixel medium format camera and specialty macro lens capable of imaging a 4x5 cm surface at 5 micron resolution in full 16 bit color. The system is automated such that after each surface grind, the sample is cleaned, travels to the opposite end of the bed from the grinder wheel, is photographed, and then moved back to the grinding position. This process establishes a comprehensive archive of the specimen that is used for digital reconstruction and quantitative analysis. For example, in one night, a 7 cm thick sample can be imaged completely at 20 micron horizontal and vertical resolution without human supervision. So far we have built digital reconstructions of what may be one of the oldest animals ever found in the fossil record—a cm-sized sponge-like animal from 650 million year old rocks of South Australia (Figure on opposite page). We also have imaged the oldest calcifying animal fossil Cloudina, compound chondrules from an L-Chondrite meteorite, and the porosity structure of carbonate cemented reservoir rocks considered a target for geological carbon sequestration.

My group also has begun a number of new field projects, including: (1) Hadean and Archaean records of Earth’s magnetic field from Western Australia, (2) Neoproterozoic records of true polar wander and equatorial glaciation in northern Ethiopia, (3) Geometry and Ecology of Ediacaran microbial reefs hosting Earth’s most ancient calcifying animals in southern Namibia, (4) Paleontological and geochemical records of the Cambrian explosion in animal diversity from a newly discovered lagerstätte, Ellesmere Island, (5) Stratigraphic and geochemical records of the frequency and magnitude of ice volume variability during the Late Paleozoic Ice Age in the American Southwest and the United Kingdom, and (6) a study of modern muds and porewaters in the Bahamas to understand how seawater geochemistry actually is recorded in carbonate sediment.

In the classroom, I continue to focus on teaching students to collect data, analyze them quantitatively, and write about them scientifically. After another three-year freshman seminar with Prof. Frederik Simons (this time in Cyprus, 2011-2013), I have begun a new
course this Fall (2014) with Writing Program Director Amanda Irwin Wilkins entitled Measuring Climate Change: Methods in Data Analysis & Scientific Writing. In this course, students use drone-derived photographs and elevation models of landscapes, georeferenced field observations of the natural world, and data mining of the primary literature in combination with quantitative modeling and interpretation to answer questions like: How have ancient climate changes been preserved in modern landscapes and the rock record? How is climate changing now, and how do we measure it? What impact does climate change have on modern human society, and how have humans affected climate change? How do we quantify the uncertainties on measurements of climate change, and how do we communicate these uncertainties to the public? The ultimate goal of the course is to provide underclassmen with the tools and experiences needed for successful Junior and Senior independent research.

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Recent relevant publications


Figure 1: Digital reconstruction of a 650 Ma sponge-like fossil.
It is now evident that there are complex relationships between terrestrial vegetation and the atmosphere, and that these relationships are not stationary. Indeed, our current epoch has been called the “Anthropocene” out of the recognition that large-scale human interventions within the Earth System have implications for terrestrial ecosystems and the atmosphere. My research resides at the center of this 3-way intersection between terrestrial ecosystems, the atmosphere and anthropogenic drivers of global change. I seek to understand the natural laws that, at this intersection, govern the flows of water, energy and carbon between terrestrial ecosystems and the atmosphere, and that ultimately determine the dynamics of terrestrial ecosystems and the atmosphere. My approach is to develop state-of-the-science predictive models that enable my research group to answer fundamental questions at the intersection of ecosystems and climate in the Anthropocene. Two examples of my recent research are outlined below. Others can be found at www.princeton.edu/scale.

1) How will large-scale deforestation of tropical rainforests affect temperature and precipitation? About 20% of the Brazilian Amazon has now been converted to pasture or agriculture. An additional 37% is unprotected by any form of regulatory regime and may conceivably be deforested during this century. The potential for such remarkable changes in the landscape have spurred research into how deforestation affects climatic variables such as temperature and precipitation. Although a consensus has emerged that the Amazon itself would become, on average, warmer and drier in response to large-scale deforestation, we still do not know how non-average behavior, like extreme weather events, will be affected by Amazon deforestation. In addition, some studies have indicated that Amazon deforestation could impact other parts of the world. However, this work has remained controversial and the physical mechanisms have not always been clearly articulated.

Recent research in my group has addressed these issues. One important finding was that the deforestation of the Amazon can lead to increases in the frequency and intensity of extreme weather events, including the cold air incursions that impact southern South America during the southern hemisphere winter. These cold air incursions are of great interest because they are occasionally strong enough to cause significant damage to frost-sensitive crops. Our work has shown that these cold air incursions can become stronger and more intense in response to the deforestation of the Amazon. This result is surprising because the simulated changes occur in southern South America, far from the deforested region, as well as in the deforested region itself. Nevertheless, we have shown that it is possible to describe the physical mechanism that underlies these changes.

Research in my group has also shown that the deforestation of the Amazon can have large impacts on the climate of the western United States (Figure 1). Our model simulations have predicted that the deforestation of the Amazon can lead to reductions of winter precipitation of about 20% for parts of the northwest U.S. and California. Such a change can have a large effect...
on critical agricultural and natural ecosystems in this sector. We explained these changes in precipitation in terms of a detailed physical mechanism that linked deforestation to global scale atmospheric impacts, highlighting how changes in atmospheric dynamics and thermodynamics in the Amazon sector can lead to planetary scale Rossby waves in both the northern and the southern hemispheres. These waves ultimately caused the atmosphere over the northwest U.S. to become drier in simulations with a deforested Amazon than in simulations with an intact Amazon forest. We found that adequate model resolution over topographic features, an important capability and distinguishing feature of our model, was critically important for resolving these dynamics.

2) Will climate change affect the seasonality of forests? Seasonality is a defining feature of many forests throughout the world. One of the most vivid expressions of deciduous forest seasonality is the growth of new leaves and the coloring of old leaves. These seasonal biological processes are intertwined with seasonal changes in the atmospheric state, but the mechanisms linking atmospheric changes to the biological changes of different species of trees remain poorly understood. Until we achieve improved mechanistic understanding of these linkages, it will remain a challenge to predict how vegetation seasonality will respond to the warming temperatures and novel precipitation regimes that are expected to occur in the coming decades.

My research group seeks to develop mechanistic understanding of deciduous forest seasonality and to understand how that seasonality will respond to climate change. We are interested in the seasonality both of temperate deciduous forests that drop their leaves in the cold season and seasonally dry tropical forests that drop their leaves in the dry season. For both temperate deciduous and seasonally dry tropical forests, we seek to (i) develop relationships between environmental variables (e.g., temperature, precipitation) and seasonal ecosystem events (e.g., growth of new leaves); (ii) understand why different relationships exist for different species; (iii) assess how future climate change will impact vegetation seasonality; and (iv) determine how biogeochemical cycles, land-atmosphere interactions and forest competitive dynamics are affected by changes in vegetation seasonality.

Our work has led to several key findings. First, in the deciduous forests of the eastern U.S., we have used widespread ground-based observations to show that leaf emergence in the spring is controlled by both winter and spring temperatures. Leaf emergence is generally earliest in the case of a cold winter and warm spring, and latest in the case of a warm winter and cool spring. In collaboration with researchers from the Geophysical Fluid Dynamics Laboratory (GFDL), we found that our newly developed representation of vegetation seasonality that included the effect of winter temperatures affected model simulations of forest carbon storage by about 5%.

Second, my group’s work has brought together a new, continental-scale dataset from the United States Geological Survey and statistical techniques that are new to ecological modeling (but established in the geophysics community) to develop new predictive models of the timing of spring leaf emergence and autumn leaf coloring for deciduous forests of the U.S. We have found that global warming over the next 100 years can advance the timing of spring leaf emergence by up to 17 days, representing about 10% of the growing season. This means that trees have about 10% more time to carry out photosynthesis, so it is almost as if they were getting a 10% “raise” in their carbon “paycheck”.

Third, our results also indicate that vegetation seasonality in some parts of the U.S. will be more strongly affected by climate change than vegetation seasonality in other parts of the U.S. Although leaf emergence will occur earlier in both the southern and northern U.S., changes will be more pronounced in the northern U.S. This implies a continental scale convergence in the date of leaf emergence. Interestingly, we predicted the opposite spatial pattern for autumn; leaf coloring will occur later in both the southern and the northern U.S., but changes in the southern U.S. will be more pronounced.

