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Eos

SCIENCE NEWS BY AGU

Gardening in Moon Soil

Utah Rocks

Hot Springs Clues in Tibet

FIELD TRIP

Some researchers trek along active fault lines, others launch drones into Category 4 hurricanes. Either way, it's time for an adventure.

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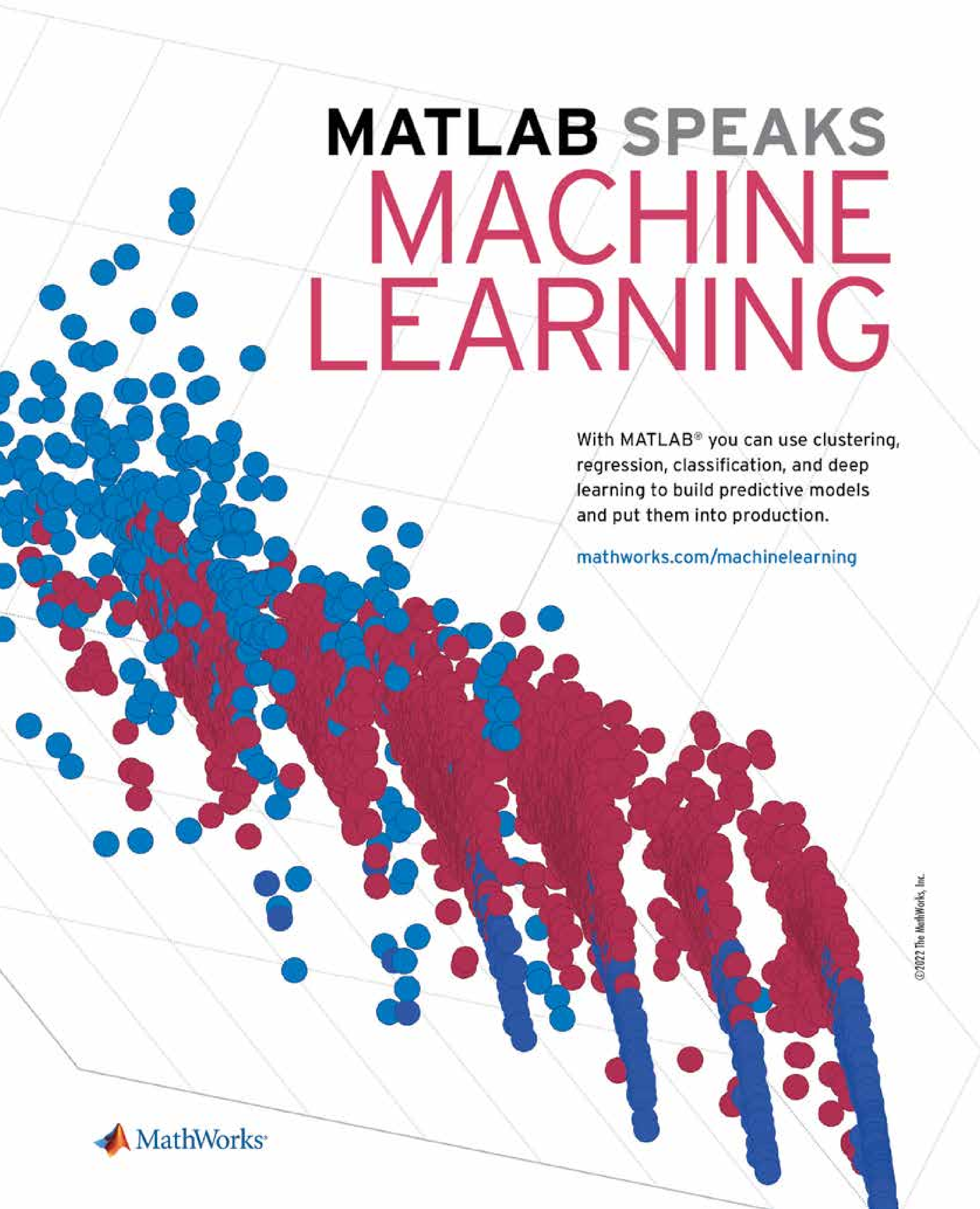
AND SPACE SCIENCE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Adventure Time

Every issue of *Eos* is for you, the explorer. Whether you're strapping into a helicopter to fly over a volcano, sifting through data to find patterns, or reading through the latest science news, you're dedicated to seeking the new and wonderous.

Our July issue is all about that urge to set out on a voyage of discovery. Of course, that isn't always possible to do in person, but Earth and space scientists are innovators when it comes to bringing the world to our doorstep. In "An Unprecedented View Inside a Hurricane," Gregory R. Foltz and colleagues write about their clever use of technology to get an incredible view from inside a category 4 storm: Turn to page 22 to read about this partnership with NOAA to develop the saildrone that spent days surfing four-story-high waves inside Hurricane Sam—and how the scientists will use the data they collected to improve hurricane intensity forecasts.

Then we follow a class of students in their first trek into the field. An international team set out to deploy a seismic network in Sumatra, Indonesia, to learn more about the Sunda subduction zone, the source of devastating hazards in the region. Karen Lythgoe and her colleagues from the Earth Observatory of Singapore and Universitas Syiah Kuala write about their work in "Striking Out into the Field to Track Slip on the Sumatran Fault."

They recruited a team of students from their institutions—two of whom, Dian Darisma (left) and Wiwik Ayu Ningsih, are featured on this month's cover—to get their hands dirty placing seismic nodes into the ground all around the Aceh region. Turn to page 30 to read about how they approached the many challenges of this type of fieldwork, from explaining their research to local police and village leaders (who often did not speak the same language) to leeches and tree cover that obstructed GPS signals to a pandemic and the perils of leaving instruments unattended for an extended period of time.

Next, let's take our seismometers and head somewhere cooler: Greenland. Evgeny A. Podolskiy writes about deploying seafloor instruments near a calving glacier front in "Arctic Unicorns and the Secret Sounds of a Glacial Fjord" on page 36. Glaciological processes can be difficult to study, largely because deploying instruments close enough to monitor them is dangerous work. Read on to learn about how Podolskiy's team at the Arctic Research Center in Hokkaido, Japan, managed to get their instrument to the bottom of Bowdoin Fjord, how their hard work was saved by an Inuit whale hunter, and what their seismic data also told them about the notoriously reticent local wildlife—narwals.

Finally, don't put down the issue before reading the Opinion on page 19 by Marjorie Cantine. "Playing it Safe in the Field" is an essential chapter in this issue dedicated to fieldwork. Going out to have incredible, life-changing adventures and keeping yourself and your colleagues safe should not be mutually exclusive pursuits. Cantine is leading one of a few efforts to better understand—and thus be able to prepare for—dangers in the field.

Once you have your adventures in the field and the lab and everywhere in between, remember to come back and tell us about them. Begin telling your tales of how science really gets done at eos.org/submit.

Heather Goss, Editor in Chief

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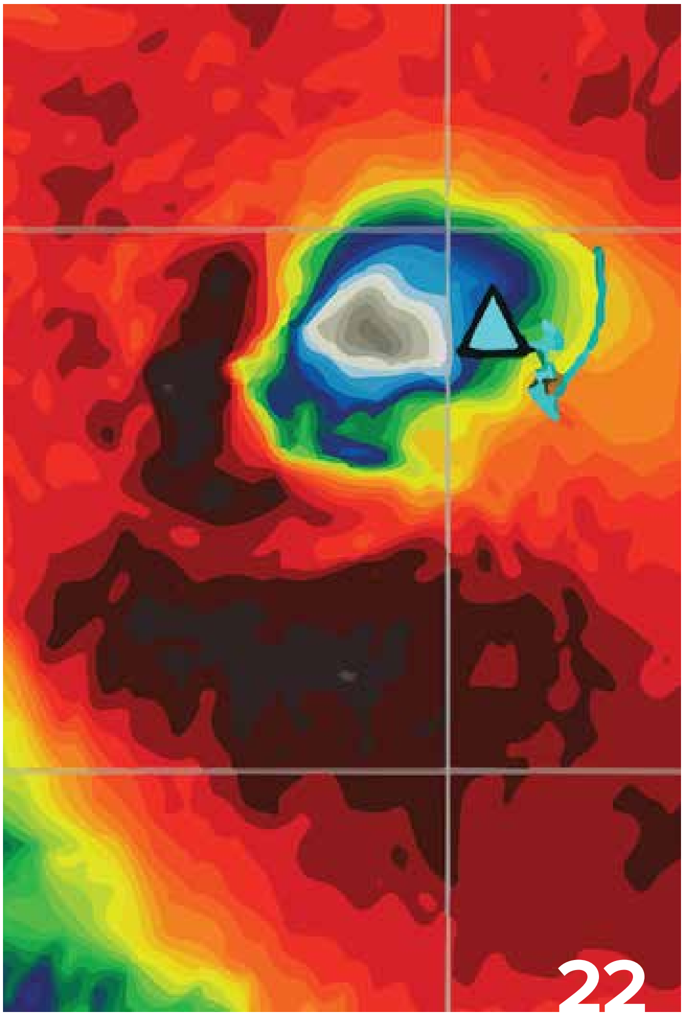
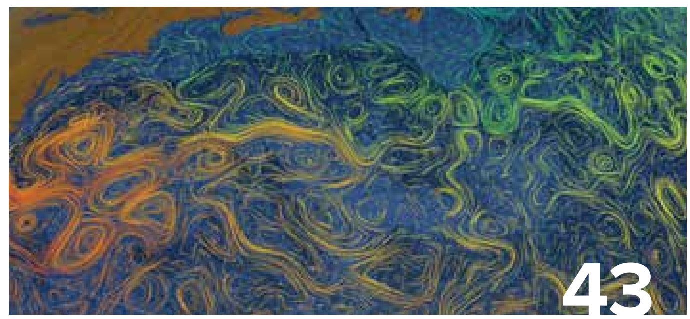


Features

On the Cover

Universitas Syiah Kuala students Dian Darisma (left) and Wiwik Ayu Ningsih deploy a seismic node near the village of Mane in Aceh, Indonesia. Credit: Karen Lythgoe



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Lunar Soil Can Grow Plants

Lunar regolith is capable of growing greenery, but plants grown in younger lunar soil were less stressed than plants grown in more mature soil. These experiments were the first attempts to grow plants in actual lunar regolith rather than soil simulant. The results, which were published in *Communications Biology*, are a critical step in understanding how future long-term residents of the Moon may be able to produce their own food and oxygen through lunar agriculture (bit.ly/lunar-soil-plants).

This Arabidopsis *plant was grown in lunar soil for about 2 weeks. Credit: Tyler Jones, UF/IFAS*

"It's really good news that plants can grow in the lunar soils," said coauthor Robert Ferl, a space biologist at the University of Florida (UF) in Gainesville, during a press briefing. The challenges that the plants experienced showed that "there is some very interesting biology, lunar biology, lunar biological chemistry, that's yet to be learned. But the bottom line is that until it was actually done, nobody knew whether plants, especially plant roots, would be able to interact with very sharp, very antagonistic soils that the lunar regolith presents."

"It's really good news that plants can grow in the lunar soils."

The Moon Is Stressful

The researchers sowed *Arabidopsis thaliana* (thale cress) seeds in small quantities of regolith preserved from the Apollo 11, Apollo 12, and Apollo 17 landing sites, as well as in lunar soil simulant. *Arabidopsis* plants, which are related to mustards, cauliflower, broccoli, kale, and turnips, have been grown in a wide variety of soils and environments, including in space.

"It is edible, but it's not especially tasty," said lead author and plant biologist Anna-Lisa Paul of UF. "We learn a lot that can be translated into crop plants from looking at *Arabidopsis*." Moreover, *Arabidopsis* plants are small and have a growth cycle of about a month, which is ideal when trying to grow them in about a teaspoon's worth of lunar regolith.

The researchers found that all three lunar soils were capable of growing plants, but with some difficulty. Compared with the control samples grown in lunar simulant soil, plants grown in actual lunar regolith had more stunted root systems, slower growth, and less extensive leaf canopies. They also exhibited stress responses like deeper green or purple leaf pigmentation. Although all of the plants grown in lunar soil were stressed, some were more stressed than others. Those grown in Apollo 11 regolith were the most stressed, and those in the Apollo 17 regolith were the least stressed.

Although Apollo 11, 12, and 17 all landed in basaltic mare regions of the Moon, the sites exhibited some key differences. Regolith at the Apollo 11 site is considered to be the most mature soil of the three. The site has been exposed to the lunar surface the longest, which has led to the soil being weathered by the solar wind, cosmic rays, and micrometeorite impacts. These maturation processes can alter the chemistry, granularity, and glass content of the regolith. The other two sites have also been "matured" by these processes but to lesser extents, Apollo 17 least of all.

The team performed gene analysis on the plants after 20 days of growth and found that the regolith-grown plants showed stress responses related to salt, metals, and reactive oxygen species. Those results suggested that much of the plants' difficulty was related to the chemical differences between lunar regolith and lunar soil simulant, such as the oxidation state of iron—lunar iron tends to be in an ionized metallic state, whereas simulant and Earth soils tend to contain iron oxides that are easier for plants to access. Ionized iron results from interactions with the solar wind, which explains why the most mature soil, that from Apollo 11, grew the most stressed plants.

"The simulants are incredibly useful for, say, engineering purposes.... They're wonderful for determining whether or not your rover is going to get stopped in the soil," said coauthor Stephen Elardo, a planetary geochemist at UF. "But when you get down to the chemistry that's accessed by plants, they're not really one to one. The devil is in the details, and in the end the plants are concerned about the details."

"The devil is in the details, and in the end the plants are concerned about the details."

Choose Your Resources Wisely

These results show that lunar regolith is capable of supporting the growth of plants, which will be an integral component of any long-term lunar habitat. Plants will be able

Anna-Lisa Paul harvests plants for genetic analysis. Credit: Tyler Jones, UF/IFAS

to support key functions like water recycling; carbon dioxide removal; and oxygen, food, and nutrient production.

"It's a well-organized and thought-out experiment to test growing plants in actual lunar regolith returned from the Apollo 11, 12, and 17 missions," said Edward Guinan, an astronomer at Villanova University in Pennsylvania who has conducted plant experiments in Moon and Mars soil simulants. "As the authors point out, the test plants are stressed and don't grow well. The plants have characteristics of plants grown in salty or metal-rich soils. Maybe trying different terrestrial plants that do well in poor or salty soils might be an interesting follow-up." Guinan was not involved in this research.

This study also shows that although plants can be grown using in situ lunar resources, where those resources come from will be important for the plants' growth success.

Regardless of where future lunar explorers build a habitat, "we can choose where we mine materials to use as a substrate for growth habitats," Paul said. "It's where the materials are mined from that makes a difference, not where the habitat exists."

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

Million or Billion? Narrowing Down the Age of Mantle Processes

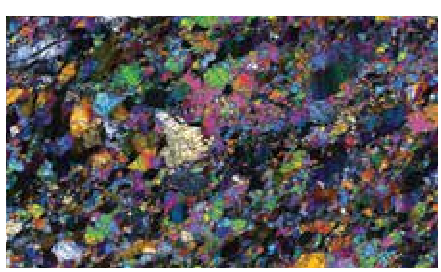
As tectonic plates jostle one another, collisions can cause the bottom of the ocean to end up on land. Formerly underwater sequences of oceanic crust and mantle, called ophiolites, help geologists not only to disentangle the history of how these rocks went skyward but also to discern past exploits of Earth's mantle.

In a recent study published in the *Journal of Petrology* led by Natasha Barrett while she was a doctoral student at the University of Alberta, Barrett and her team examined samples from jungle-encased ophiolites collected more than 40 years ago from Papua New Guinea, an island nation just north of Australia (bit.ly/ophiolites-guinea).

The spreading center that produced these ophiolites was likely erupting basalt seafloor about 70–55 million years ago—around the time the dinosaurs died. However, scientists suspected that the ophiolites's lowermost mantle rocks, which have strange geochemical signatures, must have come from mantle that melted eons before, likely during the Archean, between 4 billion and 2.5 billion years ago (when life was restricted to single-celled organisms). Barrett and her team demonstrated that the ophiolites' lowermost mantle is instead much younger and proposed that it melted in a modern subduction zone setting, forcing petrologists to rethink how these geochemical signatures developed.

Leftovers

Some scientists think that before the dinosaurs' demise, oceanic lithosphere hanging off the northern edge of Australia plunged into the mantle, producing a trench and spreading center on the seafloor where new oceanic crust erupted. Past the proposed spreading center may have been yet another subduction zone accommodating the disappearance of the Pacific plate into the mantle, with a string of volcanoes poking above the water. Eventually, these disparate pieces of Earth's surface—northern Australian fragment, spreading center, and volcanic island arc—collided, with the remnants of these events preserved in parts of New Guinea.



Scientists analyzed peridotites like this, from ophiolite in Papua New Guinea, to better understand the complex geology of the region. Credit: Natasha Barrett

"In the Archean, the mantle was hotter, so you expect to have more melting."

Today, New Guinea—an island split between the countries of Indonesia and Papua New Guinea—peers above various Pacific seas. This scrap of mostly continental crust, which connects to Australia when sea level decreases, hides those ophiolites below its lush vegetation.

