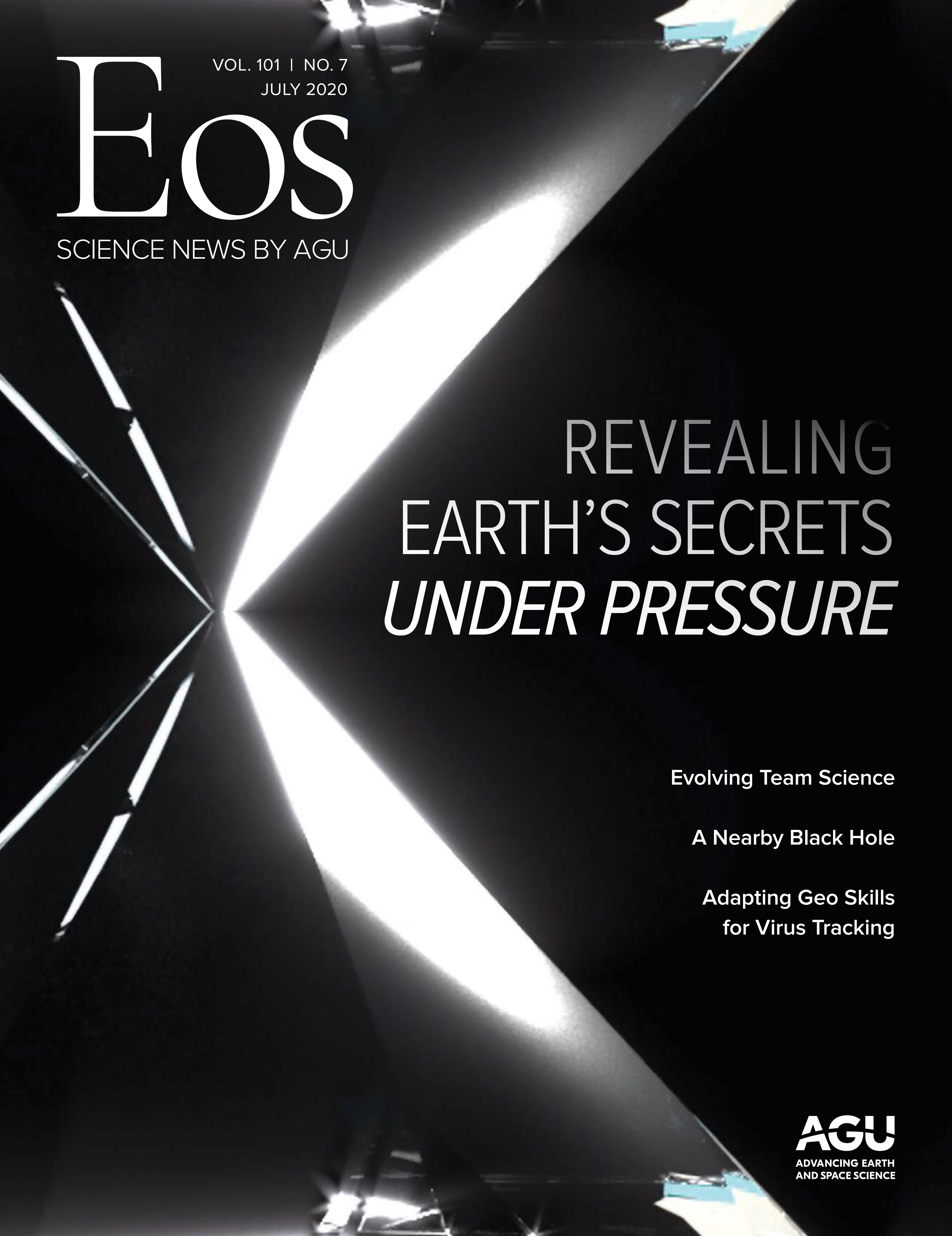


Eos

VOL. 101 | NO. 7
JULY 2020

SCIENCE NEWS BY AGU

REVEALING EARTH'S SECRETS *UNDER PRESSURE*

Evolving Team Science

A Nearby Black Hole

Adapting Geo Skills for Virus Tracking

AGU
ADVANCING EARTH AND SPACE SCIENCE


MATLAB SPEAKS
MACHINE
LEARNING
With MATLAB® you can use clustering, regression, classification, and deep learning to build predictive models and put them into production.
mathworks.com/machinelearning
MathWorks®
@2020 The MathWorks, Inc.

A Dive into the Deep Earth

Around 50 years ago, scientists interested in the composition, mineralogy beneath the Earth's surface and other related questions were spread throughout many disciplines: tectonophysics, petrology, and geomagnetism, among others. When they began organizing their research under a new name—mineral physics—"it became evident that new scientific advances would provide dramatic progress in our understanding of Earth's interior," writes Robert Cooper Liebermann in his retrospective of AGU's Mineral and Rock Physics section on p. 24.

Our July issue, which looks at those scientific advances that came from developments in high-pressure and high-temperature experimentation, is guided by insight from Sébastien Merkel, *Eos* science adviser and president-elect of the Mineral and Rock Physics section. (We also extend our appreciation to section president Wenlu Zhu for additional support.) Now a professor at the Université de Lille in France, Merkel studied physics in undergraduate school and realized that he could bring a new viewpoint to the research going on in the geology department. "I thought that re-creating planetary interiors in the lab was a fun thing," Merkel told me. And you can't beat the tech: "We run experiments in large-scale facilities with synchrotrons and high-power lasers. I like being in contact with and learning how to master those beasts."

That powerful equipment is being harnessed to explain the "new core paradox" ("Earth's Core Is in the Hot Seat," p. 36). Researchers had largely assumed that the inner core was about as old as Earth itself until an explosive 2013 paper on high-temperature experiments suggested that it was rapidly cooling—and very young, perhaps a billion years old or less. Diamond anvil cells were brought in to the field, producing new papers and a conversation on errors. "This is exciting stuff," University of Santa Cruz's Quentin Williams told *Eos* for the article. These questions "will pose a challenge for the next 15 years for the community."

Earth isn't the only planet whose insides we'd like to peer into. "The experiments for studying the interiors of other planets are very new," said Merkel. "When I was a student, we could not even dream of measuring anything at those conditions." In "Remaking a Planet One Atom at a Time" (p. 30), we report on scientists using mechanisms such as dynamic compression from high-energy optical lasers to create pressures as high as a billion atmospheres. These lasers, with as much power as a bolt of lightning, have shown us that liquid helium rains down on Saturn. And scientists are looking even farther away. "We can actually say something on the structure of exoplanets, thanks to lab experiments," said Merkel. "This is amazing."

This issue features only a small look into the potential of mineral physics. The future of these extreme experiments may provide answers to some of our most fundamental questions: How did Earth evolve from a ball of molten rock into a planet that supports life? How could it happen on other planets? What is Earth's core made of besides iron? How much water is inside Earth, and how does it affect the planet's water cycle? What are the mechanical and chemical properties that make Earth, Mars, and Venus so different?

The next generation will be pursuing these questions, which is why we began this issue with words from a mentor. "Bob [Liebermann] has trained and motivated a whole generation of scientists," said Merkel. "He was always supportive, dynamic, and community driven." Liebermann notes in his article the rise of women directing mineral physics labs and the establishment of graduate student support and early-career awards. Here at *Eos*, we are excited to watch the mineral physics community continue to grow and diversify so that it can discover answers to all of these planetary mysteries.

Heather Goss, Editor in Chief

Eos AGU ADVANCING EARTH AND SPACE SCIENCE

Editor in Chief

Heather Goss, AGU, Washington, D.C., USA; Eos_EIC@agu.org

AGU Staff

Vice President, Communications, Marketing,and Media Relations — **Amy Storey**

Editorial

Manager, News and Features Editor — **Caryl-Sue Micalizio**
Science Editor — **Timothy Oleson**
News and Features Writer — **Kimberly M. S. Cartier**
News and Features Writer — **Jenessa Duncombe**

Production & Design

Manager, Production and Operations — **Faith A. Ishii**
Senior Production Specialist — **Melissa A. Tribur**
Production and Analytics Specialist — **Anaise Aristide**
Assistant Director, Design & Branding — **Beth Bagley**
Senior Graphic Designer — **Valerie Friedman**
Graphic Designer — **J. Henry Pereira**

Marketing

Director, Marketing, Branding & Advertising — **Jessica Latterman**
Assistant Director, Marketing & Advertising — **Liz Zipse**

Advertising

Display Advertising — **Dan Nicholas** dnicholas@wiley.com
Recruitment Advertising — **Kristin McCarthy** kmccarthy@wiley.com

Science Advisers

Geomagnetism, Paleomagnetism, and Electromagnetism — **Julie Bowles**
Space Physics and Aeronomy — **Christina M. S. Cohen**
Cryosphere — **Ellyn Enderlin**
Study of the Earth's Deep Interior — **Edward J. Garnero**
Geodesy — **Brian C. Gunter**
History of Geophysics — **Kristine C. Harper**
Planetary Sciences — **Sarah M. Hörst**
Natural Hazards — **Michelle Hummel**
Volcanology, Geochemistry, and Petrology — **Emily R. Johnson**
Societal Impacts and Policy Sciences — **Christine Kirchhoff**
Seismology — **Keith D. Koper**
Tectonophysics — **Jian Lin**
Near-Surface Geophysics — **Juan Lorenzo**
Earth and Space Science Informatics — **Kirk Martinez**
Paleoceanography and Paleoclimatology — **Figen Mekik**
Mineral and Rock Physics — **Sébastien Merkel**
Ocean Sciences — **Jerry L. Miller**
Global Environmental Change — **Hansi Singh**
Education — **Eric M. Riggs**
Hydrology — **Kerstin Stahl**
Tectonophysics — **Carol A. Stein**
Atmospheric Sciences — **Mika Tosca**
Nonlinear Geophysics — **Adrian Tuck**
Biogeosciences — **Merritt Turetsky**
Hydrology — **Adam S. Ward**
Diversity and Inclusion — **Lisa D. White**
Earth and Planetary Surface Processes — **Andrew C. Wilcox**
Atmospheric and Space Electricity — **Yoav Yair**
GeoHealth — **Ben Zaitchik**

©2020. AGU. All Rights Reserved. Material in this issue may be photocopied by individual scientists for research or classroom use. Permission is also granted to use short quotes, figures, and tables for publication in scientific books and journals. For permission for any other uses, contact the AGU Publications Office.

Eos (ISSN 0096-3941) is published monthly by AGU, 2000 Florida Ave., NW, Washington, DC 20009, USA. Periodical Class postage paid at Washington, D.C., and at additional mailing offices. POSTMASTER: Send address changes to Member Service Center, 2000 Florida Ave., NW, Washington, DC 20009, USA

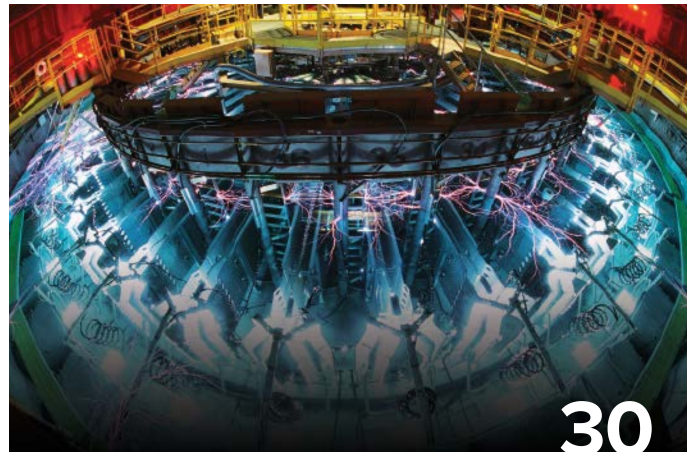
Member Service Center: 8:00 a.m.–6:00 p.m. Eastern time; Tel: +1-202-462-6900; Fax: +1-202-328-0566; Tel. orders in U.S.: 1-800-966-2481; service@agu.org.

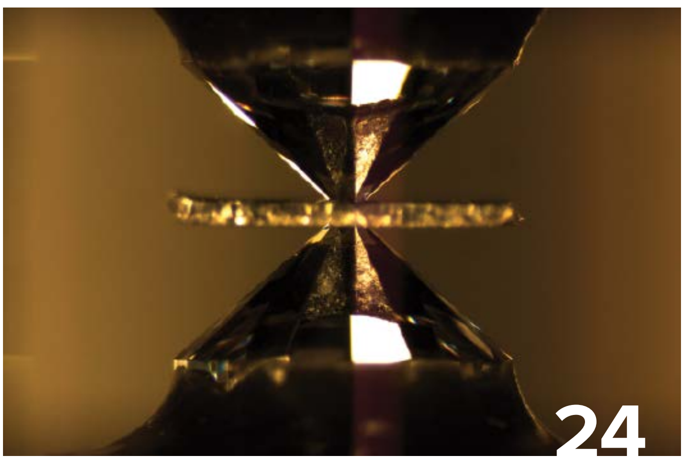
Submit your article proposal or suggest a news story to *Eos* at bit.ly/Eos-proposal.

Views expressed in this publication do not necessarily reflect official positions of AGU unless expressly stated.

FSC www.fsc.org MIX Paper from responsible sources FSC® C022085

AN ENVIRONMENTALLY FRIENDLY INK SYSTEM AGRIWEB a trademark of Flint Group





Features

On the Cover

Credit: volmon@tut.by/Depositphotos.com

Columns

AmericanGeophysicalUnion @AGU_Eos company/american-geophysical-union AGUvideos americangeophysicalunion americangeophysicalunion

Routine Monitoring Weathers the Pandemic Storm

Paul Schauer runs a level survey for a 2015 streambed scour project in Seward, Alaska, one of many U.S. Geological Survey projects that rely on regular monitoring processes. Credit: USGS

People throughout much of the United States have been strongly encouraged to shelter in place since mid-March to prevent the spread of coronavirus disease 2019 (COVID-19).

But the processes that shape Earth and its ecosystems, like the rising and falling of tides, the shifting of underground rock, and the blooming of algae in the ocean, have not come to a halt. And these processes—some of which can lead to more loss of life—require routine monitoring.

Routine monitoring involves collecting real-time data with a suite of instruments and in situ observations. Some sensors can be left for months or years at a time, but they also might fail or need maintenance. And during a time when all of us are told to stay at home, when scientists are forced to delay fieldwork and research campaigns, what does that mean for the monitors?

Earthquakes

"Earthquakes do not stop during epidemics," said Lucia Margheriti, senior researcher at the Istituto Nazionale di Geofisica e Vulcanologia in Rome. The Italian government issued strict stay-at-home orders on 8 March, when Margheriti and her team began working remotely. However, a team must be on site in the lab at all times, so the group has implemented extreme cleaning and social distancing protocols when in the same building.

Shelter-in-place orders haven't affected day-to-day monitoring operations for seismologists working for the Pacific Northwest Seismic Network (PNSN). After all, earthquakes can happen any time of day or night, said Harold Tobin, PNSN's director, Washington's official state seismologist, and a faculty member at the University of Washington. Seismologists have protocols in place for when an earthquake occurs outside normal working hours. Even without shelter-in-place orders, there's always an "on-duty" seismologist ready to be woken up at 2:00 a.m. to respond to an emergency.

"One thing that came up very early was just the fact that you can't shut down monitoring, because it's a public safety system," Tobin said.

However, the pandemic has interrupted the rollout of ShakeAlert, a system that will provide up to tens of seconds of warning before an earthquake might occur in Oregon and Washington. (California's ShakeAlert network went online at the end of 2019.) The system needs at least 100 more seismic stations to be complete, Tobin said. That requires groups of people to work together, conduct site visits, and install equipment within close quarters.

Amid the new era of social distancing, the ShakeAlert scientists won't be able to install new stations. The U.S. Geological Survey had planned to publicly roll out ShakeAlert this fall, but with the delay in new seismic stations and the fact that Washington's state emergency team had to turn their focus to the spreading pandemic, ShakeAlert will have to wait.

The Coast

In Pacific Northwest waterways, buoys in need of maintenance have been left unattended, and buoys ready for deployment can't go out yet, said University of Washington oceanographer Jan Newton. She's the executive director for a regional branch of the Integrated Ocean Observing System (IOOS), which uses various sensors to provide real-time data for things like acidification, temperature, wind speeds, and tides to private and public entities.

Newton describes IOOS as a set of "scientific oceanographic observations, but with the intention of societal benefit"—the oceanographic version of the National Weather Service.

A single buoy in Washington State's Puget Sound, for instance, could be simultaneously providing acidification data for shellfish growers, temperature data for scientific models, meteorological data for navigation purposes, and phytoplankton data to track the development of harmful algal blooms.

"People do depend on these data for things like safe navigation for making their livelihood," Newton said.

With shelter-in-place orders, IOOS employees can't do routine maintenance on their gear, some of it aging and without a replacement. For instance, an ocean acidification buoy was supposed to deploy in April, but its instruments weren't recalibrated in time because the sensor industries were also affected by shelter-in-place protocols.

Small industries, like mom-and-pop companies that take customers out fishing, "are going to be the ones that need to be fully functional," Newton said.

The Mountains

For Amanda Henderson and her colleagues at the Rocky Mountain Biological Laboratory, situated about 320 kilometers southwest of Denver, some monitoring work involves hiking or cross-country skiing into remote locations to measure vegetation or snowmelt. And doing fieldwork during a pandemic brings up a tricky conundrum.

"Being alone is safest, but given the realities of our environment, being with another person is ultimately more safe," said Henderson, who studies snowmelt around Gunnison County in the spring to understand how it affects the local waterways and the Colorado River. Some of her colleagues have to cross-country ski nearly 20 kilometers to get to their study site. In that case, they decided to drive to the trailhead separately and maintain the recommended 2 meters apart while working.

Henderson's own snowmelt monitoring work can be done solo, she said, so she's comfortable continuing to do her own routine monitoring.

The Weather

Matt Kelsch, a hydrometeorologist and weather enthusiast in Boulder, Colo., is part of the National Weather Service's Cooperative Observer Program, a weather observing network that's been in place since 1891. Across the United States, thousands of volunteers take daily weather measurements of temperature and precipitation. And because many of these stations were set up on private property, Kelsch said the weather network probably isn't much affected by shelter-in-place orders.

These weather stations are used to create long-term climatology records for regions across the United States. The records can be used by a number of groups, including scientists studying climate change and insurance companies confirming whether damage to a car was from hail, Kelsch said.

Weather forecasts could still be affected, however. These days, many commercial flights carry weather sensors, and the airline industry has seen a significant drop in traffic since the novel coronavirus came to the United States. For example, the United States saw a 73.3% decrease in air traffic in April 2020 compared with April 2019. On 7 May, the World Meteorological Organization reported a 75%–80% decrease in meteorological observations from flights. (In the Southern Hemisphere, the decrease is close to 90%.) Before the pandemic, commercial flights provided more than 800,000 meteorological observations per day.

"Even though a decrease in this critical data will likely negatively impact forecast model skill, it does not necessarily translate into a reduction in forecast accuracy, since National Weather Service meteorologists use an entire suite of observations and guidance to produce an actual forecast," said National Oceanic and Atmospheric Administration spokesperson Susan Buchanan in a statement released 24 March.

By **JoAnna Wendel** (@JoAnnaScience), Science Writer

Venus Exploration Starts in the Lab

The inside of the Glenn Extreme Environments Rig (GEER) is 1 cubic meter in volume, or about 3 feet wide × 4 feet long. Credit: GEER/NASA Glenn Research Center

In March of 1982, the Soviet spacecraft Venera 13 landed a probe on the surface of Venus. It sent back the first color photographs from the surface of another planet, revealing that Venus has a desolate landscape to match its hellish atmosphere. The probe collected and analyzed a sample of the rocky surface, and its acoustic detector measured vibrations from the wind.

Venera 13 sent back some of the best data we have to date about Venus's surface. The probe holds the record for the longest-lived Venus surface mission.

It survived for just 127 minutes.

Scientists have been trying to return to Venus's surface since the late 1980s, this time with instruments that will last for days or even months. That's where GEER comes in.

GEER, the Glenn Extreme Environments Rig at NASA Glenn Research Center (GRC) in Cleveland, Ohio, is a test chamber that can create Venus-like conditions to study how materials placed inside the chamber react.

"GEER is a highly adaptable facility that's constantly evolving its capabilities," said Kyle Phillips, an aerospace and mechanical engineer at GRC. Phillips is GEER's primary operator and test engineer. "In past tests, we've simulated conditions all the way from

GEER is a test chamber that can create Venus-like conditions to study how materials placed inside the chamber react.

Venus surface conditions—both lowlands and highlands—up through the lower atmosphere through where we expect the cloud layers to be, and just slightly above the cloud layers and the upper atmosphere."

Building Spacecraft to Last

Venera 13, its twin spacecraft Venera 14, and the eight other successful attempts to land a probe on Venus all fell prey to the same thing: temperatures hotter than 450°C, pressures about 90 times that of Earth's surface (90 bars), and a corrosive carbon dioxide–dominated atmosphere. Under those conditions, a spacecraft that might survive for years on Mars or the Moon would break down in minutes on Venus as the outer casing melts or dissolves, wires corrode, and delicate hardware warps.

The GEER team has “tested things like basic materials that one might use in a spacecraft or around the spacecraft,” said Tibor Kremic, chief of space science projects at GRC. “How do those interact with the environment? How do they fare? How did their properties and their functions change over time in a Venus surface–like environment?”

Test material is placed inside the 1-cubic-meter, corrosion-resistant stainless-steel cylinder. The test engineers then ramp up the pressure, temperature, and gas composition inside the chamber and hold it steady for days, weeks, or even months. “Currently, GEER can replicate temperatures from near ambient up to 1,000° Fahrenheit—that’s 537°C,” Phillips said, “and it can replicate pressures from ambient to rough vacuum to…94 bars.”

“We have done work over time in understanding what materials would be viable for long-term missions and which are not,” said Gary Hunter, a senior electronics engineer with GEER. For example, “copper, you might think, is just fine to use for electrical conductors. Turns out, don’t use copper. In fact, gold would be a better material to use because the reactivity on the Venus surface and at those temperatures is different, and the materials that are viable are different, than you might see in standard high-temperature operations on Earth.”

GEER has been operational since 2014, and the team has already made huge leaps forward in terms of designing Venus-durable spacecraft. During a test a few years ago, “we demonstrated electronics operational in Venus surface condition for 21 days,” Hunter said. Computer chips turned out to be fairly durable. “The longest time anything else had ever lasted before that point in terms of electronics on the surface of Venus…was approximately 2 hours. To go 21 days was showing a significant step up in what might be possible [in] Venus surface exploration.”

To Venus and Back in 80 Days

In its longest test to date, the GEER team subjected common geologic samples to a simulation of Venus’s harsh surface conditions for 80 continuous days.

“We tested geologic material, so glasses, basalts, minerals, things that we expect

Some types of metal wiring react at Venus-like surface conditions, causing electronics to break down. Shown here is a metal wire before (top) and after (bottom) a test in the GEER chamber. Credit: GEER/NASA Glenn Research Center

might be on the Venus surface,” Kremic said, “to understand how they might change or what they might look like if we’re trying to identify them remotely.” A basalt or a glass or a silicate might have a different spectrum or appearance on Venus than on Earth, the Moon, or Mars.