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Recent relevant publications


François M. M. Morel

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Research in our group aims at understanding at the molecular level the interactions between the chemistry and microbiology of marine and terrestrial ecosystems that govern the global biogeochemical cycles of elements, including carbon and nitrogen. A focus of this work is on trace metals, some of which (e.g., iron & zinc) are essential and catalyze biological transformations as cofactors of key enzymes, while others (e.g., mercury & arsenic) are pollutants that can reach toxic concentrations in the environment. Part of our research is motivated by the ongoing change in the chemistry of marine and terrestrial ecosystems brought about by the increase in atmospheric CO2, including ocean acidification. We approach our work with a mix of laboratory and field experiments using a variety of chemical, microbiological, biochemical and genetic tools, as appropriate. Our work is also informed by theoretical considerations from a number of disciplines ranging from bioinorganic chemistry to geology and ecology.

**Nitrogen fixation**

Nitrogen fixation, the conversion of atmospheric N2 gas into ammonia is a major source of bioavailable nitrogen, a limiting factor for the fertility of many marine and terrestrial ecosystems. This process is catalyzed by the nitrogenase enzyme which uses iron, molybdenum or sometimes vanadium as cofactors. We are exploring how the bioavailability of these trace elements, which depends on the chemistry (acidity and redox state) of the medium affects N2-fixation. Our results show that N2-fixation is limited by molybdenum in some tropical forests and that the acidification of the oceans reduces the efficiency of nitrogenase. Nitrogen isotope data from ancient sediments imply an important role for iron-only nitrogenase in past anoxic environments.

**The bioavailability of trace metals**

The bioavailability of trace metals to microorganisms is modulated by their complexation to organic compounds. Some of these compounds are released by the microorganisms themselves in a form of chemical warfare. Using novel experimental protocols, based on the unique isotopic signatures of the metals of interest, we have begun to identify metal
complexing agents in culture media and natural samples. We have also recently shown that weak metal complexing agents can serve as shuttles and greatly increase the bioavailability of strongly bound metals. An unexpected result of this weak ligand mechanism is, in some instances, a decrease rather than an increase in trace metal bioavailability upon acidification of the medium.

Ocean acidification

Ocean acidification results from the dissolution of about one third of anthropogenic CO$_2$ emissions to the Earth’s atmosphere into the oceans. Studying its biological and ecological effects is made difficult by the fact that several chemical parameters change along with increasing CO$_2$ and hydrogen ion concentrations (decreasing pH). An expected effect of increasing CO$_2$ is a decrease in the energy expended by phytoplankton on their Carbon Concentrating Mechanism (CCM), leading to a higher photosynthetic efficiency. Following previous work on carbonic anhydrase, a key CCM enzyme, we have used mass spectrometric measurements of cellular carbon fluxes to quantify the energetic cost of concentrating CO$_2$. But laboratory and field experiments have shown variable effects of increased CO$_2$ on net phytoplankton growth. We are now examining if the beneficial effect of increased CO$_2$ may be alleviated by an increased harvesting of light energy or by a compensating physiological effect of decreasing pH.

High latitude oceans

High latitude oceans are major contributors to global primary production and potentially most vulnerable to global change. A combination of field studies at Palmer station in Antarctica and laboratory experiments with cold-adapted phytoplankton species are providing us with new insight into the chemical and biochemical mechanisms that sustain high productivity at very low temperatures and how they may be affected by global change. High photosynthetic rates at low temperatures can be achieved because photochemical light harvesting pathways are largely temperature independent, and because the concentrations of key proteins (such as that of the carbon-fixing enzyme RuBisCO) are elevated to compensate for slower catalytic rates. In addition, the carbon concentrating mechanism is able to maintain near saturation of carbon fixation with minimal energy expenditure, as a result of the high solubility of CO$_2$ and the low half saturation constant of RuBisC0 at low temperature.

Mercury

Mercury is one of the most toxic trace elements. A fraction of mercury in anoxic environments is converted by bacteria to methylmercury, a compound that accumulates in the biota via the food chain, resulting in animal and human exposure through consumption of fish. We investigate the biochemical mechanism of mercury uptake and methylation, and the environmental factors that influence the rate of methylmercury formation. We have established that mercury uptake by both methylating and non-methylating bacteria is an active process that is highly dependent on the characteristics of the sulfur compounds that bind ionic mercury in the external medium, with some promoting uptake and methylation and others inhibiting both.

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Recent relevant publications


Molecular geochemistry of aquatic systems

One of the challenges in environmental sciences is to gain a better perspective of interactions between various compartments of the Earth surface, which includes water, minerals, biota and their byproducts, and to use it to predict biogeochemical processes such as mineral weathering, elemental cycling and the fate and transport of contaminants. I am passionate about exploring the structure and coordination of chemical species in aquatic systems and their impact on biogeochemical reactions. I conduct studies at the atomic level, and tie them with field studies from selected Earth surface environments to evaluate different biogeochemical processes. We combine spectroscopy, microscopy and isotope geochemistry methods in exploring the identity, distribution and dynamics of different chemical species in environmental matrices. A summary of my research interests is presented here.

Chemistry of iron in aqueous and soil systems: Structure and chemistry of amorphous phases in the natural systems

Amorphous and poorly crystalline phases of Al and Fe occur in abundance, as a norm, in all Earth surface environments, and play an important role in the geochemical cycling of elements. These metastable phases convert to crystalline phases in time; however, the links between composition and structure, and stability (or reactivity) of these phases are poorly understood. My research group is studying: i) coordination and structure and stability of Al and Fe polymers and amorphous phases formed from the hydrolysis of these ions in the presence of different ligands (e.g. Cl-, dissolved silica and organic carbon) and cations (e.g. Al in Fe-phases, or vice versa), and ii) surface hydroxyl composition and reactivity of amorphous phases as their structure evolves.

Amorphous Fe(III) hydroxides are known to convert to stable minerals, such as goethite and hematite, if given enough time and at elevated temperatures, with goethite being the most common phase under conditions tested in our study. Our research suggests that the stability of amorphous Fe(III)-hydroxides varies from a few days to years, which depends on several physico-chemical variables and the type of associated co- and counter-ions. Measured enthalpies of dissolution also supported the observed relative stabilities of these amorphous phases. These results imply that small changes in the stoichiometry, because of entrained impurity ions during the amorphous phase formation, have a major impact on the stability of amorphous phases. In addition, our experimental and theoretical studies suggest that ferric polymers form with abundant edge-sharing Fe-polyhedra during Fe(III) hydrolysis, and with trapped ligands in different coordination geometries preventing corner-sharing Fe polyhedral linkages. Expulsion of ligand and formation of abundant corner-sharing Fe-Fe polyhedral linkages were found to be the key steps in the conversion to crystalline goethite.

These studies suggest that the amorphous phases are highly stable under the geochemical conditions encountered in the environment. Our current studies are focusing on the nature of surface hydroxyls on the amorphous Fe(III)-hydroxides and their relationship to nano-goethite of different sizes (10-200 nm) using surface sensitive probes, and their reactivity with different gas phase species. Using a combination of these datasets, I hope to develop a systematic approach to evaluate the behavior of amorphous metal hydroxide phases. Colloidal Fe-oxides in Natural Waters: Composition, Structure & Role in Biogeochemical Processes

As the soluble organic molecules and their Fe complexes, discussed above, enter into natural waters, redox, photochemical and other processes modify the coordination chemistry of Fe complexes. This can influence the concentration and structural characteristics of colloids formed in these natural waters, which in turn influence the solubility and bioavailability of associated metals. Similar reactions are also expected in the atmosphere, where dust particles interact with water and undergo photochemical processing, and are responsible for transporting different forms of Fe to open oceans. My goal is to evaluate the chemistry of Fe colloids (composition, structure and their chemical evolution) and associated organic carbon in natural waters, and their influence in different biogeochemical reactions using X-ray nanoprobe.

We have been developing a synchrotron based
spectromicroscopy method for detailed speciation of amorphous and crystalline Fe-phases using the Fe L-edge XANES spectroscopy (von der Heyden et al. 2012), and their association with Al and organic carbon (von der Heyden et al. in review). Using this method we are studying the characteristics of Fe colloids in the Southern Ocean (where Fe is the limiting nutrient), Gulf of Aqaba, and in tropical freshwater lakes (where P is the limiting nutrient but its behavior is tied to colloidal Fe). Our studies indicate that Fe is present in the particulate fraction in the Southern Ocean; however, the forms of Fe and their association with organic matter vary significantly between the coasts of South Africa and Antarctica. The solubility of these different Fe-phases is expected to be different, and thus to influence Fe (and other associated nutrient) availability to organisms.