Unique Ophiolites

If intrepid geologists came upon a complete ophiolite, they would walk through seafloor sediments, lavas and intrusive igneous rocks of the crust, and mantle rocks called peridotites that are rich in the greenish mineral olivine. Barrett compared the lowest layer of mantle peridotite, which is what was left over after the mantle melted, to a squeezed sponge, bereft of its water (the melt, in this analogy). It is these rocks—equivalent to the wrung-out sponge—that scientists expected to be billions of years old.

In New Guinea's ophiolites, the leftover, lowermost peridotites are unique in two ways. First, they're especially refractory, which means they're filled with elements, particularly magnesium, that don't like to be in melts, said Marguerite Godard, a mantle petrologist at the French National Centre for Scientific Research who is hosted at the Université de Montpellier. Godard was not involved with this study.

Second, these rocks lack many elements already in low abundances in the mantle; these trace elements strongly prefer the melt, depleting the residue. "Highly refractory [and depleted] mantle means a lot of melting,"

A river threads its way through the green hills of Papua New Guinea. Credit: Alan & Flora Botting/Flickr, CC BY-SA 2.0 (bit.ly/ccbysa2-0)

Godard said. To get lots of melting, scientists surmised that mantle temperature must have been high. "In the Archean, the mantle was hotter, so you expect to have more melting," said Godard. "That's why we expect—in the Archean—to have refractory rocks," she explained. "Nowadays, the mantle is not so hot."

Recent data from ophiolites near New Guinea, like those on the islands of New Caledonia and New Zealand, contain similarly curious geochemical signatures, said Godard. One possible explanation for the Oceania-wide pattern posits that mantle in this region melted billions of years ago.

Mantle Mystery

To figure out just when the mantle melted (leaving behind the residual rocks in her study), Barrett turned to the rhenium-osmium geochronologic system. Radioactive rhenium decays to osmium. Rhenium strongly prefers the melt, whereas osmium stays behind. Once the rhenium goes away via the melt, the residual rock's osmium signature is locked in. That signature corresponds to the age at which the melt parted ways with the peridotite in question.

The osmium signatures Barrett found are much higher than those observed in Archean peridotites, which have similarly weird geochemistry. On the basis of these data, the melt extraction ages of the rocks in her study are not Archean, she said. Instead, the mantle below New Guinea melted sometime in the recent past, although being more specific than the Phanerozoic isn't possible without additional study, she added.

The melt extraction ages are definitely not Archean.

Because the melt extraction happened when the mantle was no longer as hot as it was during the Archean, "you have to find a mechanism" to so immensely deplete the residual peridotites, said Godard. Barrett and her colleagues proposed that this complicated subduction zone setting created these bizarre geochemical signatures in two stages. The first stage involved melting. The second involved multiple processes in which more melting was aided by water, basalt from deeper below, or something else liberated from the subducting slab underneath the spreading center. Like adding salt to ice in the winter to lower its melting point, these additions to the mantle above the subducting slab would facilitate the second stage of melting.

"They are definitely the most refractory and depleted peridotites I have ever, ever seen," said Godard, referencing that these rocks are not well studied in part because they're difficult to get to. "The mystery is why," she said. Barrett's proposed second stage of melting, she explained, "is extremely important in the system to produce those very refractory…and depleted compositions."

By **Alka Tripathy-Lang** (@DrAlkaTrip), Science Writer

Wildfire, Drought, and Insects Threaten Forests in the United States

Wildfires like the Monument Fire, which burned in Trinity, Calif., in August 2021, may be aggravated by forest management practices. Credit: CalTrans

Wildfire risk to forests across the United States is set to increase by a factor of 4, and tree mortality caused by other climate-induced factors like drought, heat, disease, and insects is set to at least double by 2099, new research shows.

"Forests in the western half of the U.S. have the highest vulnerability to each of these risks," said William Anderegg, an associate professor at the University of Utah and lead author of the paper, which was published in *Ecology Letters* (bit.ly/increase-wildfire-risk).

But risks are not confined to the West. There are wildfire risks in Florida and Georgia, as well as in parts of Oklahoma and Texas, and insect and drought risks in the northern Great Lakes states.

Anderegg explained that researchers modeled burned areas depicted by satellite imagery and used forest inventory data to ascertain other climate risks like drought, heat, disease, and insect-driven tree mortality.

The paper provides insights for improving forest conservation practices and underscores an urgent need to reduce emissions to mitigate the impacts of climate change, Anderegg said. More specifically, it highlights design and assessment flaws in climate policies like forest carbon offsets. Anderegg and the other authors question the integrity of offset projects and call for "rigorous forest climate risk assessment" for policies and programs that rely on the potential of forests to store carbon.

Reworking Forest Offset Designs

Forest offset protocols account for risks like wildfire with buffer pools—unharvested woodlands set aside to compensate for carbon losses. But, Anderegg said, such buffer pools do not account for geographical heterogeneity, like wildfire risks in California being significantly higher than those in Maine, or the fact that risks like wildfire are likely set to increase owing to climate change.

Another technique the scientific community often suggests is controlled burning. But there's a problem: Many of the forests, especially those in the West, are part of forest offset projects in California's cap-and-trade program. What this means, in essence, is that owners and managers of these forests are incentivized not to burn because carbon credits are dependent on the amount of carbon these forests can hold.

Bodie Cabiyo, a graduate research fellow in the Energy and Resources Group at the University of California, Berkeley, noted that some of these forests have grown very dense and now have a lot of carbon in them. Cabiyo was not involved in the new research.

"What worries me about the offset protocols is that they incentivize dense forests, which are at higher risk of disturbance," he said. Although management techniques like thinning can protect against future disturbances, the protocols effectively penalize such actions because they reduce carbon stocks. "So not only are these protocols underestimating disturbance risk, but they're potentially making that risk greater," Cabiyo added.

Expressing similar concerns, Barbara Haya, director of the Berkeley Carbon Trading Project, said the protocols are creating "a perverse incentive" for forest managers not to decrease carbon stock even when it is beneficial to do so. "The offset protocols are in direct contradiction with some work that's being done in California to manage forests more sustainably to reduce fire risk," she added.

"Not only are these [forest offset] protocols underestimating disturbance risk, but they're potentially making that risk greater."

Anderegg suggested that an investment framework that allows for management like prescribed burns would work better for both forest conservation and carbon sequestration.

By **Rishika Pardikar** (@rishpardikar), Science Writer

Rock Music in Utah

Scientists tracked the natural frequency of the Secret Spire rock formation near Moab, Utah. Credit: Geohazards Research Group, University of Utah

It's easy to think of Utah's statuesque red rock towers as immobile, even immovable. Yet the rock towers imperceptibly twist, rock, and sway in response to vibrations and seismic activity.

Recently, University of Utah geophysics graduate student Riley Finnegan measured the ambient vibrations of 14 large-scale structures in southern Utah, then included these measurements in a new data set of 32 similar structures in Utah and beyond. The study was published in *Seismological Research Letters* (bit.ly/Utah-vibrations).

"What [the researchers have] really done is to help us have confidence in our predictions about the specific frequencies at which these rock towers will resonate," said Devin McPhillips, an earthquake geologist with the U.S. Geological Survey who was not involved with the study.

In addition to vibrational risk assessment, the rock towers have spiritual and cultural significance for the first occupants of these lands, including members of the Eastern Shoshone, Hopi, Navajo, Southern Paiute, Ute, and Zune tribes. "These are culturally valuable landforms," Finnegan said. She hopes the data will be used not only to predict the impacts of natural disasters and human-caused vibrations but also to preserve the stunning structures.

"These data provide inputs for understanding how these landforms might respond to blasting work that's done for building roads or other inputs for vibrational damage assessments or risks," Finnegan said.

Rock Climbers Assist in Gathering Data

Prior research uncovered the impact of vibrations from helicopter flights on the Utah structures, and similar studies measured the natural frequency of mountains. Such measurements inform seismic risk assessments as well as risks from other types of vibrations. But gathering measurements is challenging.

"The individual data for each feature can be incredibly hard to obtain, usually involving technical climbing," said Jeff Moore, a coauthor of the new study.

For the current study, scientists partnered with accomplished rock climbers led by coauthors Kathryn Vollinger and Jackson Bodtker, who followed established climbing routes up to 120 meters (~400 feet) high to place seismometers, which work like sophisticated accelerometers, atop the rock formations. Using photographs, drone footage, and seismometer data, researchers created 3D models of 10 of 14 rock formations they attempted, noting fundamental frequencies of 0.8–15 hertz, or cycles per second, which were inversely proportional to tower size. They were unable to model four towers because of camera exposure from bright sunlight and hard-to-measure rotational movements, like twisting.

"You can kind of think of a tower like a guitar string that's turned on its side," Finnegan said. "You play the guitar string, and it vibrates and resonates at certain frequencies, and we hear those frequencies." Similarly, the towers vibrate at certain frequencies, though they can't be heard in the field. Researchers created amplified audio recordings of the towers along with their 3D models.

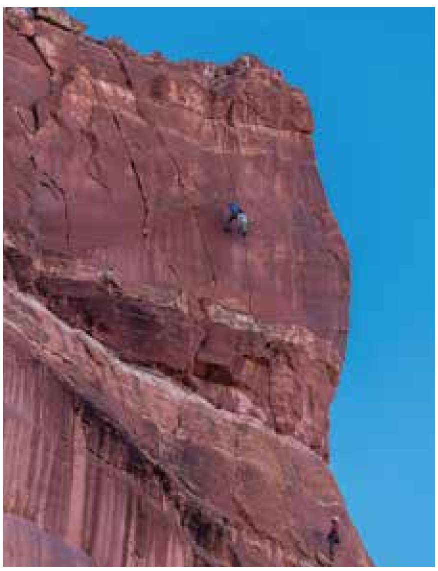
Predictive Modeling with Seismic Potential

Along with measuring frequencies, mode shapes, and damping ratios (a measurement of the decrease in swaying motion over time) in the 14 structures, Finnegan and her team gathered frequency data and tower heights from prior studies and consulting reports for structures elsewhere in Utah, as well as in Arizona, France, and Israel. Combining the compiled data with their own measurements, they confirmed a formula for determining a structure's fundamental frequency given its width, height, and composition. Using that relationship, researchers found they could roughly predict the natural frequency of unfamiliar sandstone or conglomerate rock structures.

Scientists partnered with accomplished rock climbers who followed established climbing routes to place seismometers atop the rock formations.

Researchers hope this confirmation will help others predict the dynamic and resonance properties of other rock towers without challenging climbs; the calculation requires only width and height measurements that can be taken from the ground.

"If we know something about the composition of the feature and we know about its shape, we can make a pretty good guess about what the fundamental frequency will be," McPhillips said. And such seemingly basic



Climbers descend Eagle Plume Tower in Utah after placing seismometers atop the rock formation. Credit: Eric Albright

measurements can have wide-ranging implications, from refining earthquake hazard models to developing building codes in regions prone to seismic activity, like the Pacific Northwest. Such predictability becomes even more important when scientists like McPhillips are tasked with predicting outcomes in regions that have never recorded megathrust earthquakes.

"Extrapolating from the limited historic data we have is potentially dangerous," McPhillips said. So data like Finnegan's offer some added certainty and predictability. "If we know how old these rock towers are and we can estimate how much shaking they can sustain, we can put a maximum value on the strength of past shaking, and that's really helpful for refining earthquake hazard models."

By **Robin Donovan** (@RobinKD), Science Writer

A New Index to Quantify River Fragmentation

Rivers are fragmented by large and small dams the world over, be it for power generation, water supply, or flood control. Direct impacts of such fragmentation include barriers to sediment and nutrient flow and isolation of fish populations. To better quantify river fragmentation, researchers have designed a novel index, the catchment area–based fragmentation index (CAFI), as described in a paper published in *Ecological Indicators* (bit.ly/river-fragmentation).

In contrast to current methodologies that determine river fragmentation on the basis of river length, CAFI and its derivative, the rainfall-based fragmentation index (CARFI), use catchment area as an indicator of the extent of river habitat.

Suman Jumani, a freshwater ecologist at the University of Florida and lead author of the new study, said that catchment area is a good predictor of the volume of water flowing in a stream. In addition, she added, a catchment is relatively easy to quantify, so it "works well as a proxy for in-stream habitat availability."

Robust Contribution to Quantifying Fragmentation

The new index provides a robust analysis of river connectivity, a crucial measurement of healthy rivers with aquatic biodiversity, researchers said.

Both CAFI and CARFI can be used to quantify how rivers are fragmenting in size and over time. Catchment areas increase in size as rivers move downstream, and dams positioned farther downstream in watersheds are expected to cause greater habitat fragmentation. CAFI and CARFI can account for the wildly different effects of dams depending on where they are built, whereas indices are less suited to differentiating the fragmentation effects between dams located at upstream and those at downstream positions in watersheds.

CAFI works well in areas where rainfall is largely uniform, whereas CARFI incorporates rainfall intensity in addition to catchment area, making it useful in mountainous landscapes where precipitation is highest at the ridge and reduces as streams flow downslope.

Comparing California and Karnataka

Essentially, the indices track how individual dams affect river fragmentation. This quantification allows policymakers to better evaluate development plans such as site selection for dam building and the effects of dam removal on restoration.

The researchers applied the indices to two contrasting case studies: the Klamath River in California, where not only has dam building ceased but also dam removal has begun, and the Netravati River in the state of Karnataka, southern India, where 65 dams are proposed for development. CAFI was applied to the Klamath, and CARFI was applied to the Netravati, which flows through the mountainous landscape of the Western Ghats.

The researchers found that river fragmentation on the Klamath went through three distinct phases. Dam construction between 1840 and 1910 led to minimal fragmentation across the basin because the dams were located on headwater streams that had relatively small catchment areas. Between 1920 and 1960, as dams were increasingly located downstream or closer to the main stem of the river, larger catchment areas were affected, resulting in higher basin-wide fragmentation. River fragmentation on the Klamath took another shift during the decade between

The new quantification allows policymakers to better evaluate development plans such as site selection for dam building and the effects of dam removal on restoration.

2002 and 2012, when eight small dams were removed from tributaries. Fragmentation decreased and is set to decrease further if plans to remove four more large dams from the main stem Klamath River proceed.

As for the Netravati, researchers found a "steep increase" in fragmentation after 2010, attributed largely to the construction of five new dams along the main channel of the river. Future dam construction will further

Dam development on the Netravati River in southwestern India was evaluated by a new index measuring river catchment. Credit: Divya Jose T/Wikimedia, CC BY-SA 4.0 (bit.ly/ccbysa4-0)

increase basin-level fragmentation, the paper found.

Challenges of River Conservation in India

Jumani and her coauthors emphasized that CAFI "does not replace" ground-level or even project-specific impact assessments. From a policy perspective, "this is key, because though the indices capture a lot [of data], the nuances remain to be supplemented," said Avli Verma, a researcher at Manthan Adhyayan Kendra, a nonprofit investigating water and energy development in India. She did not contribute to the new research.

In India, Verma said, the indices could help inform decisions related to emerging river interventions. Examples of interventions include demolitions and reconstructions of barrages and navigation locks, as well as the development of canals and tunnels.

The indices are particularly suited to developing countries in the tropics, which hold massive potential for future dam development. These regions are often data deficient, but with CAFI and CARFI, "catchment area can be delineated with any surface elevation model on a GIS platform and rainfall can be ascertained through global datasets such as WorldClim," the paper notes.

Other researchers disagreed about the utility of the new indices. In particular, the scope of data offered by CAFI and CARFI is very limited in a country like India, where challenges to river governance are not just data driven, said Himanshu Thakkar, a coordinator at the South Asia Network on Dams, Rivers and People. Thakkar, who did not contribute to the paper, listed some of those challenges as large-scale sand mining, deforestation, and dishonest environmental impact assessments. "We have to look at the totality of what is happening across a river's basin," he stressed.

In fact, Thakkar said, the 65 small hydropower dams on the Netravati analyzed in the new paper don't require environmental impact assessments at all. These dams produce fewer than 25 megawatts of power, and in India, hydropower facilities that produce fewer than 25 megawatts are classified as renewable energy projects and are exempt from environmental impact assessments. "There are no assessments for such projects, no public hearings, no monitoring and compliance. So how can such indices help?" Thakkar asked.

Verma, on the other hand, noted that scientists and policymakers need such studies to "have proper scientific assessment of what all we are looking at when we deal with multiple barriers to water flow in rivers." Nevertheless, she added, it is true that more ground-level information would make the study stronger, and this point is "well-flagged" in the paper.

Jumani and the other authors maintained that the indices are part of a set of tools for river governance and not intended to be used in isolation. "This index, like most other works of science, is not intended to solve or address the gamut of river governance issues," she said.

By **Rishika Pardikar** (@rishpardikar), Science Writer

Air Pollution Linked to Adverse Mental Health Effects

A mental health crisis is brewing among children and teens, and new evidence has suggested that exposure to air pollution could be one of many risk factors (bit.ly/pollution-mental-health). In a recent study, researchers found that adolescents living in areas with relatively high levels of ozone experienced a significant uptick in depressive symptoms, such as sadness, loneliness, and feelings of self-hatred.