“Copper, you might think, is just fine to use for electrical conductors. Turns out, don’t use copper. In fact, gold would be a better material.”

Tests that reveal the properties of planetary materials at extreme conditions serve a dual purpose, Kremic explained. Mission scientists can tailor their instruments to measure Venus-relevant signatures, and they can use test results as benchmarks to interpret those measurements.

The 80-day test also underscored the need for a second, smaller test vessel that could be run at the same time as the larger one. “It’s a very small, mini GEER,” Kremic said. The aptly named MiniGEER went into operation in 2019. It’s just 4 liters in volume (250 times smaller than GEER) and can be brought up to temperature, pressure, and gas composition, and back down again, much faster than its larger counterpart.

“Maybe we have two things going on or we have tests that don’t require the volume [of GEER],” Kremic said, “and this way [they] can be done quicker and at lower cost.”

The Future of Venus Exploration

NASA might be headed back to Venus in the near future—two of its four finalists for a Discovery-class mission are bound for Venus. If one of those missions is selected, the GEER facility will be involved with getting the technology mission-ready.

But the team has already been hard at work designing its own Venus mission, a small probe called the Long-Lived In-Situ Solar System Explorer (LLISSE). LLISSE would weigh about 10 kilograms and last at least 60 days on Venus.

“At Venus you get a day-to-night or night-to-day transition at least once in a 60-day period,” said Kremic, who is LLISSE’s principal investigator, “and so we want to make sure that we capture one of those.…We’re going to measure temperatures, we’re going to measure pressures, we’ll measure winds, maybe 3D winds on the surface of Venus,” as well as atmospheric composition and how all of those properties change over time. The team plans to build a full-scale ground model of LLISSE and test it inside GEER for the full 60 days by 2023.

The scientists are also exploring how GEER can adapt to simulate other places in the solar system and beyond. “The beauty and one of the unique things about GEER is that we can mix up pretty much whatever chemistry we want,” Kremic said, and new hardware might let GEER reach colder-than-ambient temperatures too.

“The results of what we’re doing will change and enhance our ability to do science, our understanding of our solar system, and of other [planetary] bodies, Venus in particular,” Kremic said, and we can “be more confident in what we send there.”

By **Kimberly M. S. Cartier** (@AstroKimCartier), Staff Writer

▶ Read the latest news at **Eos.org**

The Long-Lasting Legacy of Deep-Sea Mining

The impact of disturbing the seafloor for mining activities remains decades after the initial disturbance. Credit: ROV-Team/GEOMAR

Mining for rare metals can involve a good amount of detective work. It can take time and skill to find the most abundant sources. But in the deep ocean, metallic deposits sit atop the seafloor in full view—a tantalizing sight for those interested in harvesting polymetallic nodules.

Scooping up nodules requires mechanical skimming of the ocean floor, which disrupts the upper centimeters of sediment. This disturbance has rippling effects on sea life, but the severity and duration of ecological impact have remained largely unknown.

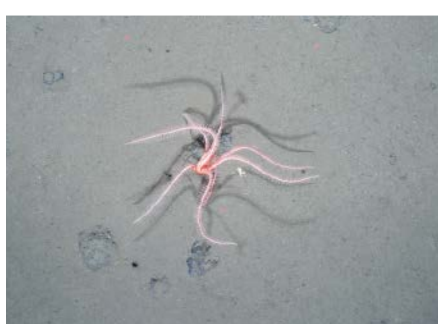
In a new study, researchers dove deep to look at mining's impact on microbial communities. They found that decades later, benthic microorganisms hadn't recovered, and researchers estimated it would take at least 50 years for some ecosystem functions to return to predisturbed conditions.

Disturbing the Peace

In 1989, scientists began a deep-sea mining experiment called the Disturbance and Recolonization experiment (DISCOL) in the Peru Basin of the South Pacific Ocean. The study simulated nodule mining by dragging a plough-harrow device over an 11-square-kilometer area, cutting and reworking the upper 10–15 centimeters of seafloor sediments.

Since the start of DISCOL, scientists have been visiting the basin to monitor the effects of mining on benthic life. In a new study in *Science Advances,* researchers focused on the smaller communities of organisms found at depth (bit.ly/mining-effects).

"We tried to answer how long a disturbance of the deep-sea floor ecosystem by simulated nodule mining could affect benthic microorganisms and their role in the ecosystem," said two of the paper's authors, Tobias Vonnahme, a marine biologist at the Arctic University of Norway, and Antje Boetius, director of the Alfred Wegener Institute. (The researchers responded to email requests from *Eos* as a group and will be referred to as "the team.")



Brisingid sea stars like this one were among the megafauna studied by earlier evaluations at the DISCOL site in the Peru Basin. The current study was the first to focus on the area's microbial community. Credit: OFOS team, AWI Bremerhaven

Monitoring Microorganisms

At the DISCOL site, the team deployed their cameras and sampling equipment and got their first look at the seafloor. "First, we saw undisturbed seafloor covered by manganese nodules and larger animals, such as octopuses, fish, and colorful sea cucumbers," they said. But the troughs soon came into view—even 26 years after the DISCOL experiment, the plough tracks were pronounced.

The researchers took sediment cores of the seafloor both within older disturbed area and in fresh, 5-day-old tracks. "Thanks to novel robotic technologies, we were able to quantify the long-lasting impacts on microbial diversity and function in relation to seafloor integrity," they noted.

After analyzing the cores from the seafloor, the team found that in the 26-year-old tracks, microbial activity was reduced fourfold. In addition, the mass of microorganisms was reduced by about 30% in the top 1 centimeter of disturbed sediment. In fresh tracks, the microbes were reduced by about half. They also found lower organic matter turnover, reduced nitrogen cycling, and lower microbial growth rates in disturbed areas.

"Benthic life—including microorganisms, which carry out essential functions such as nutrient recycling—need more than 26 years to recover from the loss of seafloor integrity," said the team.

They added that on the basis of the microbial activities they observed in the most disturbed areas, it would take at least 50 years for some functions to return. "Considering the low sedimentation rates, [full] recovery will take much longer," they noted.

"The self-healing of the ecosystem is very limited," they concluded.

This is a novel study, said Maria Pachiadaki, an assistant scientist at the Woods Hole Oceanographic Institution who was not part of the study. She added that it's the first time researchers have focused on deep-sea mining impacts on the microbial community.

Pachiadaki and her colleagues previously hypothesized that these types of "disturbances would also impact microbes, plus ecosystem functions, because microbes mediate the entire biogeochemistry of their environment." She said this study confirms their suspicions and gives a long-term record of what happens after a mining disturbance.

"Life as we know it starts with microbes," said Pachiadaki. She said one striking finding of the study was that the carbon fixation rates—or how inorganic carbon is transformed into organic carbon—decreased substantially in disturbed sites.

Pachiadaki noted that another substantial finding was the identity of the microorganisms in the benthic sediment. Specifically, the microbial communities were enriched with nitrifiers. "It's a group of organisms that make nitrogen bioavailable," she explained. "Nitrogen is one of the essential micronutrients... and the limiting factor of productivity."

The Future of Deep-Sea Mining

"Our work shows the potential long-term impact of deep-sea mining when seafloor integrity is reduced," said the team, adding that their research can be used to shape guidelines for deep-sea mining explorations.

"This is an excellent example of how scientists can guide policy makers," said Pachiadaki.

"If there is pressure moving toward deep-sea mining, there needs to be an impact assessment," she said. "And it can't be a short-term process—it needs to be a long-term evaluation."

By **Sarah Derouin** (@Sarah_Derouin), Science Writer

Humans Migrated to Polynesia Much Earlier Than Previously Thought

In the middle of Lake Lanoto'o in Samoa floats the coring raft researchers used when extracting sediment samples. Credit: David Sear, University of Southampton

The last great migration of humans to lands unknown occurred with the habitation of East Polynesia about a millennium ago. It's not an easy feat finding tiny islands scattered in an ocean.

"In terms of the scale, risk, and magnitude of the exploration, it's one of humanity's momentous achievements," said Barry Rolett, an anthropologist at the University of Hawai'i at Mānoa.

But the details of this accomplishment—and what drove it—have been shrouded in mystery.

Now a study published in the journal *Proceedings of the National Academy of Sciences of the United States of America* reports that humans arrived in East Polynesia 200–300 years earlier than previously thought (bit.ly/humans-polynesia).

Their arrival in East Polynesia—a culturally and linguistically distinct region spanning from the Cook Islands to Rapa Nui and Hawaii—coincides with a time of prolonged drought in Tonga and Samoa, their West Polynesia islands of origin. This drought may have helped spur the dangerous excursions eastward.

"It's an impressive study and an important one," said Rolett, who was not involved in the research. "It's unusual for Polynesia because there hasn't been a lot of paleoenvironmental reconstruction work done in this area."

Tracking Human Settlement Through Mud, Charcoal, and Feces

Lake sediments and mud can be used as archives of both human environmental impact and climate across the centuries, said David Sear, a professor of physical geography at the University of Southampton in the United Kingdom and the lead author on the new study. "We wanted to go and collect data along the route of the human colonization story of the Pacific and follow that story in the mud from the lakes and bogs."

Because of how remote the islands are, the researchers had to bring their own inflatable boats, build their own rafts, and transport all their equipment by hand via jungle paths to drill and collect cores of mud from each island's lake. They initially collected mud cores from Lake Te Roto on Atiu, a part of the Southern Cook Islands.

After collecting mud cores, Sear and his colleagues stored them in aluminum tubes. "You pack them into a cardboard box very carefully, put 'fragile' on the outside, go to the post office, pay 200 quid, and get it flown back to the U.K. under special import-export licenses, of course," he said.

Back in the lab, researchers scanned the mud for multiple proxies of human activity, including charcoal, which is a sign of fire, and titanium, which indicates soil erosion; together they indicate deforestation of the trees and underbrush native to the island. But the most telltale sign of human presence they looked for was something even more fundamental: feces, specifically, fecal sterols, a fatty substance found in mammalian feces. On these remote Pacific islands, there were no mammals besides fruit bats prior to the arrival of humans and pigs.

"The idea of using fecal markers is really innovative, and it works extremely well," said Rolett.

Together the evidence points to an incremental migration process with humans' first arrival in East Polynesia around 900 CE, followed by increased settlement activity over the next 200 years. This study "fills in a really important part of the puzzle of human settlement," said Melinda Allen, an archaeologist at the University of Auckland in New Zealand and a coauthor on the study. "And a lot of unconnected strands of evidence can now be pulled together as a result of these findings."

Climate Change and Migration

An extended regional drought in West Polynesia may have driven humans eastward. The researchers reconstructed regional paleoclimatic conditions of the past 2,000 years using additional lake core samples taken from islands in Samoa and Vanuatu, as well as previously published records of the Society Islands of French Polynesia. They found that human arrival in East Polynesia coincided with an intense, prolonged drought—the driest period in 2 millennia—which the researchers suggest helped drive people to migrate.

However, other factors might have led to settlement in addition to or in conjunction with drought, said Seth Quintus, an anthropologist at the University of Hawaiʻi at Mānoa who was not involved in the current study. "It's really hard to say that drought is what's causing the movement of people."

As a whole, the study "teaches us a lot about how people in the past manage and respond to different risks in their environment," he added.

Pacific Climate Change Past and Future

Sear said that there are still more climate data to analyze from the mud cores once the labs are back open: The records his team collected go back 10,000 years, and this study looked at only the most recent 2,000. Understanding how climate has changed in the Pacific is crucial because it is "one of the big engines of the global climate system," Sear said, and there are not many climate data from before the 1950s.

Better understanding of the region's climate system would not only shed light on the area's past but also benefit the almost 12 million people living in the region today.

"These people are being squeezed by rising sea levels, changes in precipitation, increasing temperatures," Sear said. "When you put that together, they're amongst the most vulnerable people on the planet."

"If we can get a better understanding of both how their ancestors changed the landscape and the climate story that goes along with that, it will help them manage their future," Sear said. "Because, of course, one of their responses to climate change in the past was to get into a canoe and move somewhere else."

"You can't do that anymore," he said. "That major adaptation strategy is no longer available to them."

By **Richard J. Sima** (@richardsima), Science Writer

SIGN UP FOR *SPACE WEATHER QUARTERLY* DIGEST

Featuring select articles from the latest issue of the AGU journal *Space Weather*, containing original research articles and commentaries devoted to understanding and forecasting space weather.

agu.org/spaceweatherdigest

AGU ADVANCING EARTH AND SPACE SCIENCE

Geoscientists Help Map the Pandemic

The mapping tool can help responders visualize where outbreaks are trending or where they may spike in the future.

The global pandemic threw a wrench into the field and lab work of most geoscientists.

But not Babak Fard. An environmental data scientist at the University of Nebraska Medical Center (UNMC) College of Public Health in Omaha, Fard has leveraged his interdisciplinary background to track and predict coronavirus disease 2019 (COVID-19) infection risks to Nebraskans.

He and his colleagues created a dashboard tool (bit.ly/Neb-COVID-19) that can help responders visualize where outbreaks are trending or where they may spike in the future. The tool is helping health care providers and public policy leaders get supplies and resources to the areas of Nebraska that need them most.

Geohealth at Work

While a doctoral student at Northeastern University in Boston, Fard mapped the risk of heat waves to residents of Brookline, Mass., using a framework tool. The project was part of AGU's Thriving Earth Exchange, in which scientists work on a problem that advances community solutions.

"We wanted to look at how these extreme temperatures affect public health," said Fard, adding that the issue has become a global concern. The team identified the hazard (heat waves) and vulnerabilities that can lead to adverse reactions to the hazard. Using these data, team members created a regional map of communities with the highest risks of detrimental outcomes associated with heat waves.

Vulnerabilities are a set of social factors that play important roles in how people react to hazards, said Fard. "For example, age is a very important factor in [heat waves]," he noted, adding that different studies show that nonwhite and minority groups are more vulnerable as well.

The team used data on vulnerabilities to identify populations at the highest risk using something called a risk framework. The more vulnerabilities a person has—age, minority status, reliance on public transportation—the higher the risk is. "One purpose of the risk framework is to enable the decision-makers to prioritize their resources to different areas that need attention during a crisis," said Fard, adding that with limited budgets and supplies, this information is crucial for prioritizing responses.

In his new position at UNMC, Fard used the bones of the risk framework his team built for heat waves for a new purpose: predicting coronavirus risks.

The tool is helping health care providers and public policy leaders get supplies and resources to the areas of Nebraska that need them most.

"The Centers for Disease Control and Prevention (CDC) identifies 15 sociodemographic variables to calculate social vulnerabilities," said Fard, noting that the data are from the U.S. census. He explained that these factors can be grouped into four categories: socioeconomics, household composition and disability, minority status, and housing and transportation. Each category gets a value, and the values are averaged to represent the risk of COVID-19 infection to the population within a geopolitical boundary, in this case, a county.

Mapping a Pandemic

And the information is all easy to read on a map. It has been highly successful for those inside the state and in neighboring states as well. Fard noted that during April there were more than 2,200 views of the dashboard tool each day on average.

The map can reveal insights into disease spreads, showing patterns and predicting virus hot spots. These data allow health professionals and government agencies to plan ahead—something Fard called adaptive capacity. "It's any measure that can help in reducing the vulnerability," he said, and can include anything from increasing the number of beds in intensive care units to addressing transportation issues.

These maps might be a crucial tool for pandemic responders, said Kacey Ernst, an epidemiologist and program director of epidemiology at the University of Arizona who was not involved with the research. "We might want to enhance our level of testing to catch more cases [in a certain area] or put up a testing center if there's an area where people would have to take the bus or public transport when they're ill to get tested," she said.

"I was impressed that [Fard] was looking at a multitude of underlying factors that might influence what the numbers would say," said Ernst. She added that she was particularly impressed with the hospital data they included. "I appreciated the fact that he didn't just put up the case numbers—that he was trying to delve a little more deeply."

Ernst said it's important to look beyond the number of cases and into why the cases are there. "It's absolutely critical to really understand the underlying population and how that might influence what you see, in terms of both differences in how diseases are reported and in how testing is being conducted."

It's important to look beyond the number of cases and into why the cases are there.

The Power of Interdisciplinary Research

The project is a perfect example of how geoscientists can think and apply their skills outside the traditional bounds of their research. "As geoscientists, we know how to work with maps and do geospatial analyses," said Fard, adding that medical geologists can go one step further and study the effect of geological factors on health. He noted that geospatial skills can add a lot of value for crisis responders who need a visual picture of where to focus.

Ernst agreed and said it is imperative, especially during a pandemic, for scientists to look critically at every data source and try to understand its limitations and caveats. "Many geoscientists do sort of broader scales, spatial scales," she said, adding that often, geoscientists "get that blessing and curse of spotty data, and you have to learn how to figure out what it actually means and what you can do with it."

In the increasingly connected world, interdisciplinary research like Fard's may become the norm, not the exception. For Ernst, this is already the case. "I am a strong proponent of interdisciplinary research teams—that's pretty much how I do all my work," she said. "It makes the research really strong when you have teams that are diverse and able to look at data from different angles."

Fard said that the framework tool is a larger part of the Nebraska Emergency Preparedness and Response effort. And although it is currently being used for COVID-19, "this framework is going to continue to be beneficial in other situations that might come up in the future," such as floods and other natural hazards.

The framework provides mayors, hospitals, and relief workers information for planning and disaster response. Fard said he hopes that seeing the success of the coronavirus framework will "inspire other organizations to use it for their purposes."

By **Sarah Derouin** (@Sarah_Derouin), Science Writer

Oktoberfest's Methane Rise Is the Wurst

Millions of people convene at large festivals like Carnival in Rio de Janeiro and Dia de los Muertos in Mexico City. These gatherings are more than just wild parties or cultural heritage, however—they're a rich trove of scientific data. Researchers now have calculated the methane emissions associated with Oktoberfest, a harvest celebration typically held in the fall, in Munich, Germany. (The 2020 event has been canceled.) The scientists found that Oktoberfest's area-normalized methane flux was about half that of an average dairy farm. Festivals—often unaccounted for in emissions inventories—can be significant, albeit temporary, sources of greenhouse gases, the team concluded.

Beer, Sausage, and Methane

At Munich's Oktoberfest, typically held over 16 days, revelers consume more than 8,000,000 liters of beer and copious amounts of grilled sausage, fish, and oxen. But the natural gas used to heat Oktoberfest's massive tents and power its grills consists primarily of methane, which is a potent greenhouse gas: Kilogram for kilogram, methane traps roughly 30 times as much energy as carbon dioxide.

Jia Chen, an electrical engineer focused on environmental science at the Technical University of Munich, and her colleagues set out to quantify Oktoberfest's methane emissions. "Festivals could be a notable methane source even though they have not yet been included in the existing emissions inventories," said Chen. "Oktoberfest is the largest folk festival worldwide."

Many Rounds for Science

In 2018, Chen and her collaborators walked and biked around the 2.5-kilometer perimeter of the Oktoberfest site carrying portable methane sensors. The team made 94 rounds with the instruments, which were about the size of a backpack and weighed roughly 11 kilograms. "It's good exercise," said Chen.

The sensors determined gas concentrations by pumping air into a cavity and then measuring the attenuation of different wavelengths of laser light. The team combined these data with wind information to accurately estimate methane fluxes. "The higher the wind speed, the lower concentration we will measure because the methane is more diluted," said Chen.

The researchers found that on average, about 7 micrograms of methane per second were being emitted from each square meter of the Oktoberfest premises. That's significant and only about a factor of 2 smaller than the flux escaping from a dairy farm, the team noted.

Roughly 20% of these emissions can be ascribed to biogenic methane produced by attendees' exhalations and flatulence, Chen and her colleagues calculated on the basis of published estimates (bit.ly/human-emissions). The remainder, the researchers suggest, likely derived from incomplete combustion in gas-powered heaters or cooking appliances.

These results were published in *Atmospheric Chemistry and Physics* (bit.ly/Oktoberfest-emissions).

"Festivals could be a notable methane source even though they have not yet been included in the existing emissions inventories."

Allowed In the Next Time

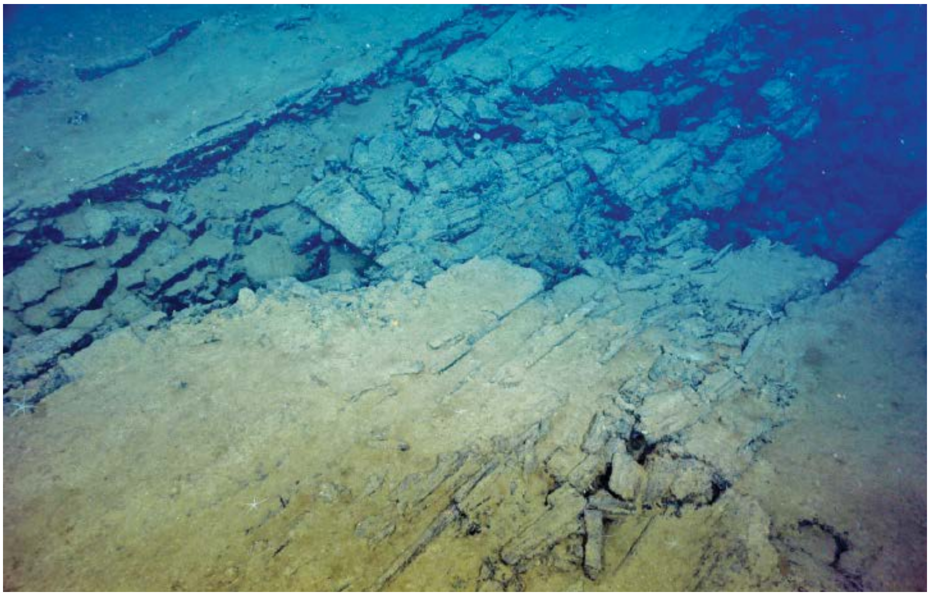
In 2019, the researchers returned to Oktoberfest, this time on the actual premises. "We were allowed to go inside," said Florian Dietrich, an engineer at the Technical University of Munich and a member of the team. "We went closer to the sources."

This time, they made measurements with portable methane sensors and also collected air samples. Back in the laboratory, they determined the ratio of ethane to methane in the samples to shed light on the origin of the emissions—biogenic sources produce very little ethane, whereas fossil fuels (e.g., natural gas) typically contain ethane. The results are being prepared for publication.

"There are so many different sources of methane," said Ben Poulter, a carbon cycle scientist at the NASA Goddard Space Flight Center in Greenbelt, Md., not involved in the research. "Studies like this help individuals understand their greenhouse gas footprint a little bit better."

By **Katherine Kornei** (@KatherineKornei), Science Writer

A Plate Boundary Emerges Between India and Australia



Mid-ocean ridges, like this one near Vancouver Island in Canada, reveal plate boundaries. Credit: Ocean Networks Canada

Tectonic plates blanket the Earth like a patchwork quilt. Now researchers think they've found a new plate boundary—a seam in that tectonic quilt—in the northern Indian Ocean. This discovery, made using bathymetric and seismic data, supports the hypothesis that the India-Australia-Capricorn plate is breaking apart, the team suggests.

Earthquakes in Unexpected Places

In 2012, two enormous earthquakes occurred near Indonesia. But these massive temblors—magnitudes 8.6 and 8.2—weren't associated with the region's notorious Andaman-Sumatra subduction zone. Instead, they struck within the India-Australia-Capricorn plate, which made them unusual because most earthquakes occur at plate boundaries.

