Eos
SCIENCE NEWS BY AGU
VOL. 104 | NO. 6
JUNE 2023

OUT OF OFFICE

FROM STORMY SEAS TO SOARING CYCLONES, INNOVATIVE FIELDWORK LAUNCHES SCIENTISTS INTO THE GREAT UNKNOWN.

AGU
ADVANCING EARTH AND SPACE SCIENCE

Into the Wild Blue Yonder

This year, our annual issue on fieldwork takes you into the blue.

NOAA's Hurricane Hunters (and a few high-tech Muppets) literally go into the azure eye of the storm for data to help forecasters, policymakers, and emergency management agencies better grapple with hurricanes in the Gulf of Mexico. Buckle up with Alka Tripathy-Lang as she catches up with Kermit, Miss Piggy, and the meteorologists who rely on them in "Hunting Hurricanes" on page 22.

From sky blue heights to cerulean depths: Geophysicists (well, their proxies) thrice dove into the South Pacific's Gofar transform fault to better understand its seismic properties. Deploying instruments ranging from ocean bottom seismographs to autonomous underwater vehicles, scientists studied electrical conductivity and hydrothermal circulation. They also established a refreshing set of best practices for research at sea—supporting a diverse team of scientists and technicians that allowed the fieldwork "to accomplish all the goals of the cruise and, at the same time, open opportunities for young scientists to gain experience and minimize disruptions to scientists' lives on land." Learn more from Margaret Boettcher, Emily Roland, Jessica Warren, Robert Evans, and John Collins in "Observing a Seismic Cycle at Sea" on page 30.

Black volcanic rock provides a break from the blue as we share a story of scientists venturing to the inland Cascades. What motivates people to undertake such scorching summer expeditions? The Columbia River Basalt Group, the "best studied flood basalt on Earth," but one whose dike systems are still shrouded in mystery. Catch up with Anthony Pivarunas, Margaret Avery, Joseph Biasi, and Leif Karlstrom in "Baked Contacts Focus a Lens on Ancient Lava Flows" on page 36.

Finally, we here at AGU are more than a little blue at the retirement of Brooks Hanson. Brooks has served as AGU's Executive Vice President for Science for more than a decade, a time during which he has been a tireless champion of science and scientists. Brooks leaves on a characteristically positive note for us here at *Eos:* He joins Xavier Comas, Sarah Kruse, Gordon Grant, and Laura Lyon in encouraging the creation of a center to convene and coordinate the dizzying sciences associated with Earth's near-surface environment; read more in "Envisioning a Near-Surface Geophysics Center for Convergent Science" on page 16.

We hope it's nothing but blue skies ahead for Brooks and the rest of our scientists navigating fresh fields of study.

Caryl-Sue Micalizio, Editor in Chief

Eos: Science News by AGU (ISSN 0096-3941) is published monthly except December by the American Geophysical Union, 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 *Eos: Science News by AGU*, 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.

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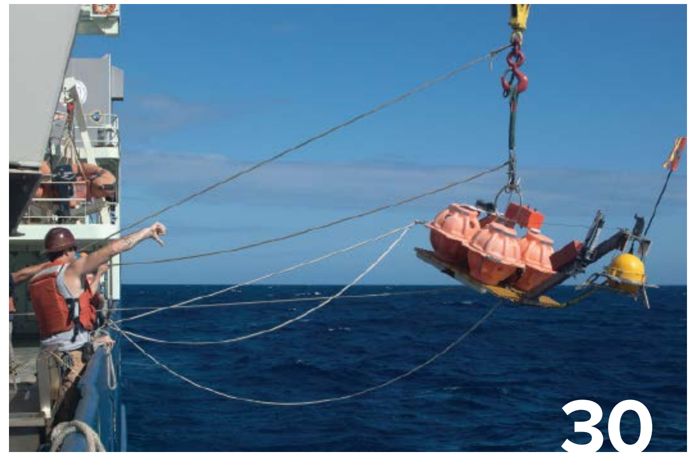
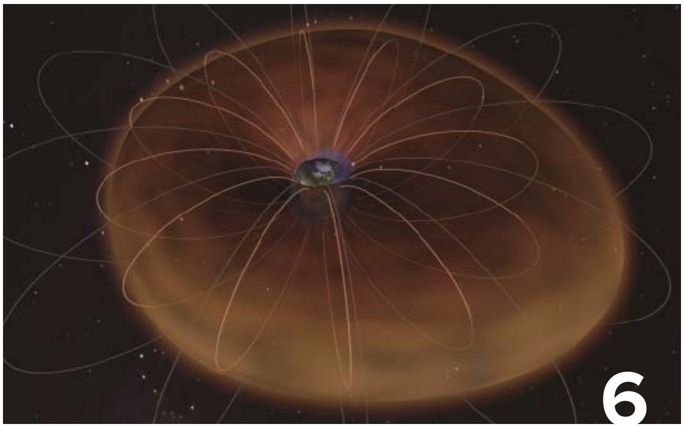
Randy Fiser, Executive Director/CEO



Features

On the Cover

Darin Schwartz, a postdoctoral researcher at Boise State University, directs deployment of a seismograph into the South Pacific from the deck of the R/V *Atlantis* in 2019. Credit: Dan Kot



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The Most Reliable and Simple Scientific Instruments in Harsh Environment

Asteroid Impacts Could Have Warmed Ancient Mars

Mars is a frigid world today, and all of its surface water is frozen solid. However, there's ample evidence that liquid water once coursed over the Red Planet. That paradox has sparked an ongoing debate: What warmed up Mars's climate billions of years ago? A team has now proposed that giant asteroid impacts—the kind that carve out basins exceeding 1,200 kilometers (about 750 miles) in diameter—might have played an important role. The team reported its results in *Geophysical Research Letters* (bit.ly/Mars-climate).

The gullies, streambeds, channels, and lake beds that pepper the Martian landscape are dead ringers, morphologically speaking, for water-sculpted terrain on Earth. The presence of hydrated minerals such as phyllosilicates and sulfates, which have been spotted spectroscopically by Mars-orbiting satellites, has provided more evidence that the Red Planet was once warmer and wetter. By dating geological features and water-altered minerals, scientists have determined that Mars must have been relatively balmy roughly 4 billion years ago.

Don't Look at the Sun

The ancient warm spells that Mars appears to have experienced can't be pinned on a seemingly obvious culprit such as the Sun. That's because our nearest star wasn't any more luminous in the past.

"The Sun was much fainter," said Lu Pan, a planetary scientist at the University of Science and Technology of China in Hefei. She explained that the Sun's power output several billion years ago was probably about 30% lower than it is today, a fact that has been troubling the scientific community for decades. "Climate modelers have been trying to figure out ways to warm up the planet," she said.

Pan and her colleagues recently proposed one possibility, and it hinges on truly catastrophic events. Building on previous research, the team suggested that giant asteroid impacts—far larger than the one that killed off nonavian dinosaurs 66 million years ago on Earth—triggered chemical reactions in Mars's crust and mantle.

In a process known as oxidation, iron-bearing minerals reacted with water present in Mars's subsurface to produce iron oxides and hydrogen gas. That hydrogen collided with the carbon dioxide already present in Mars's atmosphere.

All of that bumping together of molecules changes their electronic structure and allows them to absorb radiation at a wider range of wavelengths, an experimentally verified phenomenon known as collision-induced absorption. "These molecules become even better greenhouse gases," said Ramses Ramirez, a planetary scientist at the University of Central Florida in Orlando who was not involved in the research.

Recent research has suggested that an atmosphere composed of both carbon dioxide and hydrogen can reach temperatures above freezing (bit.ly/early-Mars). On the other hand, a carbon dioxide-dominated atmosphere void of hydrogen or other greenhouse gases can attain a top temperature of only about −40°C. "That's over 40° too cold," Ramirez said.

Go Big or Go Home

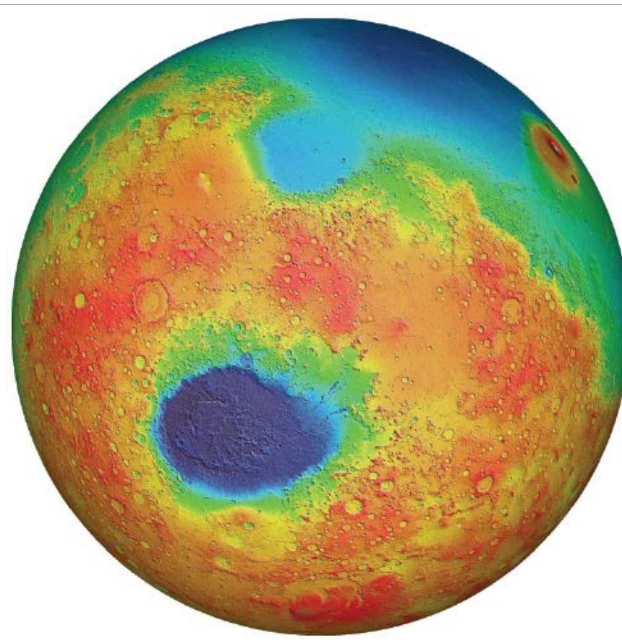
Asteroids larger than 100 kilometers (60 miles) in diameter—more than 10 times the size of Earth's dinosaur-killing impactor—excavate enormous basins when they strike a rocky body. Several such depressions persist today on Mars, including Argyre, Hellas, and Isidis. The impacts that formed those basins would have released copious amounts of hydrogen gas, Pan and her colleagues concluded, because both the asteroids themselves and portions of Mars's crust and mantle would have been oxidized.

> **"Climate modelers have been trying to figure out ways to warm up the planet."**

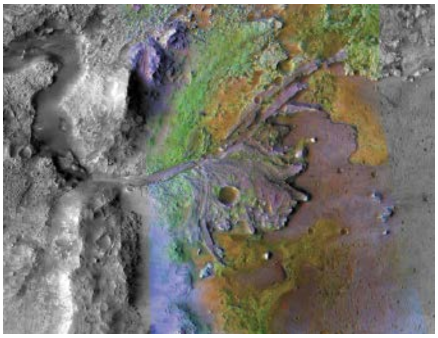
The researchers calculated that impacts that produced basins larger than about 1,200 kilometers (750 miles) in diameter would have created enough hydrogen to heat Mars's atmosphere to above freezing.

But those relatively balmy conditions wouldn't have persisted indefinitely. That's because hydrogen, being so light, tends not to stick around. "Even if you put a lot of hydrogen into the atmosphere instantaneously, it [would] escape very fast," Pan said.

On the basis of assumptions about the physical structure of Mars's atmosphere, the



The Hellas impact basin—the dark blue circular region in this false-color image from the Mars Orbiter Laser Altimeter (MOLA)—is one of the largest known impact craters in the solar system, with a diameter of roughly 2,300 kilometers (1,400 miles). Credit: MOLA Science Team



Mars's Jezero crater contains channels and other water-sculpted features like deltas. Credit: NASA/JPL-Caltech/MSSS/JHU-APL

researchers determined that on the order of a trillion molecules of hydrogen per second would have streamed out of every square centimeter of Mars's atmosphere. Taking that exodus into account, Pan and her colleagues calculated that temperatures on ancient Mars would have remained above freezing for anywhere from about 20,000 to 1,000,000 years after the largest basin-forming impacts.

Twenty basin-forming impacts occurred early on in Mars's history, according to previous research (bit.ly/Mars-impacts), and Pan and her team determined that 14 of those events could have boosted temperatures to above freezing.

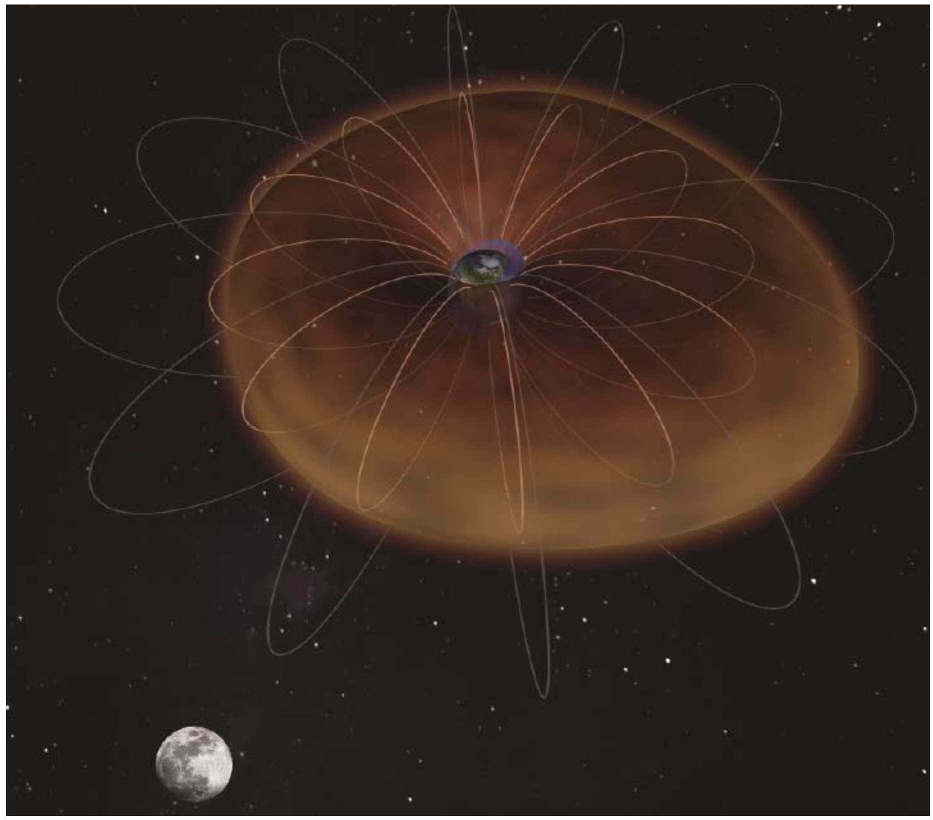
Those results make sense, said Robin Wordsworth, a planetary scientist at Harvard University who was not involved in the research. But it's important to consider the relative timing of asteroid strikes and the emplacement of Mars's water-sculpted terrain, he said.

If one is a cause and one is an effect, the two should sync up in time. But that's not always the case, Wordsworth said, because the largest impacts predate features shaped by flowing water. "The big ones happen before we see valley networks," he said. "That's one of the big challenges of the impact-driven hypothesis."

Pan and her colleagues acknowledged that discrepancy and suggested that Mars's fluvial features, in some cases, might be older than they appear. It's possible that erosion or other geological activity could have removed earlier signatures of water-carved features, Pan said. "We just don't have an exact timing of those early processes."

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

Tides Ripple Across Earth's Plasma "Donut"



The donut-shaped plasmasphere encircles Earth in this artist's concept, with our planet's magnetic field looping through it. Tides caused by the nearby Moon ripple across the surface of the plasmasphere. Credit: Quanqi Shi

Earth is surrounded by an ocean of plasma—the electrically charged fourth state of matter—and researchers have discovered tides rippling across its surface. The shifting field of plasma surrounding the planet may affect Earth's radiation belts, which can damage spacecraft or astronauts in orbit or traveling to or from the Moon. Similar tides could race around planets in other star systems.

The plasmasphere is a donut of cold plasma centered over Earth's magnetic equator within the magnetosphere—the region encompassing our planet's magnetic field. The plasma is supplied by the ionosphere, the electrically charged layer of the upper atmosphere.

The outer boundary of the plasmasphere—known as the plasmapause—is typically found 20,000–38,000 kilometers (12,000–24,000 miles) from Earth's center, although its location can vary with the seasons, solar activity, and other factors, Quanqi Shi and Chao Xiao, physicists at China's Shandong University and the study's lead authors, wrote in an email.

Plasma Tides

"In the past, lunar tides were mainly found to affect the first three states [of matter]: solid Earth tides, liquid ocean [tides], and neutral gas-dominated atmospheric tides," Shi and Xiao wrote. "Whether lunar tides can influence the plasma-dominated regions had not yet been explored."

To fill in that gap, Shi, Xiao, and their colleagues combed through a database of more than 50,000 plasmapause crossings recorded from 1977 through 2015 by NASA's twin Van Allen Probes, the five-spacecraft THEMIS (Time History of Events and Macroscale Interactions during Substorms) mission, Europe's four-spacecraft Cluster mission, and others.

Because solar flares and related phenomena can cause substantial changes in the plasmasphere, the researchers eliminated readings taken when the Sun was active, leaving almost 36,000 observations.

Their analysis revealed tides in the plasmapause that ranged from about 0.12 times Earth's radius (300 kilometers) above average at high tide to 0.14 times Earth's radius (350 kilometers) below average at low tide—a difference of just 3% in the "smoothness" of the plasmapause. The researchers published their findings in *Nature Physics* (bit.ly/lunar-tide-effects).

"Whether lunar tides can influence the plasma-dominated regions had not yet been explored."

Surprising Offset

Ocean and land tides are highest and lowest close to the new and full Moon, when the Moon aligns with Earth and the Sun, and lunar and solar gravity pull along the same line. Unlike those tides, however, the plasma tides are offset from the Moon's position in the sky by 90°.

High plasmapause tide occurs when the Moon is at first quarter, and low tide occurs 2 weeks later, at last quarter. The tidal waves in the plasmasphere occur once per day and once per month, versus the twice-per-day and twice-per-month cycles for ocean and other tides.

It is reasonable that the Moon has a small but noticeable effect on the plasmasphere, said Jerry Goldstein, a space physicist at Southwest Research Institute in San Antonio, Texas, who studies the plasmasphere but was not involved in this project. "The most surprising thing is that the largest effect is 90° away from the lunar direction," he said. "Intuitively, one might expect the largest effect to line up with the Moon."

The plasmapause tide itself is caused by the Moon's gravitational pull, according to the researchers, but the 90° offset is more difficult to explain. It doesn't vary with the lunar phase, the Earth-Moon distance, changes in seasons, or any other known factors. That means it's caused not by gravity alone but by gravity and electromagnetic forces working together, the researchers said.

One possibility is that electrically neutral winds in the ionosphere, which vary with the Moon's phase, modify electric currents that thread along magnetic field lines through the ionosphere and into the plasmasphere. The currents might disturb the magnetic field, pulling the plasmasphere out of sync with the motions of the Moon. The researchers noted that this mechanism is poorly understood, however, and "is a subject of ongoing research."

The plasma tides "may indicate a fundamental interaction mechanism in the Earth-Moon system that has not been previously considered," Shi and Xiao wrote in their email. "That is to say, lunar tides may not be ignored in the study of the magnetosphere."

"Understanding this new result is going to require a fun dive into some basic space plasma physics."

Diving into Plasma Physics

The tides in the plasmasphere could have implications for space travel and studies of other planets in our solar system and beyond.

Magnetospheres have been detected at other planets, the study's authors noted, suggesting that plasma tides "may be observed universally throughout the cosmos," opening new avenues of research into planetary systems and other bodies with strong magnetic fields.