> **"One of the things that I'm pretty startled by is that we're seeing these effects over 2-and 4-year periods."**

And this change in mental health can come about rather quickly, explained the study's lead author, Erika Manczak, an assistant professor of psychology at the University of Denver. "One of the things that I'm pretty startled by is that we're seeing these effects over 2- and 4-year periods." Perhaps even more unexpected: All of the study's 213 participants lived in neighborhoods where average ozone concentrations were below the National Ambient Air Quality Standards. "Even though these were objectively low levels of average ozone exposure, we are nonetheless seeing these effects."

To conduct this study, which was published in *Developmental Psychology*, Manczak and colleagues analyzed mental health data of children between the ages of 9 and 13 collected at several points over a 4-year period. They then compared these figures with air quality monitoring data that roughly corresponded to each participant's home address. After accounting for a range of compounding factors—like age, gender, and socioeconomic status—the researchers found that even slightly elevated ozone levels corresponded with an increase in depressive symptoms over time.

"They were able to show really clean linear symptom trends in folks exposed to high levels [of ozone] that are basically absent in folks not exposed to high levels," said Aaron Reuben, a postdoctoral scholar in neuropsychology at Duke University who was not involved in the study. "For people concerned about understanding individuals' risk for depression, I think this paper adds a lot of new value."

"Humans Are Messy Subjects"

Scientists have long known that air pollution exposure can lead to a slew of negative health effects, but "it was assumed for many years that air pollution mostly harmed the lungs," explained Reuben. Even today, ozone is frequently said to contribute to pulmonary issues like asthma and respiratory infections, "which it does, but then we realized: Maybe it could also harm organ systems closely associated with the lungs."

That, it turns out, includes the brain and central nervous system. "There seems to be some evidence in animal models to suggest that exposure to ozone and other forms of pollution can affect the activity of various neurotransmitters, as well as can encourage the expression of inflammatory proteins in the brain," explained Manczak.

All of those things have been separately implicated in the formation and development of mental disorders, said Omar Hahad, a psychologist and researcher at the University Medical Center Mainz in Germany who was not involved in the study.

Animal-based research can tell scientists only so much. After all, depression in a rat looks very different from depression in a human being. That's why these findings are often used in conjunction with observational studies, like Manczak's, to understand how these physiological mechanisms could affect people, especially vulnerable populations like children.

It's not a perfect science, though. For one, "humans are messy subjects," explained Reuben. "Almost everything in human toxicology studies is going to be correlational."

There also could be other factors coming into play that researchers cannot easily control for. "In highly urbanized areas, it's more likely that there are colocalizations of other environmental factors such as noise exposure, light, or temperatures, which we know affect mental health," explained Hahad.

Taking Precautionary Action

Nevertheless, the research by Manczak and colleagues adds to the growing list of evidence that highlights air pollution's negative effect on mental health. "I think replicating the study in a much larger sample and in different parts of the world would be really an important next step to help us be a little bit more confident in these associations," Manczak said.

In addition, more work is needed to understand how different mixtures of pollutants might alter these effects. "We don't know if the effects of these air pollutants are additive or synergistic," said Hahad.

Despite these outstanding questions, the public can still take precautionary actions, researchers said. "I'm a really big believer in paying attention to what your local air quality is and using that information to inform how you behave across the day," said Manczak, whether that be rescheduling outdoor activities on high-pollution days or donning N95 masks.

That said, individual efforts can get us only so far. "What is really lacking [are] the political actions to really address this problem," said Hahad.

Reuben agreed. "Fundamentally, when we talk about air quality, water quality, things that influence health and longevity of all of us, it has to be a societal response. You just can't do it alone."

By **Krystal Vasquez** (@caffeinatedkrys), Science Writer

Cretaceous Charcoal Gives a Glimpse into Plant Evolution

To understand Earth's remote past, paleontologists and geologists look for vestiges of history hidden in rocks. They also look for clues of life in less obvious materials such as ages-old charcoal, which can reveal how the global environment changed in the deep past and give a glimpse into how it might change in the distant future.

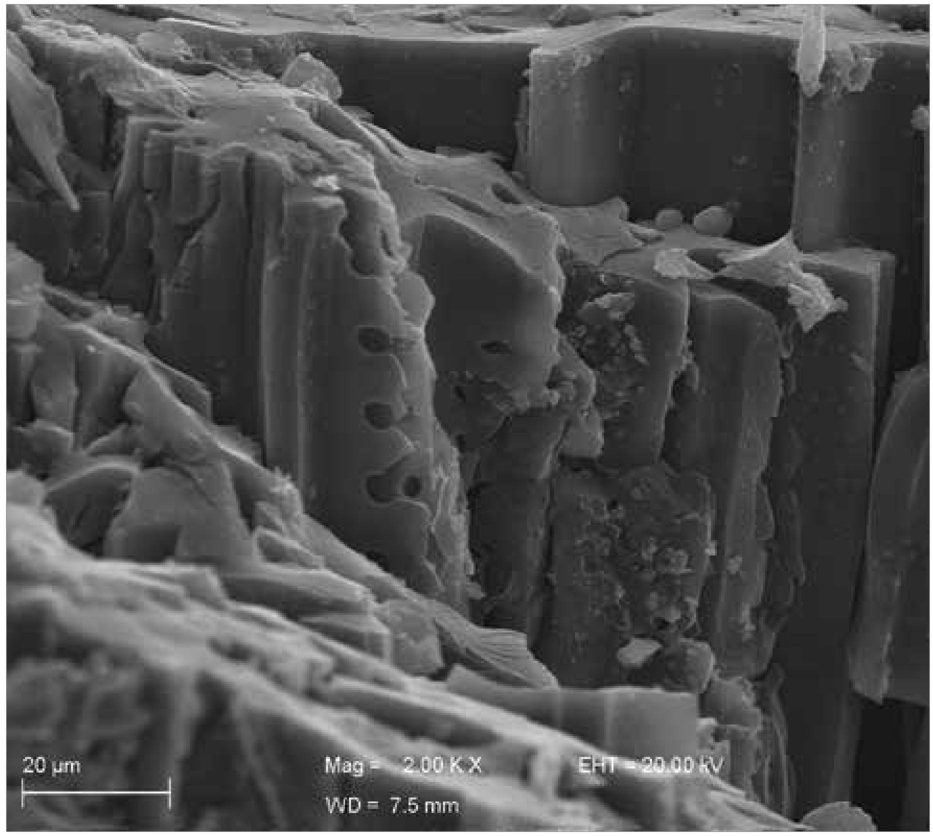
Recently, a team of researchers from Brazil, Germany, and India identified rare charcoal records of paleowildfires in the Saurashtra Basin in Gujarat, northwestern India. The material, said lead author Gisele Sana Rebelato, dates back to the Early Cretaceous (145–100 million years ago), a time when the supercontinent Gondwana was drifting apart. The paper was published in *Current Science* (bit.ly/charcoal-records).

"Whenever we talk about South America, Africa, Antarctica, India, and Australia, we're talking of our geological 'backyard,' as they were all together in Gondwana," said coauthor André Jasper, who works with Rebelato at the University of Vale do Taquari (Univates) in Brazil.

In analyzing the charcoal with both a stereomicroscope and a scanning electron microscope, the team identified charred wooden remains of gymnosperms, the flowerless plants such as conifers and cycads that dominated Earth until the Cretaceous, when they were outcompeted by angiosperms. "It was during this period," Rebelato explained, "that angiosperms, or flowered plants, emerged and expanded, in part because of fire-altered biological dynamics. As [angiosperms] had a quite short life span, one of the hypotheses is that wildfires ended up favoring them, as they grow and recover quickly."

The new research did not definitively confirm that hypothesis, in part because it lacked fossilized plants to analyze. "When we look at charcoal, we're normally looking at wooden structures, which is what can actually fossilize. And [during the Late Cretaceous] angiosperms were mostly herbaceous; they didn't have wood that could be preserved. So it's hard to make any straight correlations for now," Rebelato said.

The study, however, advances science another rung on the ladder of understanding paleowildfires as global phenomena. "There were wildfires in other regions, such as Eurasia and the Americas. For fire to have been an evolutionary driver, it must have occurred globally, not just in isolated places. So every study of this kind adds more evidence to that—and there are few descriptions from Gondwana," Jasper said.



This image, taken with a scanning electron microscope, documents Cretaceous era charcoal found at the Than Formation in Saurashtra Basin, Gujarat, India. Credit: Gisele Sana Rebelato

"For fire to have been an evolutionary driver, it must have occurred globally, not just in isolated places."

Wildfire as Part of a Broader Earth System

According to Joseline Manfroi, a paleobiology researcher at the Chilean Antarctic Institute, the new study is important to the geosciences because the Cretaceous "represents a crucial moment in Earth's geological history, having been the stage for significant environmental and geological changes across the globe. [Scientific] work that analyzes the elements that witnessed these changes, such as fossil records, enables a better understanding of the Earth system as a whole."

Paleowildfires during the Cretaceous in places like Antarctica and Patagonia, Manfroi said, point to "significant climate and environmental changes that climaxed in one of the Earth's great extinctions but also show the relevance of fire to the evolution of vegetal groups that dominate terrestrial environments today, such as the angiosperms."

Manfroi, who has worked with the Brazilian authors before but did not take part in this study, said the study of paleowildfires helps us understand "not just the frequency and environmental conditions in which these phenomena occurred, but above all the relation of fire as a perturbing and changing agent for different ecological niches in the past. [Fire] contributed to configuring the diversity and biogeography of flora in different latitudes of the globe."

Paleobotanist Ian Glasspool, a research associate in geology at Colby College, said ancient wildfires "aren't just localized, destructive, natural events but are also an integral part of the broader Earth system."

Their list of impacts is extensive, Glasspool explained, ranging from deep feedback on the global carbon cycle to influences in nearshore marine sedimentology through changes in runoff and erosion. Wildfire has a "feedback role in stabilizing the Earth's atmospheric oxygen concentration" and acts "as a 'global herbivore' through its impacts on vegetation. [It] preserves organic material; charcoal produced by fires is chemically inert, structurally rigid, and may preserve exquisite cellular, and even subcellular, three-dimensional anatomy," said Glasspool, who did not take part in the study.

Ancient wildfires "aren't just localized, destructive, natural events but are also an integral part of the broader Earth system."

The study of ancient wildfires "has become an integral factor in modeling Phanerozoic atmospheric oxygen concentration, for example. Fire may perturb ecosystems, particularly where peats are burned; the resultant tree mortality can be extreme," Glasspool continued.

"Unfortunately," Jasper warned, "the planet is burning right now. And we're mapping this kind of event across time and see [that] the consequences on life and biodiversity are not to be taken lightly.... These [wildfire] events were followed by mass extinctions."

"The problem is that we're accelerating a process that would take thousands or hundreds of thousands of years to happen," added coauthor Ândrea Pozzebon-Silva, also a researcher at Univates. "If reduced to centuries or decades, the effects of wildfires can be deleterious to humans and Earth's biodiversity at a scale not seen before."

By **Meghie Rodrigues** (@meghier), Science Writer

Hot Springs Suggest How the Tibetan Plateau Became the Roof of the World

The Tibetan Plateau has long represented both an opportunity and a conundrum for geophysicists. This vast tableland is the product of a long, slow collision between the Indian and Eurasian continental plates—a collision that began about 50 million years ago and is still going on today. As the only active continental collision site in the world, the plateau provides a unique opportunity to understand what happens when continents meet. But the long time frame and the great depths over which the collision has been occurring have left scientists puzzling over how exactly the plates are coming together.

In one model, the Indian plate is slipping neatly underneath Asia, forming two parallel layers like a cake with two tiers. In the other, the collision has caused the Indian plate to take an abrupt turn toward Earth's core, leaving the Eurasian (or Asian) plate directly on top of Earth's mantle. Scientists have long analyzed the composition of Tibet's surface rocks, as well as the area's volcanic and seismic activity, to discern which model is closer to the situation found today.

Simon Klemperer, a geophysicist from Stanford University, and his colleagues decided to take a page from geochemists' playbook to learn how the Tibetan Plateau gained the nickname "the roof of the world." Over the better part of the past decade, the researchers analyzed helium isotopes in water collected from more than 200 geothermal springs to discern from which layer of the Earth the water emanated. The team's results, published in the *Proceedings of the National Academy of Sciences of the United States of America*, suggest that the Indian plate plunges deeply beneath the Asian plate, but experts in the field say that many questions still remain (bit.ly/collision-India-Asia).

A Journey Across the Roof of the World

Klemperer and his colleagues teamed up with a group led by Ping Zhao from the Chinese Academy of Sciences. They collected samples from across a sprawling area equivalent in size to the contiguous United States west of the Rockies, traveling by car, by motorbike, and on foot and traversing dirt roads, rivers, and canyons to find the springs.

The researchers often relied on locals to help them, occasionally with surprising results. Once when they were trying to reach a spring that was surrounded by swamps, they hired a local guide to show them a relatively dry route. Misunderstanding their destination, the guide drove them to a different spring, about 80 kilometers from the nearest town, that wasn't on any map or in any list of springs the researchers had seen. The feature, new to the scientists, "was like one of the big springs in Yellowstone, with terraces and travertine and orange and yellow and white, spanning a kilometer," Klemperer said.

"One can still be an explorer, even today," he added.

Sometimes the scientists failed to find springs that had been recorded in historical lists ("travelers' tales, or maybe they just dried up," Klemperer suspected). Other times, they found that the springs had acquired diverse uses. One had been converted to a laundry facility for the Indian army, and many had become religious sites. All together, the team collected samples from 225 springs across a thousand-kilometer-wide region.

Isotope Fingerprints

Earth's layers contain characteristic ratios of the helium isotopes ^{3}He and ^{4}He, giving each layer "a specific fingerprint," said Dennis Newell, an isotope geochemist at Utah State University who was not involved with the new research.

"One can still be an explorer, even today."

When Klemperer and his colleagues analyzed the helium isotope ratios in their water samples, a stark trend appeared: Samples collected in the northern plateau had high ratios of ^{3}He/^{4}He (as one would expect if Earth's mantle directly underlies that region), whereas samples collected farther south had lower ratios.

The findings support the idea that the Indian plate plunges deep below the Eurasian plate after the two collide beneath the Himalayas. In fact, Klemperer has enough confidence in his team's results that he said, "I

Geochemical analysis of hot springs like this one is helping scientists understand how subduction works beneath the Tibetan Plateau. Credit: Ping Zhao

"I honestly believe that textbooks will no longer show two different models of Tibet."

honestly believe that textbooks will no longer show two different models of Tibet."

Purdue University noble gas geochemist Marissa Tremblay, who was not involved with the research but has collaborated with some of the authors on other projects, said Klemperer's results are in line with studies that draw on surface geology and volcanic activity to discern how the Tibetan Plateau formed. But she thinks geoscientists still need information about the past to round out their understanding of this region's history. "This is a snapshot of what things look like today. And I think over the millions and millions of years that this collision has been ongoing, this might have looked very different," she said.

Newell isn't as convinced that Klemperer's results show what's happening on the modern-day Tibetan Plateau. He pointed out that helium isotopes take time to move from the layers underlying the plateau to the surface, where the researchers collected them. Klemperer and his colleagues wrote that this transit takes place over a few millennia—a quick time frame, geologically speaking. "I would argue that it's not established in this paper that these things are moving as fast as a millennia," Newell said. "When I see this, I don't see today. I see a bit of a shadow of the past."

Tremblay and Newell both emphasized that the study represents an impressive body of work and provides a wealth of new information about an important geological region. "Now it's out there, and all of us as a community can think about it and think about alternative hypotheses," Newell said. "And that's what we do!"

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

A New Clue to Antarctic Ice Shelf Collapse

Earlier this year, Antarctica experienced one of the most significant ice shelf collapses since Larsen B in 2002.

The Hong Kong–sized Conger ice shelf in East Antarctica fell apart abruptly in late March. The collapse happened shortly after a blast of warm air shot East Antarctic temperatures 40°C above normal.

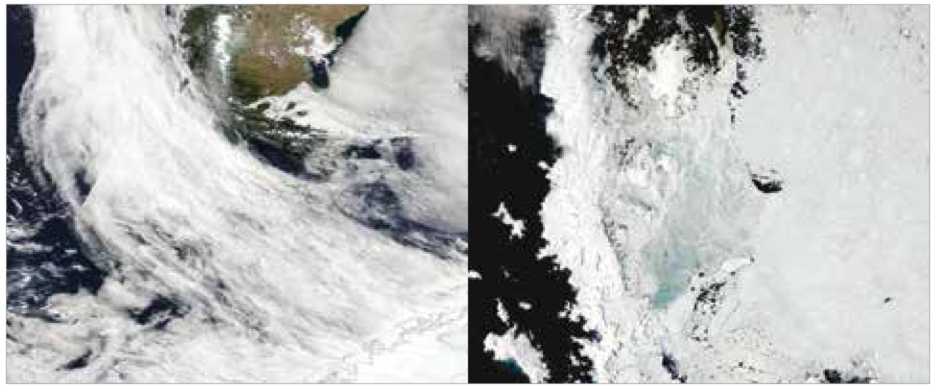
Right before the break, a particular kind of storm—an atmospheric river—swept over the continent, and scientists suspect that the storm played a role in the collapse. The Conger ice shelf "was already on its way to collapse, and it looked like this could have been the final kicker for that," said Jonathan Wille, a polar climatologist and meteorologist at the Université Grenoble Alpes.