These earthquakes "reactivated the debate" about the India-Australia-Capricorn plate, said Aurélie Coudurier-Curveur, a geoscientist at the Institute of Earth Physics of Paris.

Some scientists have proposed that this plate, which underlies most of the Indian Ocean, is breaking apart. That's not a wholly unexpected phenomenon, because the plate is being tugged in multiple directions, said Coudurier-Curveur. Its eastern extent is sliding under the Sunda plate, but its northern portion is buckling up against the Himalayas, which are acting like a backstop.

"There's a velocity difference that is potentially increasing," said Coudurier-Curveur, who completed this work while at the Earth Observatory of Singapore at Nanyang Technological University.

Zooming In on Fractures

Coudurier-Curveur and her colleagues studied one particularly fracture-riddled region of the India-Australia-Capricorn plate near the Andaman-Sumatra subduction zone. They used seismic reflection imaging and multibeam bathymetry, which involve bouncing sound waves off sediments and measuring the returning signals, to look for structures at and below the seafloor consistent with an active fault.

Along one giant crack that the team dubbed F6a, Coudurier-Curveur and her colleagues found 60 pull-apart basins, characteristic depressions that can form along strike-slip plate boundaries. The team showed that the basins followed a long, linear track that passed near the epicenters of both of the 2012 earthquakes.

"It's at least 1,000 kilometers," said Coudurier-Curveur. "It might be even longer, but we don't have the data to show where it extends." This feature, the team surmised, was consistent with being a plate boundary. An important next step was to estimate its slip rate.

"What we see in this region in the middle of the ocean is very analogous to other plate boundary regions."

Slower Than San Andreas

To do that, the scientists relied on two quantities: the length of the largest, and presumably oldest, pull-apart basin (roughly 5,800 meters) and the duration of the most recent episode of fault activity (roughly 2.3 million years). By dividing the length of the pull-apart basin by this time interval, they calculated a maximum slip rate of about 2.5 millimeters per year. That's roughly tenfold slower than the rate along other strike-slip plate boundaries like the San Andreas Fault but not much slower than the slip rates of other kinds, like the Dead Sea Fault and the Owen Fracture Zone, the team noted.

On the basis of that slip rate, Coudurier-Curveur and her collaborators estimated the return interval for an earthquake like the magnitude 8.6 one reported in April 2012. Assuming that such an event releases several tens of meters of coseismic slip, a similar earthquake might occur every 20,000 or so years, said Coudurier-Curveur. "Once you release the stress, you need a number of years to build that stress again."

These results were published in *Geophysical Research Letters* (bit.ly/new-plate-boundary).

The findings are convincing, said Kevin Kwong, a geophysicist at the University of Washington in Seattle not involved in the research. "What we see in this region in the middle of the ocean is very analogous to other plate boundary regions."

But continuing to monitor this part of the seafloor for earthquakes is also important, he said, because temblors illustrate plate boundaries. That work will require new instrumentation, said Kwong. "We don't have the seismic stations nearby."

By **Katherine Kornei** (@KatherineKornei), Science Writer

The Closest Black Hole Is 1,000 Light-Years Away

Supermassive black holes—millions or even billions of times more massive than the Sun—anchor the centers of most galaxies. But smaller black holes, at just a few solar masses, should theoretically pepper galaxies in droves. A few hundred candidates have been found in the Milky Way. Now researchers have spotted another one of these stellar mass black holes, and it holds a special honor: It's the closest black hole to Earth yet discovered. The findings shed light on the dynamics of supernova explosions that go on to create black holes, the team suggested.

Finding Wallflowers

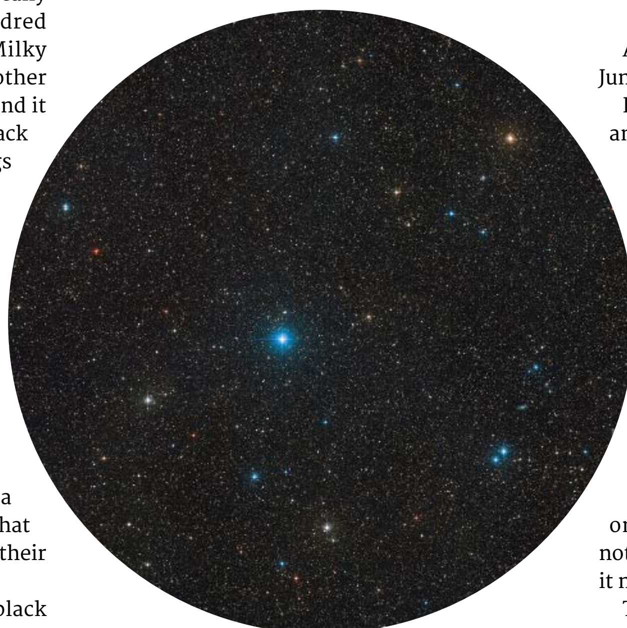
Disks of hot gas and dust glowing brightly in X-rays sometimes encircle black holes. This radiation indicates that a black hole is active and accreting matter, said Thomas Rivinius, an astronomer at the European Southern Observatory in Santiago, Chile. And it's a beacon. "We only find the [black holes] that are violently gobbling up material from their environment," said Rivinius.

It's much harder to spot the many black holes that aren't consuming matter—they don't produce X-rays. But sometimes the universe aligns itself just right to reveal these wallflower black holes. That's what Rivinius and his collaborators found when they examined HR 6819, a seemingly ordinary pair of stars about 1,000 light-years away in the constellation Telescopium.

"There are probably a million black holes in the galaxy that have binary companions that are stars."

In 2004, Rivinius and his colleagues trained a 2.2-meter telescope in La Silla, Chile, on HR 6819. "We thought it was only two stars," said Rivinius.

But to their surprise, the researchers discovered that one of the stars was wobbling in a circle. "One of them was being flung around," said Rivinius. That's the telltale sign of a companion, a nearby object that's tugging gravitationally on the observed celestial object. So HR 6819 wasn't just a pair of stars—it was three objects: one star on a relatively wide orbit and one star paired with something unseen.



Astronomers found the closest black hole to the Sun in the constellation Telescopium. Credit: ESO/ Digitized Sky Survey 2; Acknowledgment: Davide De Martin

Not a Star, White Dwarf, or Neutron Star

The scientists calculated that the mysterious third object in HR 6819 had to be at least about 4 times the mass of the Sun. That's pretty hefty—a star of that mass would pump out enough light to be visible even if it belonged to the dimmest class of stars, Rivinius and his collaborators estimated. They also ruled out fainter objects like white dwarfs and neutron stars because they're typically of much lower mass. That left one logical conclusion: The unseen object was a black hole.

That idea languished for several years, however, after tragedy struck unexpectedly:

"We thought it was only two stars."

A team member died in a car accident in June 2014. "The study stalled," said Rivinius. But last year, new results spurred Rivinius and his colleagues to revisit their findings. Another team of researchers had reported finding a black hole using the same method. Rivinius remembered seeing a press release and thinking, "Wait a second—I have something in the drawer that looks exactly the same."

The Closest One

Rivinius and his collaborators estimated that the black hole in HR 6819 was about 1,000 light-years from Earth, making it the closest known black hole. Its proximity implies that systems like this one are common. "Our neighborhood is nothing special," said Rivinius. "If it's here, it must be everywhere."

These results were published in *Astronomy and Astrophysics* (bit.ly/nearest-black-hole).

The existence of HR 6819 sheds light on the supernova explosions that create black holes, the scientists suggested. It's long been believed that such explosions are antisymmetric, meaning that they send matter flying preferentially in one direction, with the result that the black hole is launched in the other direction. But finding a black hole gravitationally bound to a star implies that in some cases, black holes aren't flung from their birthplace. That is, supernova explosions are sometimes symmetric.

Determining what fraction of supernovas are symmetric versus antisymmetric will require a larger sample of black holes. That's entirely possible research, said Todd Thompson, a theoretical astrophysicist at the Ohio State University in Columbus not involved in the research. "There are probably a million black holes in the galaxy that have binary companions that are stars," said Thompson. "That's a very big sample that we should get busy trying to understand."

By **Katherine Kornei** (@KatherineKornei), Science Writer

Building a Culture of Safety and Trust in Team Science

Members of the Next-Generation Ecosystem Experiments–Arctic (NGEE Arctic) aerial laser alti-meter team (Christian Andresen, Lauren Charsley-Groffman, Adam Collins, and Erika Swanson) take a break on a portable drone landing pad at a field site outside Nome, Alaska. Credit: Christian Andresen, University of Wisconsin–Madison

Some of the most scientifically exciting places are also some of the most difficult to study. The Arctic, for example, is rapidly changing, as evidenced by melting sea ice, thawing permafrost, disappearing glaciers, and greening hillslopes. Increasingly, scientists from around the world and across a wide spectrum of disciplines are working together to advance our understanding of this vulnerable and globally important biome.

As scientists become part of larger teams and join broader and more diverse scientific endeavors, they all must become leaders in creating cultures of safety, inclusion, and trust. Ideally, all participants on such teams, as well as local communities and other stakeholders, feel that their views, concerns, and efforts are acknowledged and respected. Such a culture facilitates the physical and emotional well-being of individuals on scientific teams and in the local communities where scientists work.

Here we share lessons learned from an "experiment within an experiment" begun as part of a large-scale, decade-long research project in Alaska. The experiment was focused on answering the question, How can we intentionally create a project-wide culture of safety, inclusion, and trust that facilitates strong cross-disciplinary collaboration and exciting scientific discoveries?

Who We Are and What We Do

Our team of more than 150 people includes empiricists, modelers, and data scientists from four U.S. Department of Energy national laboratories and from the University of Alaska Fairbanks (UAF), all working together on the Next Generation Ecosystem Experiments–Arctic (NGEE Arctic) project. Our overarching goal with the project, which began in 2012 and is now in its third phase, is to improve physical representations of the tundra in the virtual space of Earth system models that predict the future of the Arctic and the world.

NGEE Arctic team members make observations at field sites ranging from the wet, cold North Slope of Alaska to the warmer hillslopes that span the accessible road systems of the Seward Peninsula. We work separately in smaller teams, fanning out across the tundra (or, in the case of the modelers on the team, across the rugged terrain of computer clusters). We also come together for annual "all-hands" meetings to share our work and tend to our long-distance collaborations.

Since the project began, team members have published more than 200 papers and have released nearly 150 data sets. Equally important, we have grieved together for lost loved ones and joyfully celebrated the birth of 18 babies. These shared personal experiences have strengthened the professional relationships among our team members.

A Culture of Safety and Security

Many scientists work in remote places. They say good-bye to families; get on a plane, bus, or boat; and travel to patches of land or water to collect data and make discoveries that advance our understanding of the natural world.

These endeavors often require working for long hours in environments that include unique physical hazards—as well as living for weeks or months in crowded spaces that often lack basic amenities. The NGEE Arctic team, underpinned by a strong safety culture at our national laboratories and our partner institutions, has made the safety of individuals and of the team its number one concern before, during, and after field and laboratory campaigns.

We do this by encouraging rigorous planning and continuous dialogue and by questioning our assumptions regarding team safety and security. Early in the project, we spent many hours discussing and developing a culture of safety, and we prioritized listening sessions with local Alaskan institutions (e.g., our partners at the University of Alaska, Fairbanks) and scientific support groups (e.g., UIC Science in Utqiaġvik, Alaska), as well as Native corporations and the Indigenous community, to determine best practices and to learn more about the place they call home. We encoded these discussions into documents—short field and laboratory manuals, safety plans and checklists, and codes of conduct—that are required annual reading for our scientists and that established shared expectations across the team (In some cases, these provided the foundation for improved culture at individual institutions.)

Our field manual covers topics ranging from using a buddy system and emergency communication devices to negotiating rough terrain, getting necessary permits, conducting daily safety and planning meetings, and the need for respectful interactions with the surrounding communities. Our laboratory safety manual covers the planning, preparation, and training needed prior to working in on-site laboratories, as well as chemical disposal and how to appropriately store and ship samples home. Safety checklists and codes of conduct are unique to each institution but set expectations for safe, secure, and successful science. Accompanying videos emphasize how to dress for the harsh environmental conditions of the Arctic and what to do if you encounter a bear. (Hint: It depends on the bear!)

In turn, each team member is empowered to freely voice his or her opinion, up to and including an emphatic "stop" if something doesn't seem right. For instance, if a team member voices a safety concern, fieldwork is immediately suspended until a solution is found. "Stop" can also mean discontinuing an escalating discussion or even canceling a series of sampling campaigns. For example, the leadership team made the difficult decision this spring to suspend travel to Alaska given uncertainties surrounding the spread of COVID-19; we placed the safety of our team members and the surrounding communities where we live or work (especially those that may be particularly vulnerable) ahead of scientific observations.

Although the documents we created were an important part of the process, the enduring legacies are the adoption of a safety mindset that underlies all our work, a heightened understanding of the need for respect and common purpose, and a broad set of values endorsed by everyone.

As scientists become part of larger teams and join broader and more diverse scientific endeavors, they all must become leaders in creating cultures of safety, inclusion, and trust.

The scientific interests of the NGEE Arctic team range from geomorphology to greenhouse gas fluxes, from permafrost thaw to photosynthesis, from snow cover to shrubification, and from remote sensing to root-soil interactions. Credits: Roy Kaltschmidt, Lawrence Berkeley National Laboratory (top left); Stan D. Wullschleger, Oak Ridge National Laboratory (bottom left, right)

Summarized, our values promote safe and harassment-free work environments, respect for local culture and knowledge of the environment in areas and communities where we are guests, and collaboration and open science.

A Safe and Harassment-Free Work Environment

Scientific discovery is increasingly facilitated by cross-disciplinary collaboration and the inclusion of scientists from diverse backgrounds, but fostering these positive attributes in teams requires a culture in which all voices are welcomed and respected. To achieve this goal, the leadership team, along with the team members within each of the major project tasks, frequently talks about how to achieve a safe, secure, diverse, and inclusive science environment.

The leadership team has learned to listen when team members suggest improvements in culture and attitude. For example, we realized that we needed to be more transparent in our decision-making, more explicit in valuing and empowering each team member, and more inclusive in choosing the voices to guide the scientific conversation at our annual meetings. We grew to realize that uncomfortable conversations are an opportunity to grow as a team rather than something to be avoided.

Even so, there have been rare instances of inappropriate behavior in our remote field settings. Some examples include inappropriate conversations or crude humor during fieldwork, actual or perceived bullying among team members, and unwanted sexual advances or innuendos from local residents or scientists involved with other projects. These instances are recognized, acknowledged, and handled immediately.

Issues are resolved over the phone, through in-person discussions upon return from the field, or, in extreme cases, through removal from the field. The leadership team has also recognized the importance of including the injured party in decisions made to resolve a bad situation. And when appropriate and

The first annual "BARC-becue"—a combined barbeque and science fair—was hosted by UIC Science at the Barrow Arctic Research Center (BARC) building to facilitate interactions among scientists and local and Indigenous communities in Utqiaġvik, Alaska, in 2018. Credit: Ravenna Koenig/KTOO

safe, we have found that the team leader or another member of the leadership team can facilitate group discussions while scientists are still in the field to help to resolve potential interpersonal conflicts and restore and strengthen trust.

We further recommend that project safety protocols explicitly address workplace harassment and bullying. Protocols that clearly address these issues were highlighted by a National Academies of Sciences, Engineering, and Medicine report (bit.ly/NASEM-report) about combating sexual harassment and have been developed for other situations in which scientists are working in proximity at remote locations.

We Are Guests in the Arctic

As the Arctic thaws at a worrying rate, Indigenous and other local communities are visited by increasing numbers of scientists, entrepreneurs, and businesses from warmer climates. It is important that we tread lightly in these communities where we are privileged to be guests and that we conduct ourselves and our science in ways that are both ethical and inclusive.

Prior to the development of scientific research plans for the NGEE Arctic project, team members spent time with the local and Indigenous communities and Native corporation landholders to better understand their intimate knowledge of the natural processes in their world, the areas of land available for scientific endeavor and the permits needed to work in those areas, and how we could communicate our findings to the local community. In the years since, we have participated in community outreach by giving talks and teaching workshops or classes, participating in local science fairs, and providing annual reports to the Native corporations that provide us land use permits.

Recently, we invited an Indigenous Knowledge holder, Kaare Erickson of UIC Science, to speak at our annual all-hands meeting. He gave us a history of Indigenous communities in Alaska from "time immemorial" and suggested ways to improve our interactions with local and Indigenous communities. An overarching message was that Indigenous Knowledges and Western science are complementary and not competing and that Western scientists should engage Indigenous Knowledge holders before, during, and after each scientific endeavor. Echoing these conclusions, we recommend early and frequent engagement with local communities.

Prioritizing Collaboration and Open Science

The increasingly cross-disciplinary and global nature of scientific collaborations requires new ways of communicating. At the outset of our project, our sponsor in the U.S. Department of Energy's Office of Science set an expectation for ongoing and iterative cross-disciplinary collaboration between empiricists making observations in the field and in the laboratory and the modelers encoding those hard-won observations into mathematical algorithms that improve physical representations of the tundra in Earth system models.

Over time, this model-experiment interaction philosophy has become central to the way we think, plan experiments, and communicate findings. Modelers are embedded within teams addressing overarching science questions, and they often travel to the field, where they learn firsthand the complexity of natural ecosystems and the importance of good boots and duct tape. In turn, empiricists have learned to speak the mathematical language of models and are helping to guide the development of next-generation models that more faithfully simulate the processes they study.

Furthermore, across the project, we respect and value intellectual input, whether it comes from summer students or senior scientists, and we facilitate cross-project interactions in monthly conference calls. Our annual all-hands meetings feature a variety of brief "lightning" talks in which students and scientists speak about their individual research projects in formats ranging from 2-minute sales pitches, to 5-minute "Ignite" presentations featuring quick-hitting slides, to "Up-Goer Five" descriptions in which speakers use only the most commonly used words in the English language to describe their work. We also hand out awards for safety and data contributions and host "Arctic cafe" roundtables, small group discussions during which team members shuffle among tables to encourage all voices to be heard and new ideas to be considered. These activities both communicate our science and celebrate our scientists.

We underpin these new and nurtured collaborations with a philosophy of open science. Data, once collected, are immediately uploaded to a data portal where they are available to other scientists within the project. Then, when the data are published, they become freely available to scientists and citizens around the world.

We implemented a required project-wide data sharing policy very early in the project, but we were slow to recognize the way in which it could facilitate trust and collaboration among team members. For example, our data portal, which was built by our data scientists but can be accessed by anyone, is a living record of the teams that have shared their observations, simulations, or synthesized data. But it is also a feedback system that notifies data owners when data are downloaded for use by other team members or the broader community, helping to jumpstart conversations about collaboration and coauthorship. We recommend both formalizing a data management plan at the outset of a project and allocating enough resources to ensure its success; our success has been underpinned by a system that tracks both data sharing and data use.

Central to our culture is the trust that all staff have in our leadership and in each other.

Lessons Learned

Over a decade of working at remote field sites in the Alaskan Arctic, NGEE Arctic team members have learned a lot about project and safety planning, inclusive and collaborative team building, and open and immediate data sharing that we believe can be extrapolated to other scientific endeavors. Our success in these efforts emerged not only because of expectations set at the start by our sponsor and our project leaders but also because of the work of our team across many years to create systemic changes in our science culture and the way our scientists work. This success is quantified through continuous feedback—from students to mentors, from team members to the leadership team, and between the leadership team and our sponsor.

Central to our culture is the trust that all staff have in our leadership and in each other: trust to question the status quo, trust that alternative views and approaches will be heard and validated, and trust to share ideas and data. Our experiment within an experiment continues.

Acknowledgements

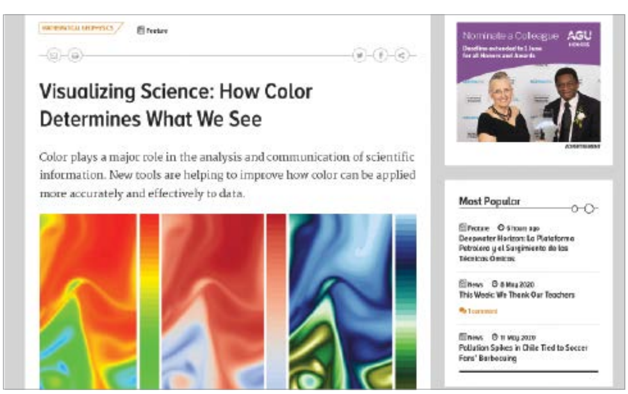
We thank the Biological and Environmental Research (BER) program with the U.S. Department of Energy's Office of Science for funding the NGEE Arctic project. We thank the participating institutions, Brookhaven National Laboratory (contract DE-SC0012704), Lawrence Berkeley National Laboratory, Los Alamos National Laboratory, Oak Ridge National Laboratory, and the University of Alaska Fairbanks, as well as the members of the NGEE Arctic team, for their leadership, collaboration, and friendship across the years. We also thank UIC Science and the Council Native Corporation, Mary's Igloo Native Corporation, and Sitnasuak Native Corporation for allowing us to conduct our research on their land. Special thanks go to Lily Cohen and Kaare Erickson for helping us appreciate each other and the Native communities that so cherish the Arctic.

By **Colleen M. Iversen** (iversencm@ornl.gov), Environmental Sciences Division and Climate Change Science Institute, Oak Ridge National Laboratory, Oak Ridge, Tenn.; **W. Robert Bolton,** International Arctic Research Center, University of Alaska Fairbanks; **Alistair Rogers,** Environmental and Climate Sciences Department, Brookhaven National Laboratory, Upton, N.Y.; **Cathy J. Wilson,** Earth and Environmental Sciences Division, Los Alamos National Laboratory, Los Alamos, N.M.; and **Stan D. Wullschleger,** Environmental Sciences Division and Climate Change Science Institute, Oak Ridge National Laboratory, Oak Ridge, Tenn.

Read it first on Eos.org

Articles are published on Eos.org before they appear in the magazine.

Visit **Eos.org** daily for the latest news and perspectives.



Visualizing Science: How Color Determines What We See
bit.ly/Eos-color

All Hands on Deck for Ionospheric Modeling
bit.ly/Eos-ionosphere

How Much Modification Can Earth's Water Cycle Handle?
bit.ly/Eos-water-cycle

Monitoring African Elephants with Raspberry Shake & Boom
bit.ly/Eos-elephants

Asia's Mega Rivers: Common Source, Diverse Fates
bit.ly/Eos-mega-rivers

Once Again into the Northwest Passage
bit.ly/Eos-Northwest-Passage

High Water on the Delta

By Nicole M. Gasparini and Brendan Yuill

Changing climate and land use practices are bringing extended periods of high water to the lower Mississippi River. New management practices are needed to protect people, industry, and the land.

By June in most years, the water height of the Mississippi River in New Orleans, La., has peaked and is falling. But 2019 was not like most years. Winter and spring 2019 brought many stories of flooding in the Midwest, notably on the Missouri River and its tributaries, which eventually flow into the Mississippi. Even before the 2019 Midwest floods made the news, though, Mississippi River water levels were higher than usual in the New Orleans area.