Earth's magnetic field plays an important role in spaceflight as well. It deflects cosmic rays and particles of the solar wind, offering some protection to craft within the magnetosphere. However, it funnels other particles toward Earth's surface or traps them in the radiation belts, potentially threatening spacecraft and astronauts, particularly when they travel to the Moon, outside the protection of the magnetic field.

"We suspect that the observed plasma tide may subtly affect the distribution of energetic radiation belt particles, which are a well-known hazard to space-based infrastructure and human activities in space," the authors noted. "It is therefore worthwhile to look for evidence of this effect in future studies."

"Understanding this new result is going to require a fun dive into some basic space plasma physics," Goldstein said.

By **Damond Benningfield,** Science Writer

This artist's rendering depicts NASA's twin Van Allen Probes, which looped through the plasmapause many times, in Earth orbit. Credit: JHU/APL, NASA

Biden Administration Considers Unprecedented Solution to Colorado River Crisis

A 23-year-long drought exacerbated by climate change has taken a toll on the Colorado River. From 2000 to 2014, the flow of the lifeblood of the American West declined to only 81% of its 20th-century average, and water levels in the river's two main reservoirs have sunk to record lows. The concern is that in the future, levels could sink low enough to reach "dead pool"—the critical point at which the river can no longer provide water and electricity to Arizona, Nevada, and Southern California.

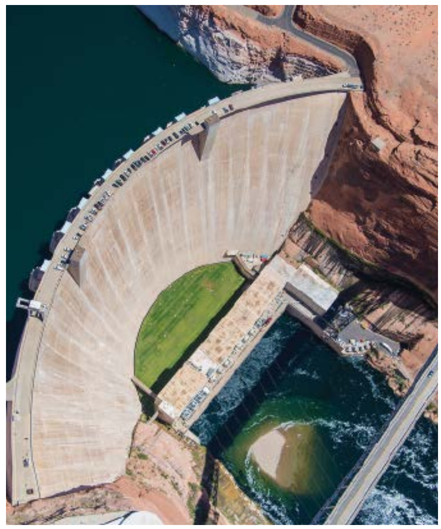
In fall 2022, in response to the crisis, the U.S. Bureau of Reclamation set an end-of-January-2023 deadline for the seven Colorado River Basin states to reach a consensus on water use reductions. Six of the seven states together submitted a last-minute proposal, but California, user of the greatest amount of Colorado River water, submitted its own separate proposal.

As temperatures increase with climate change, growing seasons lengthen, soils become drier, and more water is lost to evaporation. Consequently, it is imperative to act as soon as possible to reduce water use, said Christopher Skinner, a member of the NOAA Drought Task Force. "We can't possibly keep drawing the same amount of water out of the Colorado River and expect not to see this crisis continue," he added.

"We can't possibly keep drawing the same amount of water out of the Colorado River and expect not to see this crisis continue."

Reconsidering a Century-Old System

The basin states have been concerned about securing their share of the river's water for more than a century. In 1922, policymakers met in New Mexico to discuss, negotiate, and ultimately work out a compact apportioning the river's water between states in the upper basin (Colorado, New Mexico, Utah, and Wyoming) and lower basin (Arizona, California, and Nevada). The compact forms the cornerstone of the Law of the River—a broad term referring to the many laws and regulations that govern the use of the river's water.



The Glen Canyon Dam holds back the Colorado, creating Lake Powell, on the border between Arizona and Utah. The lake's water levels have plummeted to lows not seen since the reservoir was filling for the first time.Credit: Alexander Heilner, The Water Desk, with aerial support from LightHawk, CC BY-NC-ND 4.0 (bit.ly/ccbyncnd4-0)

On the basis of hydrologic data collected at the time—during an anomalously wet period—the compact apportioned 7.5 million acre-feet of water from the Colorado River annually to both the upper basin and the lower basin. But those data proved to be an overestimate of the average amount of water available each year, and the Colorado River was already over-allocated more than 100 years ago.

Fast-forward a century: Streamflow drought has intensified in the United States and the flow of water in the Colorado River has diminished by nearly 20%, meaning that there is even less water to meet the allocations. The Colorado River Compact defined a "rights by prior appropriation" strategy for dividing up the water in the basin. Those who claimed first historically had senior water rights and have first rights to the water today. When there is not enough water, it's the junior who suffers the cuts.

From a scientific perspective the calculations are simple: To continue to support the 40 million Americans who rely on the river for their drinking water and the basin's agricultural industry, the states have to reduce their water usage. But determining which states should bear the brunt of the cuts has proved more complicated.

Consequently, as the states have been unable to reach a consensus, on 11 April 2023 the Bureau of Reclamation stepped in with a draft analysis weighing options for water usage reduction. One option, which is aligned with the current Law of the River, considers making reductions based on the seniority of water rights. This strategy means that some users in Arizona would face drastic reductions; the water allocations to the cities of Tucson and Phoenix could be slashed. California, however, would not have to make any cuts.

"It is time for a fundamental restructuring of how we think about water allocation in the Colorado River system."

"This business-as-usual approach means the lowest-priority users take the biggest cut, and that is surely not going to work," said Jack Schmidt, director of the Center for Colorado River Studies at Utah State University.

An alternative, unprecedented approach outlined in the analysis would be to divvy up the cuts evenly among the lower basin states, reducing the water allocated to Arizona, California, and Nevada. Everybody taking the same proportional cuts might be okay in the near term, but sustainability in the long term requires more targeted and thoughtful analysis, Schmidt said. "But if it's an incremental step toward people saying that we have to move beyond the limits of the Law of the River, then it's a first step," Schmidt said. "And we have to start somewhere."

Schmidt pointed out that the Law of the River has always changed in increments, and

The Colorado River flows from its headwaters, near Parshall, Colo. Credit: Mitch Tobin, The Water Desk, CC BY-NC-ND 4.0 (bit.ly/ccbyncnd4-0)

the current situation, exacerbated by a warming climate, calls for further changes. "That said, it is important for the federal government to exert its leadership because the states have recently not been able to reach an agreement," Schmidt said.

The Bureau of Reclamation's proposals to cut water allocations for lower basin states are part of a supplemental environmental impact statement for the Colorado River. The Interior Department plans to release its final analysis of the options—including other possible solutions—this summer. At present, thanks to above average snowfall and a wet winter, "dead pool" won't happen this year, and a major crisis has been averted until 2024 at the earliest. For policymakers, that has created some breathing room to consider what modifications to the Law of the River are needed.

"It is time for a fundamental restructuring of how we think about water allocation in the Colorado River system," Schmidt said.

By **Jane Palmer,** Science Writer

Felt Reports Could Shake Up Earthquake Response

A house in Palu, Indonesia, stands on a liquefied foundation following the devastating 2018 Sulawesi earthquake. Seismologists are investigating whether crowdsourced, firsthand accounts of earthquakes could help determine the appropriate response to quakes like this. Credit: Walter Mooney, USGS

When Earth trembles, the Internet lights up. People reach for their phones to search for information and to tell others what they've experienced. Multiple seismic agencies solicit "felt reports," and now scientists are trying to use those reports to increase safety in areas where seismic instrumentation is scarce.

Seismologist Henning Lilienkamp of the GFZ Helmholtz Centre Potsdam and his colleagues recently investigated whether they could use felt reports alone, gathered through an app called LastQuake, to determine quickly whether an earthquake was high impact.

Felt reports are nothing new, but they are usually used in conjunction with data from seismological instruments. For example, felt reports collected by the U.S. Geological Survey (USGS) through its website Did You Feel It? are among multiple data sources used to create ShakeMaps, which describe the intensity of earthquakes.

Rather than replacing current systems that detect and categorize earthquakes, "our idea is to be a bit faster" while providing a very preliminary view of what's occurred, Lilienkamp said. Their model could one day be the basis for a system that advises emergency responders on whether they should respond immediately to quakes (red light), investigate further (yellow), or do nothing (green).

The current work is only a starting point, but researchers are excited about the eventual applications of felt reports. "So much of the problem of responses is getting information out as quickly as possible," said earthquake seismologist Rachel Abercrombie of Boston University.

Current Systems Face Limitations

The LastQuake app is one of three types of crowdsourced data—along with Twitter and traffic to its website—that the European-Mediterranean Seismological Centre (EMSC) uses to detect earthquakes.

The app's 1.4 million users, plus website visitors, can report shaking by clicking on one of 12 illustrations that describe different severity levels. Very minor shaking is depicted as two happy people watching TV, whereas a serious earthquake is depicted as horrified cartoon figures writhing on a street as buildings crumble.

Lilienkamp and his colleagues took these felt reports a step further by using them to calculate the probability that an earthquake was high impact. (High-impact quakes are defined as destroying at least one building, damaging at least 50 buildings, causing at least two fatalities, or causing any documented financial losses).

The researchers were not able to reliably identify high-impact earthquakes. However, all the earthquakes that their model assigned under 1% probability of being high-impact were in fact low-impact events, suggesting that the system could be used to identify some situations that don't require a response.

"So much of the problem of responses is getting information out as quickly as possible."

The rareness of high-impact earthquakes presents an inherent difficulty in studying them, said seismologist Mostafa Mousavi of Stanford University. Most of the events that Lilienkamp and his colleagues analyzed were low-impact earthquakes, Mousavi said, making the model much more prone to detecting those events—perhaps sometimes even erroneously. Systems based solely on felt reports could be valuable, he added, but "it is a difficult problem."

If felt reports can help emergency responders quickly get to where they're needed, the idea is worth pursuing, Abercrombie said: "If you're trying to rescue people alive, it's much easier at the beginning."

When high-impact earthquakes occur, there's usually no question as to whether help is needed. These events often produce the so-called donut effect: a ring of plentiful reports far from the epicenter, with only sparse reports where the most damage occurred, explained seismologist Ina Cecić of the Slovenian Environment Agency. The recent earthquakes in Türkiye and Syria produced this pattern, Lilienkamp said.

Even the uncertain suggestion that an earthquake warrants attention might sometimes be useful. Lilienkamp pointed to the 21 June 2022 earthquake that occurred in Afghanistan as an example. The region has little seismic instrumentation, so scientists from the EMSC initially couldn't tell whether the quake had affected residents. "It turned out that more than a thousand people died," Lilienkamp said.

Felt data were "how seismology actually started."

LastQuake received 50 reports—the minimum necessary to run the model—within about 8 minutes, and the model likely would have suggested that a response was warranted.

Many Paths Forward

Felt reports are just one of the ways seismologists are using both high- and low-tech instruments to make earthquakes easier to detect, said Cecić. For example, Japan, Mexico, and parts of the United States have services that alert people to nearby earthquakes before the shaking reaches them. Google provides a service that draws on data from accelerometers built into Android phones. Cheap, user-friendly earthquake detectors called Raspberry Shakes are taking the place of expensive seismometers in many parts of the world.

Adding felt reports to this arsenal is a modern revival of "how seismology actually started," Mousavi said. Long before seismic instruments existed, people recorded their experiences with earthquakes on whatever media was available.

As reporting apps become more versatile and widely used, returning to more intuitive devices may be key to increasing safety worldwide.

By **Saima May Sidik** (@saimamaysidik), Science Writer

Godzilla Gets a Forever Home on the Ocean Floor

Tokyo Cheapo

If you dive deep enough into the western Pacific Ocean, you just may come across Godzilla. A group of ridges on the seabed resembling the king of monsters was named after the beast's body parts and will be officially recognized as such in nautical charts, the Japan Coast Guard has announced.

The feature known as the Godzilla Megamullion Province is located in the Parece Vela Basin of the Philippine Sea, around 600 kilometers (370 miles) southeast of Japan's southernmost coral reef, Okinotorishima. The ridges were first reported after a 2001 survey of the area by marine geologist Yasuhiko Ohara and colleagues from the Japan Coast Guard's Hydrographic and Oceanographic Department, who undertook several research cruises into the area.

Also known as oceanic core complexes, megamullions are a relatively recent discovery, and scientists are still probing how they work. Megamullions are dome-shaped rises generally found along slowly spreading mid-ocean ridges. Characterized by ridgelike structures, megamullions are thought to form during spreading episodes when faults expose deep magmatic or mantle rocks on the seafloor.

Roughly 155 kilometers (100 miles) long by 55 kilometers (30 miles) wide, the Godzilla Megamullion has ridges reaching heights of 2,500 meters (8,200 feet).

"The Godzilla Megamullion is the largest known oceanic core complex on the Earth and is more than 10 times larger in area than those developed on the Mid-Atlantic Ridge," said Ohara, citing a 2014 study he coauthored that describes the feature's characteristics (bit.ly/Godzilla-Megamullion).

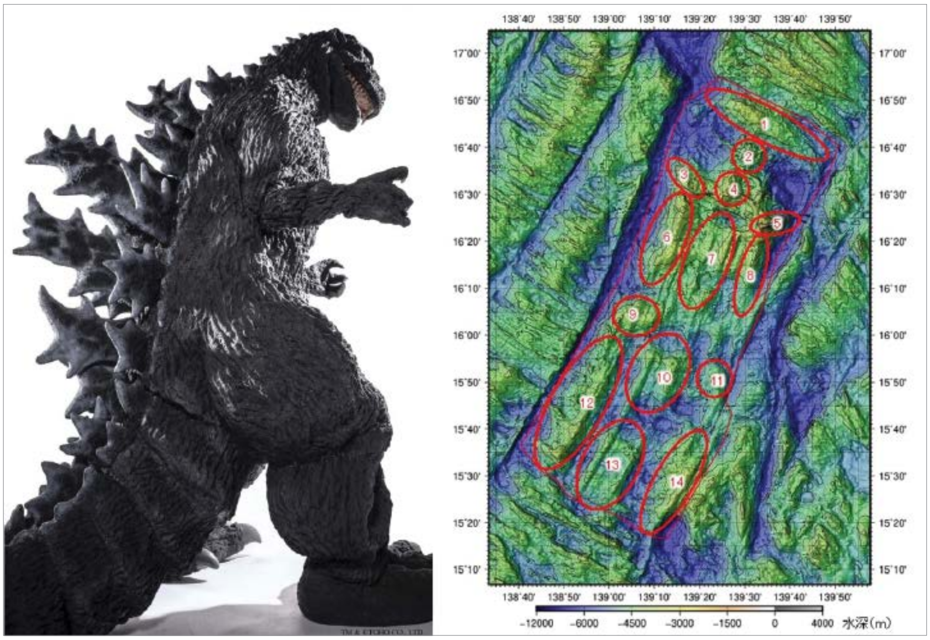
It may take a bit of imagination, or creative squinting, but you might be able to make out the shape of Godzilla lying face down on the seafloor.

Hat Ridge and Head Peak are next to two deeper areas above the monster's shoulders, which are situated near roughly parallel rises that form its arms, backbone, hip bones, legs, and tail. "The individual 14 names were the result of a beautiful coincidence," said Ohara.

"The Godzilla Megamullion is the largest known oceanic core complex on the Earth and is more than 10 times larger in area than those developed on the Mid-Atlantic Ridge."

An Ocean of Monikers

Japanese researchers chose the Godzilla moniker for both the feature's enormous size and its relative proximity to the monster's island of origin. In the 1954 sci-fi classic produced by Toho Co., Godzilla emerged from the sea near fictional Odo Island, which some fans situate in the region of Okinotorishima.



The ridges of the Godzilla Megamullion are named after the monster's body parts: (1) Hat Ridge, (2) Head Peak, (3) West Shoulder Ridge, (4) Neck Peak, (5) East Shoulder Ridge, (6) West Arm Rise, (7) Backbone Rise, (8) East Arm Rise, (9) West Hipbone Rise, (10) North Tail Rise, (11) East Hipbone Rise, (12) West Leg Ridge, (13) South Tail Rise, and (14) East Leg Ridge. Credit: Toho Co. Ltd./Japan Coast Guard

Toho's "chief Godzilla officer," Keiji Ota, said in a statement last year that it was an honor for the megamullion to be named after the monster, which has appeared in more than 30 films. "As far as we know, it is the first time for such a feature [to be] named after a fictional monster," said Ohara.

The Pacific is riddled with interesting nomenclature. Japan has the Shichiyo Seamount Chain, named after the days of the week. Off Hawaii's coast one can find the Musicians Seamounts, honoring such composers as Beethoven, Mendelssohn, Tchaikovsky, and Gershwin. Farther south, a collection of vents west of Easter Island has been given the names of such cartoon characters as Homer Simpson, Scooby, Tweety, and Road Runner.

Standardizing Names

With a 2022 approval by the Sub-Committee on Undersea Features Names (SCUFN), part of the General Bathymetric Chart of the Oceans (GEBCO) Gazetteer, the 20-year wait for the Godzilla Megamullion to get an official name ended; the recent decision was related to the giant reptile's individual body parts.

GEBCO was established in 1975 to create a policy on name standardization. It falls to the SCUFN to recognize whether a proposed name is suitable.

"One can find names from mythology, flowers, painters, marine scientists, and famous historic people. It's not easy sometimes to avoid sensitive issues," said the International Hydrographic Organization's Yves Guillam, who serves as SCUFN secretary. Despite Godzilla and Homer Simpson, he said, "in general, the SCUFN favors famous worldwide recognized high-level marine scientists, oceanographers, and hydrographers.… SCUFN efforts are driven to remain realistic, pragmatic, efficient, based on the available short resources allocated to the international recognition of undersea feature names."

Scientists hope the Godzilla Megamullion will yield insights into the dynamics of back-arc basins.

By **Tim Hornyak** (@robotopia), Science Writer

Supercharged El Niño Could Speed Up Southern Ocean Warming

When easterly winds weaken over the tropical Pacific Ocean, a string of weather extremes unfolds all over the globe, with impacts ranging from flooding in South American deserts to reduced monsoon rains in India and Indonesia. This shift in wind and water currents, known as the El Niño–Southern Oscillation (ENSO), will become more intense if global temperatures continue to rise.

Research now has revealed that projected changes to this global weather maker will also influence the remote Southern Ocean. Using the latest climate models, scientists have shown that enhanced El Niño events will likely speed the heating of deep-ocean waters around Antarctica, with the potential for accelerated melting of the continent's land-held ice.

Melting Uncertainties

Scientists are concerned about how stronger El Niño events could affect the Antarctic because of the potential for sea level rise. The Antarctic Ice Sheet holds about 60% of the world's fresh water—enough to raise global sea levels by around 70 meters.

Satellite measurements have shown that the Antarctic Ice Sheet has been melting steadily over the past 2 decades. But owing to the remoteness of Antarctica and the challenge of collecting data directly from the ice or surrounding ocean, scientists still don't fully understand the processes influencing Antarctic ice loss, leading to uncertainties in projections of global sea level rise.

"We know very little about how ENSO intensification will impact the Antarctic climate."


A new iceberg broke off from Antarctica's Brunt Ice Shelf on 22 January 2023. Credit: NASA Earth Observatory

Changes to ENSO complicate sea level projections further. "We know very little about how ENSO intensification will impact the Antarctic climate and, in turn, how that could drive ice loss," said Wenju Cai, a climate scientist at the Commonwealth Scientific and Industrial Research Organisation (CSIRO), Australia's national science agency.