Chemistry of natural organic molecules in aquatic and soil systems and at interfaces

One of the bottlenecks in our understanding of the elemental cycles is related to the speciation of C, N, S, and other elements associated with organic molecules, and their variation in the environment. For the past several years, my research group has been developing and using the X-ray spectroscopy and spectromicroscopy methods for studying the chemistry of natural organic molecules in their pristine state. Using these methods I am investigating: i) functional group composition of natural organic molecules in soils and sediments, and its variation along climate gradient and impact on elemental cycles, ii) chemistry of natural organohalogens: coordination chemistry, rates of formation and their role in biogeochemical reactions in the environment, and iii) functional group chemistry of bacteria-water interfaces.

Functional group chemistry of natural organic molecules along climate gradient

Using the X-ray absorption spectral database we developed for organic molecule functional groups, we have been successfully examining the speciation of C, N, P, S, Cl, and Br functionalities of natural organic molecules. By combining with other complementary spectroscopy information, we are examining the functional group composition of organic carbon and other associated elements (e.g. Fe, Mn) in soils of different climates, P-dynamics in lakes, and halocarbon chemistry in different environments. Our X-ray studies are revealing the abundances of different organic molecule functional groups and their dynamics in these systems, and this would not have been possible with the other traditional methods. Because permafrost soils are the largest reservoirs of soil organic carbon, and global warming and associated thawing of permafrost soils is of a major concern, our studies in the last two years focused on soil organic carbon dynamics in these types of soils. Our studies suggest that the bulk and extractable organic carbon composition of mineral cryosols is more aliphatic-rich and oxygen-poor than that obtained from soils of other climates, which typically consist of poly-

phenols and lignin. These differences are attributed to the variations in the organic carbon sources and their mineralization (Sanders et al. to be submitted). Based on these findings we are currently studying the soils of transition zones, such as boreal forests, and micro-climate gradients that exist therein to evaluate the organic carbon chemistry and stability.

Chemistry of natural organohalogens

While manmade organohalogens are widely distributed throughout the biosphere and are characterized by varying degrees of persistence and toxicity, natural production of organohalogen compounds is gaining recognition as a significant contributor to the organohalogen burden in the environment. Although numerous marine sources of organohalogens have been identified, which include algae and sponges, knowledge of the terrestrial sources of organohalogens is less complete. Despite their omnipresence in the environment, several issues related to the structure, stability and toxicity of natural organohalogens, processes responsible for their formation, and the impact of different environmental variables on their rates of formation are poorly understood. The focus of my research is aimed at developing profound understanding on the chemistry of natural organohalogens and their influence on various biogeochemical processes, and the specific goals are to: i) acquire comprehensive speciation information on natural organohalogens in natural waters, soils and sediments, ii) identify the biogeochemical processes involved in the formation of organohalogens and determine their evolution and fate in the environment, and iii) develop conceptual model for halogen cycle in the environment and evaluate its association with other elemental cycles.

To understand the biogeochemical processes involved in organic molecule halogenation in terrestrial systems and their rates, we built field stations in the Pine Barrens and on Princeton University campus. The datasets obtained from these revealed different stages in the halogenation of plant material during its weathering. Our recent X-ray and high resolution electro-spray mass-spectrometry studies using natural isotopic abundances of Cl indicated that a majority of chlorinated organic molecules in weathering plant material are associated with the soluble polyphenols, and organic molecule halogenation is significantly different along the climate gradient. We are also investigating how global warming and associated rises in sea level and flooding of low lying freshwater wetlands influences the halogenation reactions in coastal systems. The contact of buried soil organic carbon with halogens could impact halogenation reactions in salt affected soils and cause halomethane emissions into the atmosphere. Measurements are in progress for the release of ozone depleting organohalogen molecules from these environments.

In summary, my team conducts interdisciplinary research to address some of the fundamental questions in geochemistry of the Earth surface environment.
Recent relevant publications


Over the past few years our research has focused on the microbial carbon cycle of the deep terrestrial subsurface and of Arctic permafrost. To identify those microbial groups that are actively cycling carbon and the carbon metabolic and anabolic pathways that they are utilizing we apply Next Generation Sequencing, protein spectrometric analyses, geochemical analyses, stable isotope and radiocarbon analyses and amino acid racemizaton analyses. Our research in the Arctic assesses the impact global warming is having on the release of the greenhouse gases, CO₂ and CH₄. Our research in the deep terrestrial subsurface of South Africa is determining the carbon feedstock for subsurface life and how this changes as a function of depth. The long-term survival of subsurface ecosystems has implications with respect to petroleum biodegradation, life on Mars and the origin of life. Finally we are developing portable instruments for measuring the C and H isotopic composition of CH₄. The principle projects of our Geomicrobiology Group are described below and more details can be found at our web page.

Isotopic analyses of CH₄ in the field (Y. Chen)

On Earth the ability to measure the C and H isotopic composition of CH₄ in the field, on ship or underwater would greatly increase the data points that could be obtained during seasonal cycles and would lead to a far greater understanding of the environmental controls on the emission of this important greenhouse gas as a function of global warming. From our NASA Astrobiology Science and Technology Instrument Development grant, Associate Research Scholar Yuheng Chen, working with the Mahaffy laboratory at Goddard Space Flight Center and the Lehmann laboratory at the University of Virginia, constructed a near-IR, continuous, cavity ring-down spectrometer for the C and H isotopes of CH₄. This instrument is capable of measuring both the δ¹³C and δ²H of atmospheric CH₄.

Last year he completed development and successfully tested the CH₃D line of our portable CRDS. The test was performed in Greenland as part of our NASA Astrobiology Science and Technology Exploration
Program grant with the Pratt lab at Indiana University. The research project has been investigating the CH\textsubscript{4} fluxes from meromictic lakes near the western edge of the Greenland ice sheet. With the help of undergraduates working in the field Yuheng showed that he could measure the $\delta^{2}$H of atmospheric CH\textsubscript{4} of $\pm 2\%$ after 10 minutes of integration if he pre-concentrated an air sample by a factor of 50 using a small cryogenic dry shipper. Our CRDS is also being used to measure the $\delta^{13}$C and $\delta^{2}$H of CH\textsubscript{4} from leaking abandoned gas wells in Pennsylvania in a collaboration with Prof. Denise Mauzerall from Woodrow Wilson School to determine whether abandoned gas wells represent a significant source of this greenhouse gas.

**Will thawing of Arctic permafrost be a source or a sink of CH\textsubscript{4}? (B. Stackhouse, R. Sanders and M. Lau)**

Arctic permafrost underlies $\sim 16\%$ of the Earth's ground surface, but contains $\sim 1/2$ of the Earth's below ground soil organic C. Temperatures in the Arctic will increase 4-8°C over the next 100 years increasing the depth of the active-layer and thawing the underlying permafrost. With thawing the relatively undegraded permafrost organic C may rapidly biodegrade, thereby increasing CO\textsubscript{2} and CH\textsubscript{4} emissions and creating a positive feedback to global warming. Global climate models however disagree as to when and how much of this permafrost sourced CO\textsubscript{2} and CH\textsubscript{4} reaches the atmosphere and none of these models accurately replicate the hydrology, carbon composition and microbial activity of permafrost terrains.