The U.S. Army Corps of Engineers (the Corps) monitors the levees regularly when river stage (water height) hits 4.6 meters (15 feet) in New Orleans, about 0.6 meter below flood stage. Water height on the Mississippi River remained high throughout water year 2019 (which ran from 1 October 2018 through 30 September 2019), exceeding the 4.6-meter level in New Orleans on 164 days (Figure 1). In contrast, there were just 49 such days in 1991, the previous record year among data going back to 1990.

The vulnerabilities of current water management practices on the Mississippi River were readily apparent in water year 2019, when the unprecedented amount of water had a variety of effects, including stressing ecosystems and contributing to shipping accidents and disruptions. The water level was still elevated in July 2019 when Hurricane Barry moved into the Gulf of Mexico and threatened to compound the situation with storm surge, which could have been catastrophic. The high water has continued into this year. As of 15 May, the Mississippi River had exceeded the critical 4.6-meter monitoring threshold on 87 days in water year 2020, compared with 91 days by the same date in water year 2019. Extremely high antecedent soil moisture and abnormally high snowpack throughout the Missouri River Basin this year, along with record precipitation regionally, has led to yet more flooding along the lower Mississippi.

To protect people and industry, the Corps has engineered the river to a large extent. The deltaic Mississippi River, or the final 540 kilometers of the river before it enters the Gulf, is lined with more than 483 kilometers of concrete and rock revetments that prevent channel migration and the formation of new distributary channels [*Smith and Winkley*, 1996]. The Mississippi River and Tributaries Project includes an extensive system of levees that help keep the river and its tributaries in place and prevent flooding. There are levees on the deltaic Mississippi River all the way to Venice, La. (about 16 kilometers from the rivers mouth), and to date, no levee built to the Mississippi River Commission's current standards, implemented in 1978, has ever failed [*U.S. Army Corps of Engineers*, 2014].

The lower Mississippi River winds its way through Louisiana, carrying water, sediment, and nutrients from 31 states to the Gulf of Mexico. Credit: ISS Crew Earth Observations Facility and Earth Science and Remote Sensing Unit, Johnson Space Center

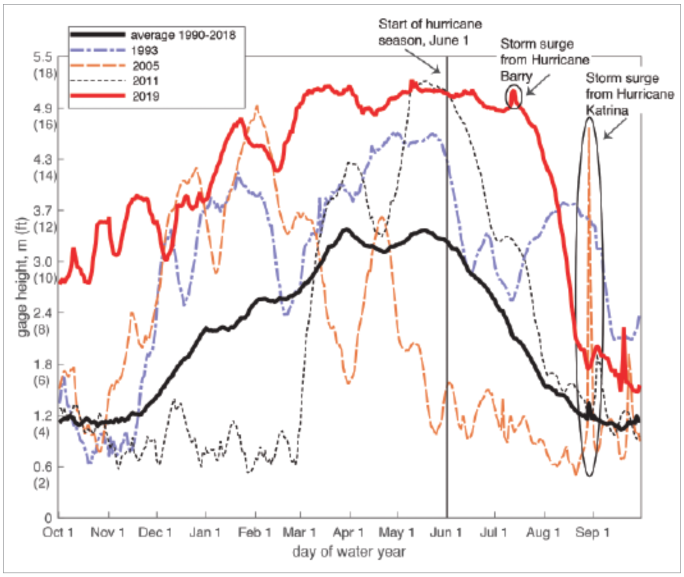


Fig. 1. Select years and daily average (computed using water years 1990–2018) of Mississippi River height in New Orleans as recorded by the U.S. Army Corps of Engineers' Carrollton gauge (01300). The river was higher than average every day in water year 2019; the Bonnet Carré Spillway was open from 27 February to 11 April and from 10 May to 27 July. In water year 1993, there was major flooding in the Midwest, and gauge height in New Orleans was above average for most of the year, but the Bonnet Carré Spillway was never opened. Data from water year 2005 show the storm surge from Hurricane Katrina. There was extensive flooding on the Mississippi River in water year 2011, and the Bonnet Carré was open from 9 May to 19 June.

Despite all the engineering of the river—including control structures, spillways, and a stabilized channel—there are now new challenges for managing the deltaic Mississippi River. Historically, river management practices have been designed assuming stationarity, or the concept that the mean and the window of variability in river flow are not changing [*Milly et al.,* 2008]. However, because of the effects of climate change, including increasing annual precipitation, and land use changes in the watershed that deliver more water downstream faster, the past is no longer a good indicator of the future when it comes to river flow. In other words, designing flood control practices using historical flow information, such as a static, 100-year flood estimate, is no longer reasonable.

When a river overtops or breaks its levees, water inundates the surrounding floodplain, which decreases the flow, and the flood hazard, downstream. In fact, deliberately breaking levees—long an illicit means of flood control, as in the Great Mississippi Flood of 1927 when people blew up levees around New Orleans to save themselves—can be part of an effective water management plan. But the deltaic Mississippi River needs more than broken levees to make that water management plan sustainable.

Controlling Nature

Upstream of the Gulf, the Mississippi River becomes part of a distributary delta system. In its natural state, the river split into multiple branches, and the main distributaries periodically switched locations. There have been five main distributary systems of the Mississippi delta in the past 5,000 years [*Coleman,* 1988]. Today the Mississippi River distributary system splits into two main branches. The larger branch is the 540-kilometer stretch that we refer to as the deltaic Mississippi River; the secondary branch is the Atchafalaya River, which flows about 230 kilometers to the Gulf (Figure 2). Although these two branches started naturally, they are now in a highly engineered state.

McPhee [1989] poetically documented the story of how the deltaic Mississippi River became one of the most engineered rivers in the world in his book *The Control of Nature.* Key to the story—which, like the river, has many twists and turns—is that the Corps determined that the percentage of flow coursing down the two distributaries should remain permanently as it was in 1950: 70% down the Mississippi and 30% down the Atchafalaya [*Mossa,* 1996].

In 1954, Congress acted on the Corps' recommendation and authorized the Old River Control Project. Today the Corps continues to manage the Old River Control Structure, which controls this flow distribution on a minute to minute basis (Figure 2). The current system of structures, which was upgraded and added to after the catastrophic Mississippi flood of 1973, can handle a discharge of up to about 20,000 cubic meters (700,000 cubic feet) per second into the Atchafalaya River. For comparison, the average flow in the Niagara River in Buffalo, N.Y., upstream of Niagara Falls, is about 5,700 cubic meters (200,000 cubic feet) per second. Had the Old River Control Project not been in place during the flood of 1973, most of the flow would have likely switched to the Atchafalaya River.

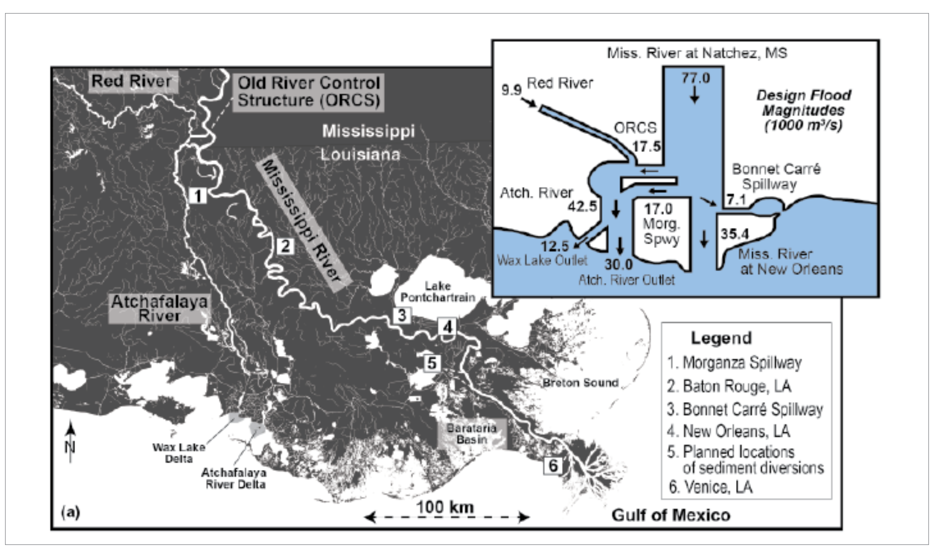
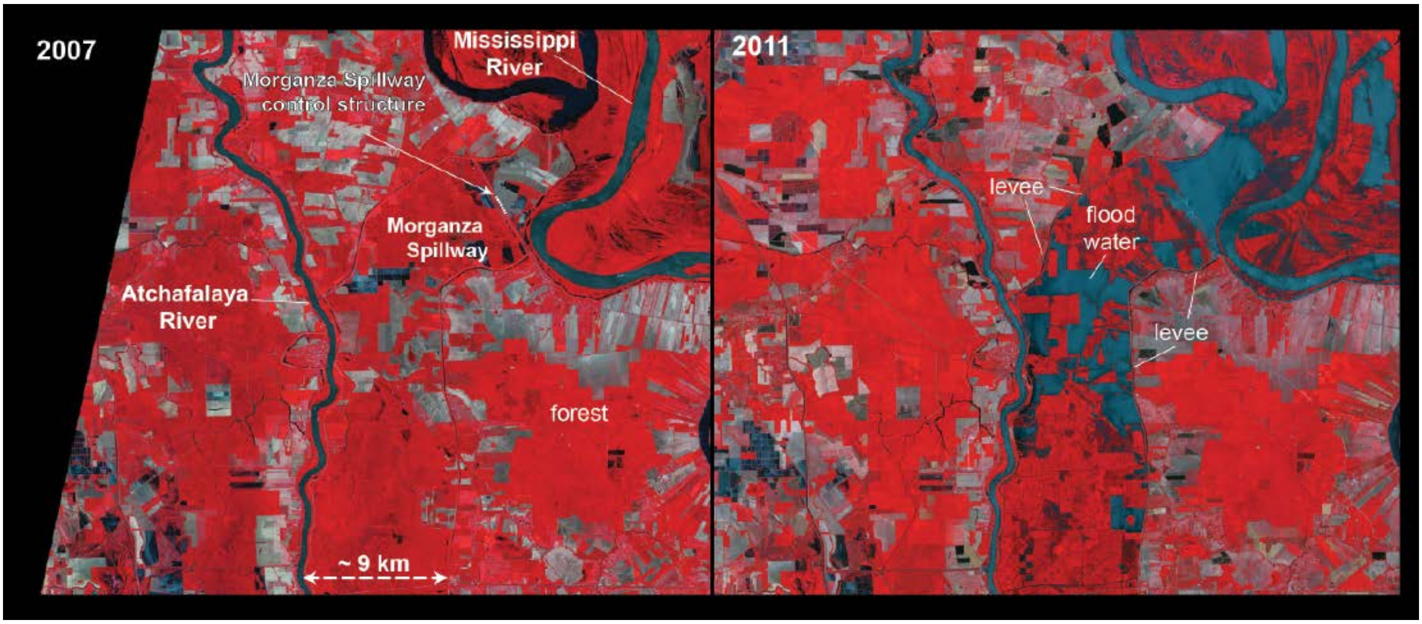


Fig. 2. Setting of the deltaic Mississippi River and locations discussed in this article. Only rivers and surface waters in the state of Louisiana are shown. The inset illustrates the U.S. Army Corps of Engineers' design flood, which indicates the approximate maximum flows that different structures and rivers are engineered to withstand.



False-color images of the Morganza Spillway and surroundings created with data from NASA's Terra satellite. The image at left was taken on 21 April 2007, during an average flood season on the Mississippi River. The image at right was taken on 18 May 2011, 5 days after the spillway was opened, by which time floodwater had spread roughly 30 kilometers south of the spillway. In these images, clear water is blue, sediment-laden water is dull blue gray, and vegetation is red. Light gray rectangular patches are likely cleared farm fields. Credit: NASA Earth Observatory images by Robert Simmon, using data from the NASA/GSFC/METI/ERSDAC/JAROS and U.S./Japan ASTER Science Team

Diverting High Flows on the Mississippi

Maintaining flow within a range that sustains beneficial uses while limiting flooding in the deltaic Mississippi River is critical for numerous reasons. Both New Orleans and, farther upstream, Baton Rouge, Louisiana's capital, have ports with extensive shipping and train yards and are surrounded by billions of dollars of industry, including oil refineries and chemical plants that depend on the deltaic Mississippi River.

To protect these areas, the Corps also controls two major spillways to release water away from the deltaic Mississippi River during floods (Figure 2). Upstream of New Orleans but downstream of Baton Rouge is the Bonnet Carré Spillway, which was built in response to the Great Mississippi Flood of 1927 and became operational in 1931. This spillway is designed to release up to about 7,000 cubic meters (250,000 cubic feet) per second of water into Lake Pontchartrain, a brackish lake connected to the Gulf, offering relief primarily for the greater New Orleans area and downstream.

Between 1931 and 2008, the Bonnet Carré was opened eight times. Between 2008 and 2018, it was opened four times. Last year was the first in which the spillway was opened twice in a single year, and it has been opened once so far in 2020 as of 15 May. Even with the Bonnet Carré open, flow in the deltaic Mississippi River remained high in 2019 (Figure 1). Opening the spillway comes with costs. For example, the oyster season has historically been less productive when the Bonnet Carré Spillway is opened because the brackish waters of Lake Pontchartrain may freshen significantly. Further, the river water entering Lake Pontchartrain often has very high nutrient loads—enriched by farm runoff from 32 states—that promote toxic algae blooms, which are especially deadly to benthic marine animals like oysters.

The bigger of the two spillways is the Morganza, situated downstream of the Old River Control Structure and upstream of Baton Rouge. Morganza is designed to take up to 17,000 cubic meters (600,000 cubic feet) per second of flow from the deltaic Mississippi River and drain it into the Atchafalaya Basin. Because there are homes and farms in the Atchafalaya floodplain that can be affected by such drainage, opening the Morganza is more controversial than opening the Bonnet Carré, and it has been opened only twice in its history: during the 1973 and 2011 floods. There was talk of opening it again in June 2019, but that did not happen.

Conservation of mass means we cannot make water disappear. So sustained high water means greater potential for flooding—whether it is purposely induced by humans via spillways or not. And more water on the floodplains of both the deltaic Mississippi River and the Atchafalaya River, which endangers people, crops, and wildlife like the indigenous Louisiana black bear.

In 2019, the total load of commodities shipped on the Mississippi River was 25% lower than the 10-year average.

High Stage Raises Concerns

High stage on the deltaic Mississippi River throughout the summer has implications for water management. On the basis of data from 1990 to 2018, the average river stage in New Orleans is about 3.4 meters (11 feet) and dropping on 1 June, when hurrican season officially begins (Figure 1). On 1 June 2019, river stage was at 5 meters (16.5 feet). Hurricane-induced storm surge from the Gulf can increase the stage in the deltaic Mississippi River in New Orleans and even Baton Rouge. For example, Hurricane Katrina drove the river stage up by about 3.4 meters in just 1 day (28–29 August 2005; Figure 1).

The levees all along the deltaic Mississippi have been improved since Hurricane Katrina. Because peak flood season for the deltaic Mississippi River and peak hurricane season do not generally coincide, however, the river levees are not designed to accommodate storm surge on a flooded river. When Hurricane Barry threatened New Orleans in mid-July 2019, the river stage was about 4.9 meters (Figure 1). Levee heights vary, but the lowest levees are at about

A dredge works through the night to clear shoaling along the Mississippi River at New Orleans in response to the prolonged high river discharges of 2019. Dredging of the delatic Mississippi River continues 24 hours a day, 7 days a week, except during perilous weather. Credit: Brendan Yuill

6.1 meters. Luckily, the storm impacts were not as great as initially forecast, levees on the deltaic Mississippi River did not overtop, and a Katrina-scale disaster was averted.

High stage also means that the levees are at greater risk of failing. As river water piles up on levees, the added weight increases the susceptibility of the underlying soil to seepage and formation of sand boils that may undermine the integrity of levees over time.

Even when levees do not overtop or fail, prolonged flooding has impacts on industry. Navigation on the winding deltaic Mississippi River is always complicated and requires different ship captains with localized knowledge in different stretches of the river even in the best of circumstances. However, higher stage means swifter flow, making the river much harder for ships to navigate. There are more shipping accidents, sometimes resulting in deaths, when the river is high.

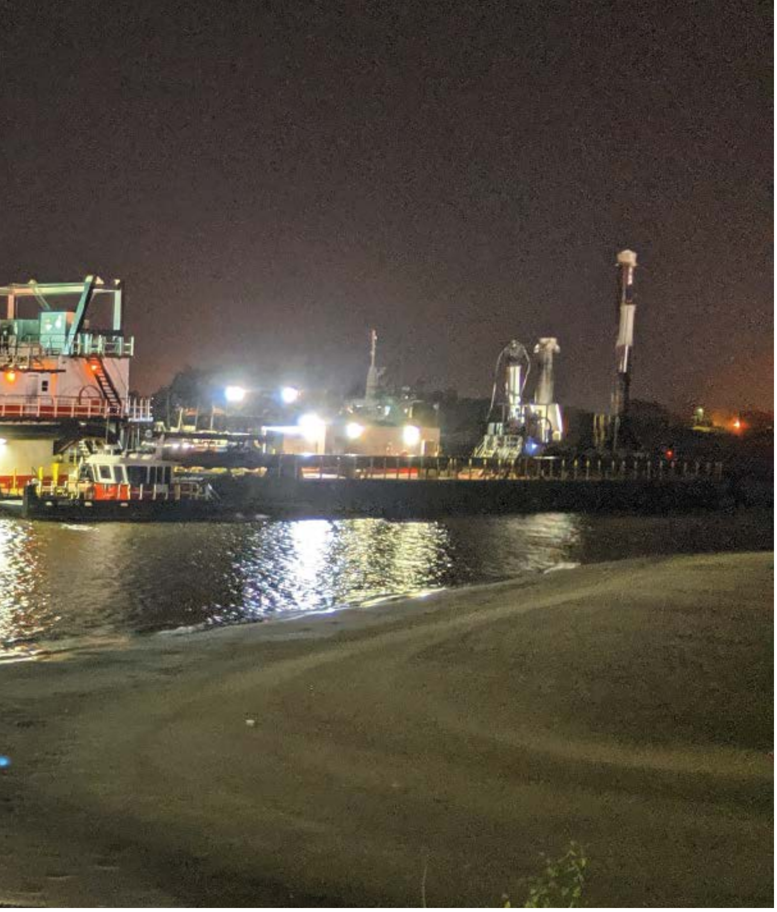
Stronger currents also mean that ships at anchor can be unmoored and drag their anchors. More space is required between anchored vessels, resulting in fewer spots for anchorage, and some ports become entirely unusable in high water. Tugboats also push smaller loads at higher discharge, further resulting in reduced shipping. In 2019, the total load of commodities shipped on the Mississippi River was 25% lower than the 10-year average. Downstream trips are faster, but upstream trips are slower and require more fuel. And dredging efforts cannot keep pace with siltation at the mouth of the river, limiting the size of ship that can come up the river.

The only real certainty is that past recipes for managing the river through hard-structure engineering will not be adequate given all the stressors on the system.

A Silver Lining

Amid the challenges of prolonged flooding is the silver lining that higher flows on the deltaic Mississippi River could contribute to land building. Coastal wetlands protect New Orleans and all of southern Louisiana from the impacts of hurricanes. An often-cited statistic is that Louisiana loses an area of wetland the size of a football field of wetland every hour, or 42.9 square kilometers per year, because of natural delta deterioration processes exacerbated by subsurface fluid withdrawal and construction of canals [*Couvillion et al.,* 2011]. The $50 billion Louisiana Coastal Master Plan aims to reduce this land loss, and one of its proposed strategies involves harnessing natural delta-building processes to create land through sediment diversions from the deltaic Mississippi River into selected areas of shallow deteriorating marshes.

Optimized sediment diversions would occur only during high-stage, sediment-laden discharges to maximize the amount of river sediment entering receiving basins in the coastal marshes while minimizing the introduction of fresh water into saltwater ecosystems. The state of Louisiana is currently designing two large sediment diversions, each with a flow conveyance capacity of about 2,100 cubic meters (74,000 cubic feet) per second, to be located roughly 50 kilometers downstream of New Orleans (Figure 2). Ultimately, the land-building potential of these projects will depend on sea level rise; however, numerical modeling suggests they could produce 20–60 square kilometers of new marshland, or an area the size of the modern Wax Lake delta, over 5 decades of operation.



There are caveats to this approach, however: As we have learned from spillway operations, altering salinity in the estuaries surrounding the delta may negatively affect habitat for species such as oysters, brown shrimp, blue crab, and bottlenose dolphins. In addition, a wide range of stakeholders managing or making a living from coastal resources would likely be affected by sediment diversions, creating many legal and economic constraints that may require selective use of diversions and limit potential land building.

An Uncertain Future

The future of the deltaic Mississippi River remains uncertain, in part because it is surrounded by many changing systems. Over the past century, the upstream network that delivers water and sediment to the deltaic Mississippi River has been highly engineered. Dams control flooding and reduce sediment supply, whereas increased channelization of the network changes flow patterns and travel times. The watershed has also seen extensive urban and agricultural development, which leads to faster and greater-volume deliveries of water to the Mississippi network.

Climate change will also continue to have multiple impacts. During 1986–2015, much of the Mississippi watershed experienced increases in precipitation of 5% to more than 15% compared to 1901–1960 [*Easterling et al.,* 2017]. On the downstream end, the number of hurricanes overall and the number of very intense hurricanes are predicted to increase [*Kossin et al.,* 2017]. Further, relative sea level rise will drive the terminus of the river upstream.

The design of flood management infrastructure has typically relied on historical precedent, such as flood frequency records. These designs must account for the possibility that future conditions look significantly different from those of the past. Efforts to modernize planning are helped by the fact that researchers have made great strides in improving abilities to predict future conditions through the development of high-quality community hydrologic and climate numerical models [e.g., *Kauffeldt et al.,* 2016]. Ambitious physical laboratory models are also providing opportunities to test the effects of proposed experimental river management projects such as those related to sediment diversions.

Ultimately, the only real certainty is that past recipes for managing the river through hard-structure engineering will not be adequate given all the stressors on the system. After large floods, there are often discussions about relocating people away from floodplains and about changing zoning laws, but as the amount of time since a disaster increases, the sense of urgency for such changes dwindles. The urgency is now here to stay.

Creative, although possibly unpopular, solutions beyond infrastructure are also required to manage the deltaic Mississippi River. The most effective options for the long term are nature-based solutions that leverage ecosystem functions, such as fostering vegetation growth to dissipate storm surge [*Barbier et al.,* 2013], and that are more adaptable to changing environmental conditions than concrete and steel structures are. Tough decisions, including abandoning some areas where people live, may be part of the answer as well, and these discussions are already occurring. Solutions must not put the entire burden of change on marginalized socioeconomic communities, however, as has occurred with other development projects in the region, such as the siting of new industrial plants. An equitable solution that relies on sound science should be the priority.

Many groups have roles to play in addressing the future of the deltaic Mississippi River, from scientists, engineers, and river managers to stakeholders, politicians, and the public. The question now is whether these groups will be brave enough to embrace innovative and perhaps yet to be designed solutions.

Acknowledgments

We thank R. Waid, A. Ferchmin, and R. Perez for information on shipping conditions and boating accidents during Mississippi River floods and J. Corbino for information on dredging practices.