In a study published in *Nature Climate Change,* Cai and his colleagues used climate models to make the first assessments of how ENSO intensification could affect Antarctic climate (bit.ly/Antarctic-El-Nino).

A Range of Climate Models

According to Cai, most climate models project an increase in ENSO variability by 2100, indicating that both phases of ENSO, warm El Niño and cool La Niña, will likely become stronger and more frequent in the future.

"ENSO influences many aspects of the Antarctic climate, driven by the changes it exerts on atmospheric and ocean circulation around the continent," said study coauthor Ariaan Purich, a climate scientist with Monash University in Australia.

In their study, the researchers investigated how more frequent ENSO events could affect the Southern Ocean over the next century, assuming a business-as-usual scenario in which greenhouse gas emissions remain uncurbed.

To do this, they analyzed projected changes to sea ice, ocean temperatures, winds, and heat fluxes across a group of 31 global climate models produced as part of the Coupled Model Intercomparison Project Phase 6 (CMIP6).

The researchers assessed the spread of ENSO variability changes across the models. "Simulating the impact of climate change on ENSO is a challenging task in itself," said Mat Collins, a climate scientist with the University of Exeter in the United Kingdom who was not involved in the study. "The novelty here is that [the researchers] bring together a range of climate models to disentangle complex climate responses."

Deep-Ocean Warming

The researchers found that an increase in ENSO variability over the next century will lead to changes in circulation in the Southern Ocean, causing accelerated warming of Antarctica's deeper waters. The reason is that the slower easterly winds that blow over the region will reduce the upwelling of deep warm waters.

The analysis also showed that although the ocean surface will warm more slowly, the deeper ocean around Antarctica will warm more quickly, exposing the ice shelves that fringe the continent to heat from below.

These shelves do the important job of holding back glaciers on land. Deep-ocean warming could destabilize and melt the floating ice, allowing land-held ice sheets to slide more easily into the ocean, raising sea level. The researchers cannot say at this stage how deep-ocean warming will affect ice loss because the CMIP6 models don't include interactive ice shelves or ice sheets.

"What's new is that we now have a preview of how [Antarctic ice shelves] could respond as El Niño intensifies."

"Scientists have known from satellite observations that Antarctic ice shelves typically lose mass during El Niño events," said Helen Fricker, a glaciologist with the Scripps Institution of Oceanography who was not involved in the study. The loss occurs because an influx of warm water melts the ice shelves from below, she explained. "What's new is that we now have a preview of how they could respond as El Niño intensifies."

Fricker added that continued efforts to collect observational data from the Antarctic are needed to complete the picture of ocean and ice shelf interactions. Purich agreed. "This is an important part of the puzzle," she said. "But there are still many unknowns surrounding the processes influencing ocean circulation and ice melt on the Antarctic shelf."

The researchers said they plan to build ice sheet models into future analyses to help them get a better handle on how the ocean warming they observed could affect rates of ice melt.

By **Erin Martin-Jones** (@Erin_M_J), Science Writer

In New Zealand, Fish Are Helping Scientists Find Gold

A freshwater galaxiid of a newly discovered, undescribed species swims in the Pomahaka River in southern New Zealand. Credit: Daniel Jack

New Zealand straddles the boundary of two tectonic plates and as a result is in a constant state of upheaval. As mountains rise and fall, rivers are split, diverted, and joined. In some cases, they have even reversed flow.

A geologist, a biologist, and an ecologist recently put their expertise together to simultaneously trace the movement of fish and gold through the country's rivers. The results point to hidden riches, and the team's approach has informed research around the world.

Along for the Ride

Caught amid New Zealand's geological turbulence are tiny native freshwater fish—species in the genus *Galaxias.* Over millions of years, galaxiid populations have been split by river capture—the diversion, by geological change, of rivers into different catchments.

In the southern province of Otago, rivers also carry gold eroded from the basement schist across the landscape. Nineteenth-century miners flocked to Otago to dredge, pan, and sluice its lucrative waters.

Gold is also found in Otago's neighboring province, Southland. Because Southland has far less gold-bearing basement rock, geologists have deduced that a large river system once carried most of this gold from Otago to Southland.

Today, though, the two provinces are separated by a mountain range, described by University of Otago geologist Dave Craw as a "Hadrian's Wall," which prevents water from flowing between them.

Casual Conversation

In the late 1990s, Craw met up with his University of Otago colleague biologist Jon Waters. Waters was struggling to explain another unlikely connection between Southland and Otago: a galaxiid species he'd found living on both sides of the drainage divide.

Craw had an explanation for him: The river the fish lived in, the Nevis, had, at some time in the distant past, been reversed by the rising mountains, cutting the fish population in two. The pair immediately realized that they could use the rate of genetic divergence between the two fish populations to pinpoint the date of that reversal. "We essentially wrote a paper straightaway," Craw said.

They went on to apply the same techniques elsewhere in Otago. "We started looking for more clues, and we've continually found more," Waters said. "There are places where the fish record is strong and the geology isn't, and places where the geological record is strong and the fish are less informative. But by putting the two together, we can put the pieces of the jigsaw puzzle together."

"We started looking for more clues, and we've continually found more."

From numerous studies, the team calibrated a "geogenomic clock" that they can now apply to river capture queries around New Zealand. It's also helped them predict where old, gold-bearing rivers may be buried.

Fish genes, Craw said, are often far more useful than rocks for narrowing down the exact timing of geological events—something that is crucial when looking for mineral deposits. "You need to know what rivers went where, and when," he said.

Craw and Waters, along with ecologist Ciaran Campbell of the Otago Regional Council, recently turned their attention to Southland. In their latest study, published in the *New Zealand Journal of Geology and Geophysics,* the group used fish dating as one tool to predict

Gold flakes from the Waikaia River in Southland, New Zealand. This gold was transported to the province millions of years ago by a river that no longer exists. Credit: Dave Craw

where a number of old, gold-bearing rivers had flowed (bit.ly/fishing-for-gold). In doing so, they also identified a probable new species of galaxiid.

Pedro Val, a geomorphologist with the City University of New York who was not involved in the study, pairs fish genes with sediments to date river changes in the Amazon Basin. "It makes total sense," he said. "Fish are passively inhabiting the river. If the rivers are changing, fish are going along with it, and the same with sediment. It's kind of the perfect scenario where you get two independent things showing the same process."

Fish Genetics Around the World

The collaborative approach Craw and Waters developed is now used in other countries. James Albert, an ecologist at the University of Louisiana at Lafayette, studies how freshwater fish in South America have evolved in response to the uplift of the Andes.

The New Zealand team, Albert said, has "probably the most well developed system" of matching fish genetics with geology in the world.

Albert, who was not involved in the New Zealand research, explained that the close agreement between galaxiids and gravel in the New Zealand work confirmed the accuracy of the team's methods.

"One of the assumptions," he said, "is that the only way the fishes can move among river basins is when there's river capture. But it's also possible, in principle, that birds can move fish around."

That, he said, "could screw up this kind of analysis. But the patterns [they] have found here are very reasonable interpretations of the underlying geology."

Buried Treasure

The study results suggested that an ancient riverbed is lying under farmland southwest of the modern-day Mataura River. The buried river may well be loaded with gold, Craw said. Extraction, however, is not likely anytime soon.

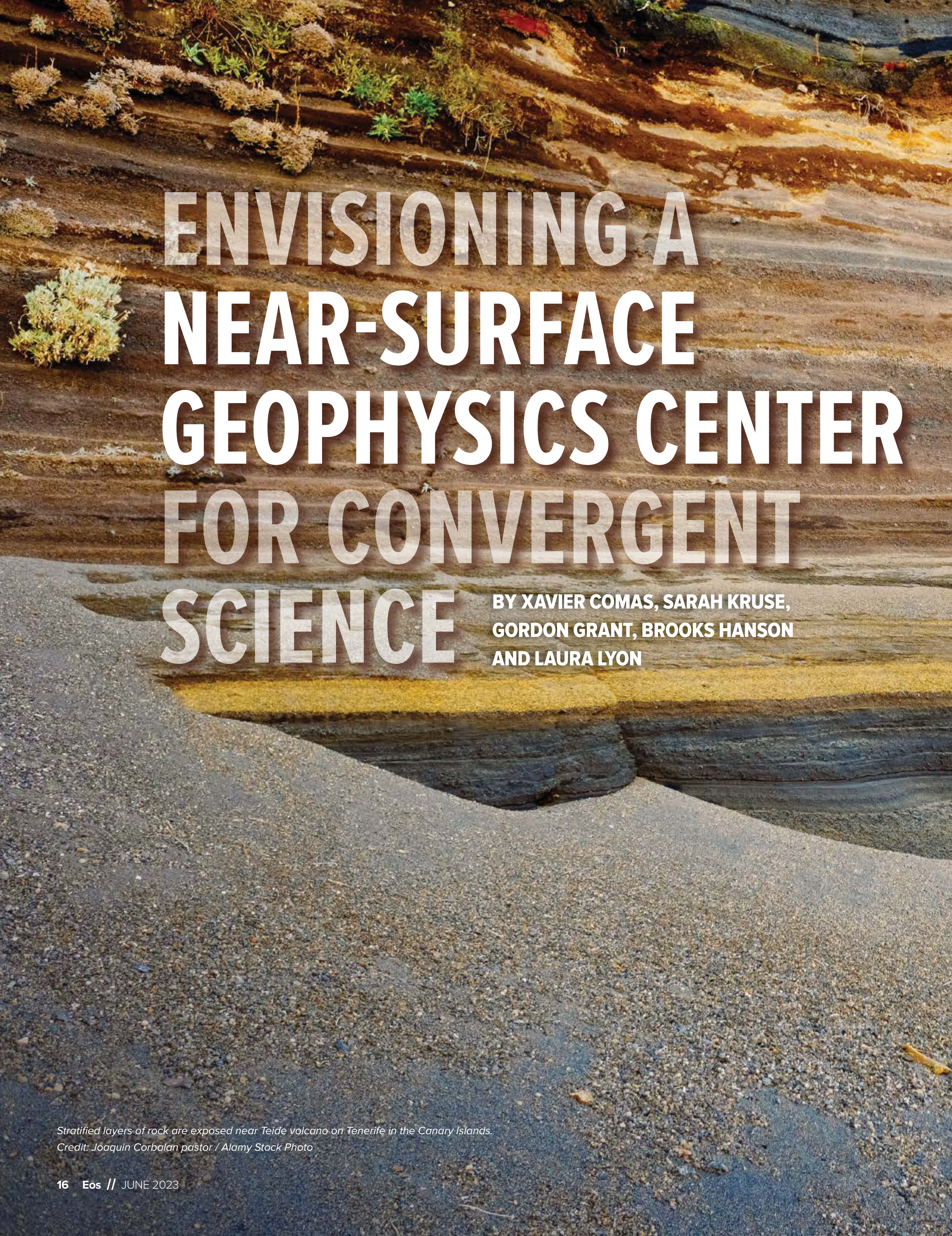
"There's probably 50 meters (164 feet) or more of gravel sitting on top," he said. "That's a lot of diesel [fuel] to remove that."

If the economics of mining were to change, however, such buried rivers may one day prove lucrative. Craw pointed out that a nearby active gold mine needed 40 meters (130 feet) of gravel removed to become operational. "It can be done," he said. "So maybe in 20 years' time, they'll take the top off it."

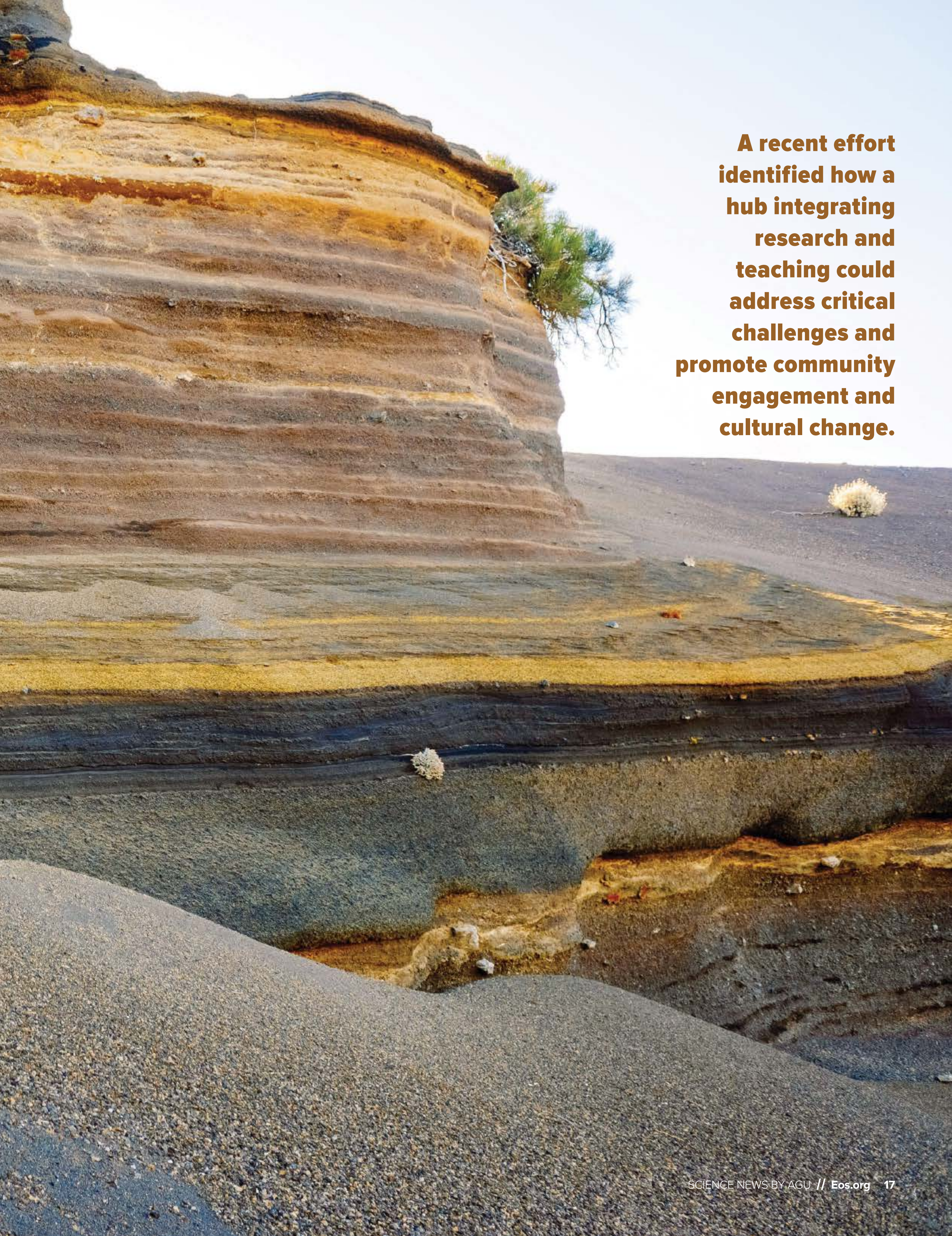
By **Bill Morris,** Science Writer

ENVISIONING A NEAR-SURFACE GEOPHYSICS CENTER FOR CONVERGENT SCIENCE

BY XAVIER COMAS, SARAH KRUSE, GORDON GRANT, BROOKS HANSON AND LAURA LYON



Stratified layers of rock are exposed near Teide volcano on Tenerife in the Canary Islands. Credit: Joaquin Corbalan pastor / Alamy Stock Photo



A recent effort identified how a hub integrating research and teaching could address critical challenges and promote community engagement and cultural change.

Earth's near-surface environment, which extends from the ground surface to a depth of several kilometers, is but a small fraction of the planet. Yet its importance cannot be overstated for all of us who call it home. This region hosts most of the rock, mineral, soil, groundwater, ice, and surface water resources we use daily and is where the effects of serious natural hazards like earthquakes, volcanic eruptions, floods, and landslides are concentrated.

Critical processes in the near-surface zone operate at all scales, from microbe-mineral interactions to groundwater flow and solute transport to the movements of faults and tectonic plates. Understanding these processes is central to using vital resources sustainably, safeguarding ourselves against natural hazards, and addressing other critical scientific and societal challenges in the 21st century, such as soil and water pollution, energy transitions, and the effects of climate change. Yet because this region is mostly underground, the dynamics, fluxes, and pathways of water, magma, and carbon, for example, are largely cryptic and must be probed or sensed using a variety of geophysical methods.

The crosscutting discipline of near-surface geophysics (NSG) is the gateway for understanding this cryptic environment. In size, scope, and impact, NSG has been growing extensively over the past 2–3 decades, thanks to the emergence of many new techniques, methods, and data sets on local to global scales. Together these innovations are providing richer, more efficient, and more detailed views of the subsurface. NSG is now positioned to provide important advances in our understanding of key elements of this environment that sustain and constrain life, much as remote sensing methods have transformed our knowledge of Earth's surface.

NEAR-SURFACE GEOPHYSICS (NSG) IS NOW POSITIONED TO PROVIDE IMPORTANT ADVANCES IN OUR UNDERSTANDING OF KEY ELEMENTS OF THE SUBSURFACE THAT SUSTAIN AND CONSTRAIN LIFE.

Students from Florida Atlantic University conduct a ground-penetrating radar survey in June 2018 along the Rio Blanco in El Yunque National Forest in Puerto Rico. Credit: Xavier Comas

Against this backdrop, in May 2020 the National Academies of Sciences, Engineering, and Medicine (NASEM) delivered a report to the National Science Foundation (NSF) that provided recommendations for addressing 12 priority research questions over the next decade [*National Academies of Sciences, Engineering, and Medicine*, 2020]. Among the recommendations was that NSF fund a national NSG research center. The recommendation was made because near-surface imaging has become an essential tool for many Earth science fields and because such a center would enable novel observations and insights bearing on many of the priorities highlighted in the report, including questions related to volcanism, seismology, geohazards, hydrogeophysics, biogeophysics, the critical zone, and climate change.

NSF subsequently asked AGU to convene communities of NSG scientists to further explore and report on the need for and value of a potential NSG center. Here we highlight key aspects and results of this exploratory effort.

Earth in Time

The NASEM report, titled *A Vision for NSF Earth Sciences 2020–2030: Earth in Time*, was intended to guide the NSF Earth Sciences division's research programs to address the priority questions identified. Some of these questions are directly relevant to the interests of the NSG community. For example, how is Earth's water cycle changing? How does the critical zone influence climate? How can Earth science research reduce the risk and toll of geohazards? In alignment with the recommendation to create an NSG center, the report also recommends implementing a continental critical zone initiative to develop and deploy a major mapping campaign to characterize the subsurface critical zone over large areas.

NSF currently funds a range of Earth science facilities and consortia. Those most closely associated with near-surface studies include the Seismological Facility for the Advancement of Geoscience (SAGE) and the Geodetic Facility for the Advancement of Geoscience (GAGE), both operated by the EarthScope Consortium; the National Center for Airborne Laser Mapping (NCALM); the Center for Transformative Environmental Monitoring Programs (CTEMPs); and the Consortium of Universities for the Advancement of Hydrologic Science Inc. (CUAHSI).