In collaboration with our colleagues at McGill University in Canada we obtained 40 one-meter long cores from an ice-wedge polygonal terrain on Axel Heiberg Island. These intact cores sampled the seasonal active layer and underlying permafrost and represent mineral cryosol, the type of soil that comprises 80% of the Arctic tundra. Ph.D. student Brandon Stackhouse working with many undergraduates has completed a two year thawing experiment at 4.5°C during which he monitored changes in the CH\textsubscript{4}, H\textsubscript{2}, O\textsubscript{2}, CO and CO\textsubscript{2} gas fluxes, and changes in the microbial compositions and activity. He has discovered that the active layer contains aerobic methanotrophs with a high affinity for CH\textsubscript{4}, so much so that they oxidize the CH\textsubscript{4} released from the underlying permafrost before it reaches the atmosphere and they make the active layer a net CH\textsubscript{4} sink for atmospheric CH\textsubscript{4}. Assembly of metagenomic reads from our colleagues at the University of Tennessee-Knoxville has identified the methanotroph as a member of the USC\textsubscript{c} clade. Mapping of proteomic sequences derived from protein extracts of the same experiments to the assembled contigs of the methane monoxygenase gene by Associate Research Scholar Maggie Lau has confirmed that this USC\textsubscript{c} is active and responsible for the observed atmospheric CH\textsubscript{4} uptake. The intact core flux measurements are consistent with field measurements during the past three summers and confirm that the high-Arctic tundra is acting as an atmospheric CH\textsubscript{4} sink. Our data also predict that the rates of atmospheric CH\textsubscript{4} uptake from field data and from experiments suggest that most of the Arctic tundra will act as CH\textsubscript{4} sinks and will help modulate increasing atmospheric CH\textsubscript{4} concentrations during global warming. Rebecca Sanders (North Central College) has discovered through X-ray-fluorescence and FT-ICR-MS analyses that the soil organic carbon of these samples is much different from that of temperate zones and may not be as susceptible to rapid oxidation to CO\textsubscript{2} with warming temperatures.

**What controls the carbon cycling rate in the deep subsurface? (M. Lau and D. Sanders)**

The terrestrial deep subsurface biosphere comprises a significant fraction of the Earth's living biomass. The active subsurface microbial communities are responsible for converting organic carbon to CO\textsubscript{2} and CH\textsubscript{4} but their in situ rates are only known to within 2-3 orders of magnitude. The primary reason for all of this uncertainty is the inaccessible nature of the terrestrial deep subsurface. We are fortunate to obtain access to environments as deep as 4 km by working in the Au, diamond and Pt mines of South Africa. The goal of our NSF-funded project was to determine the organic sources for the subsurface microbial communities of the fluid-filled fractures and which microorganisms were actively utilizing the carbon.

*Over the past few years we have uncovered several surprising results:*

1) I discovered that D/L analyses of the amino acids of the microbial community from deep fracture water sites indicates that the protein doubling time is $\sim 1$ year, not the centuries previously believed to be the case from simple geochemical models. This tells us that carbon uptake rates are governed by the rate of aspartic acid racemization and that the assumptions made in our biogeochemical models are wrong. We believe that they are wrong because these models do not consider extensive recycling of respired carbon, particularly CH\textsubscript{4}.

2) Combined $\delta^{13}$C and $^{14}$C analyses of lipids, DNA, DIC, DOC and CH\textsubscript{4} have revealed that $\sim 80$ kyr old biogenic CH\textsubscript{4} is the primary source of carbon for all bacterial lipids at depths up to 1.3 km. This is impressive given that methanogens comprise only $\sim 1\%$ of the total community.

3) Maggie Lau discovered from RNA analyses of 1 and 1.3 km deep fracture water the first record of the “active” deep subsurface microbial community and she has also discovered, with the help of many undergraduates, that methanogenic and N\textsubscript{2} fixation genes are actively being expressed. The active fixation of N\textsubscript{2} we believe indicates that N is relatively limited when compared to carbon sources and the energy available to metabolize them.

4) Ph.D. student Cara Magnabosco has discovered that methanogens are not active in the deeper fractures, but that the acetyl-CoA enzyme is broadly distributed amongst several species suggesting that CO\textsubscript{2} and perhaps CO is the source of carbon for these sites.
Incorporation of estimates into a risk management framework coastal flood risk as climate changes with a view toward
falling into three broad categories: 1) Developing a new, NOAA/GFDL lab collaboration with the
also modeling the underlying physical mechanisms, in
yielding new estimates of the rate of loss of the Antarctic
work. We developed an updatable Bayesian method
Borgonie, G., A. García-Moyano, D. Litthauer, W. Bert,


Recent relevant publications


My research over the past two years has largely fallen into three broad categories: 1) Developing a new, probabilistic approach to estimation of sea level rise and coastal flood risk as climate changes with a view toward incorporation of estimates into a risk management framework. We developed an updatable Bayesian method yielding new estimates of the rate of loss of the Antarctic ice sheet and its contribution to sea level rise. We are also modeling the underlying physical mechanisms, in collaboration with the NOAA/GFDL lab at the Forrestal Campus. 2) Evaluating impacts of climate change with an emphasis on human responses, particularly migration, with a heavy emphasis on statistical approaches. We have applied econometric statistical approaches both to large, state/national census data in the case of Mexico and province-level household survey data in the case of Indonesia and begun to unravel the specific causal relationships and channels through which climate changes influence migration. 3) Supervising and interpreting ethnographic research on expert assessment processes in order to develop an understanding of diverse institutional approaches to formulation of expert judgment with a view toward improving the process. After performing three interview-based case studies, including of Intergovernmental Panel on Climate Change (IPCC) assessments, we began a unique observational study on panels of the National Research Council.

I expect to extend the sea level rise/ice sheet work by applying our Bayesian estimation procedure to the other components (aside from ice sheets) of the sea level rise/storm risk problem. The climate/migration/impacts work will expand to explore outcomes of migration processes for sending and receiving regions. We have asked permission to expand the assessments study to allow direct observation of the IPCC assessments. A new area for research will be the application of Bayesian techniques to substitute for process-based modeling (where the latter cannot be sufficiently developed) in order to provide risk estimates for other physical aspects of the climate problem.

Recent relevant publications


The present is a precarious moment in the history of planet Earth. The dramatic amplification of climate fluctuations over the past 3Myr (million years)—see Figure 1—has brought us to one of the brief periods of temperate conditions that separate prolonged Ice Ages. The next Ice Age seems imminent, but a sharp rise in atmospheric CO₂ levels that started a century ago because of human activities is inducing global warming. What will the consequences be? Climate models provide answers but the uncertainties in the forecasts have remained frustratingly large over the past few decades, mainly because clouds are the Achilles heels of the models. Those ephemeral phenomena, which both cool the planet (by reflecting sunlight) and warm it (by providing a greenhouse effect) have a net cooling effect today, but what will it be in a world with higher CO₂ levels? The different answers from different models call for tests to determine which cloud parameterizations are the most accurate. The Last Glacial Maximum (LGM) some 20,000 years ago is, in principle, an excellent test because the lower atmospheric CO₂ levels at that time are known accurately. Models that reproduce LGM conditions should therefore be able to determine the relative contributions to those cold conditions of lower CO₂ levels and of an altered cloud-cover.

Unfortunately, uncertainties about LGM conditions are so large that it is unclear whether El Niño or its opposite La Niña prevailed in the tropical Pacific at that time. Conditions in the Pliocene and early Holocene, which could also serve as tests, are similarly topics of debate. The models can assist with the interpretation of the uncertain observations, but how can the observations then be used to test and improve the models? Weather prediction demonstrates how this can be done by means of a marriage of reductionist and holistic methods.

Up to World War II weather forecasting was a holistic exercise in identifying evolving patterns in complex maps drawn on the basis of data collected over vast areas. The invention of electronic computers capable of solving the equations that govern atmospheric motion introduced entirely different reductionist methods. Today weather forecasting is such a sophisticated interplay between observations and a hierarchy of models (from the highly idealized for explaining phenomena, to the complex for predicting weather) that forecast models whose development depends on observations, can detect errant observations. Can the methods of weather prediction be applied to climate forecasts?

The short time-scales of weather phenomena facilitate the acquisition of vast amounts of data for testing models. Climate lacks that advantage but has different assets: recurrent signals. The most familiar one, the seasonal cycle, has facilitated the development of climate models enormously because its climatology reduces uncertainties in the data (by identifying what all Januaries, Februaries etc. have in common), and because its complex spatial structure—the cycle is composed of different phenomena in different parts of the globe—is a stringent test for models. The cycle nonetheless has limitations: its brevity precludes the testing of gradual processes, those associated with decadal changes in the oceanic circulation. The records fortunately have three additional prominent cycles, related to Milankovitch forcing, variations in sunlight attributable to variations in orbital parameters.