References

Barbier, E. B., et al. (2013), The value of wetlands in protecting southeast Louisiana from hurricane storm surges, *PLoS One, 8,* e58715, https://doi.org/10.1371/journal.pone.0058715.

Coleman, J. M. (1988), Dynamic changes and processes in the Mississippi River delta, *Geol. Soc. Am. Bull., 100,* 999–1,015, https://doi.org/10.1130/0016-7606(1988)100<0999:DCAPIT>2.3.CO;2.

Couvillion, B. R., et al. (2011), Land area change in coastal Louisiana from 1932 to 2010, *U.S. Geol. Surv. Sci. Invest. Map, 3164,* scale 1:265,000, https://doi.org/10.3133/sim3164.

Easterling, D. R., et al. (2017), Precipitation change in the United States, in *Climate Science Special Report: Fourth National Climate Assessment,* vol. 1, edited by D. J. Wuebbles et al., pp. 207–230, U.S. Global Change Res. Program, Washington, D.C.

Kauffeldt, A., et al. (2016), Technical review of large-scale hydrological models for implementation in operational flood forecasting schemes on continental level, *Environ. Modell. Software, 75,* 68–76, https://doi.org/10.1016/j.envsoft.2015.09.009.

Kossin, J. P., et al. (2017), Extreme storms, in *Climate Science Special Report: Fourth National Climate Assessment,* vol. 1, edited by D. J. Wuebbles et al., pp. 257–276, U.S. Global Change Res. Program, Washington, D.C.

McPhee, J. (1989), *The Control of Nature,* Farrar, Straus, and Giroux, New York.

Milly, P. C., et al. (2008), Stationarity is dead: Whither water management?, *Science, 319,* 573–574, https://doi.org/10.1126/science.1151915.

Mossa, J. (1996), Sediment dynamics in the lowermost Mississippi River, *Eng. Geol., 45,* 457–479, https://doi.org/10.1016/S0013-7952(96)00026-9.

Smith, L. M., and B. R. Winkley (1996), The response of the lower Mississippi River to river engineering, *Eng. Geol., 45,* 433–455, https://doi.org/10.1016/S0013-7952(96)00025-7.

U.S. Army Corps of Engineers (2014), Mississippi River and Tributaries Project: Levee system evaluation report for the National Flood Insurance Program, Miss. Valley Div., Vicksburg.

Author Information

Nicole M. Gasparini (ngaspari@tulane.edu), Department of Earth and Environmental Sciences, Tulane University, New Orleans, La.; and **Brendan Yuill,** The Water Institute of the Gulf, Baton Rouge, La.

▶ Read the article at bit.ly/Eos-Mississippi-flooding

REFLECTING *on a* HALF CENTURY *of* MINERAL *and* ROCK PHYSICS *at* AGU

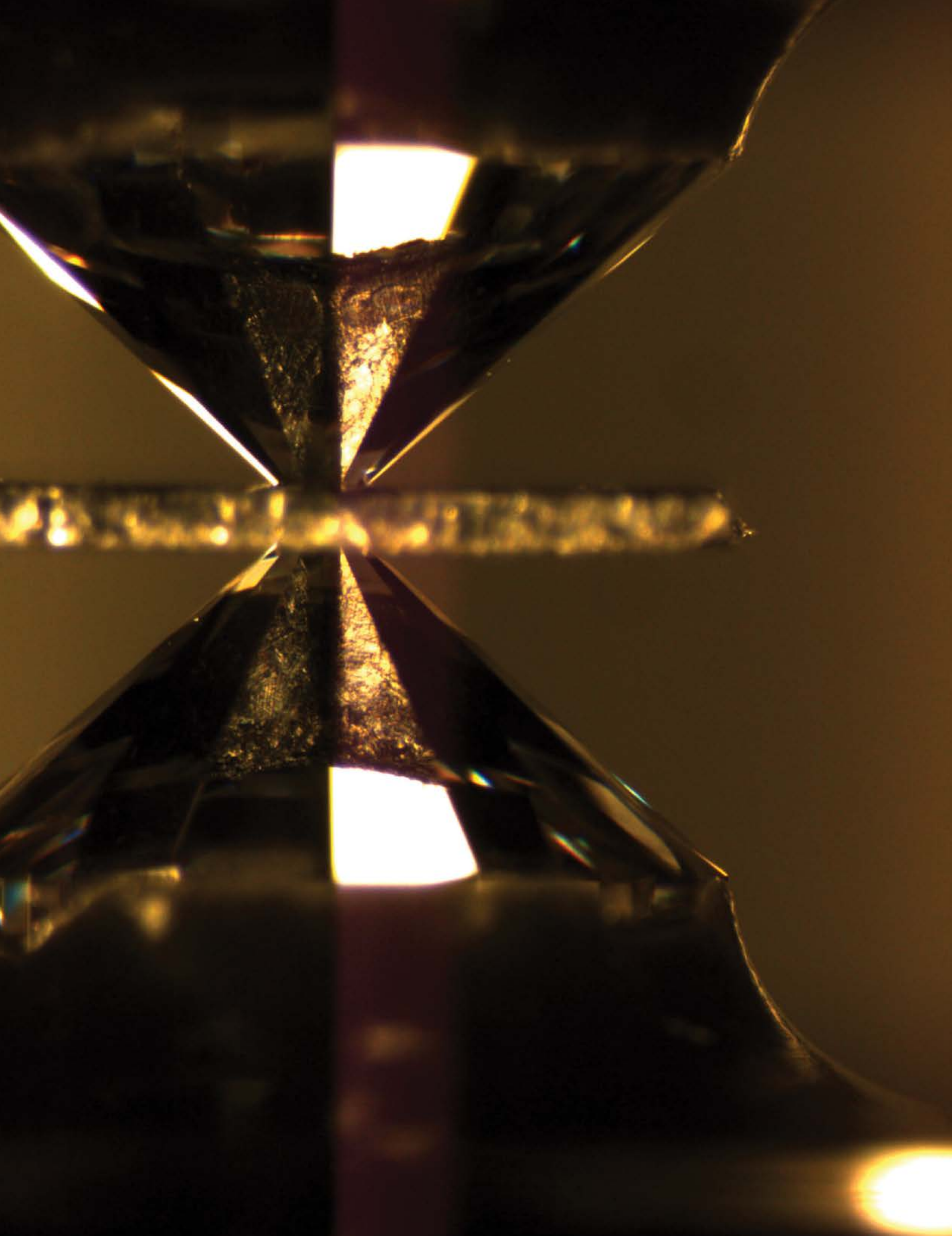
by ROBERT COOPER LIEBERMANN

Research fields focused on the physical properties of Earth materials emerged in the 20th century and have been making major contributions within geoscience ever since.

Two giant earthquakes in the 1960s—one in Chile (1960) and one in Alaska (1964)—generated free oscillations of the entire planet and provided important new seismic data that were incorporated into improved velocity and density models of Earth's interior [e.g., *Dziewonski and Anderson,* 1981; *Kennett et al.,* 1995]. To interpret what these velocity and density models revealed about the composition and mineralogy beneath the surface—and to address other, related questions in Earth science—new experiments involving Earth materials at high pressures and temperatures were needed. Efforts to facilitate these experiments led to innovations in instrumentation—such as diamond anvil cells and large-volume presses [e.g., *Bassett,* 2009; *Liebermann,* 2011], which could produce pressures and temperatures representative of the deep Earth—and helped spur the emergence of mineral physics as a distinct discipline with the geosciences.

The term mineral physics was coined by Orson Anderson when he established his experimental lab at Columbia University's Lamont Geological Observatory in 1964 [*Liebermann,* 2019]. Now the discipline is widely considered one of three pillars of geophysics, along with geodynamics and seismology. Geophysics as a whole advances by close cooperation among researchers in these fields. The role of mineral physicists is to investigate properties of minerals, knowledge of which is essential to interpreting seismic data accurately and running realistic geodynamic simulations. To be useful in such applications, mineral properties must be

Diamond anvil cells have been a mainstay of research in mineral physics since the instrument was invented in the late 1950s. Credit: Steve Jacobsen/Northwestern University



studied over the wide range of pressures, temperatures, and chemical compositions seen in the interior of Earth (or, for some researchers, in the interiors of other terrestrial planets), but these materials and conditions present several challenges.

Today scientists are tackling these challenges through a combination of experimental and computational methods. Experiments typically offer more precise information at lower pressures and temperatures, whereas computational work offers more detailed information at conditions more challenging to re-create in experiments. Although studying bulk material properties is vital to understanding planetary behavior, atomistic inspection of these complex materials is necessary to understand why they behave the way they do. A connection is thus established between atomic- and planetary-scale phenomena, which mineral physicists are in a unique position to illuminate [*Wentzcovitch and Stixrude,* 2010].

MINERAL PHYSICS FINDS ITS PLACE AT AGU

Through the 1970s, the mineral physics community began organizing an initiative to establish a formal role at AGU. At Spring Meeting 1982 in Philadelphia, a small group of researchers met for lunch to develop a proposal for AGU recognition. In response to the proposal, in 1983 the AGU Executive Council approved the establishment of an All-Union Committee on Mineral Physics. Among others who assumed early leadership roles, Anderson was the founding chair, and I served as the committee's first foreign secretary, a role in which I cultivated connections with mineral physics laboratories throughout the world.

Mineral physics is a diverse field that includes the study of crystal structures, thermochemical properties, physical properties, equations of state, and phase equilibria of minerals and their chemical analogue compounds. These parameters are all interrelated, yet for much of the 20th century they were traditionally studied and reported by researchers in disparate fields who represented different AGU sections. Studies of equations of state and elastic constants, for example, were usually included under Tectonophysics, whereas studies of magnetic mineral properties fell under Geomagnetism and Paleomagnetism, and crystal structure and phase equilibria studies appeared under Volcanology, Geochemistry, and Petrology. The extent of this issue was highlighted during AGU's Spring Meeting 1983, when discussions about silicate mineralogy and petrology were held concurrently in seven different sessions sponsored by five different sections.

It was apparent that experimental and theoretical investigations into the relationship between interatomic forces and physical properties of minerals were central to current problems in the Earth sciences, such as whether the upper and lower mantles are chemically distinct. But research efforts were fragmented, with little coordination or cooperation among researchers with different backgrounds and objectives.

To address this situation, the mineral physics community sponsored many conferences and workshops beginning in the 1980s [e.g., *Schock,* 1985; *Navrotsky and Weidner,* 1989; *Ahrens et al.,* 1989]. From these workshops, it became evident that new scientific advances would provide dramatic progress in our understanding of Earth's interior. These meetings clearly marked the emergence of the discipline of mineral physics into the mainstream of geophysics.

Several workshops focused, for example, on the importance of emerging synchrotron X-ray sources in enabling high-pressure experiments at the national laboratories of the U.S. Department of Energy and the Cornell High Energy Synchrotron Source supported by the National Science Foundation [*Bassett et al.,* 1988; *Smith and Manghnani,* 1988; *Sutton et al.,* 1988]. As Bill Bassett told me while I was preparing this article, "These synchrotron facilities quickly became the focus of many mineral physics experiments; X-ray diffraction patterns at high pressures and temperatures could be obtained every few seconds rather than [taking] a week." A camera added to the instrumentation soon allowed correlation of visual observations of changes in mineral properties with the diffraction changes. The camera also made it possible to aim the X-ray beam at specific portions of a sample "and thus watch phase transitions and reactions proceed step by step," according to Bassett. Real-time X-ray imaging allowed observation of strained portions of minerals surrounding inclusions and other internal structures, and reactions between solids and fluids could also be studied.

The mineral physics community sponsored many conferences and workshops beginning in the 1980s. These meetings clearly marked the emergence of mineral physics into the mainstream of geophysics.

Numerous important findings emerged from early applications of synchrotron radiation in mineral physics, including the proposal that phase transitions in olivine are the origin of deep-focus earthquakes [*Furnish and Bassett,* 1983].

PIONEERS IN ROCK DEFORMATION

If Francis Birch, who described the chiefly silicate mineralogy of Earth's mantle in a seminal paper [*Birch,* 1952], is recognized as the "father of mineral physics" [*Liebermann,* 2019], then David Griggs is rightly called the "father of experimental rock deformation," according to Terry Tullis, who cited *Griggs's* [1936] *Journal of Geology* paper "Deformation of rocks under high confining pressures" in his tribute to Griggs at AGU's Fall Meeting 2019. Griggs, who developed a widely used high-pressure

Harry Green and Pamela Burnley with a modified Griggs rig, used in rock deformation experiments, in Green's laboratory at the University of California, Davis in the early 1990s. Credit: Jim West

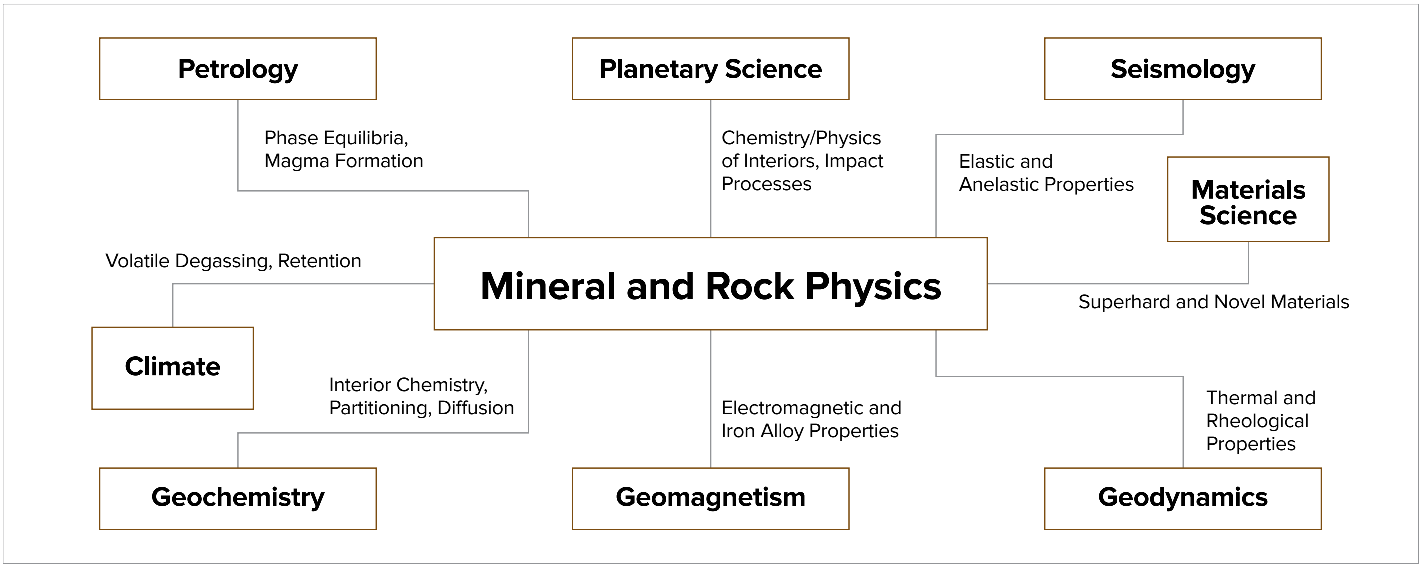


Fig. 1. The field of mineral and rock physics is intimately connected to many other geoscience disciplines. Credit: Robert Cooper Liebermann

apparatus known as the Griggs rig, and Birch were students of renowned physicist (and posthumous namesake of bridgmanite, Earth's most abundant mineral) Percy Bridgman at Harvard; as Brian Evans of the Massachusetts Institute of Technology (MIT) has noted, both Bridgman and Birch also contributed to rock mechanics, via their own work and through their influence on Griggs and on Bill Brace. Griggs, at the University of California, Los Angeles, and Brace, at MIT, nurtured the careers of many students in rock mechanics using a variety of experimental apparatuses.

The growth and vitality of mineral and rock physics as a discipline are perhaps best illustrated by the number of scientists who have been involved in experimental and theoretical research.

I recall a time at a Gordon Conference in the late 1960s or early 1970s at Kimball Union Academy in New Hampshire when some of us young scientists were sitting outside a cottage listening to Griggs and Brace discuss the current state and future of rock deformation research in the United States. For young graduate students and postdocs, it was an exhilarating experience to be in the presence of such "giants" in the field, but it was also a chance to see firsthand how scientific leaders could relate and convey their visions of a discipline, notwithstanding the fact that they were in competition for some of the same bright young minds.

Prompted by the earlier formation of the mineral physics group and by the realization that researchers studying rock mechanics were failing to connect with the larger membership of AGU, many students of Brace and Griggs, now leaders in the field, met one year in the early 1990s on the steps outside the conference center in San Francisco, where the AGU Fall Meeting was being held, to discuss establishing a new AGU focus group. At Brian Evans's suggestion, the committee formed by this group was named Physical Properties of Earth Materials (PPEM). The motivation for creating the new committee "was the fact that the physical behavior of the Earth owes to a system of materials, including not just minerals or rocks, but other noncrystalline solids and liquids," Brian told me recently. Because of interactions among these various materials' properties—such as elastic and inelastic behavior, electrical and fluid transport properties, and a host of behaviors during chemical reactions—"the behavior of the system may be quite different from a simple sum of the behavior of the components." This is now a well-accepted idea.

A GROWING FIELD

In 1993, soon after the formation of the PPEM committee, Steve Kirby from the U.S. Geological Survey's Earthquake Hazards Program and I orchestrated a merger of the two focus groups and, after an arm-wrestling contest over what to name the newly conjoined group, selected the name Mineral and Rock Physics to give both disciplines more strength and visibility within AGU.

The combined focus group evolved to become a full-fledged and flourishing section of AGU in the early 2000s, and over the ensuing decades, high-impact research in the field has continued unabated. For example, experiments on artificially produced minerals at the high pressures and temperatures at which they are stable—conducted using ultrasonic interferometry [*Li and Liebermann*, 2014] and Brillouin spectroscopy [*Speziale et al.*, 2014]—yielded new data on densities and seismic velocities for minerals at pressures into the lower mantle. And theoreticians have had increasing success in explaining the physical properties of minerals using fundamental principles; *Wentzcovitch and Stixrude* [2010] provide an excellent summary of the state of the art in theoretical and computational methods in mineral physics and applications to geophysics.

Although the members of the Mineral and Rock Physics section constitute only about 1% of the total AGU membership, they exert a disproportionate influence because mineral and rock physics is intimately connected to many other geoscience disciplines, including seismology, planetary science, petrology, geochemistry, geomagnetism, geodynamics, and even materials and climate science (Figure 1).

A good illustration of this interrelationship involves the experimental discovery by *Murakami et al.* [2004] of the postperovskite phase of bridgmanite ($MgSiO_3$) coupled with its theoretical verification by *Tsuchiya et al.* [2004]. These two developments offered a possible explanation of the puzzling D" region at the base of the lower mantle, where seismic velocities increase more slowly with depth, and spawned an explosion of communication between geodynamicists, seismologists, and mineral and rock physicists. Even if the perovskite-to-postperovskite phase transition hypothesized in 2004 is not the explanation for the D" layer, this enhanced communication was a desirable outcome.

The growth and vitality of mineral and rock physics as a discipline are perhaps best illustrated by the number of scientists who have been involved in experimental and theoretical research. With the assistance of many colleagues, I assembled informal tabulations documenting the large increase in the number of scientists in mineral and rock physics who held academic faculty appointments in U.S. universities in the 1960s and the 2010s. Whereas in the 1960s there were mineral physics faculty in 10 laboratories at 9 universities, in the 2010s there were faculty in 62 laboratories at 35 universities. Similarly, whereas there were rock mechanics faculty in 7 laboratories at 6 universities in the 1960s, there were faculty in 38 laboratories at 22 universities in the 2010s. A related and significant development has been the emergence of many women now directing laboratories: In the 1960s, no mineral physics or rock mechanics laboratories were directed by women, whereas in the 2010s, women headed 29% of mineral physics labs and 27% of rock mechanics labs. Anecdotally, similar trends of growth have occurred in nonacademic institutions in the United States and in international institutions (although accurately tabulating those scientists is more difficult), as well as in populations of students and other researchers in these fields.

Today the Mineral and Rock Physics section of AGU sponsors awards for graduate students and early-career researchers to recognize outstanding contributions by promising young scientists engaging in experimental and/or theoretical studies of minerals and other Earth materials. It is these researchers who will build on what has been accomplished in mineral and rock physics in the past half century and who will continue unraveling the physics and chemistry that govern how the solid Earth works.

ACKNOWLEDGMENTS

It is a pleasure to acknowledge the many colleagues in mineral physics and rock mechanics who contributed to this article, including Jay Bass, Bill Bassett, Mike Brown, Pam Burnley, Tom Duffy, Bill Durham, Brian Evans, Steve Kirby, Dave Kohlstedt, Andy Kronenberg, Sebastien Merkel, Alex Navrotsky, Bob Schock, Terry Tullis, Quentin Williams, Renata Wentzcovitch, Jin Zhang, and Wenlu Zhu. I am also grateful to Quentin Williams for modifying the Williams-Lattimore diagram. I thank Tom Duffy and Brian Evans for their review of an earlier draft of this article.

REFERENCES

Ahrens, T. J., et al. (1989), Frontiers in mineral physics: Report of the Mineral Physics Committee of the AGU, AGU, Washington, D.C.

Bassett, W. A. (2009), Diamond anvil cell, 50th birthday, *High Pressure Res., 29*(2), 165–186, https://doi.org/10.1080/08957950802597239.

Bassett, W. A., et al. (1988), Synchrotron radiation, applications in the Earth sciences, *Eos Trans. AGU, 69*(52), 1,675–1,676, https://doi.org/10.1029/88EO01260.

Birch, F. (1952), Elasticity and constitution of the Earth's interior, *J. Geophys. Res., 57,* 227– 286, https://doi.org/10.1029/JZ057i002p00227.

Dziewonski, A. M., and D. L. Anderson (1981), Preliminary reference Earth model, *Phys. Earth Planet. Inter., 25,* 297–356, https://doi.org/10.1016/0031-9201(81)90046-7.

Furnish, M. D., and W. A. Bassett (1983), Investigation of the mechanism of the olivine-spinel transition in fayalite by synchrotron radiation, *J. Geophys. Res., 88,* 10,333–10,341, https://doi.org/10.1029/JB088iB12p10333.

Griggs, D. T. (1936), Deformation of rocks under high confining pressures: I. Experiments at room temperature, *J. Geol., 44*(5), 541–577, https://doi.org/10.1086/624455.

Kennett, B. L. N., E. R. Engdahl, and R. Buland (1995), Constraints on seismic velocities in the Earth from traveltimes, *Geophys. J. Int., 122,* 108–124, https://doi.org/10.1111/j.1365-246X.1995.tb03540.x.

Li, B., and R. C. Liebermann (2014), Study of the Earth's interior using measurements of sound velocities in minerals by ultrasonic interferometry, *Phys. Earth Planet. Inter., 233,* 135–153, https://doi.org/10.1016/j.pepi.2014.05.006.

Liebermann, R. C. (2011), Multi-anvil, high-pressure apparatus: A half century of development and progress, *High Pressure Res., 31,* 493–532, https://doi.org/10.1080/08957959.2011.618698.

Liebermann, R. C. (2019), The Orson Anderson era of mineral physics at Lamont in the 1960s, *Minerals, 9*(6), 342–360, https://doi.org/10.3390/min9060342.