Wille is part of a team that released new findings this month on the effects of atmospheric rivers on ice shelves in West Antarctica. Although it's too soon to tell exactly what led to the collapse of Conger, which is on the other side of the continent and had been disintegrating for years, new research from Wille suggests that atmospheric rivers coincided with many of the past calving events in the White Continent's most vulnerable region, the Antarctic Peninsula.

The research found that 13 of 21 calving events on the peninsula between August and March during the years 2000 through 2020 happened within 5 days after an atmospheric river.

"When ice shelves collapse, the glaciers which feed into them speed up and contribute more to sea level rise," said glaciologist and climate scientist Alexander Robel of the Georgia Institute of Technology.

Most ice shelves in Antarctica are thinning, and the Antarctic Ice Sheet has already contributed about 7.4 millimeters to sea level rise between 1992 and 2020, according to the Intergovernmental Panel on Climate Change.



Left: This atmospheric river, shown as a stream of clouds flowing from top left to bottom right, swept over the remnants of Antarctica's Larsen A and B ice shelves on 25 January 2008. The outline of the Antarctic Peninsula is drawn to show its location under the clouds. The tip of South America sits at the top of the image. Right: Broken ice crowds along the Antarctic Peninsula after a strong atmospheric river in January 2008. Credit: Jonathan Wille

A Perfect Storm

Atmospheric rivers occur around the world, but they bring a perfect storm to Antarctica's fragile peninsula. The storms hold vast amounts of moisture and heat and deliver extreme rain, snow, whipping winds, and unusually warm temperatures, causing melting and fracturing of the ice below.

Scientists have an increasing appreciation of extreme events that can have disproportionate consequences. One study found that unusual melting events were necessary to kick off a large ice shelf collapse weeks to months later (bit.ly/melting-collapse). "This new study indicates that such anomalous melt events are almost exclusively caused by atmospheric rivers," said Robel, who was not involved in the work.

The latest study relied on a tailor-made algorithm that detects atmospheric rivers.

Atmospheric rivers help protect Thwaites Glacier by coating it in snow.

The researchers studied satellite observations and used a regional climate model to identify 21 calving events on Larsen A and B between 2000 and 2020.

Atmospheric rivers make landfall on the Antarctic Peninsula about one to five times per austral summer, and of the 21 calving events identified, an atmospheric river preceded 13 of them within 5 days.

The group also analyzed the collapse of Larsen A in 1995 and calving at Larsen C in July 2017 and found intense atmospheric rivers preceding both. The work was published in the journal *Communications Earth and Environment* (bit.ly/larsen-a-1995).

Thwaites Not Threatened by Atmospheric Rivers

Although the findings are the first systematic study of atmospheric rivers over a 2-decade history on the Antarctic Peninsula, it's unclear how they relate to other regions, including Conger. Even the nearby Wilkins ice shelf, which sits on the peninsula, could not be studied because of clouds obscuring satellite images.

Elsewhere on the continent, Thwaites Glacier, dubbed the Doomsday Glacier, is particularly unstable and could cause 65 centimeters of sea level rise. There, atmospheric rivers protect the ice sheet from surface melt by coating it in snow, said Michelle Maclennan, a Ph.D. candidate in atmospheric and oceanic sciences at the University of Colorado Boulder.

This research shows that scientists need a better understanding of fast-changing events on ice shelves, said glaciologist Helen Amanda Fricker at the Scripps Institution of Oceanography, who was not involved in the work. Doing so is vital for predictive models.

Until then, said Willes, scientists will need to track the effects in real time.

"In the future, when we see atmospheric rivers head toward Antarctica, especially the ones that are really powerful, this is something we should pay attention to," he said. "And see what happens afterward."

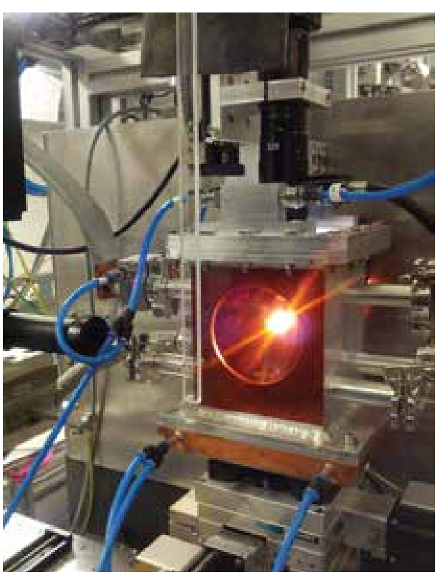
By **Jenessa Duncombe** (@jrdscience), Staff Writer

How a Newly Discovered Mineral Might Explain Weird Mantle Behavior

Diamonds, X-rays, and lasers aren't just for detective dramas filled with heists and hijinks. They are among the tools that experimental petrologists use to re-create conditions in Earth's mantle, whose mysteries remain mostly hidden many hundreds of kilometers below the surface.

In work reported recently in *Nature*, scientists led by Julia Immoor used these tools to create an elusive mantle mineral in the lab: davemaoite, also called cubic calcium silicate perovskite (bit.ly/mantle-mineral). After synthesizing the finicky mineral, they then deformed it to measure its strength—a technical breakthrough, said Sang-Heon "Dan" Shim, a mineral physicist at Arizona State University who was not involved in the new study. In their analysis, Immoor and her colleagues discovered that davemaoite, which exists naturally only between about 660 and 2,900 kilometers below Earth's surface where pressures and temperatures are high enough, may be surprisingly soft. The finding raises intriguing questions about roles the mineral could play in subduction and the formation of seismically anomalous regions in the lower mantle.

These cube-shaped crystals of perovskite are made of calcium, titanium, and oxygen. Credit: Rob Lavinsky, iRocks.com, CC BY-SA 3.0 (bit.ly/ccbysa3-0)



A sample of perovskite is heated in the experimental chamber under vacuum as two diamond anvils within apply pressure. Throughout the entire experiment, the sample can be analyzed with an X-ray beam. Credit: Hauke Marquardt, University of Oxford

Under Pressure

Davemaoite is the third most abundant mineral in the lower mantle, yet it's notoriously difficult to study because of its instability at Earth's surface, said Shim.

The problem, said corresponding author Hauke Marquardt of the University of Oxford, is that to truly be davemaoite, the mineral's crystal structure must be cubic, which means that the smallest repeating arrangement of atoms, called the unit cell, must form a cube. However, under natural conditions at Earth's surface, davemaoite's unit cell stretches in one direction, forming a rectangular prism, not a cube. Called tetragonal calcium silicate perovskite, this warped davemaoite-esque material shows great strength under mantle pressures while at room temperature.

Creating the high pressure expected at 1,200 kilometers deep—firmly within the range at which davemaoite forms—is relatively simple. All Immoor needed was a diamond anvil cell, in which the tip of one diamond is compressed against another, with a smidge of sample powder composed of calcium, silicon, and oxygen between the two. Such a setup can reach pressures well beyond those occurring at Earth's greatest depths. Once the experiment reached the target pressure (about 30 gigapascals), she and her colleagues turned up the temperature.

However, reaching the high temperatures of the lower mantle is more complex. Lasers used to heat samples can result in uneven heating, so Immoor and her team used a resistance heater made of two graphite sheets that allowed them to raise the temperature to a consistent 1,150 K—nearly 900°C—while also ensuring enough space for an X-ray beam to pass through. The X-ray beam, said Marquardt, served as a probe of the compressed sample's mineralogy by allowing the periodic collection of X-ray diffraction patterns during the experiment, providing confirmation that davemaoite both formed and deformed.

Davemaoite may be surprisingly soft in the only place with high-enough pressures and temperatures for it to easily exist—Earth's lower mantle.

For a successful experiment, every piece of the apparatus must be precisely placed, the temperature must be carefully monitored, and, scientists said, fingers must be crossed that the diamonds in the anvil cell don't break.

During a 10- to 12-hour experiment that extended into the wee hours of the morning, Immoor described how just as a colleague was considering heading home to sleep, she and her team realized they couldn't leave. "We knew, at this moment, that we were able to synthesize this cubic calcium perovskite," she said. And then they deformed it. Unlike other synthetic minerals that can be quenched and studied outside the diamond anvil cell, davemaoite would revert to its warped, tetragonal relative. To that end, Immoor and her colleagues continued the experiment, watching how the impinging diamonds deformed the fresh davemaoite.

From their data, after numerous rounds of checking their calculations, the researchers found that unlike its noncubic cousin, davemaoite's strength and viscosity are substantially lower than those of the other minerals (bridgmanite and ferropericlase) that make up the lower mantle. The finding was a surprise, Immoor said.

Blobs or Folds?

When slabs of oceanic lithosphere—comprising crust and the uppermost mantle—slide into subduction zones, scientists surmise their eventual fates from theory, experiments, and tomography, in which seismic waves help image Earth's innards, like a global CT (computed tomography) scan. But why and how some features form in the mantle remain unclear. The new findings about davemaoite may shed light on these deep mysteries.

Though the entirety of a slab of oceanic lithosphere would weaken upon reaching the lower mantle, the crustal component should contain more davemaoite than the corresponding portion of upper mantle. Considering this compositional difference, it's possible that the weaker former crust could peel away, or delaminate, from its erstwhile mantle partner, said Marquardt, with the crustal portion falling to and accumulating at the core-mantle boundary. This process might explain the existence of tomographically observed large low-shear-velocity provinces (LLSVPs), he said. These blobs, which cover about a quarter of the core-mantle boundary, might in turn help explain the curious chemistry of hot spot volcanoes.

These slabs might be folding like toothpaste.

However, said Karin Sigloch, a seismic tomographer at the Centre National de la Recherche Scientifique Géoazur laboratory in Sophia Antipolis, France, who was not involved in this study, oceanic crust is such a small component of subducted slabs that it may not explain the voluminous presence of LLSVPs. Instead, she said, it might be more likely that weakened, delaminated crust—if it exists—ends up forming smaller features known as ultralow-velocity zones.

Formation of davemaoite may alternatively explain the observation that subducting slabs appear to thicken when they reach the transition between the upper and the lower mantle (corresponding to depths of about 550–700 kilometers), said Sigloch. These slabs might be folding like toothpaste, just where davemaoite begins to appear, she said.

When slabs are only as strong as their weakest part, their deformation, or even their disintegration, becomes increasingly plausible.

By **Alka Tripathy-Lang** (@DrAlkaTrip), Science Writer

Playing It Safe in Field Science

The most memorable individual I've met during fieldwork weighed about half a ton. My team was taking samples of sedimentary rocks one morning on a remote island in Svalbard, Norway, when he surprised us. The furry white boulder lumbered toward us under the Arctic summer Sun, then stood up and eyed us as we yelled at him and quickly packed our samples to retreat, just like we'd practiced. Later, we watched him sleep near the shore from the deck of our sailboat. His shagginess and curiosity reminded me of a dog—but he was a hungry polar bear.

That day, he stayed hungry, and we stayed safe. And ever since, he's been the fodder for a field story I've told many times. Hang out with Earth scientists for any time at all, and you'll hear stories like this: misadventures and near misses in the field. The antagonists of these stories are diverse—annoyed buffalo, helicopters, rushing rivers, flat tires, cacti, and more.

Depending on who's listening, these stories sound like invitations to high adventure or good reasons to stay home. The tales may be thrilling—and offer glimpses of specific risks and solutions—but when it comes to informing systematic approaches for avoiding risk in the field, they are, literally, anecdotes. What field scientists need for this purpose are data.

Experienced field researchers are applying data-driven approaches to categorize risk. Some of us are sifting through historical records to identify patterns, whereas other colleagues are focused on creating systems to collect better information on future incidents. Together, these efforts build resources for field scientists to use so we can be as prepared as possible before we go into the field—and remain safe and sound while we're there.

Hang out with Earth scientists for any time at all, and you'll hear stories of misadventures and near misses in the field.

The author hikes across the rocky landscape of Svalbard during fieldwork in 2017. Credit: Adam Jost

Let's Talk

As a sedimentologist who works and teaches in the field, I wanted to help develop a quantitative understanding of risk during fieldwork across field areas, seasons, and settings. Collecting relevant data is challenging because people rarely report minor incidents and close calls. The best paper trail I found was for the most extreme outcome of risk in the field: death.

I collected reports of deaths during geological fieldwork since 2000 from English language obituaries and news reports to better understand sources of risk in the field. My work with this data set shows, among other findings, that vehicles are the leading cause of accidental death during fieldwork, followed by environmental causes like drowning, animal attack, and falls from height, similar to the main causes of death during outdoor recreation at U.S. national parks [*Cantine*, 2021].

Death is a rare event in the field, so that initial research has provided limited, though helpful, insight into risk. To expand my perspective, I began interviewing field scientists to learn about their experiences. I've spoken with people who have worked from the poles to the tropics, using everything from helicopters to scuba equipment to explore our planet. Although these conversations are, yes, anecdotes, collecting them systematically can help illuminate patterns, provide examples of good and bad practices, and identify lessons learned that become clear to participants only after some time to reflect has passed.

Collecting anecdotes systematically can help illuminate patterns, provide examples of good and bad practices, and identify lessons learned

Mariusz Potocki, a glaciologist with experience doing fieldwork in extremely remote areas like Antarctica and high-altitude mountains, spoke to me about how swiftly weather conditions can worsen. "I'd say the most dangerous part of fieldwork is the unpredictability of nature and how it might catch you unprepared," he said. Severe weather lasting for days or weeks may leave researchers without sufficient food to weather storms, for instance.

Potocki suggested that expedition leaders be certain that all team members or subgroups within teams have the supplies and skills needed to be self-sufficient when the unexpected happens. Such preparations might simply mean making sure each vehicle on a field trip has at least one passenger who knows how to change a tire or reminding participants to pack medication in carry-on rather than checked luggage. He described how field leaders he admires take responsibility even for basic chores, from melting snow and ice for water to looking after tents. Their care with seemingly small tasks models how the well-being of the group is a shared responsibility.

Some of my conversations with field scientists have highlighted how even though field teams can be sources of new friends, mentors, and collaborators, they can also be sources of risk.

For work in more extreme or demanding environments, when specialized technical skills are required, it also matters that leaders demonstrate care for safety making the time and effort to ensure that participants are prepared. Tauana Cunha a postdoctoral fellow at the Smithsonian Tropical Research Institute who studies marine gastropods, described to me how a visit to work with collaborators started with a group scuba excursion to check her diving skills and comfort in the water before she was approved to work in a smaller group. Such exercises, though time-consuming, build mutual confidence and trust within teams, and they help protect researchers from getting into situations for which they're not prepared.

Some of my conversations with field scientists have highlighted how even though field teams can be sources of new friends, mentors, and collaborators, they can also be sources of risk, especially in the close-quarter and isolated environments where fieldwork often takes place. One survey found that the majority of sexual harassment and assault experienced by scientists in the field was perpetrated by fellow team members [*Clancy et al.*, 2014]. I spoke with Anne Kelly, now deputy director of The Nature Conservancy in Alaska, who has spent several years managing field stations and promoting change in the culture around gender-based and sexual harassment.

Kelly insists inclusive culture is a safety issue. "When teams don't trust each other, accident rates go up," she said. Kelly coorganized the Workshop to Promote Safety in Field Sciences, held in March 2021, which resulted in recommendations for how trip organizers can foster safe working environments in the field, from developing situation-specific codes of conduct to making communication devices and emergency transportation broadly available. The National Science Foundation seems intent on adopting similar goals: Recent draft updates to the agency's *Proposal and Award Policies and Procedures Guide* include a new requirement that grant applicants submit a plan for how they will promote a safe and inclusive field research environment.

"One major challenge is that bad behavior in the field doesn't always meet the threshold of illegality," Kelly said. Finding meaningful ways to react and respond to such behavior is an important challenge for field programs, Kelly advised.

Having these conversations has made me reflect on the safety measures I take in the field, as a researcher and as an educator. In planning field trips, for example, I now explicitly account for and teach students about driver fatigue as an important logistical constraint. And I have a greater appreciation for the important role that team leaders play in managing the safety of their groups in the field. Through these conversations, I've also met people taking on the challenges of chronicling and improving field safety in other ways.

Gathering the Data

An important approach to categorizing and managing field risk is encouraging and standardizing future reporting of incidents by researchers and students. Kurtis Burmeister, an assistant professor at Sacramento State University, has taught field safety leadership courses at universities and colleges for years. He also directs the Wasatch-Uinta Field Camp and is leading a group developing the Safe Field Experience Reporting (SaFER) System, a mobile app that will allow field trip participants to log safety-related incidents anonymously. Burmeister told me the realization of the need for something like the SaFER System grew out of a sense of what was missing from field safety conversations—detailed data about safety incidents, large and small, during geological fieldwork—as well as of the limitations of collecting incident reports on paper.

"At 61, it really bothers me to see my younger colleagues at other museums make the same dangerous mistakes I made in my twenties."

The proposed SaFER System will not only track physical and psychological traumas but also provide an important record of incident-free time spent in the field. That means SaFER will be able to quantify how incident rates vary by participants, activities, and settings. Such measures are difficult to calculate with currently available information, pointed out Kevin Bohacs, a member of the SaFER team who led the field safety task force at ExxonMobil Upstream Geoscience from 2003 to 2018. But they are "critical to understanding the relative risk of fieldwork [compared with] other activities students frequently participate in, like collegiate sports or jogging.