Figure 1: Amplifying climate fluctuations (associated with Ice Ages) over the past 5 million years in a time-series of the isotope $\delta^{18}O$ from sediments on the ocean floor, which provides a measure of polar temperatures.
One member of the trio is the response to precession of the equinoxes which redistributes sunlight over the course of a year without altering the annual average. Precession is therefore forcing at the high frequencies of the seasonal cycle so that the response, a modified seasonal cycle, is energetic in the swift atmosphere—see the intensified monsoons in Figure 2a—is weak and sporadic in the slower ocean (Figure 2b), and is almost absent from the lethargic glaciers (Figure 2c). Another member of the trio is the response to variations in the tilt (obliquity) of the Earth’s axis which redistribute sunlight in space without affecting the global average. This alters the temperature gradient between the equator and poles, thus influencing the swift atmosphere, and the global oceanic circulation and glaciers too because, annually averaged, this forcing is non-zero. Its period, 40,000 years, is so long that the response is almost in phase with the forcing, with tropical sea surface temperatures rising and falling as glaciers wax and wane. From about 3 to 1Myr (million years) obliquity was the dominant signal, but then, around 1Myr, a third signal, in the shape of a saw-tooth became dominant in some records. What happened at that time? The relative importance of the three prominent signals changed around 3 and 1Myr ago even though there were no changes in the Milankovitch forcing at those times. This indication that the Ice Ages involve more than Milankovitch forcing raises the following question: are recurrent Ice Ages possible in the absence of that forcing? The answer is “yes” because feedbacks can sustain trends that lead to thresholds that reverse the trends. For example, the albedo feedback of glaciers can cause glaciers to grow until they are so huge that they become unstable—reach a threshold—disintegrate, and then start growing again. Around 3Myr ago the appearance of northern continental glaciers and of cold, cloud-covered equatorial waters, inevitable consequences of global cooling that started early in the Cenozoic, introduced albedo feedbacks that contributed to the cooling trend that persisted up to about 1Myr in Figure 1. At that stage additional feedbacks involving atmospheric dust and CO2 levels came into play, accelerated the trends, and made possible the saw-tooth. From this perspective, the Last Glacial Maximum was a threshold, as were the occasions 3 and 1Myr ago, so that disputes about conditions at those times are not surprising, and can be resolved by paying attention to the contrasts between preceding and subsequent conditions.

To Milankovitch, glaciers were isolated phenomena that wax and wane in response to local variations in sunlight, but the more plentiful data available now paint a far more complex panorama. There are three separate Ice Age cycles, each similar to the seasonal cycle in being composed of a suite of different phenomena in different parts of the globe, including glaciers in high latitudes and altitudes. Milankovitch forcing induces two of these cycles, but merely paces the third whose trends, sustained by feedbacks, reverse at thresholds. The response to precession is of special interest because it provides information about past seasonal cycles, and the effect of obliquity and saw-tooth cycles on the seasons. Since the superposition of the three signals changes continually—see the bottom panel of Figure 2—simulation of the seasonal cycle at different times amount to tests for theories and models. Such simulations are already producing valuable results, demonstrating which treatment of clouds enables a model to reproduce permanent El Niño conditions of the early Pliocene.

A marriage of methods that are reductionist in focusing narrowly on three recurrent signals, and holistic in subjecting models to a variety of tests from different occasions in the past, promises to help resolve disputes about past conditions, to provide explanations for the Ice Ages, and to assist with the development of improved models for the prediction of climate changes that global warming will bring.

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**Figure 2: Insolatio at 0°N on June 21 (red), a measure of precession, superimposed on normalized records of**

(a) The isotope δ18O in caves in southern China, a measure of local rainfall.

(b) Sea surface temperature in the eastern equatorial Pacific.

(c) The isotope δ18O in cores from the ocean floor, a measure of global ice volume

(d) Obliquity variations (in black).
Recent relevant publications


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In my work I combine numerical and analytical modeling with seismic, geodetic and laboratory observations, in order to better understand brittle deformation of the Earth's crust. Most recently I have been applying this approach to studying slow fault slip, earthquake nucleation and the micromechanics of friction.

One of the major geophysical discoveries of the past decade has been that of “episodic slow slip and tremor” in many of the world's subduction zones. Most known faults either slip steadily at the plate tectonic rate, or spend most of the time “locked” and slip only during brief earthquakes, with slip speeds of order m/sec and propagation speeds of order km/sec (the speed of sound in rock). Slow slip events, on the other hand, have average slip speeds of only ~0.1 μm/s and propagate up to 300 km along strike at remarkably consistent rates of ~10 km/day. In terms of energy release they are comparable to magnitude 6–7 earthquakes, but they last for weeks rather than seconds. They have the additional remarkable property that they recur quasi-periodically, at intervals ranging from several months to a few years, depending upon location.

Coincident in time and space with the geologically-observed slow slip is a new (to us) seismic signal termed “tectonic tremor.” Unlike typical earthquakes, which have impulsive P-wave and S-wave arrivals, tremor is a low-amplitude signal that can last for minutes to hours and that most often lacks clearly identifiable wave arrivals. Tremor is thought to consist of myriad “low frequency earthquakes” on the plate interface, comparable to magnitude 1–1.5 earthquakes in size but with durations roughly 10 times longer. The cause of this longer duration is unknown. Tremor has since been discovered on the deep extension of the San Andreas fault, about 10–15 km below the depth range of typical earthquakes. It thus provides an opportunity to probe the behavior of the deepest portions of plate boundaries.

In addition to representing a previously unrecognized style of fault slip, episodic slow slip and tremor are relevant to seismic hazards assessment. Slow slip increases the stressing rate on the locked portions of faults capable of producing magnitude 9 earthquakes. The up-dip extent of slow slip has also been interpreted by some as indicative of the expected down-dip extent of future major subduction-zone earthquakes. If correct, this would bring strong ground shaking considerably closer to downtown Seattle than had previously been thought. When slow slip was first discovered, the question for theoreticians was “How is it that slip over such a large region can accelerate but then decelerate without leading to an earthquake?” Now the problem is in some sense reversed; there are more proposed underlying mechanisms for slow slip than there are observational constraints to choose between them. My group works to obtain such observational constraints, and to conduct the numerical simulations necessary to narrow the range of plausible physical models of slow slip.

Some years ago graduate student Jessica Hawthorne used borehole strainmeter data to show that slow slip in Cascadia is modulated, at the tens of percent level, by the semi-diurnal tide. In 2013 she published 2 papers designed to use this observation to test one of the favored mechanisms of slow slip (the modulation, produced by tides whose amplitude can be estimated, is neither a few percent nor close to 100 percent). In the first paper she employed a fracture energy balance to derive the first physically-based estimate of the recurrence interval of slow slip in numerical simulations. With reasonable parameter values her models can reproduce observed slow slip stress drops, recurrence intervals, slip speeds and propagation speeds. Adding the tidal loading, she showed that to also produce the observed tidal modulation seems to require that one push the boundaries of reasonable parameter space more than one would like. In addition, the “back-propagating fronts” that arise naturally in the tidal simulations propagate more slowly than is observed. Together, these shortcomings indicate that to match existing observations requires more complicated friction laws or perhaps (in some not-yet-understood way) material heterogeneity. These are topics of ongoing research.

Because the spatial and temporal resolution of GPS data is quite poor, tremor locations currently provide the most detailed images of the space-time history of slow slip. Tremor catalogs from Cascadia, for example, and to a lesser extent Japan, have shown that in addition to the stately along-strike migration of the main slow slip front at ~10 km/day, secondary events arising behind the main front propagate up- or down-dip, or back along strike, at speeds tens to hundreds of
times faster. Nonetheless, because tremor lacks impulsive wave arrivals and can be active on multiple regions of the fault simultaneously, tremor cannot be located using standard earthquake location algorithms. For the past 2 years I have collaborated with John Armbruster at Lamont to develop a “cross-station” tremor detection/location algorithm, that correlates seismograms from the same event at different stations, as opposed to more common “cross-time” tremor location methods that correlate seismograms from different events at the same stations. Applied to southern Vancouver Island, our method has produced the most accurate tremor locations in the world, with relative errors of less than 1 km. This has generated high-resolution images of the rapid tremor migrations that arise behind the main slow slip front. Most often these secondary fronts start at or within about 1 km of the main tremor front and propagate back along strike, or propagate up- or down-dip at or within 1–2 km of the main front. Recently published and ongoing work involves combining observations of the width of the tremor fronts with numerical and analytical models, in order to interpret the different propagation speeds in terms of differences in slip speed and stress drops between the main and secondary events.