Murakami, M. K., et al. (2004), Post-perovskite phase transition in $MgSiO_3$, *Science, 304,* 855–858, https://doi.org/10.1126/science.1095932.

Navrotsky, A., and D. J. Weidner (Eds.) (1989), *Perovskite: A Structure of Great Interest to Geophysics and Materials Science, Geophys. Monogr. Ser.,* vol. 45, AGU, Washington, D.C., https://doi.org/10.1029/GM045.

Schock, R. N. (Ed.) (1985), *Point Defects in Minerals, Geophys. Monogr. Ser.,* vol. 31, AGU, Washington, D.C., https://doi.org/10.1029/GM031.

Smith, J. V., and M. H. Manghnani (1988), Synchrotron X-ray sources and the new opportunities in the Earth sciences: Workshop report, *Rep. ANL/APS-TM-3,* Argonne Natl. Lab., Lemont, Ill.

Speziale, S., H. Marquardt, and T. S. Duffy (2014), Brillouin scattering and its application in geosciences, *Rev. Mineral. Geochem., 78,* 543–603, https://doi.org/10.2138/rmg.2014.78.14.

Sutton, S. R., et al. (1988), Synchrotron X ray sources in the Earth sciences, *Eos Trans. AGU, 69*(52), 1,666–1,675, https://doi.org/10.1029/88EO01258.

Tsuchiya, T., et al. (2004), Phase transition in $MgSiO_3$ perovskite in the Earth's lower mantle, *Earth Planet. Sci. Lett., 224,* 241–248, https://doi.org/10.1016/j.epsl.2004.05.017.

Wentzcovitch, R., and L. Stixrude (Eds.) (2010), *Theoretical and Computational Methods in Mineral Physics: Geophysical Applications, Rev. Mineral. Geochem. Ser.,* vol. 71, xvii + 484 pp., Mineral. Soc. of Am., Chantilly, Va., https://doi.org/10.1515/9781501508448.

AUTHOR INFORMATION

Robert Cooper Liebermann (robert.liebermann@stonybrook.edu), Department of Geosciences and Mineral Physics Institute, Stony Brook University, Stony Brook, N.Y.

▶ **Read the article at bit.ly/Eos-MRP**

Remaking a Planet One Atom at a Time

BY KIMBERLY M. S. CARTIER

When is a planet not a planet? Where does helium rain? How can water be solid and liquid at the same time? For answers, scientists put common planetary materials under extreme pressure and watched what happened next.

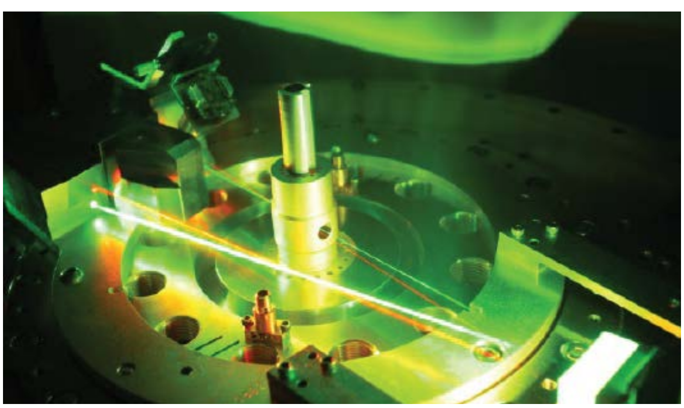
Sandia National Laboratories' Saturn accelerator (above) and its more powerful Z machine are pulsed power machines. They deliver high-power X-ray pulses to drive test samples to extreme temperatures and pressures. Credit: Randy Montoya, Sandia National Laboratories

In one of the most technologically advanced laboratories ever built, a high-energy laser powers up. It fires a pulse of light that lasts just fractions of a second, striking minuscule samples of the most common materials in the universe.

The shock wave might create never-before-seen types of matter that exist in the hearts of planets. Or it might create minerals that lay strewn across the cratered surfaces of moons and speckled through asteroids and meteorites, dutifully keeping a record of their chaotic past.

It sounds like science fiction—and, in fact, has been portrayed as such on the big screen (see image on p. 33). But these experiments are science reality and take place at not one but many high-energy laboratories around the globe. The technique is one example of dynamic compression, named for its speed and the intense pressure created. Rapidly squeezing planetary materials replicates the processes that take place in the interiors of planets and during energetic events like collisions and impacts.

“We started thinking about how to really synthesize the conditions of planetary interiors in the laboratory,” said Arianna Gleason, an experimental mineral physicist at SLAC National Accelerator Laboratory and Stanford University in Menlo Park, Calif.



Lasers help align the hardware and diagnostic tools before the Z machine is fired. During compression, X-ray lasers are often used to take data. Credit: Sandia National Laboratories

We’re “taking the minerals that we’re used to seeing every day—quartz, feldspar, stuff that humans have constant contact with—and asking the question, What do they look like, and what are their properties at extreme conditions?”

Hydrogen, helium, methane, water, silicates, iron—all of these common planetary materials can change between solid, liquid, and gas inside or on the surface of a planet depending on the pressure and temperature. These atomic-scale changes can determine whether the planet has a core and a mantle, whether it has a magnetic field, whether it survives a catastrophic impact, and whether it can support life.

For more than half a century, dynamic compression experiments have allowed scientists to see what happens to ordinary planetary material at the center of the Earth. The inner workings of larger planets and exoplanets have only recently been accessible from the lab.

> **We’re “taking the minerals that we’re used to seeing every day...and asking the question, What do they look like, and what are their properties at extreme conditions?”**

Diamonds, Guns, and Lasers

Before all of the moving parts of dynamic pressure experiments came the steady pressure of static experiments, in which scientists “synthesize these high-pressure and -temperature conditions, but...hold them at those conditions over a long period of time—minutes, hours, even years,” Gleason said.

The most common tool for this is called a diamond anvil cell, which squeezes samples literally between a rock and a hard place. “One’s been in my drawer for years,” said Gleason. Once a sample is under pressure, the scientists can check for any changes to its chemistry, molecular or crystal structure, visual properties, and phase.

“The community has been working at pressures at the order of a hundred gigapascals, 1 million atmospheres, for something approaching 50 years,” said Raymond Jeanloz, a planetary scientist at the University of California, Berkeley. (The pressure at Earth’s surface is 1 atmosphere.) “A hundred gigapascals is an important pressure for our field because that roughly corresponds to...the core-mantle boundary of the Earth.” The center of Earth’s core is about 3 times that pressure, which is well within reach of the newer, smaller diamond anvil cell designs that focus the same amount of force on a smaller sample size to generate larger pressures.

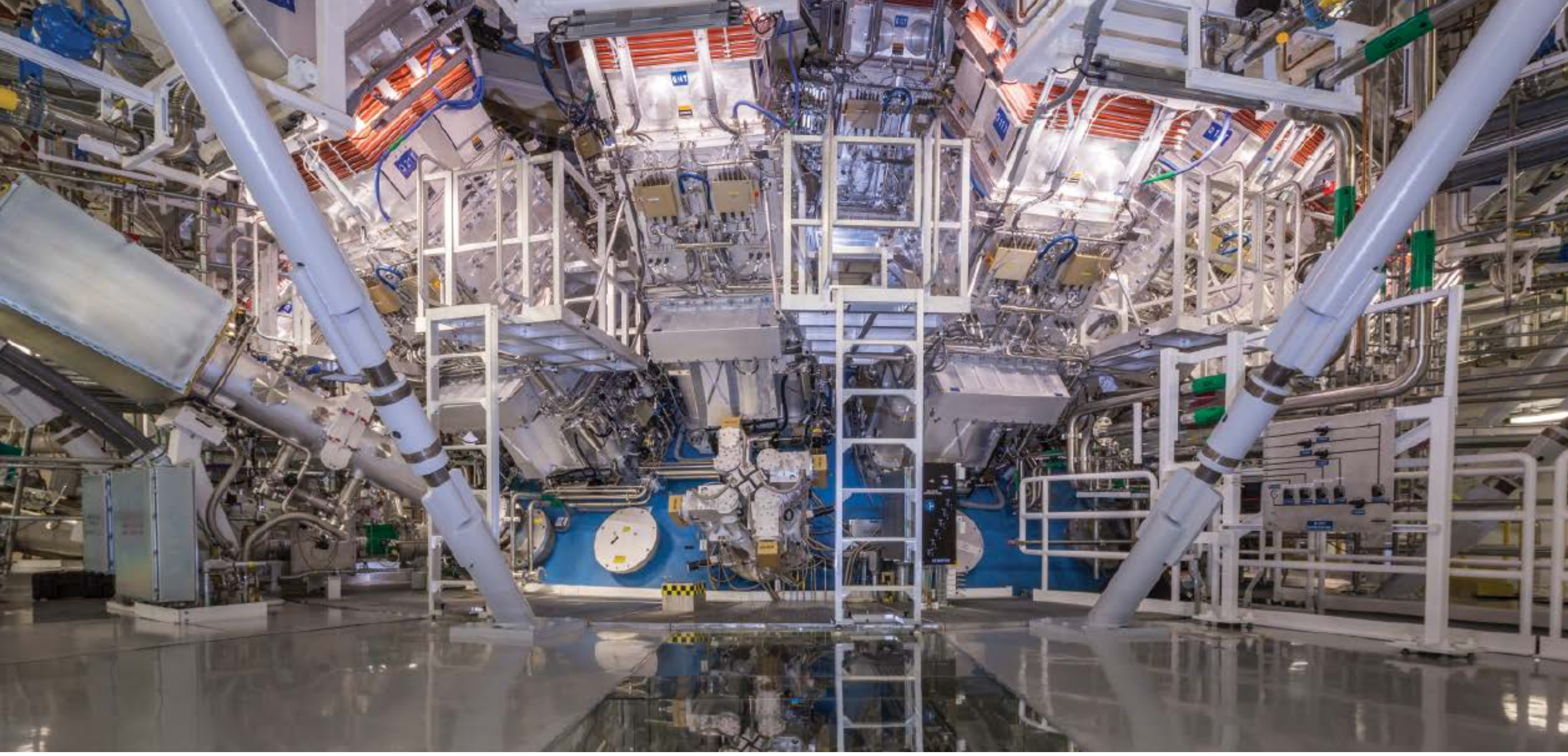
“Static compression definitely lays the groundwork and is the bedrock of the compression community in mineral physics,” Gleason said. But diamonds are only so strong, and test samples can get only so small. Dynamic compression can reach the higher pressures found within ice giant, super-Earth, and gas giant planets and allows us to study events like impacts, in which change occurs rapidly. “We’re talking about a really accelerated way of applying pressure.”

“Back in the beginning of the field,” said June Wicks, “there would be big gas guns located in basements of academic institutions, and that [technique] was the foundation of measuring equations of state.” Projectiles fired at very high speeds strike a target sample within a test chamber, and then scientists can watch pressure waves propagate through the target and study the changes.

Wicks, a planetary scientist at Johns Hopkins University in Baltimore, Md., uses laser-driven compression experiments to study how atoms and molecules move and interact inside planets. In the past 20 or so years, Wicks said, compression using high-energy optical lasers, like the one at SLAC National Accelerator Laboratory, has advanced to the front of the field.

“You focus [the laser] on your sample, it turns the surface into a plasma, and that plasma expands and sends an equal and opposite pressure wave into your sample,” Wicks said. All of this takes place in a few billionths of a second.

Using lasers and pulsed power sources, “people have studied materials to pressures as high as a billion atmospheres...a thousand-fold increase” over what’s achievable with static compression, Jeanloz said. Shorter laser pulses achieve higher pressures as more power strikes the sample all at once.



Laser-driven compression can shock planetary materials into states of matter that exist only in the deep interiors of planets. Shown here is the target bay of the National Ignition Facility, one of the leading instruments for these experiments and also the set of the Starship Enterprise*'s warp core in* Star Trek: Into Darkness *(2013). Credit: Damien Jemison, Lawrence Livermore National Laboratory*

"It's as much power as is in a bolt of lightning in a split second," Gleason said.

Helium Rain Brightens Saturn

On Earth it rains liquid water, but on Saturn it rains liquid helium. We know this because experiments using the lasers at the National Ignition Facility at Lawrence Livermore National Laboratory in Livermore, Calif., have validated predictions of when hydrogen and helium mix together and when they separate, a property called miscibility.

"Hydrogen is the most populous element in the universe, and hydrogen is somehow involved in every planetary body" as itself or within compounds like water and methane, said Takuo Okuchi, an associate professor at Okayama University's Institute for Planetary Materials in Japan. "Its chemical state is very, very different depending on its environment, [in essence, its] pressure and temperature condition."

At the pressures found inside Jupiter and Saturn, Okuchi explained, hydrogen becomes metallic, meaning that hydrogen atoms are so tightly packed that their electrons overlap. Liquid metallic hydrogen sustains the magnetic field inside these gas giant planets. (Inside Uranus and Neptune, water becomes metallic, Okuchi said.)

"At high enough pressures and temperatures, hydrogen and helium dissolve into one another and they make a continuous fluid," said Sarah Stewart, a planetary scientist at the University of California, Davis. "They're not a gas anymore because they're at such high pressure, but we call it a fluid. But then there's a boundary where if you go below a certain temperature, helium will form droplets and then rain down into the interior."

"It's like oil and water," Jeanloz said.

Saturn is about 50% brighter than it should be based on its age, and Stewart explained that this might be because helium rains on Saturn but not on Jupiter. "This is an idea that's been around for a while, but only recently have we been able to get to those conditions in the lab."

"These atomic-level changes have planet-sized implications," said Wicks.

"At high enough pressures and temperatures, hydrogen and helium dissolve into one another and they make a continuous fluid."

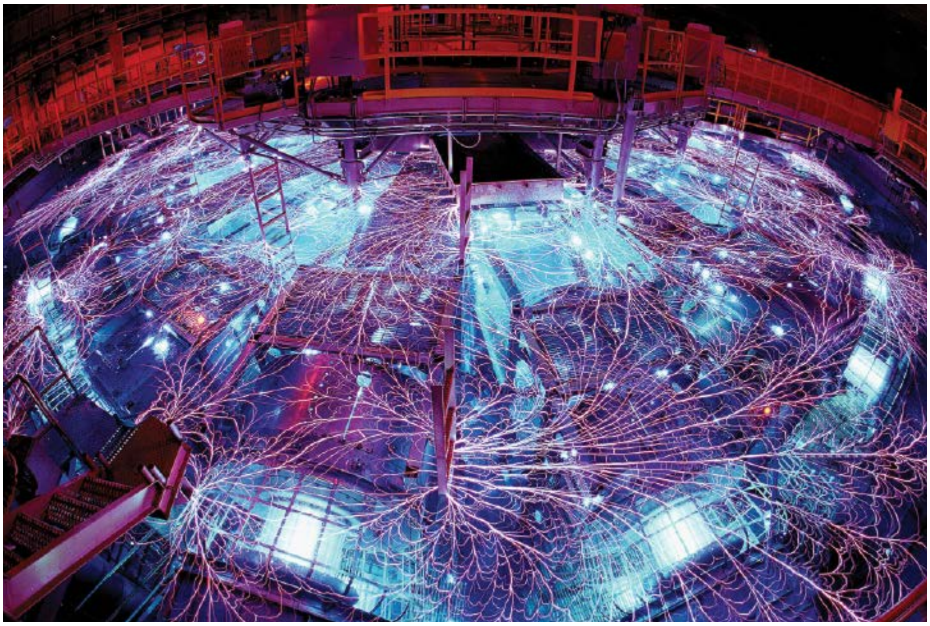
Diamonds Decorate Neptune's Sky

Ice giants like Uranus and Neptune have a higher fraction of methane (CH_4), water (H_2O), and ammonia (NH_3) than gas giants do, and dynamic compression experiments have shown that rain there gets even stranger. A team led by Dominik Kraus explored what happens to a pure hydrocarbon material when it's exposed to the conditions inside a planet where it might exist—in this case, Neptune.

"We have now seen the formation of nanodiamonds," said Kraus, an experimental physicist at Helmholtz Zentrum Dresden Rossendorf in Germany. The pressures of the nanosecond laser compression broke the molecular bonds holding hydrogen and carbon together and compressed the carbon into nanometer-scale diamonds. The discovery confirmed a long-held theory.

Experiments like this highlight an advantage that laser compression has over diamond anvil cells. Both types of experiments often use the brightest X-ray sources to analyze the microscopic structure of the samples before, during, and after compression. But when you're looking for the signatures of tiny diamonds, Kraus said, it's easier if the compression itself isn't done with diamonds.

Moreover, hydrogen "reacts with any surrounding material," Okuchi said, including the capsule that contains the laser target. So does water, another common planetary material. "By using a very strong laser beam, we immediately compress the material within nanoseconds" and make multiple measurements within that same time frame. "This is the best way to measure at such extreme conditions without any contamination, without any reaction."



The Z machine uses electrical currents and magnetic fields to generate high temperatures, high pressures, and high-powered X-rays. Scientists have used this instrument to understand the equations of state of common planetary materials. Credit: Randy Montoya/Sandia National Laboratories

Taking the results of nanosecond experiments and applying them to planetary timescales can be a "fuzzy" endeavor. "Certainly, something that happens in nanoseconds will also happen in millions of years," Kraus said. "The question is, What else can happen that we cannot see in our small timescales?"

The ultrashort timescale, essential for driving planetary materials to planetary pressures, is also this method's "biggest weakness," according to Wicks. "We're trying to ask questions about…the fate of the interior of a planet, which is on superlong timescales, with an experiment that's 1 nanosecond.… The more extreme the states that we get to, the shorter the timescale you have to do it in."

Solid–Liquid Water Complicates Ice Giants

A better understanding of the material processes inside Uranus and Neptune can also help us understand the most common type of exoplanet.

Among extrasolar planets, Kraus said, "there's this big abundance of mini-Neptunes, which are probably the same as Uranus and Neptune, just without much of the hydrogen-helium atmosphere. So, really, a thick, icy mixture."

Experiments published in 2018 revealed that "icy" is much more complicated for ice giants than previously thought. "We found this unusual superionic state for water that exists only at high pressures and temperatures that are similar to what we expect inside Neptune and Uranus," said Marius Millot, a physicist at Lawrence Livermore National Laboratory. "Superionic ice is a new state of matter."

Millot led the team of researchers who discovered this previously unknown state of matter. They used first a diamond anvil cell and then Rochester University's Omega Laser Facility to force the water to crystallize into this new state.

"For water, [superionic ice] is a state where the oxygen atoms that form the H_2O molecule that we're familiar with continue to form a solid lattice, like in ice that we know," Millot said. "But unlike the ice we know and that is in our ice cubes, in superionic ice the hydrogen is actually free to move around within this lattice of oxygen. Basically, the hydrogen atoms are moving around almost like a fluid within the solid crystal made of the oxygen. It's a very unusual solid-liquid state."

"We're trying to ask questions about...the fate of the interior of a planet, which is on superlong timescales, with an experiment that's 1 nanosecond

At the pressure of an ice giant's mantle (roughly 200 million atmospheres), superionic ice melts at temperatures near 4,700°C, much hotter than its environment. The team confirmed the ice's novel crystal structure in later research. "It could be that this superionic ice actually doesn't melt even inside Neptune and Uranus," Millot said, and so the planets could be quite solid.

The flowing hydrogen atoms carry a charge with them, and so they interact with and possibly influence the planets' magnetic fields. What's more, the structure and energy transport within the planets can alter other observable phenomena like weather, according to Kraus.

The trouble in applying these new discoveries to our ice giants comes from the lack of observational data. Uranus and Neptune were each visited only briefly by Voyager 2 in the 1980s, and so we lack detailed knowledge of the planets' gravities, magnetic fields, weathers, and compositions that could better unite experiments and theory.

Kraus explained that experimentalists are working with the teams designing a possible future ice giant mission. Compression experiments constrain what conditions a probe might encounter, identify what data mission scientists need to collect, and put observations into context.

Conducting high-pressure experiments "starting with our ice giants is already very difficult," Kraus said. To then apply our knowledge to exoplanets, "you need to rely on those constraints that you already have for all our planets to think [of] what can also be possible."

Earth Was Unmade and Made Again

Beyond improving our understanding of the current state inside planets, dynamic compression is also an invaluable tool for understanding sudden, transient high-energy events like impacts that can knock planetary evolution off course.

Consider the Earth and Moon. The chemical signatures of Earth rocks and Moon rocks suggest that a major impact long ago scraped material off Earth that then formed the Moon. But by combining high-pressure mineral physics and computer simulations, Stewart's lab found that for some time after this impact, the Earth might have ceased to be a planet.

Instead, Earth was a synestia: a molten and fluid iron-rock blob, maybe shaped like a doughnut or flying saucer. "We're used to thinking of the atmosphere being separate from the rock," Stewart said, "meaning the gases that we're breathing. Part of us trying to understand what happened after the giant impact was the miscibility of the outer parts of a synestia in our calculations. The iron, the rock, and the atmosphere are all dissolved into one another in a single fluid. They are all entirely miscible."

The synestia Earth was constantly changing its shape and sections rotated at different speeds, which violate the definition of a planet. "We were looking at the actual thermodynamic states and how they had changed and tried to understand what was produced by looking at the material properties," Stewart said. "That was what really opened the door for us to figure out that the planet could turn into something that was a new thing."

"Simulations are key to understanding impact phenomena, and we can't re-create all the conditions in the lab by doing impacts in the lab because we don't have the gravitational forces that you need in a real planetary event," Stewart said. "We gather basic material data about rocks and minerals," but simulations and ab initio modeling are essential to understanding what they mean for planetary evolution.

Many Planets Are Fuzzy Inside

Earth gained a Moon and became a planet once more, but learning the conditions under which iron and silicates mix together raised new questions about whether they fully separate into distinct layers within a planet. The textbook-standard planet model with defined layers of iron, silicate, and air is the bedrock of our theories of how planets transport heat and generate magnetic fields. However, experiments on iron-silicate alloys suggest that the boundaries might be much blurrier.

"Planets that are super-Earths could look like an Earth—iron core, rocky layer, and then just a thicker atmosphere—or they could look very different in that it's so hot on the inside that now iron and rock can dissolve into one another and there's not a clearly separated metal core," Stewart said.

"And then the same thing at the interface between what would have been the surface and the atmosphere," said Stewart. "The interior can reach high enough pressures and temperatures that that atmosphere-surface boundary becomes fuzzy as well, where part of the atmosphere dissolves into a magma [and] part of the magma actually dissolves into the atmosphere."

"Our conception of layered planets may be completely false. We haven't been able to measure this experimentally yet, but we will [be] in the next 10 years," Wicks said.

Impacts Record Solar System History

Roughly 4 billion years ago, the inner solar system was showered with bolides. Radioisotope dating of the minerals created by impacts can estimate when it happened, and shock features in grains can reveal how large an impact was. "The zircon age or baddeleyite age plays a very important role for us to constrain the whole history" of the bombardment, said Ai-Cheng Zhang, a professor of mineralogy at Nanjing University in China. "But for some of [the zircons], we don't know the exact meaning of the age" or precisely what it indicates.

Zhang studies the minerals that form through high-pressure impact events in samples of asteroids, Mars, and the Moon. "We want to understand why there are some differences between the impact records in different samples. Are they related to impact velocity? Or related to the heliocentric distance from the Sun? Currently, we don't know very well," Zhang said. "This information is critical for establishing a model to understand the dynamics in the solar system, especially the inner solar system."