None of these institutions, in their missions or research portfolios, spans the full scope of NSG science, methods, or applications, hence the call to establish a broader, more integrative center focused on convergent science—one of the "10 Big Ideas" NSF proposed in 2017—that merges approaches and tools from diverse fields to stimulate discovery.

NSF's request to AGU to explore the recommendation for an NSG center followed two other recent requests by the agency to several science societies asking for input on addressing convergent science related to climate change solutions and geohealth. Responding to those prompts, AGU engaged its member communities to produce reports and recommendations around those topics [*Hanson et al.*, 2021, 2022a]. Recently, AGU also proposed that NSF create a Convergence Accelerator track for community science and climate resilience [*Pandya et al.*, 2023].

All of these reports highlight the growing need for integration and broader coordination across the sciences; new ways of organizing, funding, and fostering science; and new approaches to science education and connecting communities with science to meet grand challenges facing society (Figure 1). An NSG center could serve as a test bed for implementing and evaluating strategies to address these needs while simultaneously accelerating work on priority questions identified in the *Earth in Time* report.

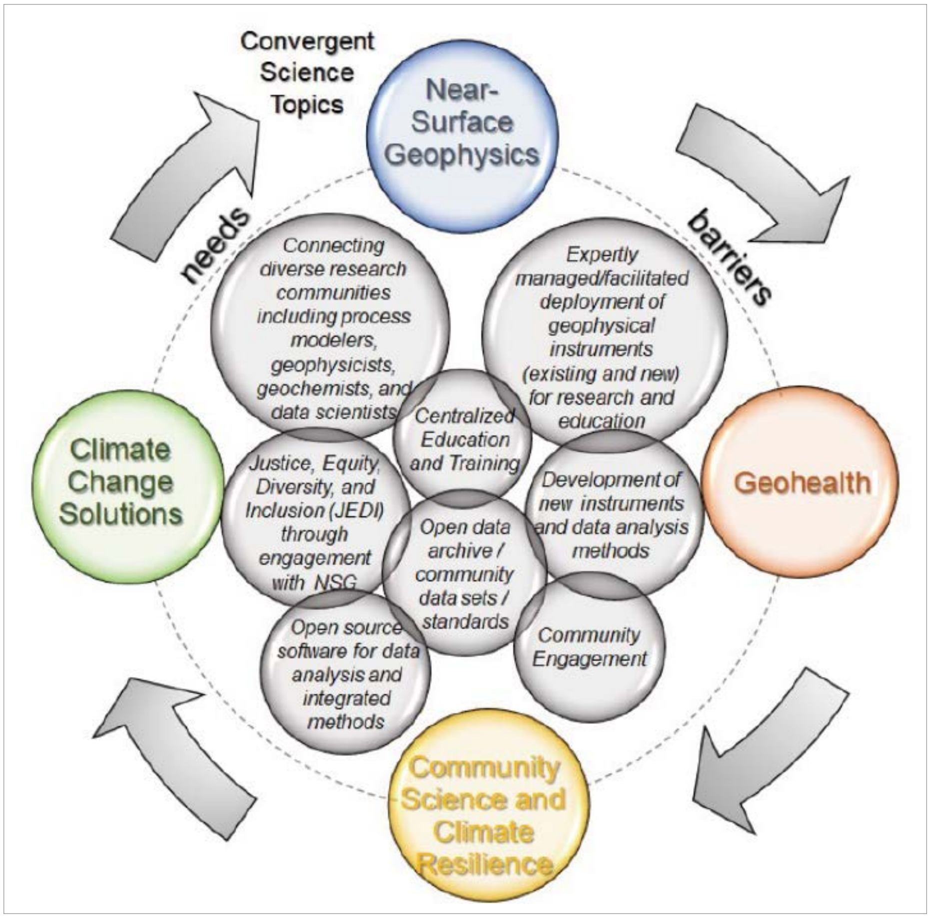


Fig. 1. Near-surface geophysics is connected to many other disciplines and critical societal issues. A near-surface geophysics center could enable convergent work on these challenges and help overcome key barriers inhibiting broader applications.

Gathering Community Input

To assess the high-priority science and broader impacts that could be advanced through an NSG center (the scope of which was not defined or constrained) and provide guidance to NSF, we developed a large, structured community engagement and ideation process [*Hanson et al.*, 2022b]. This process was guided by a 12-member steering committee representing diverse expertise in NSG applications and Earth science education. Committee members spanned from early-career to established senior scientists and had extensive experience working in both academia and government agencies and with research consortia such as CUAHSI and the Incorporated Research Institutions for Seismology (IRIS).

The committee distributed a 37-question survey to AGU and Society of Exploration Geophysicists (SEG) members working in NSG. These members responded about education needs in NSG, their awareness of current methods and techniques, impediments to addressing research priorities, and how to improve inclusivity and accessibility in the discipline. Results from 769 responses to this survey were used as the initial input for a series of three virtual workshops held in March and April 2022 that gathered 177 participants.

The survey and workshops had four main goals:

1. Define high-priority science questions aligned with the *Earth in Time* report that require access to integrated NSG instrumentation and expertise or advances in instrumentation or methodology.

2. Identify bottlenecks or gaps in current science infrastructure that impede such studies.

3. Identify impediments to recruitment and retention of students into NSG from 2-year colleges and institutions serving underrepresented students.

4. Envision capabilities of a national NSG center that would support efforts to answer high-priority questions; reduce the impediments identified; and enhance justice, equity, diversity, and inclusivity (JEDI) in NSG.

Output from one event was used as input for the next. In the first workshop, participants condensed 780 open-ended science questions identified by respondents to the initial survey into 24 key science questions. In the second workshop, participants focused on 13 representative key science questions and identified hundreds of related barriers, needs, and potential solutions. Finally, in the third workshop, attendees defined eight integrated opportunities from those needs and solutions, and these opportunities informed the effort's final recommendations to NSF.

Barriers and Opportunities

The 13 key questions selected illustrate the breadth and impact of NSG and the need for an integrative approach to advance science and address societal challenges while preparing the science workforce for the future. These questions include, for example, how NSG as a field can enable new discoveries about past land use and archaeological sites, help to manage ground and water resources globally, improve understanding of earthquake effects, characterize processes and fluxes in the critical zone, and expand diversity in the Earth sciences.

Major challenges common in NSG research include the acquisition of spatially rich data sets and real-time monitoring to improve the spatiotemporal resolution and prediction of processes, better quantifying the environmental and community effects of these processes, and using this knowledge to advance progress toward JEDI. In addition to these challenges, workshop discussions revealed other major barriers that hinder deployment of NSG widely and effectively, along with needs to help overcome barriers (Figure 1). These needs include the following:

1. Connecting different research communities—including process modelers, geophysicists, geochemists, and data scientists—both to raise awareness of NSG's versatility and to foster deep interdisciplinary collaborations.

2. Expertly managed and facilitated deployment of a broad pool of geophysical instruments to support research by geophysicists and allied communities and to provide education about, training on, and best practices for the instruments' use.

3. Centralized educational infrastructure, pedagogies, and expertise that would supplement geophysics expertise at institutions and enable different research communities and user groups to participate in NSG more equitably.

4. Improving JEDI in NSG by establishing research partnerships with local stakeholders to enable coproduction and application of science in traditionally underserved communities and by advancing training opportunities to engage a broader range of potential practitioners.

5. Development and deployment of new instruments and data analysis methods to improve multiscale subsurface monitoring and generate information that is not obtainable with available technologies.

6. Open data archives housing standardized data that follow FAIR (findable, accessible, interoperable, and reusable) guidelines—as well as education, training, and outreach about leading community data practices—to enable interdisciplinary data reuse and combining of data sets and to extend the outreach of data collected.

7. New open-source software for data analysis, integration, and visualization—and for education—that fills gaps in and advances capabilities of existing software to improve the efficiency of scientific studies and encourage students' exposure to and interest in NSG.

8. Community engagement to grow local knowledge and capacity and engender public trust in and understanding of NSG's uses and applications because the discipline directly informs our understanding of major societal challenges such as resilience against hazards and climate change; water, food, and energy security; improving public health; and supporting sustainability.

The importance of addressing the needs stated above strongly reinforces the recommendation in the *Earth in Time* report that NSF fund an integrative NSG center with a broader scope than exists at current facilities.

The community effort during the workshops also produced final recommendations to NSF about overarching attributes and values that an NSG center should embody. These recommendations focus on how a center should create a vibrant community of practice in NSG, push for needed improvement in NSG with respect to JEDI, enable widespread and state-of-the-art NSG education and training, provide access to and promote development of needed NSG equipment, empower NSG data and software, elevate NSG job opportunities, and lead in outreach and public engagement.

A more detailed discussion of these recommendations is given by *Hanson et al.* [2022b].

Common Themes of Convergence

The recent NSG report is one of four such documents focused on convergent science topics that the Earth sciences community has provided to NSF in the past 2 years [*Hanson et al.*, 2021, 2022a, 2022b; *Pandya et al.*, 2023]. Key themes in these reports overlap greatly: Each addresses similar needs and barriers, specifically related to extended monitoring, integrated data and computing resources, expanded education and training, and community engagement. They all also recommend hub or center models for effectively integrating diverse science efforts.

EACH OF THESE REPORTS ADDRESSES SIMILAR NEEDS AND BARRIERS, SPECIFICALLY RELATED TO EXTENDED MONITORING, INTEGRATED DATA AND COMPUTING RESOURCES, EXPANDED EDUCATION AND TRAINING, AND COMMUNITY ENGAGEMENT.

This overlap casts NSG in an ideal position—via an NSG center—as a bridging discipline that can enable discovery science and engage communities and society broadly to converge toward needed solutions. An NSG center could serve as a larger testing ground than is currently available for potential strategies and solutions that, if successful, could then be applied elsewhere.

Collectively, these recent efforts around convergent science indicate that approaches to funding, education, organization, rewards, and connections across the Earth sciences must be strengthened and better aligned to address critical 21st-century challenges.

Acknowledgments

This work was supported by NSF grant EAR-2139353 to AGU.

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Author Information

Xavier Comas, Florida Atlantic University, Boca Raton; **Sarah Kruse,** University of South Florida, Tampa; **Gordon Grant,** U.S. Forest Service, Corvallis, Ore.; and **Brooks Hanson** (bhanson@agu.org) and **Laura Lyon,** AGU, Washington, D.C.

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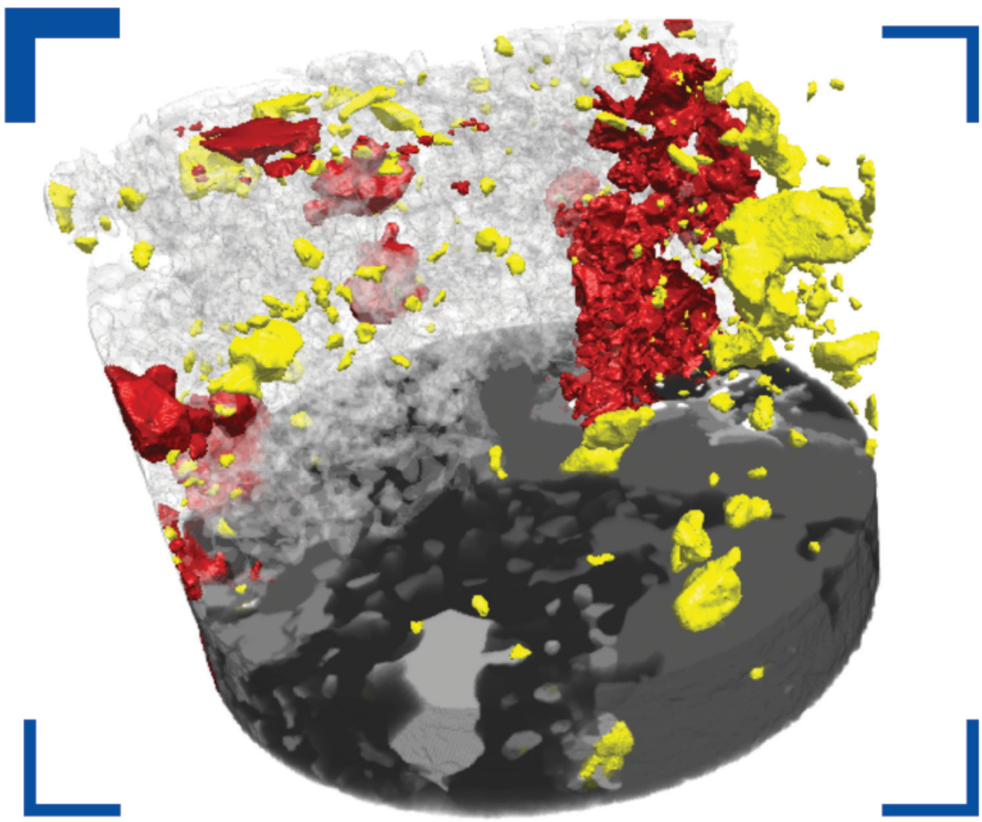
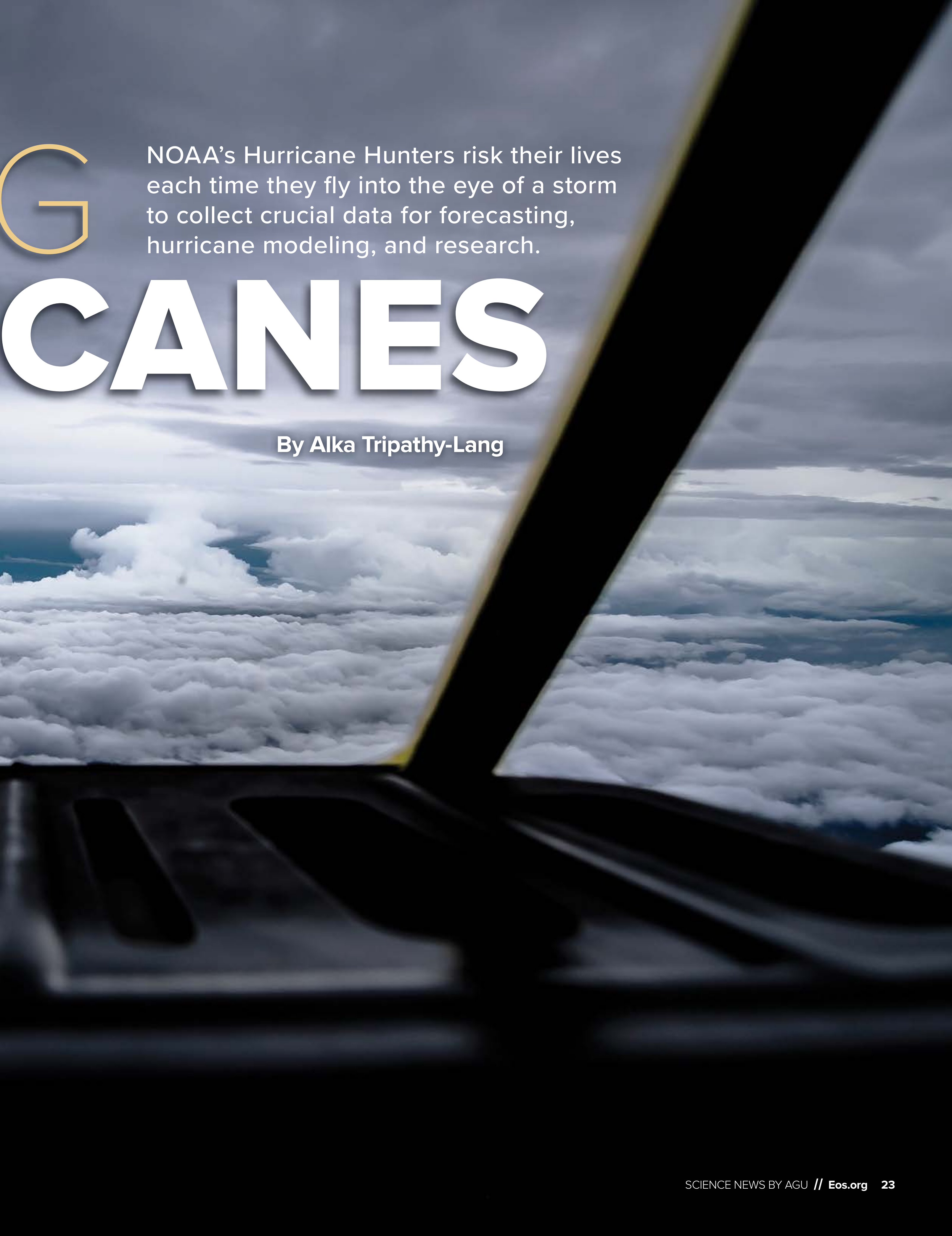


Hurricane Hunters approach Hurricane Florence in 2018. Credit: U.S. Air Force/Getty Images News via Getty Images



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CANES

NOAA's Hurricane Hunters risk their lives each time they fly into the eye of a storm to collect crucial data for forecasting, hurricane modeling, and research.

By Alka Tripathy-Lang

When Heather Holbach was a child growing up in Wisconsin, she was terrified of thunderstorms and tornadoes. To quell her fears, she would watch the Weather Channel to learn more about storms. Eventually, she moved to often sunny, sometimes stormy Florida and obtained undergraduate and postgraduate degrees in meteorology from Florida State University, where she remains.

As a member of NOAA's Hurricane Research Division, Holbach spends most of her time at a computer, studying storms. But between 1 June and 30 November each year, she often can be found high above the Atlantic Ocean and Gulf of Mexico. Holbach flies with NOAA's Hurricane Hunter aircraft, which ferry scientists directly into the eye of any hurricane encroaching on the United States or partner nations in the Gulf and Caribbean.

"Hurricane forecasters have the responsibility of assessing and forecasting a hurricane's location, strength, and size so that we can warn the appropriate people in harm's way," said National Hurricane Center senior hurricane specialist Robbie Berg. Hurricane Hunters collect data that are vital to these forecasting efforts, which can save lives and property.

"It's like grilling a steak," Berg said. "We can watch a fillet on the grill while it's cooking and have a fairly good idea of its doneness. But you never really know for sure unless you use a meat thermometer or cut into it. The same goes for hurricanes," he explained. "Satellite pictures give us a general idea of a storm's intensity or center location, but we don't really know for sure unless a Hurricane Hunter reconnaissance aircraft can fly into the storm."

Meet the Muppets

In 1943, U.S. Air Force Colonel Joe Duckworth was the first pilot to fly into a hurricane. This was during World War II, so even incoming hurricanes remained top secret as U-boats prowled U.S. waters. When Duckworth and his navigator returned from their adventure in a two-seater, single-engine propeller airplane, nobody believed them, said Jack Parrish, who hunted hurricanes with NOAA for more than 40 years. Duckworth took a meteorologist back to the hurricane's eye that same day to document the feat. Hurricane hunting was born.