Graduate student Yajun Peng is now extending our cross-station algorithm to regions beneath Vancouver Island that require more elaborate data processing because of pronounced “shear-wave splitting” along the path from source to station. By correcting for this he is able to image larger contiguous regions on the fault and extend the range of behaviors we are able to observe. He is exploring the application of the method to seismic array data from the Olympic Peninsula to the south, and John Armbruster is having success applying the method in Japan. We hope to show that our high-resolution technique is widely applicable.

Running numerical models of slow slip requires adopting a constitutive law capable of describing the time-varying frictional strength of the host fault. The simplest class of laws that captures much of what is known about frictional sliding is termed “rate- and state-dependent friction,” meaning that the strength depends upon not only the sliding rate but also the “state” of the sliding surface (some combination of the true area of microscopic contact points and the intrinsic strength of those contacts). It is our lack of a detailed physical/chemical understanding of how “state” evolves, even in controlled laboratory environments, that makes applying numerical models of fault slip to the Earth such a difficult task. Graduate student Pathikrit Bhattacharya is continuing his work reinterpreting older rock friction data and conducting new friction/acoustic transmission experiments in Chris Marone’s lab at Penn State. Acoustic transmission is a new tool in rate-state friction studies, but very sensitive because it depends strongly on the “state” of the sliding surface (slower slip speed = larger true contact area = higher transmissivity across the fault). Surprisingly, Pathikrit’s re-analysis of decades-old laboratory data has shown that experiments that have long been interpreted as document-
My research interests include the global carbon cycle, the use of chemical tracers to study ocean circulation, and the impact of climate change on ocean biology and biogeochemistry. I wrote a textbook entitled Ocean Biogeochemical Dynamics published by Princeton University Press in 2006. Among my most highly cited publications are papers on ocean acidification, the role of the ocean and terrestrial biosphere in the global carbon cycle, the oceanic nitrogen and silicate cycles, the stoichiometric ratios of nutrients in oceanic organisms, and the impact of climate on the marine biosphere. Many of my scientific contributions have been on the role of the Southern Ocean in determining the air-sea balance of carbon dioxide during glacial and interglacial climate change, oceanic uptake of anthropogenic carbon and its sensitivity to climate change, and the resupply of nutrients to the upper ocean north of 30°S.

My current research group includes 2 graduate students and 6 postdocs. Many of my postdocs are co-supervised by Steve Griffies, John Dunne, and Charlie Stock as part of my longtime collaboration with the NOAA Geophysical Fluid Dynamics Laboratory (GFDL/NOAA) through the joint Cooperative Institute for Climate Science, of which I am Director. Some of my recent research publications addressed the impact of major volcanic eruptions such as Pinatubo on the carbon cycle due principally to enhanced uptake by terrestrial vegetation and the use of ocean measurements to estimate the ocean anthropogenic carbon uptake. In the area of climate & ocean circulation, we found that heat uptake in high latitudes is more effective at keeping the Earth cool than heat uptake in low latitudes and described a very large mechanism for subduction of upper ocean waters in the Southern Ocean due to formation of polynyas. In ocean biogeochemistry, we investigated vertical migration by zooplankton and its impact on the biological pump and the effect of large-scale nutrient fronts and their role as barriers and gateways to nutrient exchange. We explored the impacts of global warming on biological productivity and fisheries in the ocean through foodweb modeling and changes in the migrations of marine taxa in surprising directions, but always tracking temperature changes.

An additional major activity of my group over the past year-and-a-half has been to obtain NSF funding for a long-term study of Southern Ocean carbon and climate observations and modeling. Our goal is to put ~180 robotic Argo floats with biogeochemical sensors into the Southern Ocean. With this many floats, we would get 10x to 30x the number of biogeochemical profiles currently being obtained from ships. Part of this work includes an eddy permitting simulation of the global climate with a 1/10th degree ocean, work done in collaboration with GFDL/NOAA. In addition to my own group and collaborators at GFDL, external collaborators involved include Ken Johnson of MBARI, Lynne Talley of UCSD/SIO, Steve Riser of the University of Washington, Joellen Russell of the University of Arizona, and Heidi Cullen of Climate Central. I am very excited by this project, which I think will transform our understanding of the Southern Ocean.

More papers and projects can be found by visiting: https://www.princeton.edu/geosciences/people/sarmiento/publications/

Recent relevant publications


Following the elevation of the new radiogenic isotopes lab to “fully operational” status in 2012, much of my time has been invested in training students and post-docs in the lab such that now it is relatively self-sustainable, and generating world class U-Pb geochronological data. The research currently focuses on U-Pb geochronology of the minerals zircon andapatite, applied towards three ends. The first application involves using zircon as a vessel towards understanding the timescales of formation and geochemical differentiation of continental crust. Following detailed field campaigns involving geologic mapping and sample collection in the Alps and the continental US, the lab work pioneers new methods of combining zircon geochemistry with geochronology as a means of attaching absolute time constraints to geochemical processes in magmatic systems. This new approach can now be fully carried out on campus by using instrumentation at PRISM and taking advantage of existing and upgraded ICPMS instruments, which are now located in the Higgins laboratory in the sub-basement of Guyot. Both the field and lab data are used in unison to gain a better understanding of where, how, and how long it takes to differentiate mantle-derived basaltic magma into the higher-silica igneous rocks that make up the continental crust. An outgrowth of this work is a better understanding of the rates of heat transfer and rheological change in the continental crust during subduction and collision-related magmatism. Graduate students Kyle Samperton and Brenhin Keller and recently-departed postdoc Mélanie Barboni are all working on projects related to continental crust formation.

The second main application of zircon U-Pb geochronology being pursued in the lab relies on dating magmatic zircon from volcanic ash beds intercalated within sedimentary strata as a means of calibrating events in earth history. Sedimentary rocks are the primary record keeper of events in earth history that relate geologic, biologic, atmospheric and oceanic processes, and understanding these processes often requires absolute time constraints from geochronology. Graduate student Jon Husson is currently applying these methods to provide a new age for the Silurian-Devonian boundary and calibration of the rates for the associated carbon isotope excursion in Helderberg group, New York. Husson’s main thesis project, done in collaboration with Profs. Adam Maloof and John Higgins, involve building a detailed litho- and chemostratigraphic record of the Wonoka Fm., South Australia, which records the deepest carbon isotope excursion in earth history. The origin of the carbon isotope excursion remains unknown, but has received much attention, in part because it follows several Cryogenian snowball earth glaciations and precedes the Cambrian biotic explosion.

In addition to ongoing work calibrating the rates and causes of mass extinction and biologic recovery associated with the Triassic-Jurassic transition ca. 200 Ma, a new collaboration with Prof. Gerta Keller attempts to date the eruption of the Deccan traps large igneous province. This giant volcanic sequence has been implicated as a driver in the end-Cretaceous extinction event, which killed the dinosaurs among other flora and fauna ca. 65 Ma. Following a successful field campaign with graduate student Kyle Samperton, undergraduate Preston Kemeny, and a graduate student collaborator from MIT (Mike Eddy; Princeton undergraduate ’11), we are currently processing samples to extract and date zircons that constrain both the timing of onset and duration of the traps (with some success so far!). These data will be critical to build a detailed timeline of events that relate the extinction, the volcanic eruptions, and of course the famous meteorite impact that is also implicated in this disaster.

A new research project got underway in the summer of 2013, which in many ways harkens back to my Ph.D. thesis research, which involved understanding the rates and mechanisms of plate tectonics during the Archean (2.5-4.0 billion years ago). Adam Maloof, two graduate students (Scott MacLennan and Jenn Kasbohm), an undergraduate field assistant and I spent the month of June in western Australia mapping and collecting samples for two projects that integrate paleomagnetism, geochronology, and U-Pb thermochronology, to understand vertical and horizontal plate motions of the Pilbara craton between 3.4 and 2.7 billion years ago. These projects address the question of whether or not plate tectonics existed in the Archean and if so, whether these processes are the same as they are now despite conjecture about higher mantle and crustal temperatures at that time.