The SaFER team has identified a pilot group of Earth science field schools that have agreed to implement the SaFER app once it's built. The data this group generates will constitute the first cross-institutional data set of safety-related incidents during geoscience education. Burmeister, Bohacs, and their colleagues anticipate that the results will help identify best practices for safety during camps and other instruction in the field.

Another ongoing effort to document field safety, this one stretching somewhat farther back in time, has been undertaken by Darren Tanke, a senior technician at the Royal Tyrrell Museum of Palaeontology who collects and prepares fossil specimens for scientific research and public display.

"At 61, it really bothers me to see my younger colleagues at other museums make the same dangerous mistakes I made in my twenties," said Tanke. For more than a year, he has been creating a vast, centuries-spanning archive of deaths and near misses across field, lab, and even office work in archaeology, paleontology, and geology. His aim with the project is to commemorate those who've died in pursuit of scientific understanding as well as to provide information to make these disciplines safer for future researchers. Tanke reached out to me after reading my recent paper, seeing an overlap in our areas of interest.

His database draws on a variety of sources, including old newspaper clippings and posts on Internet message boards. Piecing together accidents and near misses from these incomplete and sometimes confusing accounts isn't straightforward, and distilling all the information to pull out useful patterns and lessons will take time, Tanke noted. Already, though, the archive includes more than 2,000 reports, beginning with incidents in the 1800s. Together, Tanke and I plan to publish these findings, which document how some risks that geoscientists face are intergenerational, like snakebites and heat exhaustion, whereas others aren't, allowing us to understand how fieldwork has changed—or stayed the same—through time. For now, Tanke is focused on expanding the database, and he invites potential contributors to reach out to him with any stories that should be included (see Acknowledgments).

Changing for the Better

Fieldwork provides critical observations of the changing Earth as well as foundational training and opportunities for collaborations with other scientists. This work can leave participants permanently changed, personally and professionally. By taking field safety seriously, the research community helps ensure that these transformations are positive.

Data-driven approaches to understanding safety in the field—documenting the broad scope of past occurrences as well as cataloging future incidents—will take us far in this effort, helping craft sensible guidelines to reduce risk and expanding our perspective beyond the limits of solitary anecdotes, no matter how thrilling they are. With these insights in hand, we can teach and research in the field, confident in both the science we're doing and the way it's being done.

Acknowledgments

Thanks to all the field scientists who shared their time and experiences with me, including, but not limited to, Chris Atchison, Kevin Bohacs, Kurt Burmeister, Tauana Cunha, Anne Kelly, Chiza Mwinde, Mariusz Potocki, Darren Tanke, and Jesse Walters. Anyone interested in contacting Tanke about potential contributions to his archive can reach him at dtanke@hotmail.com.

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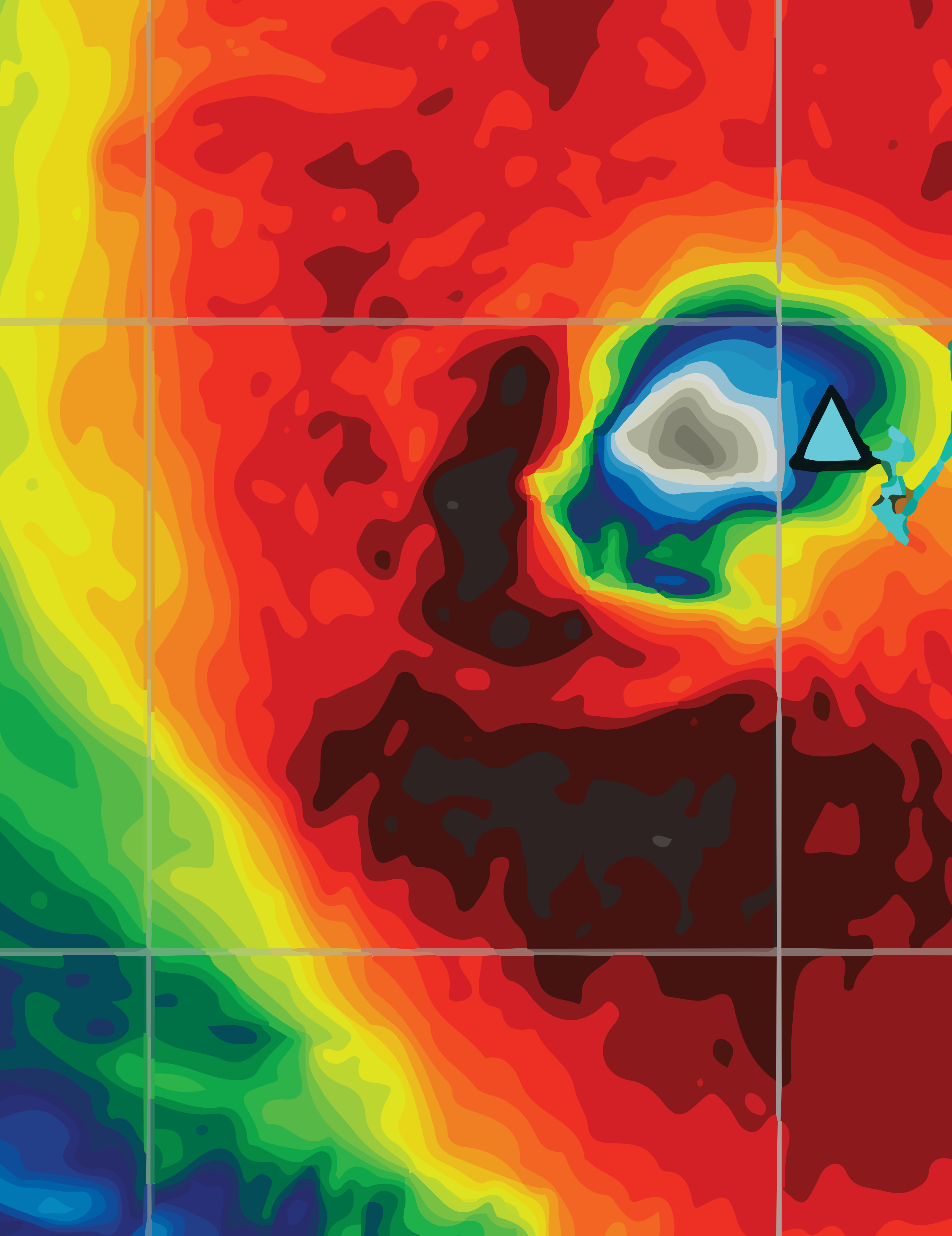

SAILDRONES SURFED THE EXTREME WINDS AND TOWERING WAVES OF A CATEGORY 4 STORM TO IMPROVE TROPICAL CYCLONE FORECASTS.

AN UNPRECEDENTED VIEW INSIDE A HURRICANE

BY GREGORY R. FOLTZ, CHIDONG ZHANG, CHRISTIAN MEINIG, JUN A. ZHANG, AND DONGXIAO ZHANG

This infrared image shows Hurricane Sam on 30 September 2021. The light blue line shows the track of Saildrone 1045 (SD-1045) from 04:00 UTC, and the light blue triangle show its location at 16:00 UTC on the same day (see Figure 4). Credit: Edoardo Mazza, University of Washington

Hurricanes are among the most severe natural hazards on Earth, often inflicting extensive damage and loss of life when they strike coastal communities. Seven of the 10 costliest natural disasters in U.S. history have been hurricanes, and the combination of continued coastal development and climate change will likely only increase the risks they pose and the damage they cause. Storms that intensify rapidly before landfall—such as Hurricanes Harvey, Michael, Laura, and Ida in just the past 5 years—pose particularly serious threats because they often reach major hurricane strength and leave limited time for preparations and evacuations.

The accuracy of hurricane track forecasts has steadily increased over the past several decades. However, intensity forecasts have seen uneven progress and significantly less improvement overall since 1990 [*Cangialosi et al.*, 2020]. Predicting rapid intensification, normally defined as an increase in maximum wind speed of at least 15.5 meters per second (30 knots) in 24 hours or less, remains extremely challenging and is a top research and forecast priority [*Gall et al.*, 2013; *Cangialosi et al.*, 2020]. If we are to continue improving hurricane intensity forecasts, we will need further advancements in our knowledge and understanding of the processes that affect hurricane intensification. We will also need expanded measurements of the ocean and the atmosphere ahead of and within hurricanes, as well as improvements to hurricane forecast models.

Last year, NOAA scientists deployed five saildrones in regions of the western Atlantic Ocean and the Caribbean Sea where hurricanes have been historically prevalent. In August, the scientists and pilots in charge of remotely operating the saildrones got a chance to practice positioning them ahead of Tropical Storms Fred and Grace. But the real test came in September as Hurricane Sam headed westward across the Atlantic.

Interactions of Air and Sea

The ocean and its interactions with the atmosphere play critical roles in hurricane intensification, supplying heat energy that is converted into the mechanical energy of a hurricane's winds. Turbulent heat exchange, called

Saildrones float dockside at Saint Thomas, U.S. Virgin Islands, awaiting deployment. In summer 2021, five saildrones chased three tropical storms—and one category 4 hurricane—in the Caribbean Sea and the Atlantic Ocean to capture the first close-up, sea surface views from inside such major storms. Credit: Saildrone Inc., © 2021

enthalpy flux, between the ocean and the atmosphere depends on sea surface temperature, air temperature, wind speed relative to the ocean surface, and humidity. The rate at which the enthalpy flux increases with increasing wind speed is not well known for hurricane force winds of 35 meters per second and higher [*Bell et al.*, 2012]. The uncertainty is due in large part to a scarcity of direct flux measurements at the ocean-atmosphere interface inside strong hurricanes.

The ocean exerts drag on surface and low-level winds, producing a shearing effect that reduces hurricanes' intensities. There are many open questions related to the processes that govern the resulting exchange of momentum between the ocean and a hurricane. For low to moderate winds (less than 30 meters per second), it is known that the ocean-atmosphere momentum exchange, or wind stress, increases with increasing wind speed. However, the rate of that change, called the drag coefficient, is less certain for winds exceeding hurricane strength. The drag coefficient is affected by wind speed; by wave age, slope, height, and direction; and likely by smaller-scale features such as sea spray and sea-foam [*Holthuijsen et al.*, 2012]. These processes are very difficult to measure directly in major hurricanes. Changes in the drag coefficient alter a hurricane's winds, and if those changes are not correct in forecast models, intensity predictions will be less accurate.

Most elements of the sustained global ocean observing system, such as Argo floats, surface drifting buoys, moored buoys, and ship-based measurements, are not optimized for hurricane observations: They sample conditions too infrequently, are spaced too far apart, or cannot be moved into the path of a hurricane [*Domingues et al.*, 2019]. In the past several years, remotely controlled ocean gliders, which profile the upper 1,000 meters of the ocean, have proven to be valuable in collecting hurricane observations from below. The inclusion of glider and other in situ ocean observations in forecast models has been shown to decrease forecast errors, increasing the models' value for hurricane intensity prediction [*Le Hénaff et al.*, 2021].

The view from above, in the form of ocean-atmosphere measurements from hurricane reconnaissance aircraft, is another central piece of the observational network [*Rogers*, 2021]. Targeted measurements from aircraft offer high-resolution data within and around specific hurricanes but are limited to a time span of only a few hours.

To help fill gaps in the observations from above and below, continuous measurements of air-sea enthalpy and momentum fluxes at the sea surface are required. These measurements are needed beginning days to weeks before a hurricane's arrival and continuing as a storm's eyewall, the ring of clouds and strong winds surrounding the eye, passes by, as well as in its wake. Our goal has been to collect the data needed to start filling these observational gaps.

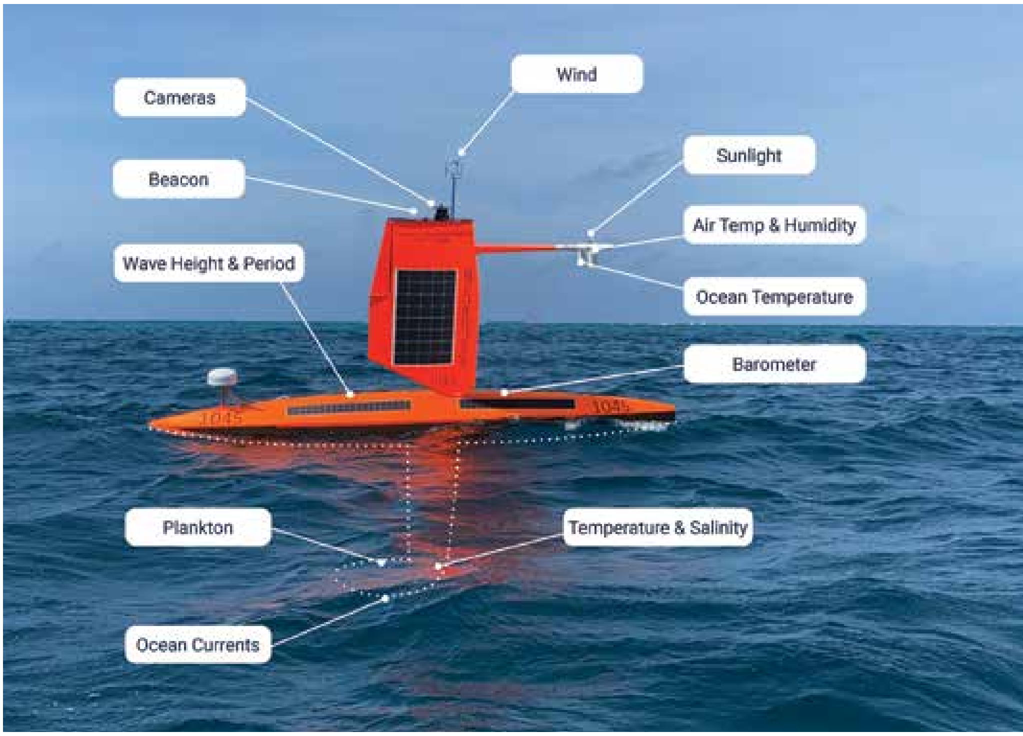

Fig. 1. The extreme weather saildrone developed for use in hurricanes is equipped with a camera and a suite of different sensors. Credit: NOAA and Saildrone Inc., © 2021

A Surface Drone Designed for Hurricanes

Engineering and technological advancements in uncrewed surface vehicles (USVs) over the past decade brought us closer to this goal [*Mitarai and McWilliams*, 2016; *Meinig et al.*, 2019], setting the stage for the experimental 2021 Saildrone hurricane mission. Saildrones are wind- and solar-powered USVs capable of acquiring and transmitting high-quality ocean-atmosphere measurements continuously in real time while traversing some of the harshest and most remote areas of the ocean for a year or more.

The extreme weather-equipped saildrones we used came about through a partnership between NOAA and Saildrone Inc. and emerged from successive rounds of testing and refinement of their design, scientific sensors, and real-time data acquisition and transfer capabilities (Figure 1).

Standard saildrones designed by Saildrone Inc. feature a rigid 5-meter-tall sail and are built to travel at up to 4 meters per second in low to moderate winds. In contrast, the emphasis for the extreme weather saildrones was on survival and transmission of high-quality data while sailing in the large, destructive breaking waves of a major hurricane.

To accomplish this, the sail was shortened to 3 meters, the center of mass of the entire saildrone was lowered to help prevent capsizing, and the durability of the sensors and their housings was improved so they could repel sea spray and survive complete submersion in large breaking waves. After a 3-month test mission in the

BY MID-AUGUST, A TRIO OF TROPICAL STORMS PROVIDED OPPORTUNITIES TO PRACTICE POSITIONING SAILDRONES AHEAD OF APPROACHING STORMS.

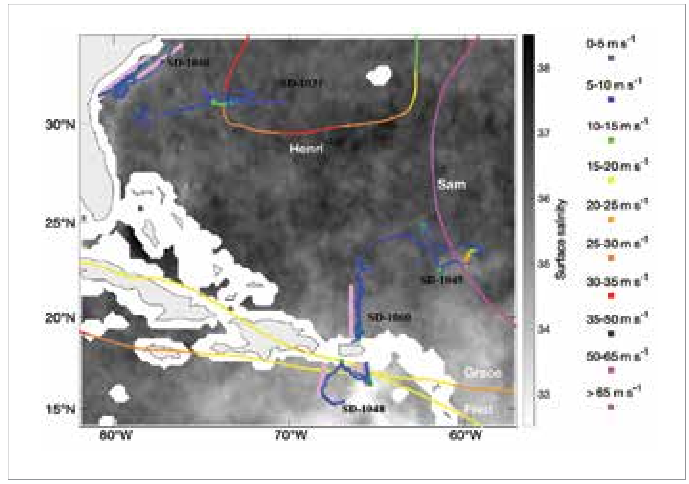

Fig. 3. The actual meandering saildrone trajectories for the 2021 season, labeled with saildrone numbers, are shown here (colors along these trajectories represent hourly averages of measured wind speed). Smooth lines trace the paths of tropical storms and hurricanes that passed close to a saildrone (colors represent maximum 1-minute sustained wind speed). Bold pink lines represent repeat tracks of underwater gliders. Background shading shows the satellite-measured surface salinity, averaged for 25–29 September 2021 prior to Hurricane Sam's arrival at SD-1045.