Today, NOAA's Hurricane Hunter fleet includes two Lockheed WP-3D Orion aircraft, built for the agency in the 1970s. The design of these planes, commonly referred to as P-3s, is a modified version of the P-3 Orion flown by the Navy, said Commander Adam Abitbol, who has been piloting these planes for NOAA since 2014. The pair of P-3s first took flight in 1976 and 1977. In the 1990s, the planes were affectionately styled as Kermit and Miss Piggy. The Muppet-monikered aircraft have been penetrating storm eyewalls for nearly 50 years.

Kermit and Miss Piggy each have four engine-driven propellers, which receive power instantaneously, helping pilots respond quickly to severe turbulence and a fire hose of precipitation, said Ken Heystek, an Aircraft Operations Center maintenance controller and former flight engineer. These planes can fly low—below 3,000 meters (10,000 feet)—and slow, at 210 knots, while their payload of scientific instrumentation collects data for both immediate forecasting and research projects designed to illuminate how hurricanes work.

NOAA's Miss Piggy aircraft flies into storms to collect data. Credit: Nick Underwood, NOAA

NOAA has a third plane for hurricane hunting: a Gulfstream IV-SP jet nicknamed Gonzo, thanks to its elongated nose. Gonzo surveils the environment around a brewing hurricane, jetting as fast as 450 knots as it soars 12,000–14,000 meters (41,000–45,000 feet) above the ocean, said Jason Dunion, a scientist with the University of Miami and NOAA's Hurricane Research Division, who has served as lead project scientist on all three aircraft.

Because Gonzo is a jet, the signal from pilot to throttle to engine is not immediate, explained Heystek, which is one reason this aircraft does not fly directly into most storms. But because Gonzo can fly high and fast, it collects data over a much larger area than the P-3s.

Aircraft operation and maintenance fall to NOAA's Aircraft Operations Center, located in Lakeland, Fla. The flight crew, which includes NOAA Commissioned Officer Corps pilots and navigators, as well as flight directors, technicians, and flight engineers, all fit within this organization.

When a storm poses a threat to coastal U.S. regions or Caribbean partner nations, the planes will most often be tasked by the National Hurricane Center to fly operational missions designed to improve immediate forecasts.

For storms that do not pose a direct threat and for which there is no operational tasking, other NOAA groups can task the aircraft for research. For instance, the Hurricane Research Division has more than 20 ongoing experiments between the three aircraft to explore what makes a hurricane tick, said Dunion, who serves as the division's field program director.

The Center for Satellite Applications and Research (which falls under NOAA's National Environmental Satellite, Data, and Information Service, or NESDIS) can also task the P-3s for research focused on satellites and remote sensing of winds at the ocean surface. The National Weather Service uses satellite data daily for forecasts, said Paul Chang, who leads the Ocean Surface Winds Team at NESDIS. Now, flying into storms is standard when calibrating and evaluating satellite instruments and improving products, as well as testing future satellite technologies, he said.

Preparing for Takeoff

"There's a lot that goes into stepping on that plane and taking off," Abitbol said.

Gonzo flies above storms to gather big-picture data. Credit: Nick Underwood, NOAA

Crews for Kermit and Miss Piggy are scheduled to be on call to fly about 6 months in advance and include both the flight crew, who work for the Aircraft Operations Center, and the science crew, which usually includes scientists from both the Hurricane Research Division and NESDIS.

When the P-3s are tasked for operational forecasting, crews will usually fly for six consecutive days in 10- to 12-hour-long shifts, Abitbol said. Each shift includes about 2 hours for preflight preparation and anywhere from 8 to 10 hours of flying. The crew must have a minimum of 12 hours between landing and their next scheduled preflight briefing. The seventh day is rest. "Flying through a hurricane is exhausting," he said.

About 2 hours before takeoff, the pilots spend about 30 minutes meeting with the navigator, the flight director, and the lead project scientists from the science crew in an office—away from the aircraft—to discuss mission objectives and safety, said Ashley Lundry, a former (and occasionally current) flight director who is now chief of programs for the Aircraft Operations Center.

Flight directors are also meteorologists, and they conduct the briefing using remote sensing data, buoy data, and even data collected from the flight that just landed, Abitbol said. "They are flying meteorologists, which is a very critical task."

In the preflight briefing, "we talk every leg of the plan out," Lundry said. That includes where the storm is, how to get there and back, what might be expected once the plane is in the storm, what precautions are necessary, whether the storm is expected to rapidly intensify, whether there are any issues with foreign airspace, and whether any other planes will be nearby (like the 53rd Weather Reconnaissance Squadron of the Air Force Reserve Command, which is also tasked operationally by the National Hurricane Center and where Lundry made her first foray into hunting hurricanes).

"Understanding who is tasking us dictates how we fly our mission profile," Abitbol said. Operational flights tasked by the National Hurricane Center have a standard reconnaissance pattern shaped like a rotated figure four.

Research flights might require even more eyewall penetrations to find maximum wind speeds, so those flight patterns may look different, said Zorana Jelenak, a scientist at the University Corporation for Atmospheric Research (UCAR) who is part of the NESDIS Ocean Surface Winds Science Team.

"THERE'S A LOT THAT GOES INTO **STEPPING ON THAT PLANE AND TAKING OFF**."

Regardless of mission type, the lead project scientists discuss not only objectives but also additional research requests during the preflight briefing. "We can all still get a lot of research done during those standard operational flights," Chang said.

All Aboard

When the crew board the aircraft—typically between 14 and 20 people on Kermit or Miss Piggy—they might detect the heady aroma of musty airplane, overbrewed coffee, sweaty bodies, and oil-filled machinery. One crew member reported feeling nauseated as soon as the smell hits, whereas others don't notice it at all.

Should someone get sick, "I can't turn the plane around and go home," Abitbol said. To that end, some crew members take motion sickness medication before the flight and recommend visitors do the same. (Members of the media, politicians, and guest scientists occasionally join a flight.)

Each season's inaugural flight requires science crew members to sign a waiver acknowledging the obvious: that they're going into a hurricane. The science crew must also listen to an additional safety briefing to remind everyone of emergency exits, life jackets, and oxygen, Holbach said. Safety is paramount.

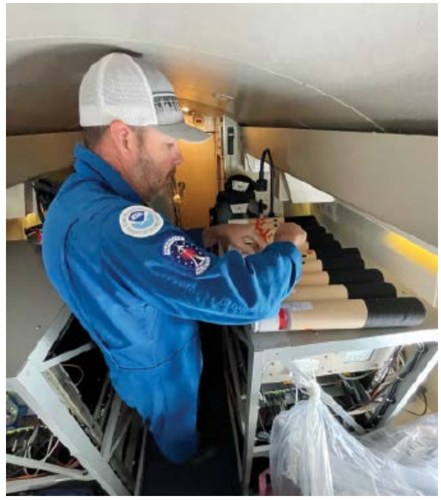
Aboard the plane, the science crew prep their instruments and electronics, check for any last-minute glitches, and download any data or imagery they might need. The pilots walk the aircraft to check the integrity of the plane and to ensure that all systems are functional.

Thirty minutes before takeoff, a pilot conducts the planeside briefing, during which the plan and expectations discussed in the earlier preflight briefing are conveyed to the entire crew. "We get an understanding of what the next 8 to 10 hours looks like, and then we'll take off," said Abitbol.

Sky Crew

In the cockpit, or flight station, two pilots sit—one on the left to steer the plane and one on the right to pay attention to everything else. Nestled in between is the flight engineer, whose hands are on the levers that control power to the engines. The flight engineer must be vigilant about maintaining a speed of 210 knots, Heystek said: too fast, the plane becomes stressed; too slow, the engines stall out.

Behind the flight station sit both the flight director and the navigator, who work as a team with the pilots. The navigator guides the aircraft to intercept the storm, develops the tracks the plane will take through the eyewall, and monitors fuel levels to ensure the aircraft gets home safely. The flight director interprets incoming radar and environmental data that help thread the plane through the storm safely while accomplishing the science mission. The flight director also functions as a liaison between the scientists and the flight crew. "Having a translator between the science and the flight crews can be a big help," said Parrish, who was a flight director from 1983 to 2021. This translator can be especially important when scientists don't have much flight experience, he said.



Scientific systems analyst Gabe Defeo prepares dropsondes aboard Gonzo during a mission to Hurricane Larry on 5 September 2021. Credit: Jason Mansour, NOAA Commissioned Officer Corps

The rest of the cabin contains several science stations. Each station has a flat-screen monitor on which anyone aboard can pull up various data sets being collected. For instance, data from the nose radar used for navigation and the lower fuselage, or belly, radar used for spatial awareness and research are available on the screens of scientists and flight crew alike.

A data technician and a systems engineer ensure that anything broken is fixed, that the communication systems are running, and that the instruments and data flow are working, Jelenak said.

Both P-3s have a tail Doppler radar contained in a little cone that sticks off the back of the plane, Lundry said. This radar maps winds and precipitation both above and below the aircraft every 1.5 kilometers (about 1 mile) along the flight track, Jelenak said. The radar scientist on board ensures that the data are properly processed and transmitted to National Hurricane Center scientists, who analyze the storm's structure, and to the Environmental Modeling Center of the National Weather Service for assimilation into hurricane models, said Holbach, who sometimes fills this role.

Both planes also have an Airborne Vertical Atmospheric Profiling System (AVAPS) technician responsible for launching dropsondes—biodegradable tubes about the size of a Pringles can—out of a chute. Shortly after release, a parachute attached to the dropsonde deploys, slowing its descent as it collects pressure, temperature, and humidity data, Holbach said. A GPS tracker charts the dropsonde's position to within tenths of a meter, which can be converted to wind speed. "As it's falling, it's transmitting its observations back to the plane, so we can actually see it on a display," she said.

Once the dropsonde reaches the ocean's surface, onboard software checks for any issues, such as whether the dropsonde fell too fast or any sensors were bad. "We have to do some extra, manual quality control of the data before we send it off the plane," Holbach said. The data then travel to the National Hurricane Center for storm analysis.

Preparing to fly into Tropical Storm (later Hurricane) Barry in 2019, the Hurricane Hunter flight crew and lead project scientists sit for the preflight briefing led by the flight director. Credit: Jonathan Shannon, NOAA

Flying Kermit into Hurricane Ian in 2022, the pilot to the left steers the plane and one to the right pays attention to everything else. The flight engineer nestled in between controls power to the engines. Credit: Nick Underwood, NOAA

Holbach is an expert on the Stepped-Frequency Microwave Radiometer, which determines how fast the wind is moving just above the ocean surface. When Holbach was a doctoral student working with this instrument aboard the P-3s, she would watch the ocean surface out of the window. "I was able to…see how [the surface] was changing with my own eyes and relate that back to the data in a way that I would have never been able to do if I hadn't been out there."

Chang, Jelenak, and other NESDIS scientists work on several different instruments, including the Imaging Wind and Rain Airborne Profiler, or IWRAP, originally developed by the University of Massachusetts. This instrument measures wind speed and direction along a vertical profile between the plane and the ocean surface and "is an advanced version of some of the instruments that we fly on satellites," Jelenak said.

"HAVING A TRANSLATOR BETWEEN THE SCIENCE AND THE FLIGHT CREWS **CAN BE A BIG HELP**."

During some research missions, the plane flies directly under the appropriate satellite to compare measurements. The detailed profiles produced by IWRAP are revolutionary because the result is equivalent to deploying a dropsonde every 150 meters (500 feet), Jelenak said. Dropsondes are single-use items that cost several hundred dollars, and only so many can be dropped per flight. They also drift with the wind, so their profiles aren't purely vertical, she explained.

IWRAP produces near-real-time data that will eventually be used operationally in forecasting models. "Not many people get to work on this bridge between research and operations," Jelenak said.

Through the Wall

As the P-3s head toward a storm, everyone wears headsets that help them communicate with one another while the droning engines drown out most other noise. "During the more relaxed portions of the flights," Dunion said, "we do sometimes all talk over the headsets together." That relaxed time can be anywhere from 30 minutes to 2 hours as the plane flies at about 6,000 meters (20,000 feet).

Learning Limits

Kermit and Miss Piggy typically fly at altitudes between 2,500 and 3,000 meters (8,000 and 10,000 feet) while gathering data, though they can go lower. But even Muppets have limits.

Paul Chang, the Ocean Surface Winds Team leader at NOAA's National Environmental Satellite, Data, and Information Service, described one harrowing extratropical cyclone nighttime flight. Three of the four engines failed in succession. "We were going to ditch," he said, because they couldn't keep altitude. Luckily, the flight crew managed to restart the engines, and they limped back to safety.

The culprit was unexpected sea-salt accretion on the turbine blades at 900 meters (3,000 feet), Chang said. Winds can loft salt high into the atmosphere. Without rain, the salt accumulates on the blades, disrupting airflow and stalling the engines.

Miss Piggy flies through the eye of Hurricane Ida on 29 August 2021. Credit: Kevin Doremus, NOAA Commissioned Officer Corps

When it's time to descend, everyone focuses on the job, and any information the scientists wish to share with the crew on the flight deck goes through the flight director. The descent down to or below 3,000 meters (10,000 feet) usually happens about 10 minutes prior to entering the storm, Chang said. "As we're descending, we finish turning on all of the instruments [and] make sure everything's working," he said. "From there, it just becomes nonstop."

Because the seatbelt light may be on for much of the flight, even bathroom breaks and trips to the galley for water, coffee, or food must be planned, Abitbol said.

The pilots must fly straight into the eyewall. "As we go in, the wind wants to push us," Heystek said. To stay perpendicular to the wind direction, the pilots repeatedly angle the plane's nose slightly into the wind, incrementally guiding the P-3 through the eyewall, much like a crab walking sideways through the sand. Sometimes it takes mere minutes to punch through, but in certain storms, the pilots can fight the wind for 45 minutes, he said.

Hurricane Sally creates choppy seas, as seen from Miss Piggy on 14 September 2022. Credit: James Carpenter, NOAA

Pilots must also contend with updrafts and downdrafts as they fly through the hurricane's outer bands and even in the clear air near the storm. This turbulence typically pushes the plane up or down by 30 meters (100 feet), though stronger storms can drop the plane by about 365 meters (1,200 feet), Heystek said.

"You're so focused on the data," Holbach said, "that you know to hold on to things, like to hold your computer screen up, or to make sure your water bottle doesn't go flying." No matter the turbulence, the data can't wait until the next day, Dunion said. "We have to get it out while we're flying."

"Once we get into the eye, it's beautiful," Heystek said. "Calm seas, calm air." The first time Holbach saw the bowl-shaped wall of clouds towering kilometers around the eye—it took her breath away, she said.

And then, Heystek said, there's "probably a good 2 or 3 minutes before you're doing it again going out the backside."

Today's Research, Tomorrow's Forecast

NOAA's hurricane-hunting aircraft are unique because they engage in both opera-

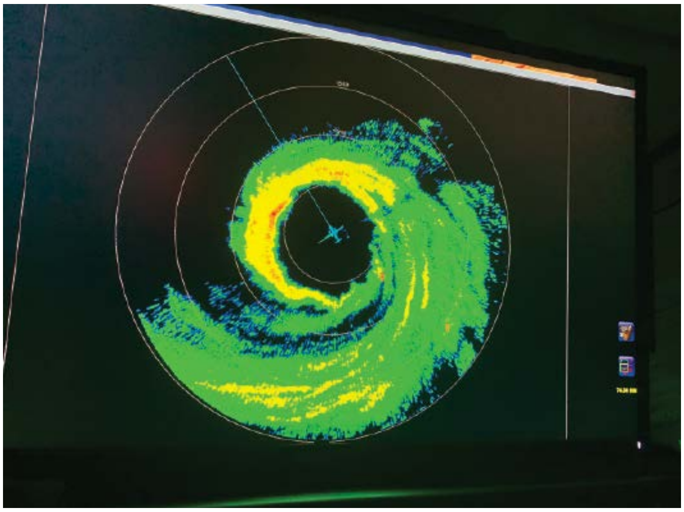
"ONCE WE GET INTO THE EYE, **IT'S BEAUTIFUL**."

Airborne Vertical Atmospheric Profiling System (AVAPS) operator James Warnecke releases dropsondes into the center of Tropical Storm (later Hurricane) Nicole on 9 November 2022. Credit: Kevin Doremus, NOAA Commissioned Officer Corps

tional and research missions. "The operational tasking for the data that the planes collect is based on research that was done 10–20 years ago," Chang said. Today's research will help future operations, which is the work that saves lives and property. "The research [is] an important reason to keep this type of capability."

Parrish, now with ECS, a consulting company, is working on the next generation of hurricane-hunting aircraft. Gonzo's successor, a Gulfstream G550, is already on order (name to be determined). Kermit and Miss Piggy will retire in the 2030s and will most likely be replaced by Lockheed C-130J Hercules aircraft, Parrish said.

"The C-130Js are a proven severe weather platform with long range: lots of power available to drive scientific instruments and computers and plenty of cabin space available for launching uncrewed expendable systems into hurricanes," he said. These systems might include instrumented flying drones, devices designed to drift on the surface of the ocean, subsurface buoys, or underwater gliders that can measure ocean depth profiles.



This photo shows data collected by Kermit's lower fuselage radar from within Hurricane Sam on 25 September 2021. Credit: Ashley Lundry, NOAA

Personal Reminders

Though both past and present Hurricane Hunters have an eye toward future planes, instrumentation, and forecasting, many of them live in Florida, where they've received personal reminders of why they must do this work. Parrish recalled living in Miami in 1992 when Hurricane Andrew totaled his home. "My work actually came home with me that time, and it wasn't a whole lot of fun."

When Hurricane Ian came calling in late September 2022, "it was coming for Lakeland, Florida," said Abitbol. The aircraft and crew evacuated to Houston to keep hurricane hunting. "We couldn't stop what we were doing to protect and take care of our own houses and families," he said.

Holbach recalled feeling a mix of emotions at the time. "With Ian, I was sick to my stomach because I knew what was coming toward Florida, but also [I had] this desire to get out there to get the information that we needed."