An ongoing, non-geochronological research focus involves the work of graduate student Brenhin Keller, involving the development of new statistical techniques applied to the growing availability of online geochemical databases. By learning and applying techniques developed in other fields more adept at dealing with big data, we have managed to extract signals out of the geochemistry of igneous rocks over 4 billions years of Earth history. These data tell an often speculated, but never quantified, story of Earth’s cooling and its effect on the processes related to formation of Earth’s lithosphere and continental crust. This work is ongoing and expanding into collaboration with Prof. Simons. It has garnered much interest that will continue to be a focus of mine in an effort to bring geochemistry into the era of Big Data.
More papers and projects can be found by visiting: www.princeton.edu/geosciences/people/schoene/publications/

Recent relevant publications


My goal is to understand how chemical, biological, physical and geological processes interact to yield the large-scale stable cycles that characterize Earth’s environment. When the focus is on chemical elements, these cycles are known as the “biogeochemical” cycles. The measurements that I bring to this goal are of the stable isotope ratios of nitrogen-bearing chemicals (most importantly, the $^{15}\text{N}$-to-$^{14}\text{N}$ ratio). Nitrogen is an element required in large quantities by life and frequently limits the productivity of ecosystems. Moreover, unlike the other similarly fundamental nutrient phosphorus, it has two stable isotopes, allowing for isotope ratio measurement. The component processes of the nitrogen cycle discriminate between the isotopes of nitrogen, opening an avenue for reconstructing the nitrogen cycle, both today and in the past.

My focus is on the ocean, for three major reasons. First, the interaction of the surface ocean with the atmosphere and the circulation and mixing of the water throughout the ocean lead to a spatial structuring of environments that is in many ways simpler than on land, making the ocean conducive to large scale quantitative integrations of physical and biogeochemical processes. Second, marine sediments provide a record of the past that is more continuous in time and space than is typically found on the continents. Third, the ocean’s biogeochemical cycles and circulation are central in setting the atmospheric concentration of $\text{CO}_2$ and regional and global climate. One of my major interests is the role of the ocean in the ice age cycles of the last three million years, in particular, in the changes in atmospheric $\text{CO}_2$ that parallel these past climate changes.

The modern global environment represents only a snapshot of a system that contains cycles and feedbacks operating on multiple time scales. Nevertheless, the modern environment is available for detailed study, of central concern to humanity, and in some ways undergoing dramatic change. Accordingly, the present is studied in its own right, as a basis for interpreting natural records of past changes, and in turn as the product of all that has come before. My early contributions to studies of the modern ocean involved the development and application of novel, high-sensitivity methods for measuring the isotopic composition of dissolved nitrogen forms such as nitrate ($\text{NO}_3^-$) and dissolved organic nitrogen. Dissolved nitrogen forms represent most of the biologically available nitrogen in the ocean, and thus their isotopic analysis provides a more integrative view of the ocean nitrogen cycle than is revealed by traditional isotopic measurements of particulate organic matter floating in or sinking through the water. My group has also harnessed the high sensitivity of our methods to allow us to analyze specific classes of particles in the ocean, allowing us to distinguish between living and dead organic matter or photosynthetic and non-photosynthetic cells and to measure the isotopic composition of specific taxa of phytoplankton.

My analytical focus in paleoceanographic and Earth history studies is on what can be learned from the isotopic composition of organic matter trapped within marine fossils. My group’s unique capabilities in this area also derive from our innovations with high-sensitivity nitrogen isotopic analysis. Most of our work to date has been on siliceous diatom microfossils recovered from sediment cores from high latitude regions and calcareous planktonic foraminifera microfossils from diverse locations. Recently, we have begun investigations of stony corals, both the corals that dominate shallow reefs and deep-dwelling corals.

Two sets of questions have motivated much of my work:

(1) The polar oceans are special domains in the ocean where the “major nutrients” nitrogen and phosphorus are not completely consumed by algal growth. What factors control the physical conditions and nutrient status of the polar surface ocean? Over the ice age/interglacial cycles of the last 3 million years, how have the characteristics of the polar ocean affected other regions of the ocean, atmospheric carbon dioxide, and global climate?

(2) The tropical, subtropical, and temperate ocean is largely characterized by nutrient impoverishment. Thus, the nitrogen inputs to these systems and the global ocean’s nitrogen budget are central to understanding the controls on their fertility. What terms and rates compose the budget of “fixed” (biologically available) $\text{N}$ in the modern ocean and the rate at which fixed nitrogen is delivered to surface waters? What are the sensitivities of the different inputs, outputs, and internal fluxes? How have the nitrogen fluxes in these systems changed over climate cycles, and how have these changes affected the fertility of ocean?

Our larger goals in this work are two-fold. First, we seek to provide insight into the connections among the carbon cycle (e.g., atmospheric $\text{CO}_2$), ocean biogeochemistry, and climate that will help to understand and predict the large-scale, long-term environmental effects of human activities. Second, we seek ultimately to integrate our findings into a simple theory for the diverse stabilizing feedbacks that appear to characterize the Earth’s biosphere and its interactions with the non-living Earth. In other words, we seek to understand why the Earth is such a stable platform for life as well as what drives the substantial environmental variations that have occurred in Earth’s past.
Of course, the isotopic measurements of nitrogen are but one set of measurements that can contribute to the questions above. Accordingly, my group makes use of a broad range of other measurements, especially through our collaborations with the group of my long term colleague Gerald Haug, at ETH Zurich. In addition, my first experiences in paleoceanographic research involved the construction and application of numerical models of the ocean/atmosphere carbon cycle, and numerical modeling is an important tool in the work of my graduate students and postdoctoral advisees.

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Recent relevant publications


My research over the last year can be summarized in a few broad categories.

Lithospheric flexural rigidity

The detailed consideration of the statistical nature of some geoscientific problems primes them for new discovery. What is the elastic thickness of the lithosphere? Some maintain that old continents respond elastically to tectonic loading and mountain building over a thickness well exceeding 100 km, but some argue instead that all the elastic strength resides in a merely 25 km thick upper region. The debate has profound implications for understanding the generation of crustal earthquakes and the long-term maintenance of stability through elastic forces in the shallow lithosphere. Both interpretations use the very same data: topography and gravity anomalies. Why are the conclusions so divergent? At the largest scales, gravitational anomalies express terrestrial dynamics such as mantle convection. At shorter scale lengths they reflect perturbations to the density structure some tens of km below the surface. In some places an isostatic balance prevails: mountains float like icebergs with roots in the deformable mantle. Where isostasy fails to explain the data, elastic, flexural stresses may support topography. Mountain-building, magmatic and other geological processes are loads that perturb an undisturbed and layered state, thereby producing gravitational anomalies. We know the differential equations that express the balance of inputs and outputs but we do not know the inputs precisely, and we only observe the sum of the outputs: gravity anomalies and surface topography. Mathematically speaking, the flexural strength is the unknown parameter of the system of differential equations. Geologically speaking, it is the depth to which elastic effects play a role in shaping the Earth’s surface. Geophysically, this quantity has much bearing on the overall rheology, or deformation-behavior, of the lithosphere, and thereby on processes such as the generation of earthquakes at depth. Vastly differing estimates have fueled the thick-versus-thin lithosphere debate. Sofia Olhede, a professor of statistical science at University College London, and I showed that reformulating the problem in a form amenable to maximum-Whittle-likelihood theory yields unbiased, minimum-variance estimates of flexural rigidity and
some auxiliary quantities, separably resolved. We derived the properties of the estimators and then showed how they can be found by a computational implementation of theoretical results that also yields analytical forms for their variance. Our procedure is well-posed and computationally tractable. The resulting algorithm is validated by extensive simulations whose behavior is well matched by an analytical theory. There are numerous tests for its applicability to the real-world situations that we are currently investigating.