"Mineral physics is about to face a big data problem," Wicks said. "Not a problem, an opportunity."

Our understanding is limited by what we know of how minerals start their radioisotope clock and what processes can reset it. Zhang has analyzed meteorites and samples returned from missions trying to figure this out. "We are still working to decipher whether impact events affected the zircon or baddeleyite age, based on our mineralogical study and geochronology investigations," he said. This will tell us whether the era of impacts happened across the inner solar system all at once or in waves.

The effort to pin down the solar system's impact history "tackle[s] the question of habitability on the early Earth and other bodies," Stewart said. "You can point to [impacts] and say maybe that's why Earth and Mars and Venus are different, but we can't really explain how that happened."

The Expanding Field of Compression

As labs in the United States, Europe, and Asia have brought newer instruments online, the extreme pressures and temperatures that planetary materials endure have become more accessible to researchers around the world.

"Depending on the pressure range and the question that we're interested in," Wicks said, "we have a slew of techniques to get to high pressure, a slew of techniques to probe the states. And those techniques are getting better and better." The facilities might be dedicated mostly to other areas of high-energy physics like nuclear fusion and plasmas, "but we get to tag along with our rocks afterward and ask our questions."

Not only are newer instruments raising the upper limit on pressure, but also they can yield more data than before from each experiment, and more quickly, too. Whereas the first laser compression facilities could fire only a few times a day, now they can test samples every few minutes.

"Mineral physics is about to face a big data problem," Wicks said. "Not a problem, an opportunity."

Some teams are looking ahead to how machine learning can guide experiment design not just to find the best tools to answer a question but also to prioritize which questions to ask first.

For some experimentalists, the next steps aim to test more realistic mixtures of planetary materials. Ice giants, after all, aren't made of only water or only hydrocarbons. Others seek to constrain material properties like electrical conductivity, viscosity, and cooling rate, which connect with large-scale planetary features like brightness, weather, and magnetic fields. Still others want to glean new information from familiar materials by leveraging the unique properties of lasers, measuring the compressed samples more accurately, and using more advanced instruments to gather data.

But high-pressure experimentalists can't answer these questions alone. "We certainly can't gather enough data on different chemical compositions to be able to finish the problem with just lab data," Stewart said. "We absolutely need modeling. And then, better constraints come from what we're seeing from the observers."

"There's room for everybody to play."

Author Information

Kimberly M. S. Cartier (@AstroKimCartier), Staff Writer

▶ Read the article at bit.ly/Eos-planet-cores

Earth's Core Is in the Hot Seat

How old is Earth's inner core? High-pressure and high-temperature experiments suggest that our planet's inner furnace may be much younger than expected.

BY JENESSA DUNCOMBE


Deposit Photos/gudinny

Emerging research from high-pressure and high-temperature experiments suggests that Earth's inner core could be a "planetary babe" just under a billion years old—younger than Earth's oceans, atmosphere, and inhabitants.

These findings represent a drastic turn from how scientists thought Earth's inner core progressed from its molten beginnings to today—and a source of a contentious debate among geoscientists.

The uncertainty lies in conflicting measurements of the fundamental properties of metal. It's unclear how efficiently iron and iron alloys conduct heat within the core, making it difficult for researchers to describe how the core has cooled over time. Mineral physicists, geophysicists, condensed-matter physicists, and dynamicists are all trying to pin down an answer.

"It's a very provocative time at the moment, I would say, in terms of core studies," said Quentin Williams, an Earth and planetary sciences professor at the University of California, Santa Cruz.

In the past decade, scientists have invented novel ways to squeeze metal samples to extreme pressures while shooting lasers to heat the samples to temperatures as hot as the Sun's surface. The experiments are tricky, however, and a consensus is elusive. In the same issue of the journal *Nature,* June 2016, two research teams published the results of separate high-pressure, high-temperature experiments—with drastically different results.

"It's a very important topic because it's basically the boundary condition for the thermal history of the Earth," said Ronald Cohen, a researcher at the Carnegie Institution for Science in Washington, D.C. The answer could rewrite our understanding of Earth's history, paving the way for discoveries in Earth's dynamics at the surface, such as volcanism and plate tectonics, and helping to elucidate faraway worlds.

Research going back to the 1950s found fingerprints of the geodynamo in Earth's oldest surviving rocks.

Earth's Electrical Generator

"I think everybody agrees that both the mantle and the core are cooling," said Peter Olson, an adjunct professor of Earth and planetary sciences at the University of New Mexico. "What we'd like to know better is how fast."

Earth's core is made largely of iron, and it's split into two parts: a small, crystallized ball of hardened iron at the center of the Earth, called the inner core, and a liquid outer core that surrounds the inner core with a "roiling mass of molten metal," said Williams. Scientists have hypothesized about inner and outer iron cores since the 19th century on the basis of the composition of meteorites.

We can thank the core for the flourishing life on Earth. Convection in the outer core sustains the magnetic field that protects us from harsh solar radiation and keeps our atmosphere intact. As liquid iron flows through a weak magnetic field, it creates an electrical current inside the planet. In turn, this current induces a secondary magnetic field, which further induces a current inside the core. This loop creates a planetary-sized electrical generator at the heart of our planet called the geodynamo.

Researchers had assumed that the inner core must be very old because research going back decades found fingerprints of the geodynamo in Earth's oldest surviving rocks, dating back nearly 4 billion years.

And indeed, the idea of an old inner core "sounded reasonable," said Kei Hirose, a professor of geophysics at the University of Tokyo and director of the Earth-Life Science Institute at the Tokyo Institute of Technology. It checked the important box: An old inner core fueled the geodynamo for billions of years by driving thermal convection in the outer core.

Metallurgy Lends a Hand

But Hirose noticed that few people had measured the thermal conductivity of iron under extreme conditions, and the few studies that had been completed, using shock wave experiments, had large uncertainties and were not easily reproducible. The thermal conductivity could be a crucial value to pinning down the core's dynamics: The core cools via both convection and conduction, and how fast it conducts heat controls how much heat is left over to drive convection.

The scientific literature listed values for the conductivity, but the values were "highly speculative," said Hirose. So instead, the team turned to research from a different field from a science based on ancient civilizations: metallurgy. Metallurgy is the study of metals, and its beginnings go back to early human settlements when forging metals was the ticket to fortifying armies. Metallurgy lives on today as a branch of materials science tasked with mineral and metal processing.

"Such literature was not known in the geoscience community," Hirose said. Combing through metallurgy papers and conducting high-temperature experiments in the lab, Hirose's team concluded that the assumed relationships between electrical resistivity and iron broke down at high temperatures, suggesting that the thermal conductivity of iron was actually quite high. If their findings were correct, the core was cooling very, very quickly.

The finding "broke all the models," said John Hernlund, a professor and vice director of the Earth-Life Science Institute. Hernlund, Hirose, and others wrote up the findings in a bombshell paper in 2013 that "created a virtual earthquake in the geophysics community," said Hernlund.

In a perspective published in the journal *Science* later that year, Olson named the issue the "new core paradox." If the core is cooling much faster than we thought, "the best way around this paradox is to think beyond the standard model of core evolution," Olson wrote. If the inner core was, in fact, very young, researchers needed to better explain how the geodynamo is driven.

Diamond-Clad Lab Work

The *Science* paper sparked a flurry of new experiments and investigation into theory.

The two papers released in the same issue of *Nature* in 2016 showed experimental takes on pinning down the core's thermal behavior.

The authors of both papers used diamond anvil cells, a high-pressure lab device. The cells contain two diamonds, polished perfectly into cones with their tips shaved off. The scientists place a thin slice of iron—no thicker than a human hair—between the diamonds' tips.

For decades, scientists have taken advantage of Earth's hardest mineral, diamond, for lab experiments. No other mineral can scratch it, and when two opposing diamonds are perfectly aligned, they can pinch a slice of iron to pressures far greater than those of Earth's core.

Hirose, who frequently used diamond anvil cells in the lab, said that even though the diamonds are strong, the slightest variation in shape can cause them to crack under high pressures. Expert polishers smooth the sides of the diamonds to within 1 micrometer, the width of a small bacterium. Hirose called one particularly skilled technician "our treasure," because few can achieve such precision.

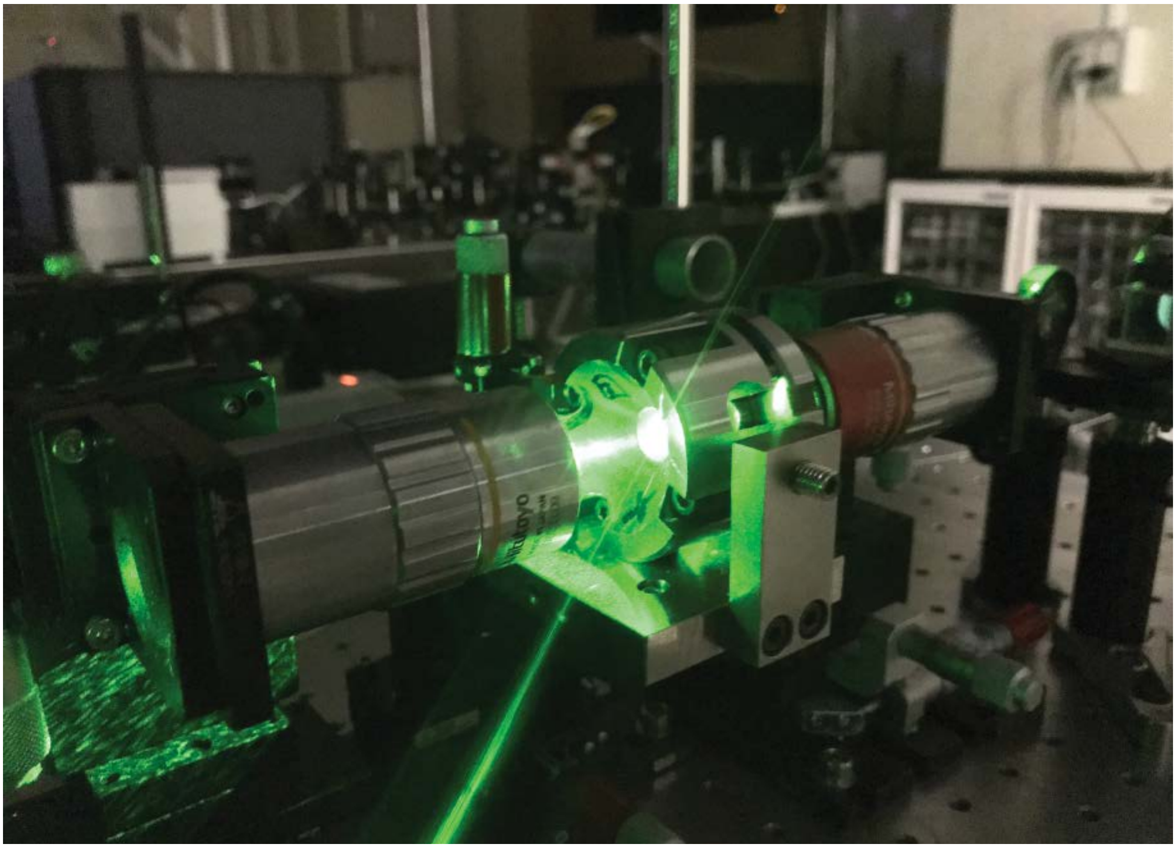
Diamonds have another plus as well: Researchers can shoot lasers through their translucent sides to send a pulse of heat into the sample. Both studies used lasers to heat their samples to thousands of kelvins.

A Tale of Two Papers

In one of the diamond anvil experiments, a team in Washington, D.C., measured the thermal conductivity of iron using two lasers to quickly heat the sample and measure its inferred temperature change.

In the other experiment, a different research team based in Tokyo measured iron's electrical conductivity, a property closely related to thermal conductivity, and then used an empirical relationship to calculate thermal conductivity.

The papers found contradictory results, and their discrepancies reveal just how difficult high-pressure experiments can be. The Tokyo group proposed a thermal conductivity value of 88 (+29/−13) watts per meter kelvin at the core-mantle boundary, whereas, the Washington, D.C., group proposed 25 (±7) watts per meter kelvin. The disparity in values may seem small but could mean the difference between an inner core that is billions of years old and a relative newcomer to Earth's internal structure.



In a thermal conductivity experiment, researchers shoot a green laser through a diamond anvil cell to heat an iron alloy sample. Credit: Kenji Ohta

The experimental differences "may have to do with the preferred crystal orientation in the samples," said Stewart McWilliams, a researcher at the University of Edinburgh and a coauthor of the study by the Washington, D.C.–based team.

Hirose, who led the team in Japan, agreed that the pressure used to compress the samples would affect the orientation of the crystal grains in iron, and the two teams had indeed taken measurements perpendicular to each other.

Stewart said he and others are now focusing on modeling the systematic errors in the experiments that could bias measurements. These errors "go a little way" in explaining the discrepancies, "but not enough," he said.

Time will tell whether a middle ground is the answer. Quentin Williams, who was not involved in either study and published a review of thermal conductivity research in the journal *Annual Reviews of Earth and Planetary Sciences,* wrote that "nevertheless, while recognizing that intermediate assertions are highly hazardous…it would not be surprising (to this author) if thermal conductivity values, with improved theoretical and experimental refinements, ultimately converged to values within a broad range of 35 to 80 watts per meter kelvin at the conditions of the top of the outer core."

Diamonds are one of the hardest materials on Earth, and scientists can use them to compress iron to pressures inside Earth's core. Credit: Kei Hirose

A Compositional Compromise

When Earth coalesced from a homogenous rubble pile into its differentiated, layered state, its material separated by density. Buoyant material like water, air, and silicates stayed on top and in the middle, and dense material like iron sank to the center.

> Discerning the thermal evolution of Earth "will pose a challenge for the next 15 years for the community."

But according to seismic research that goes back to the mid-20th century, Earth's core isn't pure iron. Seismic measurements show that it's about 10% less dense than pure iron and is composed of alloys likely including nickel and some special recipe of lighter elements, perhaps silicon, oxygen, magnesium, and carbon.

This could be good news for the core paradox, however. The presence of lighter elements may propel convection in the core, giving the geodynamo a source of convection even if thermal convection is too weak. If lighter elements cause convection, this source of buoyancy gives a work-around to the core paradox.

Cohen, Hirose, and many others are investigating the effect of lighter elements on heat transport in the core. "It is a totally, totally open question," Hirose said.

Novel follow-up studies are upping the ante as well. Kenji Ohta, an associate professor in Earth and planetary sciences at Tokyo Institute of Technology, said that his lab is exploring a way to melt samples at high temperatures and pressures, something that brings scientists one step closer to mimicking Earth's liquid outer core. Past studies have been conducted, for the most part, on solid samples.

"This is exciting stuff," Williams said of the race to find an answer. The question of the core and thermal evolution of Earth "will pose a challenge for the next 15 years for the community."

"It's the pivotal issue in Earth's evolution and the evolution of our magnetic field," Williams added. "It's something that ultimately just has to be figured out. And so, when challenges like this are posed to the community, sometimes they are answered slowly because getting a good answer is difficult. But ultimately, they will be answered. I'm really optimistic about it."

Author Information

Jenessa Duncombe (@jrdscience), Staff Writer

▶ **Read the article at bit.ly/Eos-Earth-core**


JpGU
AGU 2020
VIRTUAL MEETING
12–16 JULY 2020
agu.org/jpgu
JpGU 30
Challenges for the next generation
AGU
ADVANCING EARTH
AND SPACE SCIENCE


DEADLINE: 16 SEPTEMBER
Submit a Session Proposal
9–14 MAY, 2021
ATLANTA, GA • USA
AbSciCon
2021
agu.org/abscicon
The premier conference for the astrobiology community.

Florida Coastlines Respond to Sea Level Rise

Mangrove and marsh ecosystems in southwestern Florida have been burying carbon in their soils at increasing rates. Credit: Joshua L. Breithaupt

Sea level rise is one of climate change's hallmarks. Rising seas threaten coastal populations and can damage coastal ecosystems. Some ecosystems, though, appear to be building themselves up as the water rolls in.

In coastal mangrove forests and marshes, dead plant matter like leaves and roots does not decompose as it does in drier environments. Instead, it is "buried" in the wet ground. For some of these coastal wetlands, the burial rates seem to be increasing.

Breithaupt et al. noticed this pattern. They took soil core samples from different coastal systems in southwestern Florida to determine whether the trend was genuine or merely an illusion arising from the most common methods used to study such sites.

The scientists compared several measures, focusing primarily on the degradation of different types of organic carbon and the different tools used to quantify sediment accumulation rates. They determined that the apparent increase was not an artifact of a particular method or an illusion caused by old carbon washing away or degrading over time.

Further examination confirmed that the additional carbon was not merely washed into the study areas from other parts of the coastline or deposited by major storms. Local factors, such as the type of vegetation and the availability of nutrients, played a larger role in the carbon burial increase.

The scientists surmised that sea level rise may drive the increasing accumulation of soil carbon. Longer flood periods encourage mangrove and marsh vegetation to expand their belowground systems, producing and storing more carbon there. Rising sea levels may also allow more space for carbon to be buried and preserved.

This means that these coastal areas are both responding well to sea level rise and pulling more carbon from the atmosphere. In the past 120 or so years, organic carbon burial rates have increased by factors of 1.4–6.2 in marsh and mangrove ecosytems, with mangrove forests having the greatest gains. As a result, stored carbon stocks have increased by about 4–8 kilograms per square meter in the past century in these study areas.

However, rising sea levels still pose a threat to these systems. Rapid, heavy sediment deposits from hurricanes can smother and kill mangroves and other vegetation. Further, the waters are rising faster over time. Though these ecosystems are handling the change now, it remains to be seen how high the sea level can rise before adverse effects threaten to drown them.

This dynamic relationship between coastal ecosystems and the sea is an important factor both in carbon estimates and in predicting the effects of sea level rise. As the climate continues to change, more research is needed to estimate how widespread this phenomenon is and to inform coastal decision-making about the best ways to manage ecosystem responses. (*Journal of Geophysical Research: Biogeosciences*, https://doi.org/10.1029/2019JG005349, 2020) **—Elizabeth Thompson,** *Science Writer*

Arctic Plankton Populations Vary by Season

As temperatures rise, sea ice melts, and the ocean's chemistry undergoes significant changes in pH and salinity, predicting the downstream ecological effects of these changes is challenging, particularly in areas like the Arctic, where change is occurring quickly. Scientists often turn to planktonic species to glean insights into ecosystem health. These keystone species constitute the basis of the food web in the region and are especially sensitive to changes in the water.

In a new study, *Ofstad et al.* collected plankton samples in the spring and summer of 2016 from the Barents Sea, located north of Scandinavia and western Russia. The researchers focused on the Bjørnøyrenna crater area, which contains several methane seeps that release gas into the water, to survey how concentrations and species diversity of planktonic foraminifera (forams), as well as of the planktonic sea snail *Limacina helicina*, vary over time and in the presence of methane.

The results showed a clear seasonal signal, with populations of both living planktonic forams and *Limacina helicina* growing by an order or more of magnitude and increasing in size as spring progressed to summer. In summer, the foram community is more diverse, with the added presence of subtropical species.

To understand how methane in the water column might affect the forams—through their consumption of carbon from methanotrophic bacteria, for example—the scientists looked at isotopic ratios of carbon and oxygen in the organisms' rigid calcium carbonate shells. However, they found no evidence that the elevated methane levels in the water had a direct impact on the animals. That's not to say that the seeping methane has no effect at all: The researchers hypothesize that it could enhance primary production in the water column indirectly by, for example, carrying nutrients toward the ocean surface or increasing carbon dioxide levels in the water. Such fertilizing could have an effect on a regional scale, potentially drawing in increased numbers of other organisms—a topic that the team concludes should be studied in the future. (*Journal of Geophysical Research: Biogeosciences*, https://doi.org/10.1029/2019JG005387, 2020) —**David Shultz**, *Science Writer*

Researchers surveyed populations of the planktonic sea snail Limacina helicina *and planktonic foraminifera in part of the Barents Sea to assess how concentrations and species diversity of the organisms varied over time and whether they are affected by nearby methane seeps. Credit: Katsunori Kimoto*

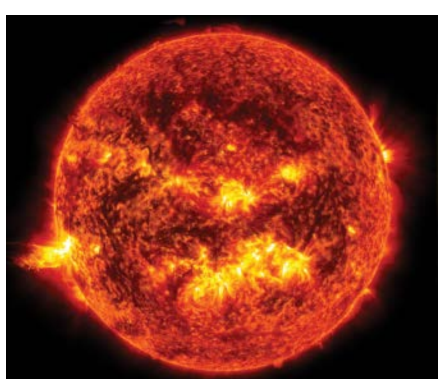
How Accurate Are Our Measurements of the Sun's Energy?

At first glance, the Sun's burning heat seems to be unvarying. To explain the differences we experience, we tend to point to cloud cover, humidity, or the dynamics of our atmosphere. However, as the Sun progresses through its 11-year cycle of activity and quiet, as well as its 27-day rotation, the radiation it bestows on Earth changes.

An instrument called the Spectral Irradiance Monitor (SIM) aboard the Solar Radiation and Climate Experiment (SORCE) satellite monitors how much solar energy bathes Earth across a range of wavelengths from the ultraviolet to the near infrared. Knowing the distribution of solar energy across this spectrum can help scientists track where on Earth this energy is absorbed, a key factor in climate change estimates. However, exposure to harsh solar radiation at shorter wavelengths causes the satellite's instruments to degrade, meaning researchers must adjust for the aging equipment to keep recording accurate measurements.

In pursuit of this accuracy, *Mauceri et al.* compared three methods of correcting SORCE SIM measurements: SIM version 25, Multiple Same-Irradiance-Level, and SIM constrained version 2 (SIMc V2). They then compared the results of these corrective methods with four independent measurements of solar energy and with two solar energy models.

The researchers found that solar energy measurements from the three correction methods matched most closely for—and were therefore most accurate for—visible light wavelengths. They also observed some surprising variation in near-infrared wavelengths, where instrument degradation is small and thus a high level of agreement between the three methods was expected. The discrepancy may be a result of artifacts from corrections made for shorter wavelengths.



During the 11-year solar activity cycle, the radiation emitted by the Sun (seen here in June 2013) varies depending on wavelength. Credit: NASA Goddard Space Flight Center

The team found the greatest variation among measurements at high-energy ultraviolet wavelengths, which also cause the most damage to the instruments. Earth is more sensitive to variations in the amount of ultraviolet radiation it receives than to variations of other wavelengths. To ensure accurate climate models, future correction methods must thus maintain accurate short-wavelength observations. Of the three correction methods for SORCE SIM data, the researchers recommend SIMc V2 for most applications, but they noted that continued research and development are still needed. (Earth and Space Science, https://doi.org/10.1029/2019EA001002, 2020) —**Elizabeth Thompson**, *Science Writer*

Tracing the Past Through Layers of Sediment

Earth's stratigraphic record preserves clues about past climates, ocean conditions, tectonics, and more. The sequence of red bed paleosoils in the Bighorn Basin of Wyoming, for example, records the paleoclimate of a global warming event 56 million years ago. Credit: Brady Foreman

The stratigraphic record—layers of sediment, some of which are exposed at Earth's surface—traces the planet's history, preserving clues that tell of past climates, ocean conditions, mountain building, and more. As Rachel Carson once wrote in *The Sea Around Us,* "The sediments are a sort of epic poem of the earth."