Author Information

Alka Tripathy-Lang (@DrAlkaTrip), Science Writer

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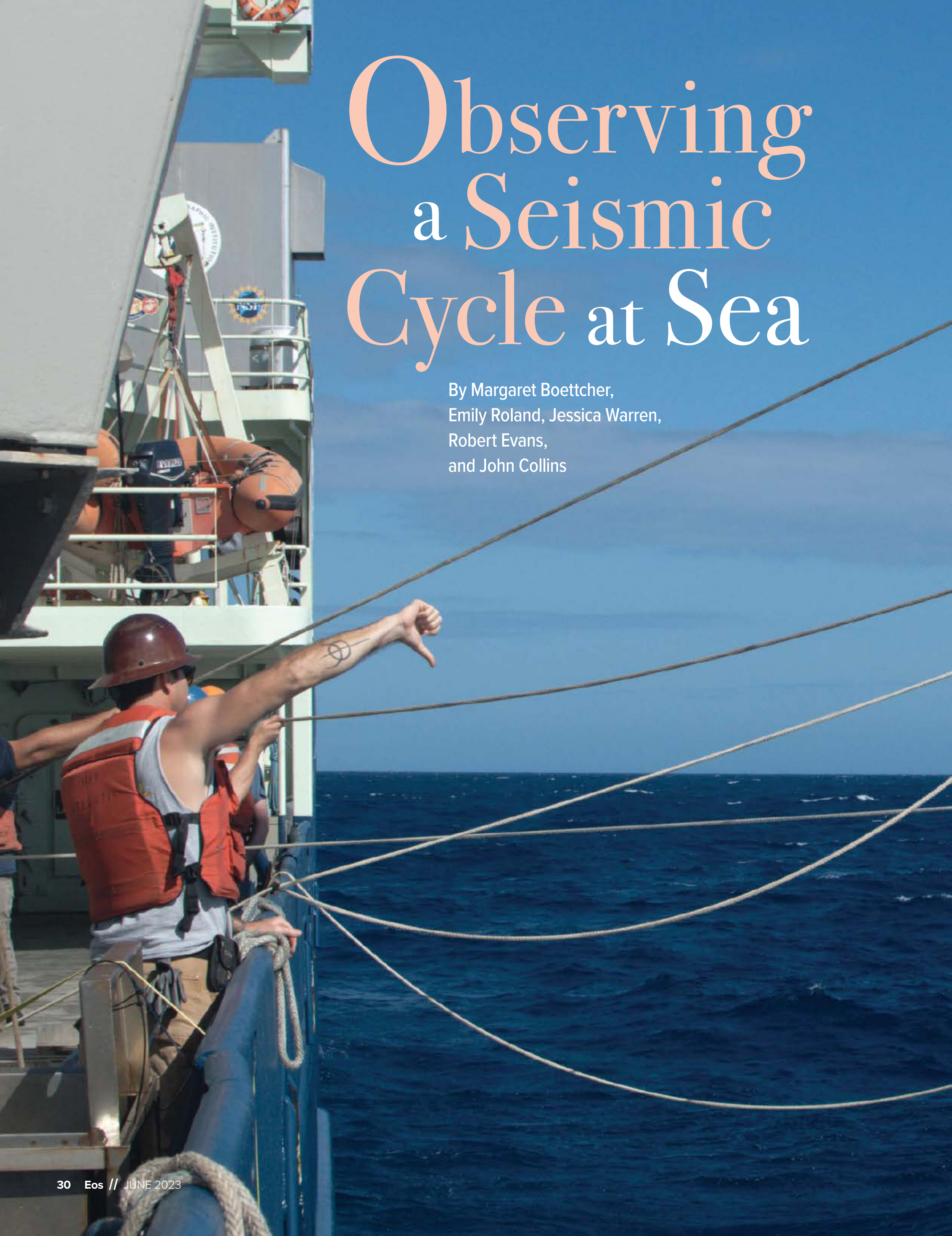


Observing a Seismic Cycle at Sea

By Margaret Boettcher, Emily Roland, Jessica Warren, Robert Evans, and John Collins

Scientists organized a trio of expeditions to document the buildup of stress leading to a large earthquake on a seafloor fault, developing innovations for successful seagoing research in the process.

Ronnie Whims (foreground), a bosun on the R/V Atlantis*, and others prepare to deploy several ocean bottom seismographs over the side of the ship in 2019. Credit: Thomas Morrow*

Earthquakes result in thousands of lost lives every year. Risks from seismic shaking could be reduced if scientists better understood major earthquakes and forecast them far enough in advance to help residents evacuate or find safe shelter. Such goals remain elusive, but studying controls on seismic cycles—the repeated sticking and slipping of faults—will reveal key insights.

We recently set out to observe and study stress buildup, earthquake rupture, and fault properties on an offshore fault thought to be most of the way through its cycle. The 170-kilometer-long Gofar Transform Fault includes three fault segments and is located roughly 1,500 kilometers west of the Galápagos Islands on the equatorial East Pacific Rise (EPR; Figure 1). This area is particularly conducive to such observations because of its short seismic cycles.

As planned, we arrived on site and placed our instruments on the seafloor in time to record the end of the seismic cycle, including a magnitude 6 main shock earthquake. Here we discuss highlights and lessons learned from our ambitious endeavor to understand this undersea fault.

Why Study Undersea Faults?

For centuries, earthquake scientists have worked to understand the evolution of stress, strength, and material properties in fault zones with enough precision to forecast the magnitude and timing of future earthquakes. The basic hypothesis of seismic cycles is that stress builds up for an extended period over a large portion of a fault and then is released suddenly in a large earthquake. Yet verifying this hypothesis with data—and understanding the many nuances of seismic cycles—remains difficult because typical repeat times of large earthquakes are 50–1,000 years.

Oceanic transform faults on the EPR are ideal targets for investigating variations in seismicity, fault strength, and fluids within the context of well-known earthquake cycles. These faults, across which tectonic blocks shift horizontally past each other, occur at boundaries between tectonic plates—in this case between the Nazca and Pacific plates—and have slip rates up to 4 times faster than that of the San Andreas Fault. They also have much shorter seismic cycles, with earthquakes of approximately magnitude 6 repeating every 5–6 years.

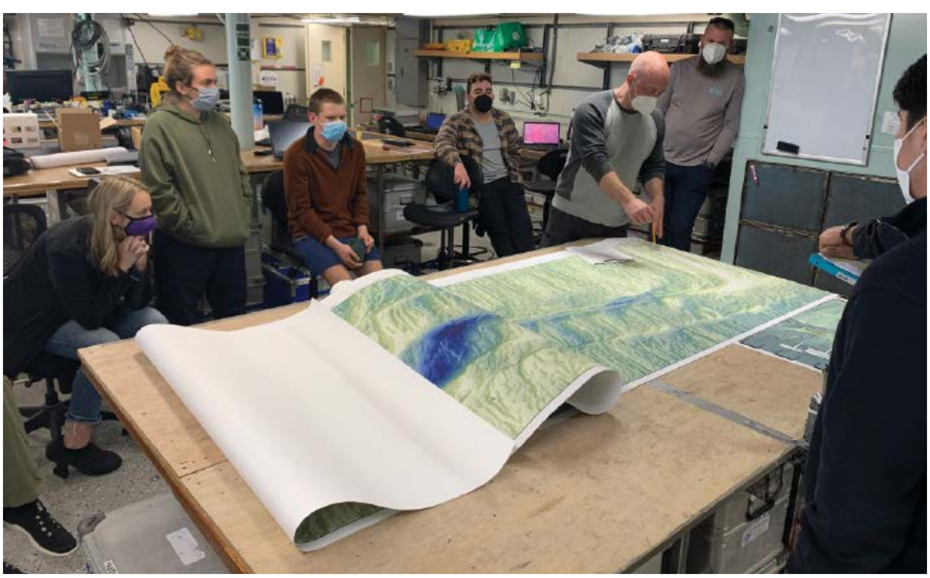
> Oceanic transform faults on the East Pacific Rise are ideal targets for investigating variations in seismicity, fault strength, and fluids within the context of well-known earthquake cycles.

A previous seismic investigation of the Gofar Transform Fault, conducted in 2008, successfully captured the end of an earthquake cycle, including foreshocks, a magnitude 6 main shock, and aftershocks [*McGuire et al.*, 2012]. That experiment prompted new ideas and questions about fault mechanics and earthquake physics.

Possibly the most surprising observation was that long-lived rupture barriers, which separate patches repeatedly struck by magnitude 6 earthquakes, are where small earthquakes (magnitude 5 or lower, with most lower than magnitude 2) occur most frequently on the Gofar Fault. This observation challenged the expectation that rupture barriers, characterized by discontinuities in fault rock composition, damage intensity (i.e., how fractured and permeable the rock is), or fluid content, serve to stop earthquakes of all sizes in their tracks.

From 2019 to 2022, we conducted a new, multidisciplinary field experiment at the Gofar Transform Fault to further illuminate the fault's cyclical behavior and address questions raised by the earlier work. Using the 2008 data set, we knew where and when (within a time window of ~1 year) to place our instruments to record another magnitude 6 earthquake.

Successfully forecasting and recording a large earthquake were great accomplishments for both experiments. Because we had to pivot and adapt our research plans on the fly as a result of COVID-19 pandemic limitations, our recent project boasts the additional major (albeit unexpected) accomplishment of revealing lessons about successfully coordinating multidisciplinary seagoing expeditions that involve remote participation and opportunities to improve the accessibility and inclusivity of such projects.



Team members on the third of three recent expeditions to study the Gofar Transform Fault plan cruise activities aboard R/V Thomas G. Thompson *during the transit to the fault in January 2022. Credit: Paige Koenig*

Many Ways to Watch an Earthquake

Our team of seismologists, geologists, geochemists, and electromagnetic geophysicists included 24 faculty, postdocs, and students from seven institutions in Canada and the United States. We originally designed what was to be a 2-year experiment involving three cruises to capture the end of the earthquake cycle on the western segment of Gofar and to record the temporally and spatially varying fault properties in a rupture barrier. However, by the time the ship schedule for our first cruise was finalized, the anticipated earthquakes on the western segment had already occurred, so we reorganized the seismic and seafloor sampling efforts to span multiple fault segments. This revamped plan provided an opportunity to address questions about the western segment while we also observed a different patch to the east that was expected to host a magnitude 6 event soon.

After departing San Diego in November 2019 on the first cruise of the project, we sailed 4,300 kilometers aboard R/V *Atlantis* to reach Gofar. There, we deployed ocean bottom seismographs (OBSs) by free fall (dropping them overboard to sink freely to the seafloor) to record microseismicity and target the sites of the next expected earthquakes on the eastern segment of the fault. We deployed additional OBSs to study a rupture barrier on the western segment using a challenging new approach that allowed us to position the instruments within roughly 20 meters of planned locations by way of a wireline equipped with an ultrashort-baseline acoustic positioning beacon. These precise wireline deployments were time-consuming (taking 3.5 hours each rather than 30 minutes for a free fall) and challenging because of ocean currents and ship motion. However, they enabled us to position three 10-instrument miniarrays within 1.5 kilometers of each other in the rupture barrier to track the evolution of fault zone rigidity in detail through much of the seismic cycle.

At night during the 25-day cruise, while the team members responsible for the OBSs were sleeping, the dredging team pulled up basketfuls of pillow basalts and basaltic breccias from seafloor transects across the Gofar Fault, providing the first rock samples from the fault and hinting at its permeability structure. These rocks should illuminate whether rupture barriers are characterized by an intense damage zone that allows fluids to penetrate throughout the fault zone, inhibiting large earthquakes [*Roland et al.*, 2012; *Liu et al.*, 2020], or perhaps by mélange-like mixtures of strong mafic protolith and weak hydrothermally altered fault zone materials. With these fault zone samples recovered, we are now assessing the intertwined effects of damage and hydrothermal alteration and their influences on fault slip behavior.

All told, during the three cruises of the project, our team twice deployed 51 OBSs and dredged rock samples from 16 sites, helping to provide a more comprehensive picture of the fault zone's seismic behavior and composition than we've ever had. We also deployed 40 ocean bottom electromagnetic instruments and conducted 14 dives with the autonomous underwater vehicle (AUV) *Sentry*. Measurements of the seafloor's electrical conductivity should provide insights into hydrothermal circulation patterns in the transform fault and whether deeper mechanisms, such as partial melts, drive that circulation. And with *Sentry*, we mapped the fault zone at high resolution (1-meter scale; Figure 2) and investigated key water column properties near the seafloor, providing additional information on the fault's structure and hydrothermal activity.

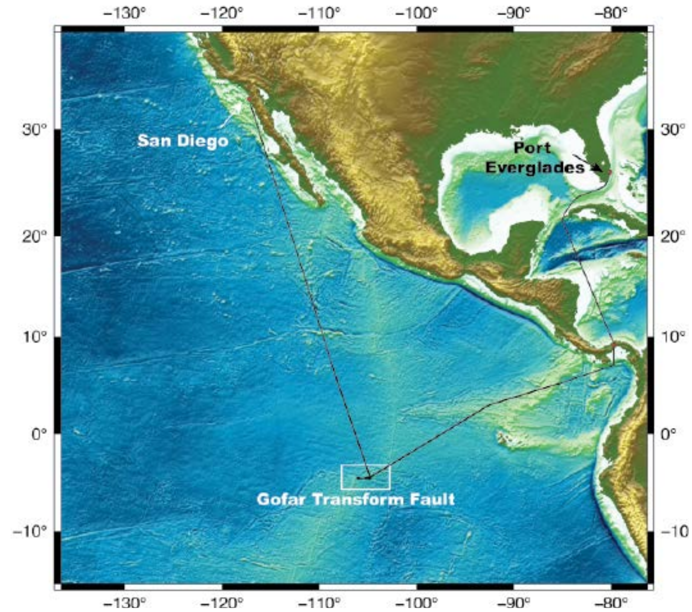


Fig. 1. Cruise tracks are shown here for the second of three cruises to Gofar, which departed San Diego in January 2021, recovered and redeployed ocean bottom seismographs (OBSs) on the fault, and then cruised to Port Everglades, Fla., in March 2021. R/V Thomas G. Thompson *was scheduled for work in the Atlantic following the expedition, hence the route through the Panama Canal. Credit: Emily Roland*

As we flew home from Manzanillo, Mexico, in mid-December 2019 after the first (and what turned out to be the simplest) cruise was complete, we were especially excited that the wireline deployments had worked (a big uncertainty beforehand), and we were looking forward to recovering those data on the next leg of the project. Of course, we didn't realize at the time that for most of us, it would be the last international trip we would take for a while.

Critical Timing and Pandemic Challenges

Four months after our initial OBS deployment, the expected earthquake on the eastern segment of the Gofar—a magnitude 6.1 event—occurred, on 22 March 2020. What we did not predict was how complicated recovering the data would be after the onset of the COVID-19 pandemic.

Batteries powering OBS clocks, which are vital for accurately tracking the timing of seismic data collected, last 12–14 months, and we needed to recover the OBSs before those clocks died. But pandemic-induced restrictions like social distancing required many research departments to operate fully remotely, and it wasn't clear when or even whether we would make it back to sea. Engineers at the Ocean Bottom Seismic Instrument Center (OBSIC) at the Woods Hole Oceanographic Institution in Massachusetts were some of the only specialists working in their labs that spring, preparing instruments for upcoming but uncertain missions.

Gofar is a 10-day steam from the nearest U.S. port, which made the trip a high-risk endeavor during the pandemic, considering the lack of medical facilities on oceanographic research vessels. If someone got sick on board, it would be weeks potentially before we could get them care back on shore. We spent months working closely with ship operators, the National Science Foundation (NSF), and OBSIC to plan (and replan) the cruise safely.

Finally, after spending 2 weeks in quarantine, a greatly reduced crew (the chief scientist was the only scientist on board) set sail in January 2021 (Figure 1), this time on R/V *Thomas G. Thompson* and wearing masks for the first 2 weeks of the 36-day voyage. That group recovered the OBSs and deployed instruments with fresh batteries to continue our experiment's data collection—and thankfully no one fell ill.

During our final cruise in early 2022, we recovered the OBSs again, mapped the fault with *Sentry*, and conducted electromagnetic surveys. This busy cruise, initially planned to last 1 month, doubled in length because of added scientific activities bumped from the second cruise and longer-than-anticipated transit times to and from port. It also set sail with a relatively small science party aboard, which presented a new set of challenges and opportunities.

Instruments deployed to study the Gofar Transform Fault included ocean bottom electromagnetic instruments (left) and the autonomous underwater vehicle (AUV) Sentry *(right). Credit: Thomas Morrow and Paige Koenig*

New Opportunities at Sea and on Shore

Throughout the pandemic, accelerated satellite Internet was commonly added to shipboard infrastructure to facilitate the support of small seagoing science teams by remote participants on shore. However, during our second cruise, it became clear that the skeleton crew at sea had plenty of work to keep them occupied without adding complications of satellite-based data sharing, lengthy email briefings, and coordination between multiple time zones.

To succeed with the complex science activities scheduled for our third cruise, we had to ensure dedicated support for shore-to-sea communications. This meant having at least one at-sea scientist committed to this task. On land, an at-the-ready group of scientists met daily to review incoming data, and a contingent of this group was on call at all hours to communicate, plan, and troubleshoot.

We also assembled a team of 12 seagoing scientists and technicians—diverse in terms of participants' career stages, genders, and backgrounds—to execute cruise activities. At-sea team members included postdocs and students who were able to join the extended cruise in place of scientists scheduled for the original 1-month cruise, many of whom had family and teaching obligations that kept them ashore. The at-sea participants also included three paid research assistants (hired out of an applicant pool of more than 90). This model of paying watch standers may foster inclusion in the geosciences by

The night crew empties a very full dredge basket of basalts and breccias onto the deck of R/V Atlantis *in 2019. Credit: Jessica Warren* improving the accessibility of research cruises to those interested in the field but who cannot otherwise afford to participate.

The new approaches we adopted allowed us to accomplish all the goals of the cruise and at the same time opened opportunities for young scientists to gain experience and minimized disruptions to scientists' lives on land. With at-sea scientists ready to assist with communications and an AUV team that was willing to be agile in the face of short-notice changes and requests, our shore-based scientists planned each 12-hour *Sentry* dive in real time from our offices and living rooms. Emails between ship and shore were sent around the clock during the 30 days on site at Gofar on the third cruise, some sharing complex dive plan details, others with simple updates about the status or events of a dive.

The level of onshore contributions to decisions at sea in this expedition was unprecedented in our experience. Given the success of the cruise, we hope the approaches we used will become more common in the future, increasing access to remote science and allowing those who can't practically go to sea to be involved in seagoing science.

Almost Half of a Seismic Cycle

In total, we recorded an oceanic transform fault earthquake catalog of more than half a million earthquakes of between magnitude 0 and 6.1. This catalog represents about 40% of the seismic cycle on multiple segments of the Gofar Transform

The new approaches we adopted allowed us to accomplish all the goals of the cruise and at the same time opened opportunities for young scientists to gain experience and minimized disruptions to scientists' lives on land.

Fault—equivalent to more than 50 years of recording on many segments of the San Andreas Fault.

With our multidisciplinary data freshly collected, we are now investigating key questions about the 4D variations in stress, strength, and other properties that govern the end of seismic cycles. What are the geological and material properties at locations that repeatedly stop large ruptures but allow intense foreshock sequences to nucleate? Are the intense foreshock sequences in rupture barriers associated with slow slip, transient fluid flow, or regions of pervasive hydrothermal alteration?