North Pacific during the winter of 2020–2021, the extreme weather saildrone was ready for a much more challenging test during the peak of the Atlantic hurricane season.

The strategy going into the 2021 mission was to position five saildrones in regions of the western Atlantic Ocean and the Caribbean Sea where, historically, hurricanes have been most likely to travel (Figure 2). During June and July 2021, three of the five saildrones were deployed from the U.S. Virgin Islands, and the other two were launched from Jacksonville, on the Atlantic coast of northern Florida. After initial vehicle and sensor testing, the mission officially started on 1 August.

Another goal of our project was to obtain simultaneous and nearly collocated measurements from saildrones and underwater gliders, which continuously measure temperature, salinity, and other ocean parameters in the uppermost kilometer of the ocean [*Miles et al.*, 2021]. Three of the saildrones were thus piloted to follow the paths of ocean gliders (pink lines in Figure 3). Raw data from all the saildrones and gliders were made available to global forecast centers in near-real time through the Global Telecommunication System and to the public through web interfaces.

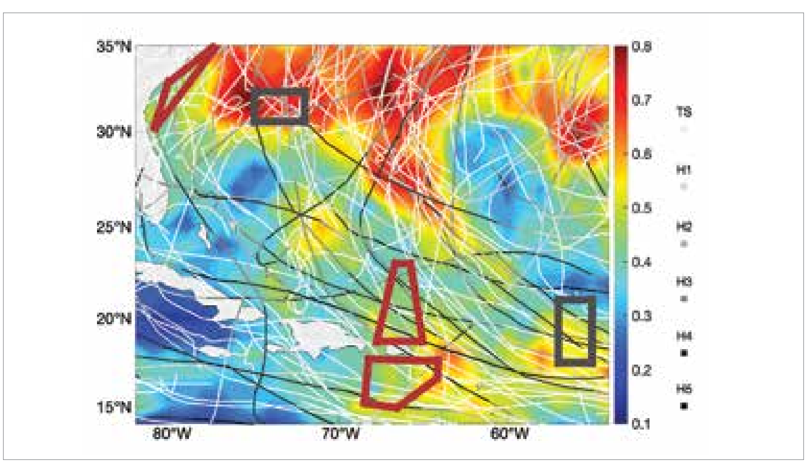

Fig. 2. The premission deployment plan called for one saildrone to patrol each of the regions shown here bounded by red or gray polygons. In the red regions, a saildrone followed an ocean glider traveling beneath the surface. In the gray regions, a saildrone traveled without a glider. The background coloration represents the probability of tropical storm force winds (>17.5 meters per second) occurring within a 200-kilometer radius during August-October, based on the averages of conditions from 2000 to 2019. Thin lines show paths of tropical cyclones during the same period, gray scale–coded by intensity: tropical storm (TS) to category 5 hurricane (H5).

Chasing Tropical Storms: A Warm-Up for Sam

By mid-August, a trio of tropical storms provided opportunities to practice positioning saildrones ahead of approaching storms (Figure 3). On 9 August, NOAA's National Hurricane Center (NHC) predicted that a tropical depression would grow near the Lesser Antilles and then intensify into Tropical Storm Fred as it passed south of Puerto Rico. We directed saildrone 1048 (SD-1048) northward to meet the approaching storm, and 2 days later, on 11 August, as Fred passed about 100 kilometers north of SD-1048, the drone recorded a maximum wind gust of 16 meters per second and a significant wave height (the average height of the highest one third of the waves) of 1.7 meters.

Two days later, NHC predicted that another tropical cyclone would form in the western Atlantic and would pass south of Puerto Rico in 2–3 days as Tropical Storm Grace on a track very similar to Fred's. The center of Grace passed directly over SD-1048 on 15 August. Although the storm had weakened to a tropical depression a few hours earlier, SD-1048 measured a maximum wind gust from Grace of 17 meters per second while SD-1060, situated north of Puerto Rico, observed a significant wave height of 2.5 meters.

The third opportunity came as Henri traveled westward in the central subtropical North Atlantic as a tropical storm starting on 16 August (Figure 3). Beginning on 15 August, SD-1031 was directed eastward to meet Henri, but near-surface winds were unfavorable, slowing the saildrone's progress. As a result, SD-1031 ended up on the weaker (western) side of Henri as its path curved northward. Although SD-1031 was only about 40 kilometers west of the storm's center as it passed on 20 August as a strong tropical storm (with maximum sustained wind speeds of 30 meters per second;

Henri later strengthened into a category 1 hurricane), the strongest wind gust measured by SD-1031 was only 20 meters per second, and significant wave heights reached 3.7 meters.

Into the Eye of Sam

A few weeks later, one of our saildrones got a chance to show what it could do inside a full-scale hurricane. On 20 September, an African easterly wave (a type of atmospheric low-pressure system) was forecast to move over the eastern tropical Atlantic and possibly intensify into a strong hurricane as it curved north of the Caribbean islands 7–10 days later. As the track forecast came into better focus, we realized that of the five saildrones, SD-1045 was in the best position to intercept the developing system. We kept SD-1045 on its slow eastward trajectory and watched as the tropical wave became a storm and then rapidly intensified into category 4 Hurricane Sam—the most powerful hurricane of the 2021 season.

On the night of 29 September, 9 days after the initial forecasts and 12 hours before Sam's predicted arrival, we planned for a complete transect of the hurricane's eye, with SD-1045 entering through the northeastern eyewall (normally the strongest part of a hurricane) and exiting through the south. However, we had no idea how the saildrone would respond to category 4 hurricane winds and waves, and we expected something on SD-1045 to fail as it traveled through dense clouds, torrential rain, and heavy windblown sea spray. Would it be the sail, one or more of the 12 scientific sensors, or the data transmission system?

When the first pictures and videos came in from Sam's northeastern eyewall during the morning of 30 September, it was clear that SD-1045 had hit its mark (Figure 4). No scientist had ever watched the towering waves and violent merging of the ocean and the atmosphere inside a major hurricane from the vantage of the ocean's surface. Most important, it appeared that all sensors were working perfectly, and the valuable data continued to arrive without interruption as SD-1045 passed inside the eastern eyewall and out through the southern half of the storm.

For 3 hours, SD-1045 weathered sustained hurricane force winds, with maximum gusts of 57 meters per sec-

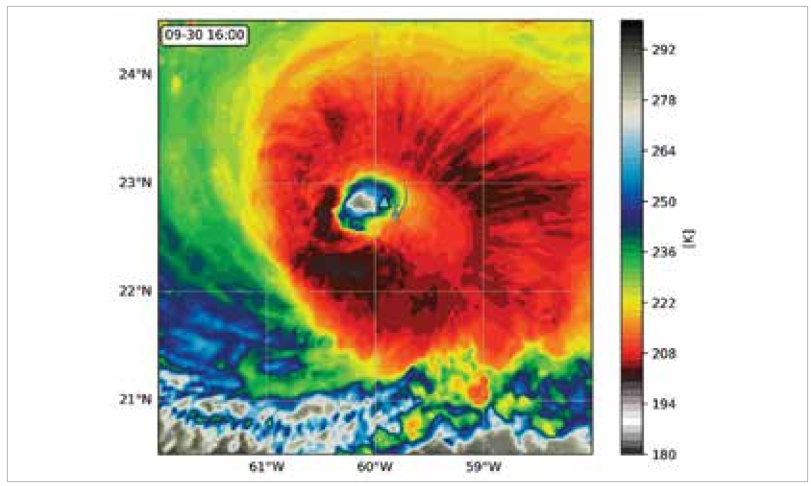

Fig. 4. This infrared image taken by a NOAA geostationary satellite shows Hurricane Sam at 16:00 UTC on 30 September 2021. The color scale corresponds to cloud-top temperature in kelvins. The light blue triangle represents the location of SD-1045 at that time, and the light blue line shows the saildrone's track starting at 04:00 UTC on the same day. Credit: Edoardo Mazza, University of Washington

SD-1045 snapped this photo as it plunged through Hurricane Sam in September 2021. Credit: Saildrone Inc., © 2021 ond (128 miles per hour; Figure 5). The significant wave height reached 14 meters, taller than a four-story building, and the highest wave measured 27.6 meters (90 feet). In the days to follow, additional data from SD-1045 further detailed the extreme conditions it faced, including sliding down giant wave faces at speeds of up to 13 meters per second and flipping over completely several times as waves crashed over it.

What We're Finding and Where We're Going

Hurricanes generally cool the ocean's surface, so it was surprising that SD-1045's data showed that the seasurface did not cool during the first half of the storm. Because of this, the ocean transferred more heat energy to the atmosphere, which maintained Sam's high intensity. The relatively warm sea surface might have resulted from Sam passing over the northern edge of the Amazon-Orinoco river low-salinity plume (lighter gray shading in Figure 3), which is known to inhibit hurricane-induced ocean cooling [*Reul et al.*, 2014].

From satellite data and a NOAA reconnaissance flight into Sam the day before, it appeared that SD-1045 may have traveled through an eyewall mesovortex, an area of high-speed rotation with a diameter of a few kilometers, that formed at the edge of the eye. These features often occur in strong hurricanes and can contribute to the formation of tornadoes when a hurricane makes landfall. The saildrone data will be analyzed to determine the possible influence of a mesovortex on near-surface atmospheric conditions such as wind and humidity.

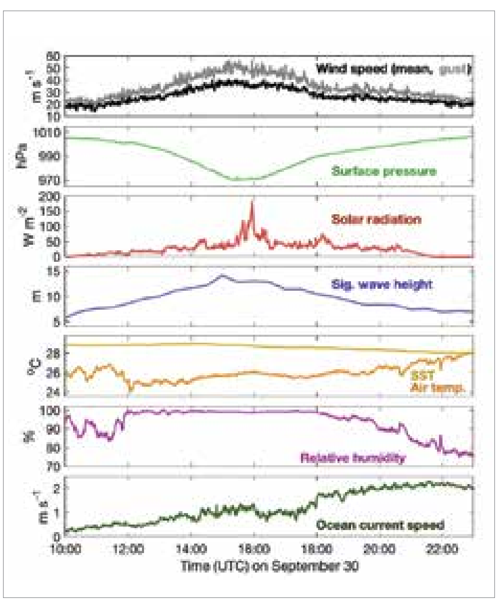

Fig. 5. These plots show 1-minute-averaged data from SD-1045 as it sailed through Hurricane Sam and collected observations of wind speed (in meters per second, m s^{-1}), surface air pressure (in hectopascals, hPa), solar radiation (in watts per meter squared, W m^{-2}), significant wave height, sea surface and air temperatures, relative humidity, and ocean current speed at a depth of 6 meters.

Additional ongoing analyses of SD-1045's data include comparisons to satellite, aircraft, and other in situ data. We are also assessing hurricane forecast model outputs and evaluating the potential to integrate saildrone data into these models to improve intensity forecasts. We will make direct calculations of the air-sea momentum flux and drag coefficient in Sam using 3D 20-hertz wind measurements and wave data obtained by the saildrone. Such high-frequency wind measurements, which are sensitive to quick wind changes, are needed because of the rapid, turbulent nature of momentum mixing.

For the 2022 Atlantic hurricane season, we have expanded coordination between saildrones and other elements of the observing system, including ocean gliders and small uncrewed aircraft systems [*Cione et al.*, 2020], as well as dropsondes and ocean probes deployed from hurricane reconnaissance aircraft.

Overall, our goal continues to be the acquisition of high-quality data on ocean-atmosphere conditions and interactions that will help improve hurricane models and intensity forecasts. The successful 2021 hurricane saildrone mission demonstrated a valuable new tool for that purpose and opened the door to a new realm of robotic ocean-observing capabilities.

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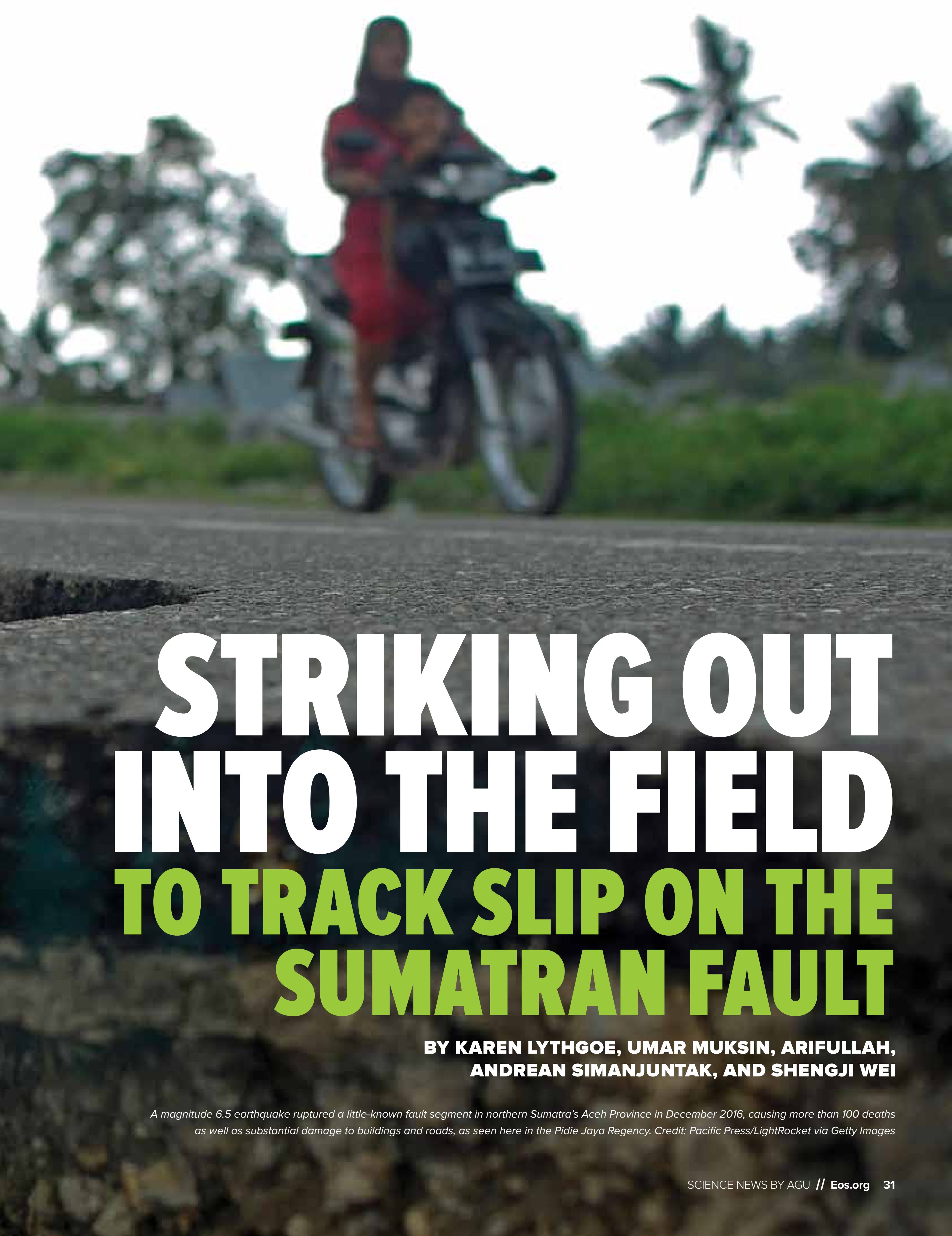
An international team overcame many challenges to deploy a dense seismic network along an understudied fault system that poses hazards to millions in Indonesia.



STRIKING OUT INTO THE FIELD

TO TRACK SLIP ON THE SUMATRAN FAULT

BY KAREN LYTHGOE, UMAR MUKSIN, ARIFULLAH, ANDREAN SIMANJUNTAK, AND SHENGJI WEI

A magnitude 6.5 earthquake ruptured a little-known fault segment in northern Sumatra's Aceh Province in December 2016, causing more than 100 deaths as well as substantial damage to buildings and roads, as seen here in the Pidie Jaya Regency. Credit: Pacific Press/LightRocket via Getty Images

The surface trace of the Sumatran fault cuts across the road between the communities of Mane and Tangse in Aceh, Indonesia. Credit: Qibin Shi

The Sunda subduction zone at Sumatra is well known as the source of the devastating 2004 Boxing Day earthquake and tsunami that inundated shorelines around the Indian Ocean. Geophysicists have studied this subduction zone, which parallels the coasts of western and southern Indonesian islands (Sumatra, Java, and others) offshore for much of its more than 5,000-kilometer length, in detail, especially since 2004. Far less known, however, is the Sumatran fault system, an onshore component of the tectonic boundary between the Indo-Australian plate to the west and the Burma and Sunda minor plates to the east. This system is one of the longest and most active strike-slip fault zones in the world, running along the 1,900-kilometer length of Sumatra.

The most seismically active region of the island is Aceh, in the far north of Sumatra. The 2004 tsunami severely affected Aceh, and its 4 million people remain vulnerable to earthquakes—particularly on the Sumatran fault and other nearby crustal faults, which run directly below dense population centers. Most recently, a magnitude 6.5 earthquake in December 2016 killed more than 100 people and caused an estimated $139 million in economic losses [*Muzli et al.*, 2018]. A lot of seismicity, including the 2016 earthquake, occurs on fault segments that are poorly understood or often even unidentified before they are revealed by damaging seismic events [*Muksin et al.*, 2019].