Yet interpreting how these sedimentary layers document Earth's past is complex and challenging. In a recently published study, *Straub et al.* identify three obstacles standing in the way of accurate stratigraphic interpretations and outline the grand challenges facing geologists trying to read the clues.

First, Earth's surface responds dynamically to the forces shaping it (e.g., climate, tectonics, and land cover change). Yet the environmental signals, or markers, of such change are often buffered and dampened by the movement of sediment, which diminishes the signals' detectability in sedimentary deposits. Second, surface conditions are recorded only when and where sediment accumulates; environmental conditions that do not coincide with this deposition are absent in the recorded history of Earth. Last, environmental clues may be missing in rock layers because of the storage and later release of sediments in landforms like river bars and floodplains. This process, called signal shredding, destroys some sediment signals left by external events like storms and earthquakes.

In the review, the authors explore these impediments in depth, examining numerical, experimental, and field findings behind each. For example, when evaluating how signals are buffered as they move through landscapes, the authors dig into the diffusion equation. The equation describes how a property is conserved in one dimension and flows down a gradient, for instance, how heat disperses through a medium. In a sedimentary context, the equation helps model the formation of alluvial fans and other topographic features.

As discussed in the study, four grand challenges confront geologists today as they try to improve interpretations of the stratigraphic record. These include the following: (1) defining the causes of landscape stochasticity across environments; (2) Increasing collaboration between research communities studying surface processes and stratigraphy; (3) Embracing hypothesis testing and quantifying uncertainty in stratigraphic interpretations; and (4) Teaching both quantitative theory and field applications to the next generation of stratigraphers.

Improving stratigraphic interpretation, the authors argue, is key to unlocking quantitative information about the past that will improve forecasts of the future. Their exhaustive review charts a path forward for using the stratigraphic record to answer basic and applied science questions. (*Journal of Geophysical Research: Earth Surface,* https://doi.org/10.1029/2019JF005079, 2020) **—Aaron Sidder,** *Science Writer*

The Climate and Health Impacts of Gasoline and Diesel Emissions

In the United States alone, it's estimated that the transportation sector produces 1.9 billion tons of carbon dioxide (CO_2) annually. It's no secret that CO_2 contributes substantially to warming the planet, but it's not the only climate-active material in the atmosphere: Emissions can have both warming and cooling effects depending on their chemistry and the timescale over which they are observed.

Heavy vehicle traffic crowds a motorway near Chepstow, Wales. Credit: jonbgem, CC BY-NC 2.0 (bit.ly/ccbync2-0)

In a new study, *Huang et al.* model the total global climate impact of gasoline and diesel vehicle emissions as well as their impact on human health. Using the National Center for Atmospheric Research's Community Earth System Model, a global chemistry-climate model, along with emissions data from 2015, they calculate the net radiative effect of the gasoline and diesel sectors to be about +91 and +66 milliwatts per square meter, respectively, on a 20-year timescale. A laser pointer produces about 5 milliwatts, so emissions from the two sectors combined are heating the planet by roughly the same amount that shining 32 laser pointers on every square meter of the Earth would. Earth's surface area is 510 trillion square meters, so that's 1.6 quadrillion laser pointers.

The researchers broke down the overall heating into individual effects from different component compounds in vehicle emissions, focusing on two broad categories of emissions: short-lived climate forcers (SLCFs), which include things like aerosols and ozone precursors, and long-lived greenhouse gases, with CO_2 being the most prominent. SLCFs from gasoline and diesel vehicle fleets accounted for about 14 and 9 milliwatts per square meter, respectively, confirming that most radiative forcing comes from longer-lived emissions.

In terms of public health, the researchers calculate that the gasoline sector causes 115,000 premature deaths annually, whereas the diesel sector causes 122,100. The researchers attribute the deaths largely to exposure to smog (ozone) and soot (particles smaller than 2.5 micrometers). The scientists also analyzed how premature death rates varied regionally and proportionally with respect to the total distance driven in a region using each fuel type. These results showed large variability by region: In some places, there were relatively few premature deaths for the large distances driven on a given fuel type, whereas in others—most notably for diesel used in India—there were disproportionately high numbers of premature deaths. (*GeoHealth*, https://doi.org/10.1029/2019GH000240, 2020) **—David Shultz**, *Science Writer*

Linking Hydrology and Biogeochemistry in a Tropical Urban Estuary

The San Juan Bay Estuary in Puerto Rico is an interconnected series of lagoons and canals that weave through San Juan, the capital city and home to nearly 350,000 people. As the city has boomed, the canals and waterways connecting the ocean with inland lagoons have become clogged with sediment, trash, and debris. As a result, conditions look drastically different than they did even in the 1970s, when residents first raised concerns about water quality in the estuary.

The challenges facing the San Juan Bay Estuary are typical of coastal, tropical urban areas around the world. Although coastal areas less than 10 meters above sea level represent only 2% of the world's land area, they are home to 13% of the world's urban population. These urban areas also tend to have low socioeconomic status and large populations vulnerable to storm surges and tropical storms associated with climate change.

In a new study of the San Juan Bay Estuary, *Oczkowski et al.* point out that surprisingly little is known about urban estuaries in tropical regions, especially given their prevalence and vulnerability. The authors evaluated nutrient cycling in the estuary, as well as how debris and sediment buildup in canals influence water quality in connected parts of the bay.

Through sediment analysis, the authors found that nitrogen fixation could be a significant source of nitrogen in the most urbanized parts of the estuary, where, for example, raw sewage enters the water. Much of the nitrogen fixation could stem from sulfate-reducing microbes, which are common in mangroves but have not been previously documented in urban systems. Furthermore, the nitrogen contributions from the bacteria appear to equal or exceed those from urban runoff and sewage.

The findings help to explain anoxic conditions, fish kills, and algal blooms that have occurred in parts of the estuary. The research also highlights how San Juan's growth and lagging infrastructure have contributed to hydrological changes and an increase in residence time for nitrogen in the water.

The study is one of the first to link the biogeochemical and hydrologic conditions of the San Juan Bay Estuary. Although San Juan was the focus of this research, the study authors lay out a plan for conducting similar research in other urban estuaries around the world. (*Journal of Geophysical Research: Biogeosciences*, https://doi.org/10.1029/2019JG005502, 2020) **—Aaron Sidder**, *Science Writer*

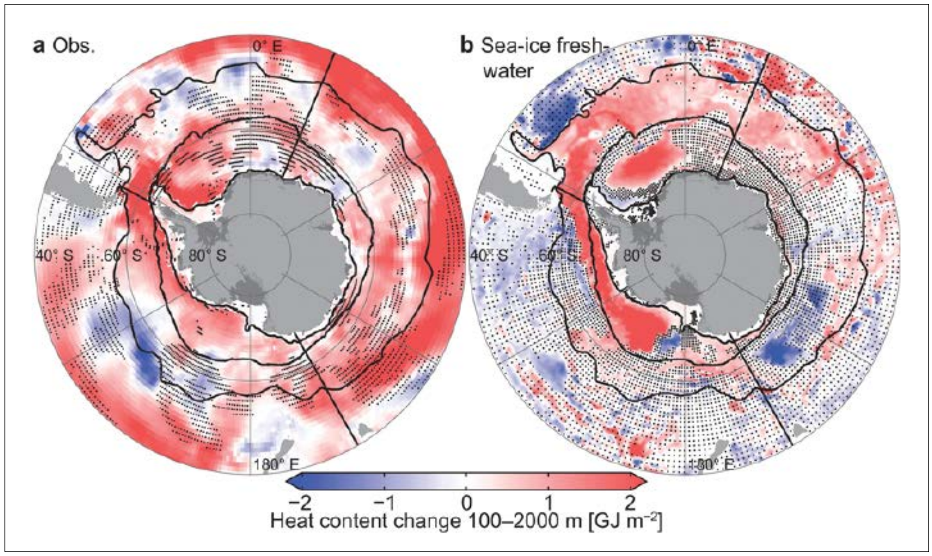
▶ Read the latest news at Eos.org

Explaining Cold and Fresh Southern Polar Ocean Surface Waters

Most of the global ocean surface has been warming in response to increased greenhouse gas concentrations. One notable exception is the ocean south of 50°S, which from the early 1980s to the early 2010s has become colder and fresher in the upper 100 meters and warmer below. Various hypotheses have been proposed to explain this trend, among them (1) increased glacial meltwater input due to ice shelf thinning and (2) increased northward transport of cold waters in response to the observed poleward shift of the Southern Hemisphere westerlies.

Haumann et al. propose a further hypothesis of increased northward transport of sea ice over that period. The team carried out a suite of numerical simulations using a regional ocean model to investigate the three hypotheses by separately increasing sea ice fluxes, freshwater input from the Antarctic continent, and ocean-atmosphere momentum input by winds.

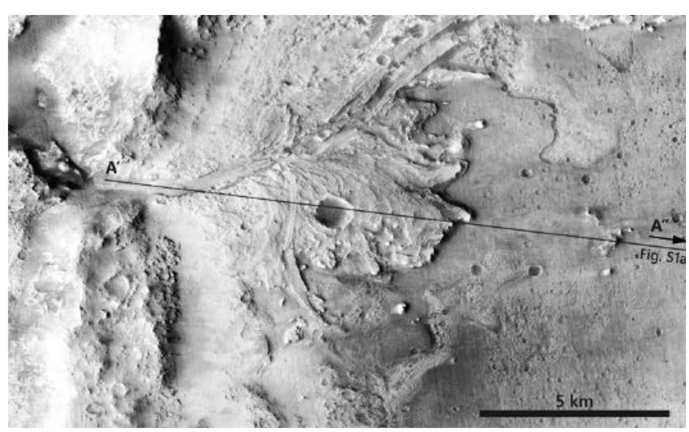
The observational trends are best reproduced in the simulations with increased lateral sea ice transport. The underlying process is elucidated, leading to freshening and cooling of the surface waters and warming of the subsurface layer. This warming has important climate implications because the heat trapped in the subsurface accounts for approximately 8% of the global ocean heat content increase over that time period. (*AGU Advances*, https://doi.org/10.1029/2019AV000132) **—Paola Rizzoli**



Observed subsurface (110–2,000 meters) ocean heat content changes from 1982 to 2011 (left) and simulated subsurface heat content change (years 6–15) in response to sea ice freshwater flux perturbation (right). Credit: Haumann et al., *2020*

How Fast Did This Ancient Martian Delta Form?

An ancient river delta is the target of the next Mars rover, chosen because it will provide insights into early Martian climate and, perhaps, yield organic material. *Lapôtre and Ielpi* have adapted a model calibrated from meandering rivers on Earth to determine how long it took this Martian delta to form. They conclude that at minimum, only a few decades were required. This timescale is consistent with the idea that ancient Mars was mostly cold and dry, with brief intervals of more clement conditions and surface water flow arising from meteorite impacts or volcanic emissions. They also argue that the relatively rapid sediment emplacement makes burial and preservation of organic materials quite likely. With luck, the rover—Perseverance—will test these predictions in the near future. (*AGU Advances*, https://doi.org/10.1029/2019AV000141) **—Francis Nimmo**



Jezero delta on Mars. Flow is from left to right; the rim of Jezero crater is visible at A'. The large number of superimposed craters indicates an ancient feature. Credit: Lapôtre and Ielpi, *2020*

▶ Sign up for the *AGU Advances* Digest: **agu.org/advances-digest**

The Career Center (findajob.agu.org) is AGU's main resource for recruitment advertising.

AGU offers online and printed recruitment advertising in *Eos* to reinforce your online job visibility and your brand. Visit employers.agu.org for more information.

Packages are available for positions that are

- **SIMPLE TO RECRUIT**
  - online packages to access our Career Center audience
  - 30-day and 60-day options available
  - prices range $475–$1,215
- **CHALLENGING TO RECRUIT**
  - online and print packages to access the wider AGU community
  - 30-day and 60-day options available
  - prices range $795–$2,691
- **DIFFICULT TO RECRUIT**
  - our most powerful packages for maximum multimedia exposure to the AGU community
  - 30-day and 60-day options available
  - prices range $2,245–$5,841
- **FREE TO RECRUIT**
  - these packages apply only to student and graduate student roles, and all bookings are subject to AGU approval
  - eligible roles include student fellowships, internships, assistantships, and scholarships

***Eos* is published monthly.**

Deadlines for ads in each issue are published at sites.agu.org/media-kits/eos-advertising-deadlines/.

***Eos* accepts employment and open position advertisements from governments, individuals, organizations, and academic institutions. We reserve the right to accept or reject ads at our discretion.**

***Eos* is not responsible for typographical errors.**

Atmospheric Sciences

The Atmospheric and Oceanic Sciences Program at Princeton University, in association with NOAA's Geophysical Fluid Dynamics Laboratory (GFDL) Seeks to fill up to three postdoctoral or more senior research positions in a research initiative aiming at advancing the fundamental understanding of the roles of clouds and radiation in affecting Earth's climate and weather, and evaluating/improving their representation in GFDL climate/weather models. The recently developed GFDL climate models (CM4 and ESM4) are among the best-performing CMIP6 models in terms of mean climate and variability. They use the same FV3 dynamical core as the current NOAA/NWS weather forecast model. CM4 also forms the basis of a prediction model (SPEAR) and can be configured into a limited-domain cloud-resolving model (CRM) for process-level studies. GFDL has a long tradition in conducting cutting-edge research related to clouds/aerosols, radiation, circulation, precipitation and extreme weather/climate events. This search represents a concerted effort to push this prominent research direction to new levels.

The first position will be in the area of aerosol-cloud interactions and indirect effects, with focus on understanding the controlling factors of the magnitude and spatio-temporal distribution of model-simulated aerosol indirect effects, using satellite/in-situ observations to validate the model representation of aerosol/cloud processes, and developing/implementing parameterizations of ice nucleation and mixed-phase cloud microphysics. The second position will be in the area of cloud feedbacks, with focus on understanding the key macro- and micro-physical processes in affecting the baseline cloud simulation and the strength of cloud feedbacks, using observations and case studies to constrain cloud feedbacks, and exploring innovative ways to better use process-level models to inform weather/climate model development. The third position will be in the area of atmospheric radiative transfer and cloud radiative effects, with focus on designing a new line-by-line atmospheric radiative transfer code that will serve as a benchmark standard for a new radiative transfer code to be used in weather/climate models, understanding the effect of SST pattern on cloud radiative effects, and improving the model representation of cloud microphysics-radiation interactions. The ideal candidates have to demonstrate a strong background in atmospheric and climate modeling, and climate science, as well as experience in using, developing, and analyzing numerical models and/or large observational datasets.

Candidates must have a Ph.D. in atmospheric physics, dynamic meteorology, Earth system science, climate studies, or related fields. The initial appointment is for one year with the possibility of renewal subject to satisfactory performance and available funding.

Complete applications, including a cover letter, CV, publication list, a statement of research interests, and contact information of 3 references should be submitted by July 1, 2020 for full consideration. Applicants should apply online to https://www.princeton.edu/acad-positions/position/16001. For more information about the research project and application process, please contact V. Ramaswamy (V. Ramaswamy@noaa.gov) for general inquiries, Yi Ming (Yi.Ming@noaa.gov) for the first position, Ming Zhao (Ming.Zhao@naoa.gov) for the second position, and David Paynter (David.Paynter@noaa.gov) for the third position.

This position is subject to Princeton University's background check policy.

Princeton University is an equal opportunity/affirmative action employer and all qualified applicants will receive consideration for employment without regard to age, race, color, religion, sex, sexual orientation, gender identity or expression, national origin, disability status, protected veteran status, or any other characteristic protected by law.

Interdisciplinary

Postdoctoral research position in arctic hydrological biogeochemical modeling

The Climate System Research Center (CSRC) at the University of Massachusetts-Amherst serves to advance understanding of the nature and causes of climate change, and the effects that those changes have had on the environment. This research leads to a better understanding of how the climate system functions. Its mission emphasizes high quality climate research at an international level, the education and training of student scholars, and outreach to the public through interactions with the media and public lectures. CSRC scholars engage the broader scientific community by publishing peer-reviewed journal articles, presenting results at conferences, and participating in working groups examining climate system dynamics.

Overview:

The CSRC seeks highly self-motivated and qualified candidates to work on development and implementation of models and advance understanding of linked hydrological and biogeochemical flows across the western Arctic. The overarching goal of the research is to quantify the timing and magnitude of terrestrial water, carbon, and energy exports and assess associated impacts of climate change. The successful candidate will lead efforts to develop and implement model algorithms of the leaching of carbon and other nutrients into river systems and processing during transit to coastal zones. The scholar will add components to a coupled modeling framework, analyze simulation estimates, and publish results. Applicants must have completed a Ph.D by the time of appointment. The initial appointment will be for one year with renewal contingent on satisfactory performance. Anticipated start date is 1 September 2020. The University of Massachusetts provides a comprehensive benefits package to Postdoctoral Researchers.

Essential Qualifications:

Ph.D. degree in earth system science, geography, ecology, physics or related field. Experience in developing, testing, and/or implementing hydrology or land surface models and deriving model evaluation metrics.

Preferred Qualifications:

Experience with the Linux operating system, shell scripting, Fortran and/or C/C++, R, Python and the ability to work in high-performance computing (HPC) environments.

Background in analysis of large data sets and file formats netCDF and HDF.

Experience in use of remote sensing data from satellite and airborne platforms such as AMSR, AVHRR, AVIRIS, MODIS, and SMAP.

Knowledge of the climate, hydrology, biogeochemistry of Arctic environments in the context of model development and applications.

Excellence in research as demonstrated through publication of manuscripts in refereed journals, presentations at scholarly conferences, and collaborations on applications for funding. A clearly expressed plan for the research investigation is encouraged.

Excellent written and verbal communication skills.

To Apply: Applicants should submit a cover letter describing relevant experience and qualifications, and a curriculum vitae, to Michael Rawlins rawlins@geo.umass.edu. Letters of recommendation will be sought from qualified candidates. All applications should speak directly to the candidate's ability to work collaboratively with colleagues and engage effectively in scholarly research. Review of applications will continue until the position filled. The University of Massachusetts Amherst is an Affirmative Action / Equal Opportunity Employer (EOE) of women, minorities, veterans, and individuals with disabilities. Applications from these and other protected groups are highly encouraged.

CLIMATE CENTRAL

CLIMATE SCIENTIST

Use science to help transform the climate conversation.

Climate Central seeks a highly motivated, creative, mid- to senior-level natural or social scientist to spearhead a strategic effort to build an unprecedented assemblage of ways to link diverse local observations and events to climate science, impacts, and solutions for dissemination to social media, journalists, and other key messengers, in near real-time.

The successful candidate will have a Ph.D. in a relevant natural or social science plus more than 10 years of research and media experience. For more information, visit https://www.climatecentral.org/what-we-do/jobs#climatescientist.

Ocean Sciences

Application for Postdoctoral Position: Using regional ocean models to improve U.S. Northeast marine fishery stock assessments

The Atmospheric and Oceanic Sciences Program at Princeton University, in association with NOAA's Geophysical Fluid Dynamics Laboratory (GFDL) and Northeast Fisheries Science Center (NEFSC), seeks a postdoctoral or a more senior scientist to conduct research on improving U.S. commercial fishery stock assessments using regional ocean models. The goals of the research are to: 1) analyze regional ocean model hindcasts of the Northwest Atlantic Ocean in relation to historical stock assessment estimates and retrospective patterns for key commercial species in the U.S. Northeast Shelf; 2) use a state-space modeling approach to incorporate physical and biological variables from the regional model hindcasts into stock assessment models; 3) apply state-of-the-art regional ocean forecasts to stock estimates.

In addition to a strong quantitative and statistical background, the selected candidate should have one or more of the following attributes: (a) a strong background in fisheries science, marine ecology, or a closely related field, and (b) experience with ocean or climate models.

Candidates must have a Ph.D. in Fisheries Science, Oceanography, or a closely related field. The initial appointment is for one year with the possibility of a second-year renewal subject to satisfactory performance and available funding.

Complete applications, including a cover letter, CV, publication list, and 3 letters of recommendation should be submitted by August 1, 2020 for full consideration. Applicants should apply online to https://www.princeton.edu/acad-positions/position/16021. For additional information, contact Dr. Vincent Saba (mailto:vincent.saba@noaa.gov).

This position is subject to Princeton University's background check policy.

Princeton University is an equal opportunity/affirmative action employer and all qualified applicants will receive consideration for employment without regard to age, race, color, religion, sex, sexual orientation, gender identity or expression, national origin, disability status, protected veteran status, or any other characteristic protected by law.

PLACE YOUR AD HERE

Visit **agu.org/advertise** to learn more about employment advertising with AGU.

AGU ADVANCING EARTH AND SPACE SCIENCE

Greetings from the field! Well, sort of.

Sometimes scientific research requires us to go to unusual places and do unusual things. In this photo, I am attached to the space frame above Biosphere 2's tropical rain forest. I have in my hands what appears to be a plastic bag but is actually a prototypical leaf chamber I am installing on a leaf of this *Clitoria* tree, one of the focal species for the Water, Atmosphere, and Life Dynamics (WALD) experiment. These chambers contain tiny samplers that capture the volatile organic compounds emitted by the leaves, helping us understand how this species responds to stress.

This is hot, sweaty work, right next to the glass, about 20 meters above the ground. My biggest concern, besides getting the chamber properly into place, is to keep sweat from dripping into it! Kind of disgusting, I know, but it's all part of working in places like this.

In the end, we gathered some good data and invaluable information on how to construct and attach the chambers for the actual experiment.

—**Jason DeLeeuw**, Research Specialist, Rain Forest, Biosphere 2, Oracle, Ariz.

Credits: Main: Laura Meredith. Inset: John Adams

View more postcards at bit.ly/Eos-postcard

Radically Simplify Soil Flux Studies

G4301/G2508

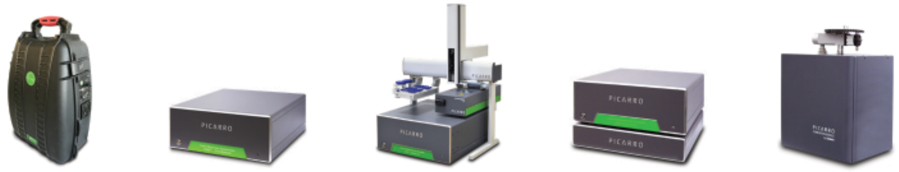
Gas Concentration Analyzers

Multi-species measurement systems to meet the world's research demands

- **G4301 GasScouter™** - extra-lightweight and portable, battery-powered analyzer measuring CO_2 and CH_4 concentrations
- **G2508** - Simultaneous measurements of critical greenhouse gases: N_2O, CH_4, CO_2, NH_3 and H_2O
- Rapidly recirculates gas from a soil chamber to provide a record of the rate-of-rise at high temporal resolution

Learn more at www.picarro.com/applications/soil/agriculture_soil_science

PICARRO



Mobile & Flight

Trace Gas & GHG

Stable Isotopes

High Performance Mid-IR

Accessories & Front-ends

© 2020 Picarro Inc.