**Ice mass loss over Greenland and Antarctica**

Spatiospectral analysis techniques have principally advanced the study of Earth’s time-variable gravity field, primarily through observations made by the ongoing paired-satellite Gravity Recovery And Climate Experiment (GRACE) mission. Gravitational acceleration measured by satellites varies on spatial scales: mapping out these variations was for a long time the dominant source of information on plate tectonics and mantle dynamics, down to the mineral-exploration and engineering scales. About a decade ago GRACE was launched with the objective to map gravity variations on temporal scales ranging from the monthly to the decadal. The data are noisy, incomplete, and collected on a roughly spherical surface, at satellite altitude. Reanalyzing existing data using optimized “Slepian” basis functions has allowed us to push the accuracy of time-variable gravity mapping to much smaller spatial scales than was previously possible. Associate Research Scholar Chris Harig and I lately have been focusing on the estimation of the slow but steady mass changes, presumably due to ice melting, that are observable in the time-variable gravity field over Greenland and Antarctica. Literature estimates based on the GRACE data products have shared two fundamental aspects. First, they have disagreed, sometimes by a factor of two, on the magnitude of the trend (mass is being lost, melting occurs, but how fast?) and on whether or not the trend has been accelerating as of late (in the last few years, compared to the decadal record of data available). Second, they have been mostly concerned with estimating spatially averaged mass loss, without much sensitivity to regional patterns. We finalized Slepian-based estimates for Greenland and Antarctica, which we consider the best to date, both in constraining the average mass change trend and its temporal evolution. Most importantly, we obtained maps of where in Greenland and Antarctica the mass changes are concentrated. In ongoing work we are applying the Slepian-function methodology to less “derived” data products from the GRACE mission, reducing model uncertainty even further by staying closer in the inversion to the inter-satellite distance and acceleration data actually collected.

**Spatio-spectral localization**

Post-doc Alain Plattner and I finished a number of papers on the theoretical aspects of spatiotemporal localization on the sphere for vector-valued functions, developing a complete inversion procedure for, e.g., geomagnetic satellite data. One of the objectives of such satellite missions is to map the lithospheric field, which contains much information about the structure and plate-tectonic evolution of our planet. Amazingly, while the instruments sent out into orbit are vector magnetometers, the data are usually analyzed one component at a time, and often two of the components are not being considered for analysis at all. Our new procedure is a comprehensive analysis method that is able to consider the joint information contained in the fully vectorial data collected at satellite altitude, and with our method, we intend to reanalyze both terrestrial and planetary data sets.

**Lithospheric structure of Venus**

Associate Research Scholar Kevin Lewis, Research Specialist Gabe Eggers, and I worked on the lithospheric structure of Venus. We are using the maximum-likelihood method that I described above to study the spatial covariance structure of the Venusian topography, gravity, and how those two fields interrelate. Our results have implications once again for understanding the structure and evolution of our “sister planet”, which, despite being so similar in many respects looks almost nothing like our own Earth: a caveat that should be heeded by all those studying “Earth-like” exoplanets (on which we have far less information than what we know about Venus!).

We used historical data collected by the Magellan spacecraft, and an important part of our study is to spell out the limitations of these relatively ancient (25-year old) mission data in order to motivate future missions to Venus.

**The Son-O-Mermaid project**

In global seismic tomography inference about the Earth is made on the basis of many hundreds of thousands of seismogram records: an inverse problem with many millions of unknowns. These unknowns are the three-dimensional description of the spatial distribution of seismic wave speeds inside the Earth, from which we derive detailed geological, geochemical, geodynamical and mineralogical images of the inner workings of our planet. There continues to be a need to improve parameterization in seismic tomography. And, there is a need to remediate the problem of having no data at all, via the design of new instrumentation for the oceans. However sophisticated our theory or performant our algorithms, nothing solves a fundamentally data-limited problem but the acquisition of new measurements. We may have vast numbers of seismograms and the capability to model them into a geologically significant understanding of the Earth, but the oceans covering two-thirds of the globe are largely inaccessible to instrumentation. My longest-horizon project has been the development of marine devices to remediate the fundamental inability to learn anything about those regions of the Earth’s mantle not visited by instrumentally recorded earthquake waves. Picking up even hundreds of such measurements in areas never before sampled is the goal of the MERMAID and Son-O-Mermaid projects. Our development of the MERMAID prototype led to several additional publications leveraging my algorithms of data detection and discrimination.
in the context of earthquake early-warning studies and
is now, thanks to Prof. Em. Guust Nolet, operational in
the Mediterranean and beyond. One Son-O-Mermaid has
been built by Bud Vincent at URI and is being scaled up
for scientific testing. Designed to overcome the remain-
ing hurdles that face MERMAID, Son-O-Mermaid is a
long-lived, freely drifting, GPS-enabled buoy that derives
energy from wave action, enough to power a vertical
array of hydrophones, a full-ocean-depth echo sounder, an
IRIDIUM satellite communication unit for near real-time
data transfer, and a digitizing and processing unit that
uses sophisticated wavelet detection and discrimination
algorithms. The Son-O-Mermaid is to be deployed by
untrained personnel from ships of opportunity, which
provides it a substantial cost advantage over conventional
e.g., ocean-bottom, tethered, moored) data collection
approaches. The many challenges overcome in building
this instrument specifically for seismology set very high
bars in terms of energy efficiency, instrument accuracy,
and longevity. Future generations of it will be easily adapt-
ed—continued funding being the rate-limiting step—to
less demanding data gathering exercises, be they physical,
chemical, or biological.

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Recent relevant publications
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Recent relevant publications


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Nitrogen (N) is a key element in all of biology because it is a major component of proteins and nucleic acids. Because biologically available nitrogen is often present in the surface ocean at vanishingly low concentrations, nitrogen is often the element that limits, and therefore controls, primary production. The biogeochemical processes and microbial pathways that control the inventory and distribution of fixed nitrogen in the ocean are the focus of research in my research group. I have led a series of oceanographic research cruises in recent years to the Pacific and Atlantic Oceans to study nitrogen cycling. Using a combination of chemical measurements, experimental manipulations with stable isotope tracers, and molecular biological data, the Ward lab measures the rates of nitrogen transformations and evaluates the biodiversity and community composition of the microbes involved.

Loss of fixed nitrogen

Two processes, denitrification and anaerobic ammonium oxidation (anammox), are responsible for the transformation of dissolved inorganic nitrogen, which is biologically available, into dinitrogen gas, which most organisms cannot use directly. Thus denitrification and anammox control the inventory of fixed N. These processes occur only in the absence of oxygen, so there are only a few places in the open ocean where they occur. Research cruises to the Eastern Tropical North Pacific (off Mexico in 2012) and the Eastern Tropical South Pacific (off Chile and Peru in 2013) were carried out in order to study N cycling in anoxic waters. Ward’s group was recently instrumental in resolving a controversy over which of the two N loss processes is most important. As summarized in a perspective (Ward 2013), the ratio between the two processes is largely determined by the elemental composition (stoichiometry) of the organic matter that fuels the metabolism of denitrifying bacteria. Thus the loss of fixed N is tightly coupled to primary production in surface waters, which is in turn controlled by the availability of fixed N. The group also studies the same loss processes in coastal sediments and salt marshes, where they produce and consume nitrous oxide but are not as tightly constrained by organic matter composition due to the much larger supply of fixed N.
Nitrogen assimilation by phytoplankton

Long the subject of oceanographic research, N uptake by phytoplankton still poses interesting problems. Ward’s current work in this area addresses the question of which types of phytoplankton use which forms of nitrogen (e.g., nitrate vs ammonium). Larger types of phytoplankton appear to be relatively more important in utilizing nitrate, even though it is present at really low concentrations in the surface water most of the time (Fawcett and Ward, 2011; Fawcett et al 2011). On research cruises in the North Atlantic (Sargasso Sea in 2012 and 2013 and Subarctic North Atlantic near Iceland in 2013 and 2014), experimental incubations were used to measure the rates of N assimilation by the phytoplankton assemblage. Physical separation of different groups by flow cytometric sorting will be used to figure out which kinds of phytoplankton assimilated which forms of N. Functional gene microarrays and transcriptomic sequencing will help to identify the composition and diversity of phytoplankton assemblages involved.

Nitrification

This is the microbial process that oxidizes ammonium to nitrate and thus completes the N cycle by providing the substrates that denitrification and anammox use in the N loss pathways. Nitrification also supplies nitrate in the upper ocean, where it can be used by phytoplankton. Ward’s early work established the basic picture of nitrification in the ocean, showing that the rate of nitrification is usually minimal in the surface will lit zone of the ocean, reaches a maximum near the bottom of the photic zone, and the decays with increasing depth (Ward 2008). Although nitrification occurs at very low rates in the surface ocean, it is still an important source of nitrate for phytoplankton, and the linkage between nitrification and phytoplankton N demand is the subject of current research. Likewise the links between nitrification and N cycling in the oxygen minimum zones is also being investigated, along with the role of nitrification and denitrification in the production and consumption of nitrous oxide.

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Recent relevant publications


Associated Programs

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