Earthquakes are produced by sudden slippage along faults caused by the buildup of stress. The occurrences and sizes of earthquakes are governed by the sizes of the areas on faults that are locked (accumulating stress that eventually will be released in an earthquake) or creeping (gradually moving, which reduces or prevents stress buildup). A detailed understanding of the distribution of creeping and locked areas in the Sumatran fault system is still missing, largely because of a paucity of geophysical monitoring. This shortage has limited the evaluation of seismic hazard and the understanding of activity and tectonic structures along the fault system.

A lot of seismicity occurs on fault segments that are poorly understood or often even unidentified before they are revealed by damaging seismic events.

We recently embarked on an effort to unravel key properties of the Sumatran fault system, using data acquired by a dense seismic network in the Aceh region. Beginning in January 2020, the seismology teams at the Earth Observatory of Singapore and at Universitas Syiah Kuala in Banda Aceh, Indonesia, deployed the first phase of the network, which comprises an array of more than 130 seismic nodes and several broadband seismometers. Many of the instruments were maintained until July 2021. The 18 months of data we collected will be invaluable in better understanding this major fault system.

Creeping and Locking in Aceh

Geodetic observations have revealed that a relatively straight portion of the Sumatran fault, running northwest-southeast through part of Aceh, is creeping [*Ito et al.*, 2012; *Tong et al.*, 2018] (Figure 1). This creeping section is bound on either end by fault bifurcations where the fault splits into two segments [*Sieh and Natawidjaja*, 2000]. At the northwestern split, the active Seulimeum and relatively inactive Aceh fault branches diverge, with the Seulimeum following a slightly more northerly trace.

Past seismic activity along the locked Seulimeum segment is evident from escarpments and offsets in stream courses. This fault segment was the source of a damaging magnitude 7.3 earthquake in 1936 (and possibly a magnitude 6.5 event in 1964), although the future hazard it poses is unclear. The inferred creeping segment hosted two recent magnitude 6 earthquakes, one in 1997 and one in 2013, and continues to exhibit very active microseismicity (very small earthquakes) [*Muksin et al.*, 2019], These intriguing facts suggest that the fault here may be able both to host large earthquakes and to slip gradually. More analysis is needed to further reveal the slip distributions of the magnitude 6 earthquakes as well as how fault slip is modulated between these competing mechanisms. To help address these vital unknowns, we deployed our instruments around both the creeping segment and the Seulimeum fault branch.

A common way to confirm whether a fault is creeping and to measure the rate at which it is creeping is to look for repeating low-magnitude earthquakes, which are produced by small, locked patches of the fault that are loaded by the surrounding creeping region. *Muksin et al.* [2019] used a temporary deployment of seismic instruments in Aceh to detect a few hundred seismic events on the inferred creeping segment; however, the geographic density of these instruments and the deployment time were not sufficient to detect repeating earthquakes. Previous studies in the region also did not acquire sufficient data to constrain the distribution of creeping and locked areas of the Sumatran fault or to interpret fault morphology, structure, and frictional properties.

This information is crucial to modeling fault rupture and thus assessing seismic risk accurately. Our densely sited nodal array presents an opportunity to detect smaller-magnitude seismicity below the sensitivity of Indonesia's sparse national broadband seismic network. To maximize the opportunity to capture repeating earthquakes, we deployed our instruments for 18 months—a relatively long-duration deployment for a nodal array.

Into the Rain Forest

In early 2020, we began the first deployment of our nodal array in Sumatra. Our team included research fellows and master's and Ph.D. students from both the Earth Observatory of Singapore and Universitas Syiah Kuala. For many on the team, it was the first time they were participating in seismic data acquisition in the field, so it offered an opportunity to appreciate the value of hard-earned seismic data—far more so than simply downloading data from a database does.

We set up our data center (as well as our planning and training operations and our instrument charging stations) at the Tsunami and Disaster Mitigation Research Center in Banda Aceh, having shipped the seismic nodes and other equipment over from Singapore. Nodes are small, low-cost, self-contained seismic monitoring instruments that in contrast to expensive broadband seismometers, can be rapidly deployed across a wide range of settings. After several days of training and planning, we dispersed around Aceh in four groups, ensuring a mix of people from both institutions in each group.

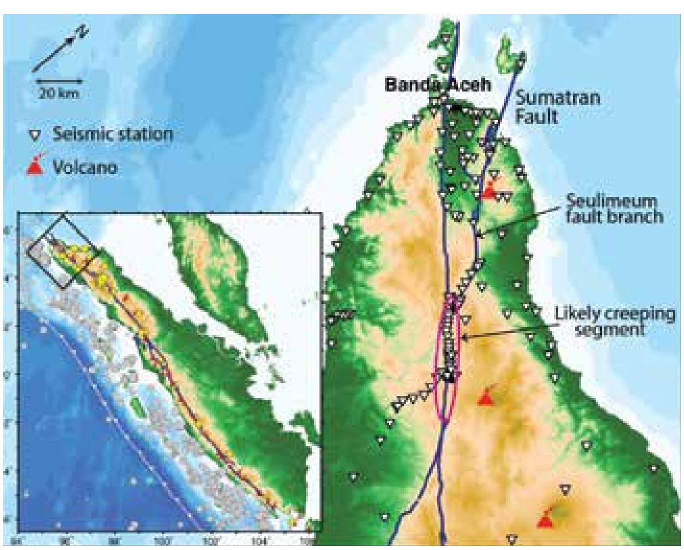


Fig. 1. The trace of the Sumatran fault, including the Seulimeum branch and the likely creeping segment, and the locations where nodal seismometers were deployed and of several volcanoes are shown in this map. The inset map of Sumatra indicates earthquakes greater than magnitude 5.5 associated with the Sumatran fault system (yellow) and on the subduction system (gray).

Each team first met with local police and village heads to explain our project and engage them in the deployment. We then had to find sites for all of our nodes. We had scoped out potential locations using satellite imagery to identify sites that would be accessible by roads or tracks, but the real-world deployments were another, far trickier matter!

A common way to confirm whether a fault is creeping and to measure the rate at which it is creeping is to look for repeating low-magnitude earthquakes.

This difficulty arose partly because working in the rain forest brought many challenges. In addition to frequent encounters with leeches, biting ants, and mosquitoes, for example, the dense forest cover made it difficult for the instruments to obtain the GPS satellite signals needed to routinely calibrate and correct their internal clocks (without which we would not have accurate and consistent timing for detected seismic signals). We learned to seek out small plantations with regularly spaced crops of palm or cocoa trees when possible, as they offered less tree cover. The fieldwork wasn't all about problem-solving, however. We also greatly enjoyed the bounty of the forest, gorging on such tropical fruits as durian, rambutan, and mangosteen straight from the trees.

Often, we relied on local residents to assist us in finding sites or to host a node on their land. Talking with locals wasn't always straightforward, though, because many people in rural Aceh do not speak the official Indonesian language and at least 10 different local languages are spoken. Having diverse teams that included people from

In February 2020, the Singapore team members were grounded and unable to travel, so it fell to the Indonesian team to continue the regular fieldwork and take over control and maintenance of the equipment.

Heavy rainfalls in June 2020 triggered a landslide that covered roughly 50 meters of roadway in Geumpang, Aceh, Indonesia. Credit: Andrean Simanjuntak

Aceh proved very fruitful for finding the best way to communicate. We were also fortunate to work with local drivers, including a retired comedian who is well known in the villages.

Many locals we talked to were familiar with earthquakes, having often experienced ground shaking, and were happy to contribute to earthquake research by hosting a seismometer on their land. Along the western coast of the island, residents had strong memories of the devastating 2004 tsunami, and several people we met had lost family members and livelihoods in the disaster. Hearing these firsthand accounts reinforced to our team, particularly the members from Singapore who had not experienced earthquakes and tsunamis before, the harsh realities of living with the threat of natural hazards, as well as the importance of our work.

Cue a Pandemic

The seismic nodes we used, chosen primarily for their relatively low cost and ease of deployment, made a survey of this scale affordable and practical. However, the nodes were originally designed for use in short-duration commercial surveys, and their battery life does not extend beyond 5 weeks. This limitation meant we had to go back into the field every few weeks to replace the instruments. After the nodes' batteries were recharged and their data were harvested, they were redeployed in the next cycle.

What no one saw coming was the COVID-19 pandemic. After the first recharging cycle, in February 2020, the Singapore team members were grounded and unable to travel for the rest of the 18-month deployment. It fell to the Indonesian team to continue the regular fieldwork and take over control and maintenance of the equipment. With tremendous effort and commitment, the members navigated local restrictions and enhanced their safety measures to do just that. Despite some periods when local restrictions prohibited fieldwork, the researchers managed to get into the field to swap out the nodes on average every 5 weeks. They also battled some extreme weather, at times facing heavy rains followed by landslides that occasionally blocked access to certain sites.

Frequent communication was critical to our team's success in the first few months of data acquisition, when the team members were becoming acquainted with the procedures, equipment, and rhythms of the project. This was especially true right after pandemic lockdowns were instituted, when the team members in Indonesia, who were just getting familiar with the equipment, suddenly had to sort out instrument problems on their own.

Thankfully, we had all met in person during the first few field cycles, forming good relationships and making sure everyone had at least minimum knowledge of how the instruments worked. Signal permitting, we used the WhatsApp messaging application to assist team members in the field with troubleshooting, for example, if there were problems initializing a node or finding a previous site. Back in the data center in Banda Aceh, the Singapore and Indonesia teams stayed connected by remotely logging in to the data system and through Zoom video chats. These chats helped to solve problems that came up when harvesting data from the nodes and with analyzing the data and planning adjustments for the next deployment cycle.

A New Chapter in Aceh Seismology

At the end of the first phase of the project in July 2021, we recovered 131 of the 138 nodes deployed in the field. The other seven were lost to machinery (e.g., one was dug up at a new construction site) or stolen or simply could not be found again. The pandemic caused us to adapt our operations on the fly and to adjust our goals for continuing work. Instead of moving the nodes to a new set of sites elsewhere in Aceh after the first deployment phase, as originally planned, we had to postpone the second phase.

Master's student Wiwik Ayu Ningsih deploys a nodal seismometer at a site near Callang, Aceh. Credit: Karen Lythgoe

These data will open a new chapter of seismology research in Aceh and help to address key questions about the Sumatran fault system.

Nonetheless, we have already gathered a unique and extensive new data set covering a major fault system that has historically received insufficient monitoring. These data will open a new chapter of seismology research in Aceh and help to address key questions about the Sumatran fault system. We expect, for example, that the detected seismicity will enable more accurate definition of the creeping and locking distribution along this section of the fault. The data may also help reveal how the creeping fault segment connects with the locked Seulimeum fault branch below the surface, what the maximum possible magnitude of future earthquakes hosted on this fault segment may be, and what fault zone structure looks like in detail and how that structure relates to both large earthquakes and creep.

The new data could also shed light on a tectonic puzzle: The Sumatran fault runs along a line of active arc volcanoes, the shape and location of which are highly correlated with the shape of the offshore subduction trench. How the arc-fault system interacts remains an open question. Information on how the depth of the seismogenic zone varies in relationship to volcanoes could prove useful, as could the basic observation of where the fault lies at depth rather than just its surface trace.

In our work with the data, we have already detected and located thousands of small earthquakes that are allowing us, for example, to map active fault branches clearly and to observe trends in seismicity with depth on the fault. And there is far more work to do. Ultimately, these new measurements represent the fruits of a successful international collaboration that effectively engaged local communities and overcame challenges, and they will be used to better understand the risks this hazardous fault system poses to those very same communities and to others across this seismically active area.

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Arctic Unicorns *and the* Secret Sounds *of a* Glacial Fjord

A SEISMOMETER DEPLOYED NEAR THE CALVING FRONT OF A GREENLAND GLACIER HAS OPENED A NEW AVENUE TO STUDY HIDDEN PROCESSES AND THE BEHAVIOR OF FJORD-DWELLING WILDLIFE.

By Evgeny A. Podolskiy

In early August 2019, an Inuit whale hunter working the coastal waters of northwestern Greenland spotted an orange object floating toward the Arctic Ocean. The object turned out to be a lost ocean bottom seismometer (OBS), an instrument typically used to study earthquakes near subduction zones and other seismicity deep below the ocean surface. For me, sitting halfway around the world in Japan, and my colleagues, news of its recovery brought a wave of relief along with reassurance that months of work had not been buried on the seafloor or washed out to sea.

Weeks earlier, we had dropped the instrument several kilometers away into the waters of Bowdoin Fjord, an inlet off the larger, 100-kilometer-long Inglefield Bredning Fjord, to test whether we could make seismic observations amid harsh and noisy polar conditions, a long-standing challenge, and to eavesdrop on nearby Bowdoin Glacier [*Podolskiy et al.*, 2021a]. Marine-terminating, or tidewater, glaciers like Bowdoin crack and split to form crevasses and calve (i.e., produce) icebergs, and meltwater gurgling down the crevasses makes sounds like a bathtub draining. Meanwhile, water flowing beneath glaciers can contribute to seismic tremor, and basal sliding can cause icequakes.

We also wanted to monitor the underwater sounds of glacier fjords and the vocalizations of discreet and shy narwhals—the elusive whales known as "Arctic unicorns"

Researchers head toward the calving front of Bowdoin Glacier in northwestern Greenland on 21 July 2019 to deploy an ocean bottom seismometer (OBS). Credit: Evgeny A. Podolskiy for their extraordinary tusks. For reasons no one fully understands, narwhals, which navigate, communicate, and find food using sound, are sometimes attracted to these noisy environments [*Podolskiy and Sugiyama*, 2020], although this behavior is not always observed [*Heide-Jørgensen et al.,* 2020]. To record their sounds in hopes of understanding their behavior, we had to get very close, because narwhals' vocal repertoire often comprises ultrasonic frequencies that are inaudible to humans and attenuate rapidly with distance.

Innovative ways are needed to monitor glaciers, fjords, and endemic wildlife in remote Arctic locations. Such knowledge is important so that we can track and better predict the effects of regional and global climate change. It also may benefit Indigenous Inuit communities who traditionally hunt and subsist on resources provided by narwhals and other fjord-dwelling marine wildlife.

CHALLENGES OF UNDERWATER CRYOSEISMOLOGY

Passive seismic monitoring—which involves sensors that receive environmental signals rather than signals from active sources like hammers or explosions—has revolutionized our ability to characterize glaciological processes by recording vibrations from icequakes and tremors [*Podolskiy and Walter*, 2016]. However, interpreting the data these instruments collect and, indeed, deploying them in glacierized Arctic environments in the first place are not simple tasks.

Strong winds and extensive surface ice cracking make for an extremely noisy seismological environment in which to record data [*Podolskiy et al.*, 2016]. During the Cold War, the United States abandoned its efforts to monitor seismicity from nuclear tests on Greenland's coasts because the noise from natural causes was so pervasive [*Podolskiy et al.*, 2021b].

Acquiring direct measurements on rapidly changing, fast flowing, calving glaciers involves dangerous fieldwork on heavily crevassed ice in a harsh climate. And there is always the possibility of losing instruments if the ice on which they sit calves into the fjord. Iceberg calving can also make accessing a glacier from the sea dangerous or impossible, although there can be windows of time between major calving events that allow boats or helicopters to approach the calving front for quick operations.

Despite these challenges, the tempting opportunity to monitor an active glacier, as well as recent advancements in deepwater technology and the realization that seafloor seismometers are sensitive to both seismic waves and whale songs [*Dréo et al.,* 2019], gave me the idea to dramatically change our perspective. Rather than placing instruments at only the noisy surface, we could deploy an OBS in the quieter submarine environment far below. From there, we could eavesdrop on sounds coming from the calving front of a marine-terminating glacier—one of the least accessible environments in the cryosphere—and detect who was visiting it.

> The plan was to drop a single (very expensive) ocean bottom seismometer (OBS) system in front of an actively calving glacier during a window between major kilometer-scale calving events.

A WARM-UP OFF JAPAN

The plan was to drop a single (very expensive) OBS system over the side of a small boat right in front of an actively calving glacier during a window between major kilometer-scale calving events. These events can completely fill the width of a fjord with hundred-meter-wide icebergs and impassable mélange, a floating mixture of smaller icebergs and sea ice.

In July 2019, the author assembles the internal parts of an OBS in a hunter's summer house in Qaanaaq village, northwestern Greenland, before deploying it. Credit: Izumi Asaji

Not only would there be physical hazards facing this deployment, but also there was the added complication that I—a glaciologist more comfortable working on ice who always gets seasick on research vessels—would be leading a team of colleagues who, like me, had little experience working with OBSs. All this added up to the need for a practice run of sorts, so that I could learn how to assemble and operate an OBS on my own in difficult conditions.

The only way to learn the ins and outs of OBS preparation, deployment, and retrieval methods was to do it firsthand, an opportunity I got thanks to Yoshio Murai, a marine seismologist at Hokkaido University. Murai invited me to participate in a research cruise focused on studying the locked segment of the subduction zone off eastern Hokkaido Island, near Kushiro, Japan, which has the potential to generate major earthquakes with accompanying tsunamis.