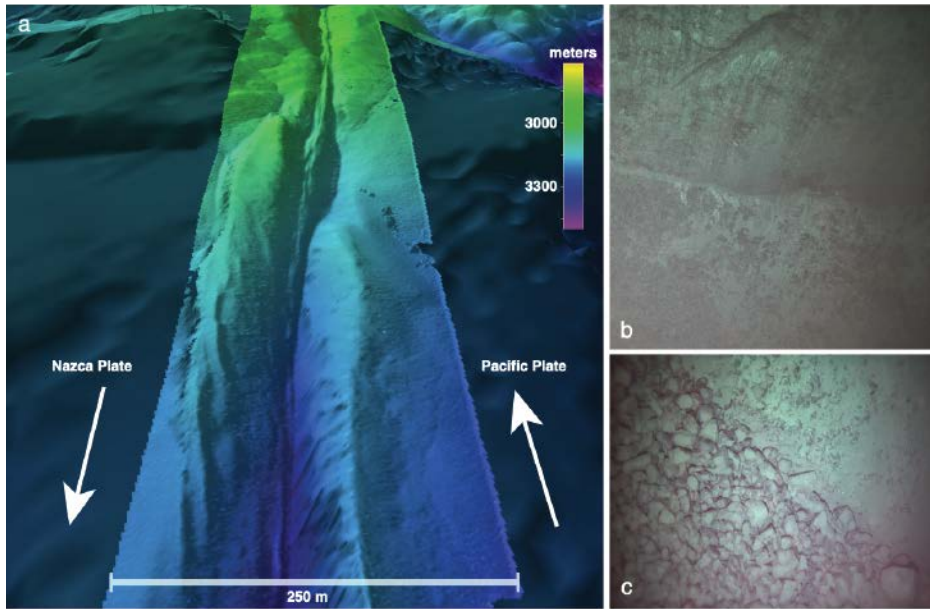


Fig. 2. (a) AUV Sentry *data showing meter-scale bathymetry of a magnitude 6 earthquake rupture zone on the Gofar Transform Fault and (b and c) photos of the base of the plate boundary fault scarp, with the scarp at top right in both photos. Credit: Emily Roland*

More Gofar Transform Fault earthquakes are just around the corner. With this integrated data set, we will be better able to explain how, where, and when these earthquakes will occur.

Acknowledgments

We acknowledge the other principal investigators of this project, including Mark Behn, Wenyuan Fan, Chris German, Yajing Liu, and Jeff McGuire, as well as additional members of the 4CASTGofar team, including Janine Andrys, Chris Armerding, Eric Attias, Melinda Bahruth, Hannah Brewer, Christine Chesley, Kate Enright, Clément Estève, Bailey Fluegel, Andrew Gase, Jianhua Gong, Jae Deok Kim, Paige Koenig, Kuan-Yu Lin, Tianze Liu, Thomas Morrow, Pamela Moyer, Jake Perez, Cécile Prigent, Darin Schwartz, and Emilia Topp-Johnson, whose work is integral to this project. Our experiment wouldn't have been possible without the dedication of the OBSIC, *Sentry*, and electromagnetic teams as well as the crews of the *Atlantis* and *Thomas G. Thompson*. This work is supported by NSF grants OCE-1832830, OCE-1832868, OCE-1833279, OCE- 2128784, and OCE-1922528.

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Author Information

Margaret Boettcher (margaret.boettcher@unh.edu), University of New Hampshire, Durham; **Emily Roland,** Western Washington University, Bellingham; **Jessica Warren,** University of Delaware, Newark; and **Robert Evans** and **John Collins,** Woods Hole Oceanographic Institution, Woods Hole, Mass.

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BAKED CONTACTS FOCUS A LENS ON ANCIENT LAVA FLOWS

By Anthony Pivarunas, Margaret Avery, Joseph Biasi, and Leif Karlstrom

The Grande Ronde River snakes through eastern Washington state amid layers of lava in the Columbia River Basalt Group. Credit: Kevin Schafer/The Image Bank via Getty Images

Two studies conducted 40 years apart show how combining field observations and thermal modeling can reconstruct the history of massive lava flows and how they altered the surrounding landscape.

THE LAVA FLOWS TELL OF CATACLYSMIC EVENTS THAT DRAMATICALLY ALTERED THE REGIONAL LANDSCAPE AND INFLUENCED GLOBAL CLIMATE MILLIONS OF YEARS AGO.

Summertime hikes among the basaltic lavas of inland Cascadia, hundreds of kilometers east of the verdant coastline and snow-capped mountains of the high Cascades, are exercises in heat management. Arid air shimmers above stacked layers of black rock—solidified lava flows—as the hot Sun looms overhead. As you stroll on these rocks in 40°C temperatures, shading your face and anticipating your next sip of water, it can be tempting to imagine you're experiencing something close to what it would have felt like in the distant past when the lava was flowing over the landscape. (Realistically, had you approached this close to flowing basalt, which can reach temperatures of 1,200°C, it would have been a far more intense experience.)

What motivates people to undertake scorching summer expeditions into these lava fields? Apart from the rugged and undeveloped beauty of the landscape, the lava flows tell of cataclysmic events that dramatically altered the regional landscape and influenced global climate millions of years ago. Scientists have been trying to understand these events for more than a century. Indeed, two of us recently set out to collect evidence recorded in these rocks of how heat from the magma that fed the flowing lava altered the existing rock it encountered on its way to the surface. Specifically, we set out to revisit a site where scientists conducted a similar study 40 years ago, applying what is known as the baked contact test to investigate preserved paleomagnetic signatures that can reveal rock's thermal history.

A vertical fin of rock (just right of center), the solidified remains of a dike that fed massive lava flows at Earth's surface in the Miocene epoch, rises from horizontal layers of older Columbia River Basalt Group rock. Credit: Joseph Biasi

History from the Heat Flow

Most of the basalts in the Pacific Northwest are part of the Miocene Columbia River Basalt Group (CRBG). Nearly all of these basalts erupted between about 17 million and 16 million years ago, making it the youngest large igneous province (LIP) in the world and therefore one of the best preserved. The CRBG consists of roughly 210,000 cubic kilometers of lava, or about 10 times the volume of the five Great Lakes combined. Put another way, it would take nearly 400 years for the Mississippi River, which pours about 17,000 cubic meters of water into the Gulf of Mexico every second [*Lafrancois et al.*, 2007], to fill the volume of the CRBG.

This vast expanse of basalt was fed by a series of dike swarms (Figure 1), clusters of vertical conduits where magma cut through preexisting host rock. These conduits sometimes reached the surface and fed lava flows while residual magma solidified in the subsurface. The largest of these clusters was the Chief Joseph dike swarm, located in what's now northeastern Oregon and southeastern Washington. The Chief Joseph swarm was the feeder system for the Grande Ronde Basalt, which is thought to have erupted starting 16.5 million years ago [*Kasbohm and Schoene*, 2018] and makes up roughly 70% of the total volume of the CRBG [*Taubeneck*, 1989].

The CRBG is the best studied flood basalt on Earth, yet many questions about its formation—and the formation of LIPs in general—remain in need of investigation, motivating scientists to keep going back to the rocks. These questions include the following:

- How long did the dike systems take to erupt their massive volumes of lava?
- How long were single dikes active, and how much magma erupted through single dikes?
- Were dikes reactivated, and if so, how many times?
- How much greenhouse gas escaped via the dikes?
- Did the host rock intruded by the dikes experience subsequent tectonic movement?
- Did groundwater affect the dikes and basalts when they flowed or in the millions of years since?

The key to answering these questions, which together reveal how the CRBG formed in fits and spurts and how it affected the environment, is to understand heat—in this case the heat introduced by the intruding dike into surrounding host rock, where it left its mark. This heating process has typically been explored either empirically using paleomagnetic methods, or numerically by modeling heat transport and diffusion through the rock. Considering that each has advantages, why not combine the two approaches?

The Baked Contact Test

In southeastern Washington along the Grande Ronde River, a 14-million-year-old dike is frozen in time, piercing vertically through flat-lying, reversely magnetized exposures of older Grande Ronde Basalt. The 18- to 20-meter-wide Field Springs dike contributed to the voluminous (720-cubic-kilometer) lava flows known as the Umatilla Member, part of the CRBG's youngest formation, the Saddle Mountains Basalt [*Buchan et al.*, 1980]. The dike is well exposed along the river, and there's even an old road tunneled through it that provides additional exposure.

Up a hillslope from the river, an ancient volcanic vent known as Puffer Butte marks the paleosurface where flowing magma from the dike spilled out onto Earth's surface. Comparing the elevations of the Puffer Butte paleosurface and the road tunnel near river level tells us that the tunnel exposes the dike at a paleodepth of 850 meters [*Buchan et al.*, 1980]. In other words, 14 million years ago, the present-day road and river would have been buried under 850 meters of rock.

Exposed as it is along the river and with its excellent paleosurface context, this scenically charismatic dike is an ideal place to apply the baked contact test as a paleogeothermometer, a means of determining the temperature at which an ancient geologic process occurred. The origins of the baked contact test date back to the early 20th-century foundations of paleomagnetic research. Bernard Brunhes, whose name is now lent to our present epoch of "normal" magnetic polarity, proposed to compare the magnetism of an igneous unit with that of adjacent host rock "baked" by the heat of the igneous intrusion to assess the stability of the paleomagnetic direction within the igneous unit [*Brunhes, 1906*]. Nearly 6 decades later, *Everitt and Clegg* [1962] proposed a more complete version of this approach that has survived nearly unmodified to the present day [*Buchan, 2007*].

As any igneous rock unit, such as a dike, is emplaced, it heats the adjacent rock by conduction. Then, as the dike and heated nearby host rock—the baked zone—cool, they both acquire a similar remanent magnetization in alignment with the orientation of Earth's magnetic field at that time and location (Figure 2). The heat conducted fades with distance from the dike, so the host rocks far away from the dike intrusion are unaffected. The distance to this unaffected, or unbaked, zone is usually equivalent to at most the width of the dike itself. At intermediate distances, a hybrid zone exists where thermal overprinting during dike intrusion creates partial remanent magnetization. This remanent magnetization is a distance-dependent mixture of the original host rock's remanence and the remanence of the magnetic field during dike emplacement.

In an ideal scenario, a continuous sampling profile from the dike, through the baked and hybrid zones, and out to unbaked host rock is collected and measured to assess fully the dike's thermal effects. The resulting profile contains both qualitative information (e.g., Was the remanent magnetization at given locations reset by the heat from the nearby dike?) and quantitative information (e.g., At what temperatures were these zones reset?).

Testing the Test

Buchan et al. [1980] reported their analysis of a detailed transect of samples from the Field Springs dike, through the baked zone, and out into the unbaked zone. They found that the magnetization in host rocks 60 centimeters away from the dike had been reset by temperatures of up to 540°C. However, the thermal model they ran suggested that rocks at that distance should have experienced temperatures as high as 614°C. In other words, the host rock at that distance didn't warm as much as it seemingly should

THE COLUMBIA RIVER BASALT GROUP IS THE BEST STUDIED FLOOD BASALT ON EARTH, YET MANY QUESTIONS ABOUT ITS FORMATION REMAIN IN NEED OF INVESTIGATION, MOTIVATING SCIENTISTS TO KEEP GOING BACK TO THE ROCKS.

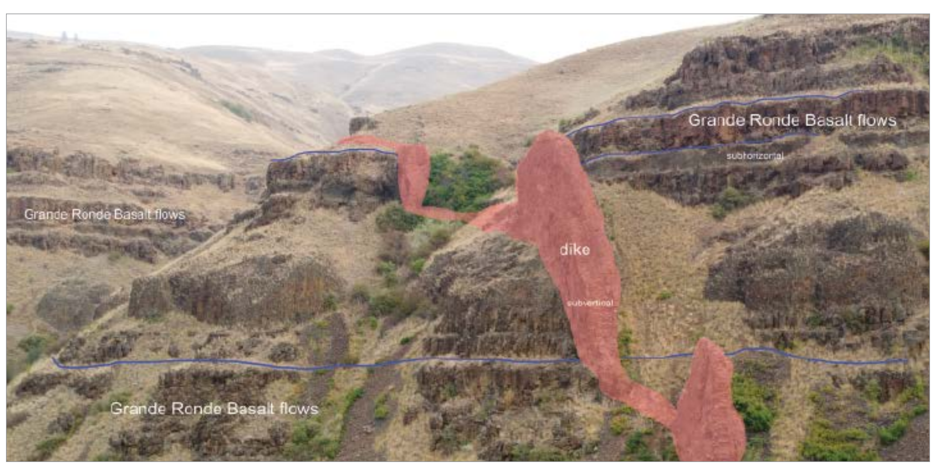

Fig. 1. This annotated photograph shows a geological interpretation of the subvertical feeder dike (red) cutting up through horizontal layers (blue) of the roughly 16-million-year-old Grande Ronde Basalt. Credit: Joseph Biasi

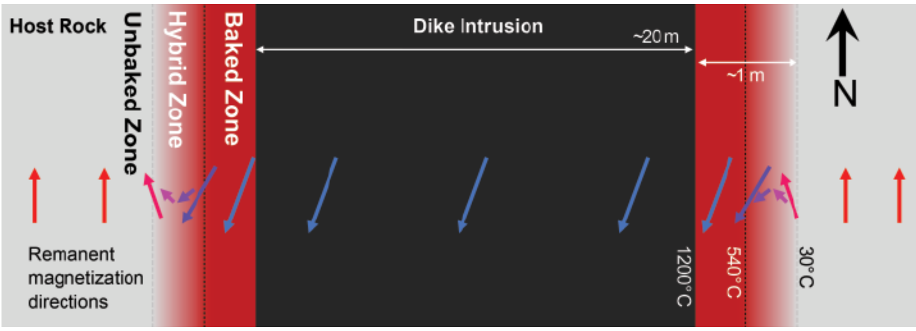

Fig. 2. This generalized illustration shows effects of the intrusion of a vertical dike on paleomagnetic directions (arrows) preserved in the surrounding rock of the baked, hybrid, and unbaked zones. Blue arrows indicate the paleomagnetic direction associated with the dike; red arrows indicate the preexisting paleomagnetic direction of the host rock.

have when the dike formed. Adjusting the determined reset temperature, the thermal model parameters, or both, within reasonable ranges was insufficient to explain this negative temperature anomaly, they found.

Buchan et al. [1980] instead explained the anomaly by suggesting that groundwater 850 meters below the surface could have moved heat away from the dike, thus narrowing the width of the baked zone. This initial work combining empirical paleomagnetic sampling and analysis with numerical modeling therefore provided indirect evidence of a previously unknown 14-million-year-old shallow aquifer.

Since that 1980 publication, the combined paleomagnetic-thermal model approach has been applied rarely [e.g., *Smith et al.*, 1991], despite its broad applicability for studying igneous systems and the valuable insights it may provide. The long-term stability of paleomagnetic information means, for example, that the approach works for studying magmatic systems with a wide range of ages (i.e., million- and billion-year timescales). So, 40 years later, we sought to retest and potentially reinvigorate the approach [*Biasi and Karlstrom*, 2021]. We paired the paleomagnetic baked contact test with a sophisticated thermal model [*Karlstrom et al.*, 2019] applied to multiple CRBG feeder dikes to allow assessment of the length of time that the dikes actively transported magma.

Capturing the timescale of magma transport and emplacement of individual LIP flows—in months to years—appears to be well beyond the ability of standard geochronological techniques such as the uranium-lead or potassium-argon decay systems [*Reiners et al.*, 2018]. However, this timescale is important in assessing the flows' environmental effects, such as atmospheric injections of carbon, sulfur, chlorine, fluorine, and mercury. *Thordarson and Self* [1996], for example, used a prior eruption duration estimate of 10 years for the Roza Member of the CRBG and then assessed how the volatiles released on that eruptive timescale would have affected the atmosphere.

Two of us headed into the field in July 2019 to reexplore the Field Springs dike studied by *Buchan et al.* [1980], also known as the Tunnel dike [*Biasi and Karlstrom*, 2021]. With temperatures soaring to higher than 38°C by 9:00 in the morning some days, we made swimming in the river and eating ice cones essential parts of our field practices.

We sampled two profiles spanning from the dike to the unbaked zone: one at the same outcrop in the tunnel that was studied 40 years ago and another at a higher stratigraphic level. Our analyses, detailed supplementary material about site locations and sampling, and published measurement-level data facilitated comparison of this recent work with that of *Buchan et al.* [1980]. Few detailed baked contact tests have been replicated, and this comparison presented a unique opportunity to assess the technique.

SO HOW DID THE TWO ROUNDS OF RESULTS, SEPARATED BY 40 YEARS, STACK UP?

Volcanic dikes protrude from surrounding horizontal basalts in southeastern Washington State. Credit: Joseph Biasi

And the Verdict Is…

So how did the two rounds of results, separated by 40 years, stack up?

Very well! Although paleomagnetic instruments and techniques have advanced in the past 4 decades, and our interpretation of the new results differed somewhat from that of *Buchan et al.* [1980], the underlying paleomagnetic data proved reproducible. Both studies found that the dike has a northerly, steeply downward pointing paleomagnetic direction (i.e., normal polarity), whereas the basalt flow cut by the dike has a southwesterly, steeply inclined upward direction (i.e., reverse polarity; Figure 3). The reproducibility also holds through the baked and hybrid zones. In both studies, measurements of samples taken in the hybrid zone exactly 60 centimeters away from the dike edge indicated that the rocks reached a maximum temperature of about 540°C.

The interpretations of magnetic resetting of host rocks in the baked and hybrid zones around this dike are similar between the studies. However, the questions the studies sought to address were different. *Buchan et al.* [1980] focused on heating near the contact between the dike and the host rock. They demonstrated with an analytic heat conduction model and scaling arguments that advection of heat by groundwater present at the time of dike intrusion was likely an important control on the width of the baked zone (i.e., the magnetic reset distance).

Biasi and Karlstrom [2021] focused on constraining the duration of magma flow through the dike using a numerical model of heat conduction. By varying the dike lifetime and thermal conductivity parameters in the model, they reproduced their empirical paleomagnetic profile data describing the reset distance. They also found that dikes in the Chief Joseph swarm were active for durations ranging from less than 1 month to several years, suggesting eruption rates of between 1.1 and 7.7 cubic kilometers per day! (Remember the Mississippi River flow rate? Seventeen thousand cubic meters per second equates to about 1.5 cubic kilometers per day.) Because the long-term eruption rate of the CRBG is much lower, these results indicate that LIP eruption activity can be highly concentrated in time.

Together the 1980 and 2021 studies confirmed that the baked contact test is a reliable method for determining a paleomagnetic temperature profile across an igneous intrusion and its contact with the surrounding rock. Such temperature profiles, in turn, can help address important unknowns related to the thermal history, both spatial and temporal, of an igneous system. That these unknowns bear on a wide variety of questions in the Earth sciences—about magma transport, paleohydrology, tectonics, paleoclimate, and more—demonstrates the power and broad applicability of combining paleomagnetism and thermal modeling.

Acknowledgments

Reviews by Scott Bennett, Rick Blakely, and the *Eos* Science Advisers helped to improve this article. Any use of trade, firm, or product names is for descriptive purposes only and does not imply endorsement by the U.S. government.

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Author Information

Anthony Pivarunas (apivarunas@usgs.gov) and **Margaret Avery,** Geology, Minerals, Energy, and Geophysics Science Center, U.S. Geological Survey, Moffett Field, Calif.; **Joseph Biasi,** University of Oregon, Eugene; also at Dartmouth College, Hanover, N.H.; and **Leif Karlstrom,** University of Oregon, Eugene

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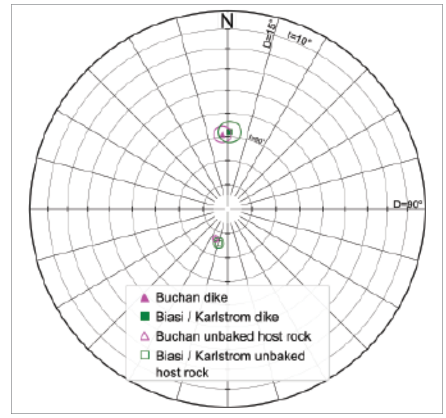


Fig. 3. The agreement between the paleomagnetic directional results reported by Buchan et al. *[1980] and* Biasi and Karlstrom *[2021] from the Field Springs dike is shown in this equal-area, lower-hemisphere stereonet. The symbols indicate the average characteristic remanence directions and their corresponding 95% confidence ellipses for the dike and unbaked host rocks reported by* Buchan et al. *[1980] (pink triangles) and* Biasi and Karlstrom *[2021] (green squares). Closed symbols indicate down inclination, and open symbols indicate up inclination.*

COVID-19 Got You Feeling Under the Weather? Don't Blame the Weather

COVID-19 hit Brazil hard, as evidenced by this COVID ward in a hospital in São Paulo. New research shows that the weather played a minor and inconsistent role in the misery. Credit: Gustavo Basso/Wikimedia, CC BY-SA 4.0 (bit.ly/ccbysa4-0)

Weather has long been known to affect the spread of common colds and flus. Temperature and humidity can influence how viruses fly through the air, how long they remain infectious outside the human body, and how susceptible people are to infections.

Since the onset of the pandemic, researchers have published hundreds of studies testing whether this applies to COVID-19, too, but conclusions have varied—possibly because of short study times, limited meteorological conditions, or oversimplified data analysis. To overcome these shortcomings, *Kerr et al.* studied the spread of COVID-19 in Brazil over 14 months, from July 2020 to August 2021.

Brazil encompasses a vast range of environments, from rain forest to savanna. Combined with the country's decentralized political approach to the pandemic, this meant the researchers could capture disease spread under a wide variety of circumstances.

In general, temperature was inversely correlated with disease spread, the researchers found. Using epidemiological and statistical modeling, they showed that when temperatures dropped into the low 20s (Celsius), the mean number of secondary infections caused by each infected person (R_t) increased by 0.05. Humidity sometimes had an even greater effect, with high humidity increasing R_t by up to 0.1, but the effect was less reliable than that of temperature.

However, the directionality of those relationships flipped depending on the timescale that the team analyzed. For instance, if only data from June to August 2021 are used, COVID-19 transmission increased as temperature increased. Similarly, if only data from March to May 2021 are used, COVID-19 transmission increased as humidity decreased. The time dependence of the relationships could explain the mixed results reported in the existing literature, the authors say.

The influence of the weather on the severity of the pandemic—albeit minor—was more consistent than the influence of lockdowns. R_t sometimes increased when governments attempted to restrict residents' movement, but just as frequently, restrictions had the opposite effect.

Two nonmeteorological factors had an outsize influence over the course of the pandemic. The number of COVID-19 cases an area had experienced in the recent past was a strong predictor of how the pandemic would progress. Surges, for example, tended to be followed by lulls. In addition, other factors had a large effect on the pandemic. For example, so-called random effects are linked with increased disease spread in Brazil's southern and southeastern regions but decreased disease spread in the north, a pattern that correlates with access to health care and social vulnerability.

Although meteorology plays a minor role in the spread of COVID-19, the authors stress that proven mitigative measures like vaccines and other public health measures are more likely to reduce disease transmission. (*GeoHealth*, https://doi.org/10.1029/2022GH000727, 2023) **—Saima May Sidik,** *Science Writer*

Munching Moose Cool Forest Floors

Moose can cool boreal forests, according to a new study. *Salisbury et al.* show that these large grazers expose gaps between trees, revealing a snowy forest floor that reflects light and keeps temperatures down.

Boreal forests are found at high latitudes in North America, Europe, and Asia where temperatures are at or below freezing for at least 6 months of each year. They cover about 17% of Earth's land surface, and their trees sequester carbon, shelter animals, and supply humans with about 25% of our lumber.

After timber harvests, the clear-cut trees grow back, and herbivorous moose make meals out of new growth. As the forests' largest herbivores, moose help determine, by way of the plants they eat and trample, how forests recover—and where the carbon goes.

In the new study, over the course of a decade, researchers tracked how clear-cut forest sites throughout Norway grew back when moose both could and could not access them. They measured how moose change the structure, composition, carbon emissions, and albedo of boreal forests that have been clear-cut.

Sites with moose grew back more sparsely than sites that excluded them. Sparse trees resulted in a thinner canopy, which allowed sunlight to reach the forest floor. The overall reflectivity of a thin canopy and a bright forest floor is higher than that of a dense canopy, especially when snow coats the ground. That bounces sunlight back to space and cools the forest for several years after clear-cutting. The effect fades over time, as the forest canopy grows denser and darker.

Clearing trees affects carbon storage, too, and that might not be great news. The moose consume a lot of plant biomass, which removes carbon from vegetation and cycles it back through soil and feces. The researchers estimate that for sites with high moose density (about one moose per square kilometer), carbon emissions and lost carbon storage from moose activity accounted for 40% of regional carbon emissions. Still, the cooling effect from increased albedo offsets about two thirds of the warming the emissions would cause, the researchers found.

The findings, the authors say, will help forest managers regulate moose species after timber harvests, control forest growth, and ultimately minimize emissions and warming from forested regions. (*Journal of Geophysical Research: Biogeosciences*, https://doi.org/10.1029/2022JG007279, 2023) **—Rebecca Dzombak,** *Science Writer*

Moose prefer munching the thin branches and nutritious leaves of deciduous trees, but acidic pine will do in a pinch. Credit: Bryan Rodriguez, Unsplash

U.S. Public Water Supply Is a Local Source of Phosphorus Pollution

In the United States, public water systems are sometimes dosed with phosphate to reduce copper levels and lead pipe corrosion. This practice can help avert humanitarian disasters like the Flint water crisis in Michigan, but because phosphorus can contribute to eutrophication, it could harm local aquatic ecosystems. For example, phosphorus that enters the environment when pipes leak or people water their lawns may find its way into rivers, lakes, and groundwater. Exactly how much phosphorus enters the environment from the public water supply, though, is unknown, making it difficult to address this source of pollution.

Flint et al. estimate for the first time how much phosphorus enters the environment from the U.S. public water supply. Using data from 2015, the team analyzed phosphate dosing concentrations, data from public water system facilities, the volume of water supplied by these facilities, and estimates of how much water is lost because of leakage and outdoor water use.

They found that about 3% of public water systems in the United States dosed their water with phosphate in 2015. Because larger systems were more likely to use phosphate, about a quarter of the U.S. population received dosed water. The practice was more common in the Midwest and the East, where many counties retain legacy lead piping.

About 5%–17% of dosed water leaked out of water mains, and 5%–21% was used outdoors. Even at the lower end of these estimates, in some counties the phosphorus that entered the environment from the water supply could exceed phosphorus coming from point sources like wastewater treatment plants or diffuse sources such as agricultural fertilizer use.

The public water supply typically isn't included in phosphorus source apportionment studies, and the authors hope their new findings can help policymakers develop more effective phosphorus management strategies. (*Global Biogeochemical Cycles*, https://doi.org/10.1029/2022GB007614, 2023) **—Rachel Fritts,** *Science Writer*

Scientists Just Measured a Debris Flow in Unprecedented Detail

Scientists measured a debris flow at the Illgraben Debris-Flow Monitoring Station in Switzerland. Credit: Sphoo/Wikimedia Commons, CC BY-SA 4.0 (bit.ly/ccbysa4-0)

Debris flows are fast-moving and highly variable mixtures of soil, rock, water, and trees that can wreak havoc on downslope communities. In these flows, small debris lags behind larger particles, but it is not clear how this sorting occurs and what that means for the hazards nearby communities might face.

In a new paper, *Aaron et al.* measured a debris flow using 3D time-lapse lidar sensors that were originally developed for autonomous vehicles. Their sensors scanned the debris flow surface 10 times per second for the entire 30-minute event. Using these detailed measurements at an unprecedented spatial and temporal resolution, they determined the velocities of the debris flow throughout the event.

The team went to the Swiss Federal Institute for Forest, Snow and Landscape Research's Illgraben Debris-Flow Monitoring Station in Switzerland. The site is a hot spot for debris flows. Since the station opened in 2000, there have been 2–10 events each year, including the 2016 Illgraben debris flow, which was caught on video.

For this study, the team focused on an event that occurred on 19 September 2021. Soon after the debris flow reached the monitoring station, there was a spike in flow velocity. Before this velocity spike, large boulders and woody debris tended to move at similar velocities. However, after the spike, boulders moved about 60%–70% slower than the woody debris.

The researchers found that the flow was highly nonuniform and unsteady. The velocity at the front of the flow ranged from about 0.8 to 2 meters per second. These front velocities were 1.2–2 times slower than the velocities of trailing material behind the flow front. Once boulders reached the leading edge, though, instead of being recirculated, they decelerated and remained a part of the flow front.

The detailed survey gave the researchers a fine-scale view of how debris flows move and how their constituent particles separate. These findings, they note, could help scientists assess and manage geohazard risks. (*Geophysical Research Letters*, https://doi.org/10.1029/2022GL102373, 2023) **—Sarah Derouin,** *Science Writer*

Rougher Faults May Generate More Earthquake Aftershocks

When an earthquake hits, it is rarely an isolated event. Foreshocks precede quakes, and aftershocks follow them. To quantify seismic hazards, scientists must disentangle the factors that contribute to these shaking sequences.

In recent years, advancements in laboratory methods have enabled deeper exploration of earthquake dynamics. Now, *Goebel et al*. present new lab findings highlighting how the roughness of the rocks sliding past each other in a fault zone may influence aftershocks.

The researchers created fractures of varying roughness in several granite cylinders ranging from 40 to 50 millimeters in diameter. Then they applied pressure to the fractured granite to simulate sliding motions along a fault. They measured the resulting seismic disturbances in high resolution in the form of acoustic emission wave measurements. The result was a realistic and manipulable simulation of actual earthquakes: Spacing and timing of the main slips, foreshocks, and aftershocks in the granite cylinders resembled those of real-world Southern California earthquakes.

New lab work suggests that rock roughness affects earthquake aftershock dynamics along faults. Credit: Dextersinister/Wikimedia Commons, CC BY-SA 4.0 (bit.ly/ccbysa4-0)

The researchers found that after a major slip along a fracture—analogous to a main earthquake along a fault—the granite cylinders underwent periods of relaxation of built-up stress as well as aftershocks. Fractures with greater roughness moved less along the fracture during the main slip event but had more aftershocks; smoother fractures had more slip but fewer aftershocks.

These findings suggest that in nature, fault surface roughness may play a key role in the production of aftershocks following a main earthquake event. (*Geophysical Research Letters*, https://doi.org/10.1029/2022GL101241, 2023) **—Sarah Stanley,** *Science Writer*

Do Volcanoes Add More Carbon Than They Take Away?

In a new study, *Zhong et al*. discovered that a volcano in northeastern China emits a small net amount of carbon each year. Over geological timescales, that could have a significant impact on our planet's carbon cycle.

Volcanic areas continue to emit carbon dioxide long after eruptions are over. Conversely, atmospheric carbon dioxide (CO_2) is constantly locked away into minerals on Earth's surface through a process called silicate weathering. Whether volcanoes release more CO_2 through degassing or capture more CO_2 through silicate weathering is an open question.

The authors of the new study investigated whether the Changbaishan volcanic area in northeast China is a net source or sink of atmospheric carbon. The region has been active for at least 2.7 million years, but it has not erupted since 1903, making it a prime spot for analyzing long-term carbon leakage.

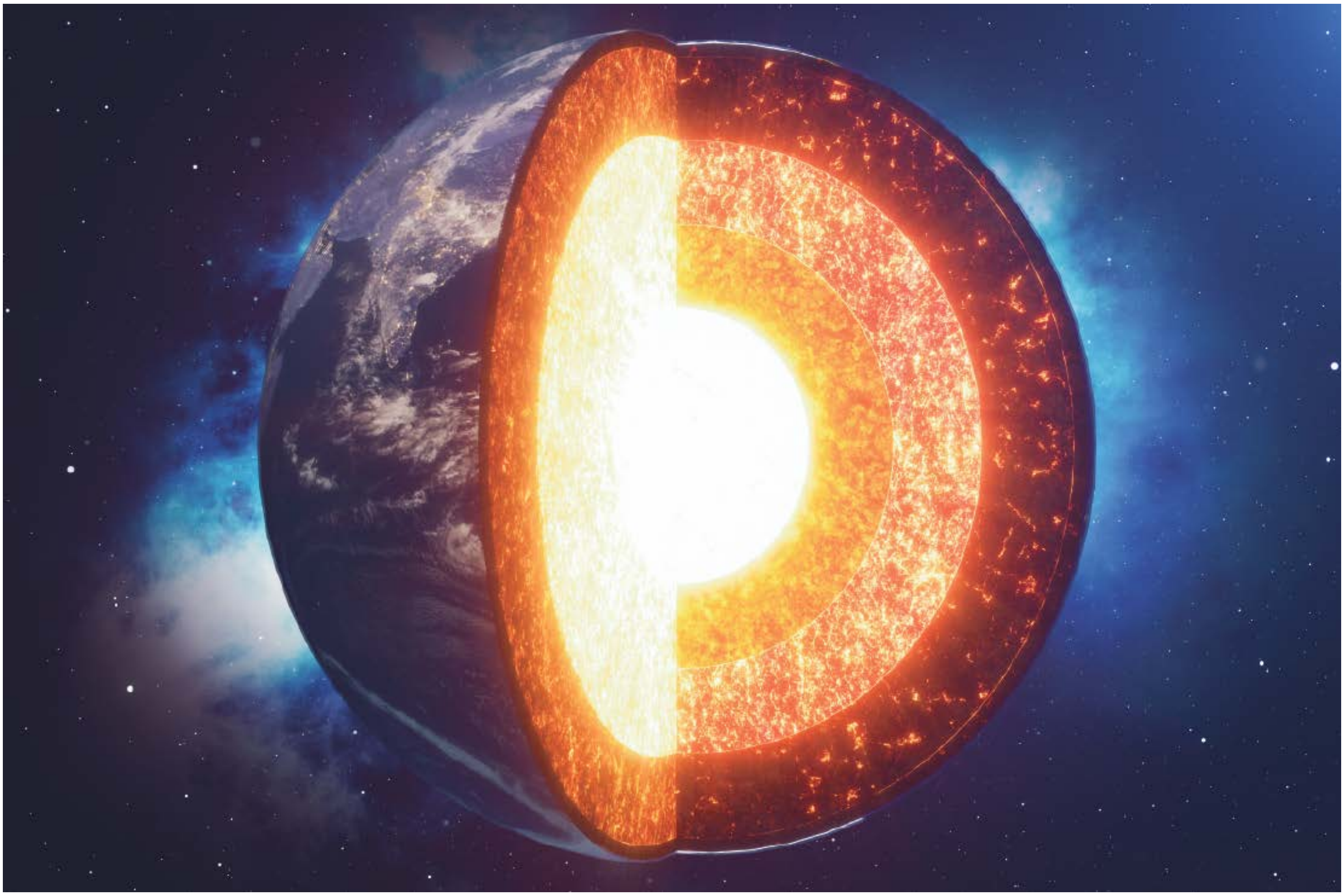
Over the course of two field seasons, in 2019 and 2020, the study authors scoured the Changbaishan region for rivers and streams. They collected water samples from around two dozen sites and used radiocarbon dating to estimate the amount of "deep carbon," meaning carbon from the depths of Earth, that had seeped into the water. They compared deep carbon estimates to estimates of carbon incorporated into minerals through silicate weathering.

The researchers found that the Changbaishan region is a small net carbon source. Every year, the region releases at least 600 more tons of carbon than it incorporates—about the amount that 41 average Americans put into the atmosphere on an annual basis. That seems small, but over geological timescales, the impact could be significant.

Changbaishan is just one of many volcanic regions around the world, the researchers point out. Future work should examine wider areas to gain a full understanding of how volcanoes contribute to Earth's carbon cycle. (*Journal of Geophysical Research: Biogeosciences*, https://doi.org/10.1029/2023JG007435, 2023) **—Saima May Sidik,** *Science Writer*

The Julong hot springs in the Changbaishan volcanic region release heat and carbon into the atmosphere. Credit: Si-Liang Li

Iron Is at the Core of This Earth Science Debate



A new study explored the structure of iron at Earth's inner core, shown in yellow and white in this illustration. Credit: iStock.com/Rost-9D

Earth's inner core is dominated by iron, which can exist as a solid material in more than one crystallographic form. (This quality allows iron to combine with other elements to form alloys.) Iron's most stable form at room temperature is the body-centered cubic (bcc) structure. At extremely high pressures, it is stable in its hexagonal close-packed (hcp) phase. Of considerable debate, however, is iron's structure at the center of Earth. In a new study, *Sun et al.* get one step closer to an answer.

The deliberation centers on the melting temperatures of iron's two phases at core pressures: 323 gigapascals at the inner core boundary and 360 gigapascals at the core center. Previous studies have struggled to estimate melting temperatures with any precision. The best guesses have had an uncertainty range of 500 kelvins.

Researchers use two types of simulations of atomic interaction to estimate iron's melting temperatures at the inner core: classical and ab initio. Both approaches have pros and cons, but neither has yet provided a clear answer. In the new study, scientists bridged the two simulation strategies to calculate the melting temperatures for hcp and bcc iron at Earth's core.

They found that iron's hcp phase is stable at the inner core. The melting temperature of hcp iron is always higher than that of the bcc form, but that difference is very small. At pressures approximating the inner core boundary, the study reports a melting temperature of 6,357 ± 45 kelvins for the hcp phase and 6,168 ± 80 kelvins for the bcc phase. At pressures similar to the core center, the melting temperature was 6,692 ± 45 kelvins for hcp and 6,519 ± 80 kelvins for bcc.

The research offers new perspectives on the structure, evolution, and dynamics of Earth's core. Future work, the scientists say, should include the effect of nickel and light elements in simulations of the inner core's structure. (*Geophysical Research Letters*, https://doi.org/10.1029/2022GL102447, 2023) **—Aaron Sidder,** *Science Writer*

Dear AGU:

Last summer, I went on a field trip to Iceland and the Faroe Islands to study wildlife and make field sketches.

In the photo, I was working at Eyjafjörður, in the north of Iceland. From this vantage point, we had great views of the fjord, where we hoped to see whales. While we were waiting for the whales, pods of white-beaked dolphins splashed by, a gryfalcon and a merlin flew by, and we were surrounded by some curious Icelandic sheep.

As a scientific illustrator, I try to capture the essence of birds in my work. I believe it's possible only after having studied them in the field. Here, I was finishing some sketches of long-tailed ducks I had seen earlier in the day.

—**Joris De Raedt,** Scientific Illustrator

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