In spring 2019, after assembling in the laboratory 10 OBS instruments—worth about half a million dollars in total— we deployed them from a large research vessel to depths of up to 3 kilometers in the Pacific Ocean, with the support of technicians operating a crane. Three months later, we retrieved the OBSs by sending them an acoustic command to release their anchoring ballasts and float to the surface.

Soon after my successful warm-up run at Hokkaido, we sent a single OBS system—comprising seismic and other sensors—to Greenland for the pilot test in Bowdoin Fjord, a key summering ground for narwhals [*Podolskiy and Sugiyama*, 2020]. This time, however, I did not have an expert with 2 decades of OBS experience by my side or a research vessel, a crane, or even a proper port to undertake the task.

TAKING THE PLUNGE IN GREENLAND

In July 2019, I set up an improvised workshop in the living room of an Inuit hunter's summer house in Qaanaaq, a settlement in northwestern Greenland with roughly 600 inhabitants. There, "on the edge of the livable world" at 77.46°N, as *Hastrup* [2019] has described it, I assembled the internal components of the OBS—the seismometer itself and the data recorder, batteries, and wiring—and vacuum-sealed them in a protected glass sphere.

On 21 July, my colleagues and I used a truck and a tiny inflatable raft to move all our equipment piece by piece from Qaanaaq to a small boat, which we motored to a small, rock-walled bay in 20-kilometer-long Bowdoin Fjord. It was the same bay where explorer Robert Peary anchored the *Falcon* in 1893. During that expedition nearly 130 years ago, Peary and his crew collected observations that document that Bowdoin Glacier was then 3 kilometers longer than it is today. In summer 2019, as we sheltered in the bay, which was still bloodstained from the day before when local hunters had butchered a narwhal and seals, I made final preparations before the deployment, installing a high-frequency hydrophone and a thermometer for recording narwhal vocalizations and water temperature. All our eggs were now in one basket, so to speak.

Finally, my colleagues, our local guides, and I reached the middle of the fjord, several hundred meters from the glacier's calving front. Here capsizing icebergs generate meters-high tsunamis much more frequently than they occur in any subduction zone, so we had to work quickly to reduce our risk of capsizing or being swept away.

> The ambient seismic noise recorded by our OBS showed that these instruments can detect continuous seismic vibrations radiating from a glacier sliding against the rock below.

As we were without a crane, we tied the OBS with rope to a metal pole held between two boats to hoist the delicate system over the water without damaging the sensitive ballast release mechanism. I then cut the rope, and the heavy instrument, together with half a year of preparations, plunged into the water. It reached the bottom of the fjord 243 meters below about 3 minutes later, ready to begin collecting data. At this depth, we assumed the OBS would be safe from the monster icebergs that occasionally calve into the fjord until we could retrieve it a couple of weeks later.

LOST AND FOUND

Because of unforeseen delays, including a major calving event on 29 July that blocked access to the fjord for days, I was unable to visit it to "call" the instrument back to the surface before my flight out of Greenland. I asked a colleague, Naoya Kanna, an oceanographer at the University of Tokyo who is experienced in mooring deployments, to do the honors, knowing the OBS retrieval was in good hands. On 6 August, however, the long-awaited morning of the retrieval, as I made my morning coffee at home back in Japan before my kids woke up, I opened an email from Naoya that read, "I sent the 'release' command to your OBS, but it never came up."

After a satellite phone call to follow up, it was clear that something had gone wrong. Did I fail to prepare the instrument correctly? Did a

The calving front of Bowdoin Glacier is seen from a helicopter on 29 July 2019. The OBS was located at the bottom of the fjord, 243 meters below the floating ice mélange and icebergs near the center of this photograph. Credit: Evgeny A. Podolskiy

massive iceberg scrape it off the ocean bottom after all, or did icebergs passing above deposit rock debris that buried the instrument? Did curious seals damage the cables? I thought I might never know. My coffee was no longer satisfying after such an extreme disappointment.

Three days later, I received another, far more welcome message from Naoya: "I am happy to tell you that a hunter found your OBS in the fjord."

An Inuit hunter, Rusmus Daorana, found our wayward instrument floating about 7 kilometers from the deployment location and left it on the coast, where Naoya found it—coated in fine glacial till—and retrieved it. The hard drives from the OBS reached me a month later, revealing that the instrument had returned to the surface about 10 hours after Naoya sent the release command. Our best guess is that the OBS sank into soft sediment (hence the till) at the bottom of the fjord, where sediment from glacial runoff accumulates very rapidly, which slowed the release mechanism. Clearly, this is a factor we need to consider in future experiments [*Podolskiy et al.*, 2021a].

Conducting cryoseismology underwater for the first time was not easy, but our experience demonstrated the tremendous potential of the approach.

SURVEYING AN ARCTIC SOUNDSCAPE

All told, the hard drives contained 432 gigabytes of continuous seismoacoustic signals from icequakes, narwhals, and other exciting phenomena. While the OBS was collecting data, an instrumented mooring 1 kilometer from the glacial terminus recorded a spike in the speed of the water current flowing out of the fjord. This spike coincided with the 29 July calving event, which was recorded in our seismoacoustic data and would have displaced a large amount of water toward the mooring. These data also represented the first underwater recording—and the closest recording of any kind to date—of a powerful glacial earthquake, which was produced by the calving event and was seismically detectable 500 kilometers away [*Podolskiy et al.*, 2021a, 2021b].

Narwhals swim near sea ice in Arctic Bay, Nunavut, Canada. Credit: All Canada Photos/Alamy Stock Photo

The OBS temperature record, meanwhile, indicated dropping deep-water temperatures at the fjord floor over the duration of the deployment, consistent with an ongoing extreme melt event at the glacier's surface amid abnormally high air temperatures. This drop suggested that the input of fresh and relatively light glacial meltwater had induced a change in the stratification of the water in the fjord [*Podolskiy et al.*, 2021a]. Among other effects, such shifts may influence melting along the ice cliff as well as the biogeochemistry of fjord waters.

Our analysis of the ambient seismic noise recorded by our OBS showed that these instruments can detect continuous seismic vibrations, reminiscent of those from slow earthquakes, radiating from a glacier sliding against the rock below [*Podolskiy et al.*, 2021b]. This information may tell us about a glacier's speed and help to constrain conditions—such as friction and the effective pressure of the overlying ice—at its base. The conditions of basal sliding at fast moving glaciers, which have important implications for projections of ice discharge and sea level, have long been unclear.

It is nearly impossible to study these conditions directly, which would require hazardous drilling near the crevassed glacial terminus. Drone mapping and GPS and radar observations, meanwhile, are collected over shorter time periods, are exposed to hazards at the surface, and require a lot of effort by operators. The ability of an underwater seismometer to hear how fast a glacier slides offers a novel way to collect continuous information about glacier motion in the noisy and harsh polar environment. Not only that, but OBSs may offer a means of detecting whether a tidewater glacier is detaching from its rocky base and becoming a floating ice shelf, a transition that affects glacial dynamics and retreat rates. This is a possibility to explore with further deployments.

It has long been known that glacial calving makes a great deal of noise underwater (although this noise has likely increased recently as glacial earthquakes have become more frequent than they were several decades ago). Indeed, our analyses of the recordings from the major July calving event suggest that calving produces some of the loudest sounds in the Arctic Ocean, like underwater explosions of several tons of TNT [*Podolskiy et al.*, 2022]. I wondered what impacts such loud sounds might have on marine mammals. From our visual observations from the boats, we knew there were mammals, including narwhals and seals, in the fjord during our campaign, but were they near the glacier during that 30-minute calving event?

In the seismoacoustic data, at the beginning of the calving event, I found tiny, but characteristic, ultrasound clicks and buzzes produced by narwhals swimming very close to the calving front. Following technical guidance from the U.S. National Marine Fisheries Service on estimating the risk of auditory injury in marine mammals, we found that glacial calving sounds are so loud

The research team drops the OBS into the water 640 meters from the calving front of Bowdoin Glacier on 21 July 2019. The portion of the ice cliff visible in the background is about 30 meters tall and extends about 250 meters underwater. Credit: Izumi Asaji

that they might damage the hearing of narwhals and seals [*Podolskiy et al.*, 2022]. This observation further highlights that an OBS can be a truly multipurpose tool in glacial settings.

MUCH MORE TO LEARN

For all the interesting observations we collected from the bottom of Bowdoin Fjord in 2019, many new questions have arisen and others remain unanswered. For example, despite our idea that the intense noise produced by calving glaciers and capsizing icebergs could harm narwhals and seals, these animals' resilience to noise exposure is still unclear. The effects of anthropogenic underwater noise, such as that from seismic air guns, on marine animals have been extensively discussed [*Protection of the Arctic Marine Environment*, 2019], but no studies have focused on loud noises from icebergs and glaciers.

Why are narwhals attracted to the dangerous calving front in the first place? It is known that subglacial meltwater plumes attract foraging birds and seals [*Lydersen et al.*, 2014] and that prey for narwhals—like Arctic cod, Greenland halibut, and other fish—inhabit glacial fjords in this region. However, some studies have suggested that narwhals do not forage much in summer, so their attraction to this noisy region at this time of year remains an enigma [e.g., *Podolskiy and Sugiyama*, 2020].

With respect to glaciers, our data showed continuous seismic tremor in summer, which is indicative of basal sliding, but does this seismic rumble also occur in winter? And does it occur at other glaciers? If so, what does this behavior tell us about how these glaciers are being affected by climate change? Also, can we detect noise from subglacial meltwater discharge and possibly determine the volume of runoff by analyzing this noise? Similarly, can we detect noise with an OBS from an ice cliff melting below the water as pressurized air bubbles are released [e.g., *Deane et al.,* 2019]?

These are all questions we are looking to address further with the limited amount of data collected during our 2019 deployment, as well as with additional data from future deployments. Ultimately, we hope to develop a long-term underwater monitoring network in the area and to integrate it with complementary multipurpose campaigns (e.g., for glacier monitoring and animal sightings).

Conducting cryoseismology underwater for the first time was not easy, but our experience demonstrated the tremendous potential of the approach to help us better understand processes and changes occurring in glacial fjords and the behavior of fjord inhabitants. These data should help scientists trying to piece together influences of tidewater glaciers on marine conditions and sea level rise, as well as Arctic communities for whom knowledge of local environments and wildlife is vital to sustaining their ways of life.

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Paired Gas Measurements: A New Biogeochemical Tracer?

Researchers studied deciduous trees with a new analytical technique to help unravel the processes that contribute to soil respiration. Credit: Dany Sternfeld/Flickr, CC BY-NC-ND 2.0 (bit.ly/ccbyncnd2-0)

Soil respiration is fundamental in terrestrial ecosystems, where plants and microbes dominate the production of carbon dioxide released to the atmosphere. Scientific understanding of the processes underpinning soil respiration remains incomplete, limiting our ability to accurately predict how the global carbon cycle will respond to the changing climate.

To gain more insight into the factors that contribute to soil respiration, scientists have developed a paired gas measurements technique to calculate the ratio of carbon dioxide produced to oxygen consumed. In tree stems and soils, this ratio is called the apparent respiratory quotient (ARQ).

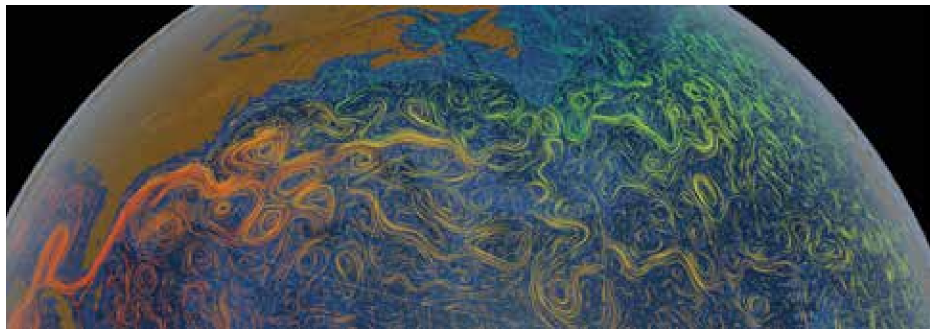
Although this ratio can be a useful biogeochemical tracer, scientists first need to better constrain the sources of its variability. *Hilman et al.* conducted a 15-month pilot study in a Mediterranean oak forest in Odem, Golan Heights. The team conducted seasonal measurements of bulk-soil respiration and the ARQs of tree stem and root tissues from both deciduous and evergreen species. They also took air samples from underlying soils.

The ARQ values in the stem and soil samples were much lower than the researchers expected for respiration occurring in carbohydrate substrates. The authors attribute this variability to nonphotosynthetic carbon dioxide fixation in the stems and to microbial breakdown of stable soil compounds that require more oxygen.

The researchers also found that the forest's soil-air ARQ measurements were typically higher than the bulk-soil ARQs and lower than the root ARQs. They argue that these differences demonstrate the potential for this technique to distinguish autotrophic sources of soil respiration (which can synthesize their own food) from heterotrophic sources.

These findings demonstrate the strong potential for paired gas measurements to unravel the processes that contribute to soil respiration. An increased understanding of the variability in ARQs should provide information that biogeochemists need to develop this technique and better predict crucial ecosystem processes. (*Journal of Geophysical Research: Biogeosciences*, https://doi.org/10.1029/2021JG006676, 2022)
—Terri Cook, *Science Writer*

Hidden Upwelling Systems May Be Overlooked Branches of Ocean Circulation



Sea surface currents and eddies swirl around the East Coast of the United States and Canada. Credit: NASA Goddard Space Flight Center Scientific Visualization Studio

Upwelling and downwelling play important roles in transporting the heat, carbon, and nutrients that affect Earth's climate. Many studies have focused on these vertical motions in the ocean, including in eastern boundary currents, along the equator, and in the Southern Ocean.

Previous research has suggested that western boundary currents (WBCs) are associated with vertical water transport, but the presence and dynamics of vertical motions in the main WBC areas have not been described to date, in part because powerful horizontal water movement and eddies associated with WBCs make it hard to detect direct WBC-associated vertical motions.

In a new study, *Liao et al.* distinguished patterns across various ocean data sets. They looked at vertical velocity using six ocean data sets spanning January 1992 to December 2009 under different ocean circulation models. Next, the team categorized five major subtropical WBC regions: the Kuroshio, Gulf Stream, Agulhas, East Australian, and Brazil currents.

Although not directly observed, indirect evidence of strong subsurface upwelling was seen in all major WBC areas in all six of the data sets. The authors say that upwelling systems are necessary for the WBCs to be in geostrophic balance. In addition, they found that vertical motion in the WBC areas is relatively deep—deeper than upwelling near the equator, for example—and that WBC upwelling can reach the surface mixed layer. This finding suggests that in subtropical regions, WBC upwelling plays a role in the vertical movement of heat and carbon, which could be significant in heat and carbon regulation in the upper ocean and atmosphere over long timescales.

In addition, observations of upwelling and associated circulation in subtropical regions suggest that WBC upwelling is a means by which various biological, chemical, and physical processes may be affected. But the authors note that more research is needed to better understand the dynamics of WBC upwelling and the role it plays in the climate system. (*Journal of Geophysical Research: Oceans*, https://doi.org/10.1029/2021JC017649, 2022) **—Alexandra K. Scammell,** *Associate Editor*

Nonlinear Effects of Wind on Atlantic Ocean Circulation

The Atlantic Meridional Overturning Circulation (AMOC) is a system of ocean currents that transports warm, salty water from the tropics to the northern Atlantic. As the water cools, it becomes denser and sinks, in a process known as overturning. The cold deep water then flows back toward the equator. This process of transportation plays a critical role in Earth's climate.

Although scientists know that surface wind stress can affect AMOC variability from year to year, the impact of wind stress on decadal timescales is less clear. In a new study, *Lohmann et al.* address this knowledge gap using the MPI-ESM (Max Planck Institute for Meteorology Earth System Model). They ran 250-year simulations in which the mean wind stress received by the ocean was modified so it was either half or double that of a reference simulation.

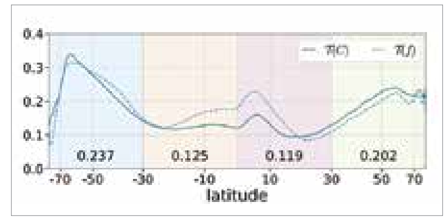
They discovered that under reduced wind stress forcing, the AMOC strength strongly decreases. Reduced heat and salt transport to the north and, subsequently, a larger winter sea ice extent and reduced surface density shut down production of the cold deep water that usually forms in the subpolar North Atlantic and the Nordic Seas.

Under enhanced wind stress forcing, the authors found that effects opposite those of reduced wind stress forcing happen initially and the AMOC strength increases. Over time, however, the AMOC weakens and stabilizes at a strength similar to what was observed in the reference simulation. The researchers attribute this nonlinear effect to a decrease in surface density (after the initial increase) in the North Atlantic and weakening of subpolar deepwater formation.

The results indicate that future intensification or weakening of jet streams in the Northern Hemisphere could affect North Atlantic circulation and climate. Further analyses with other climate models will provide additional support for the new findings, the authors say. (*Journal of Geophysical Research: Oceans*, https://doi.org/10.1029/2021JC017902, 2021) **—Jack Lee,** *Science Writer*

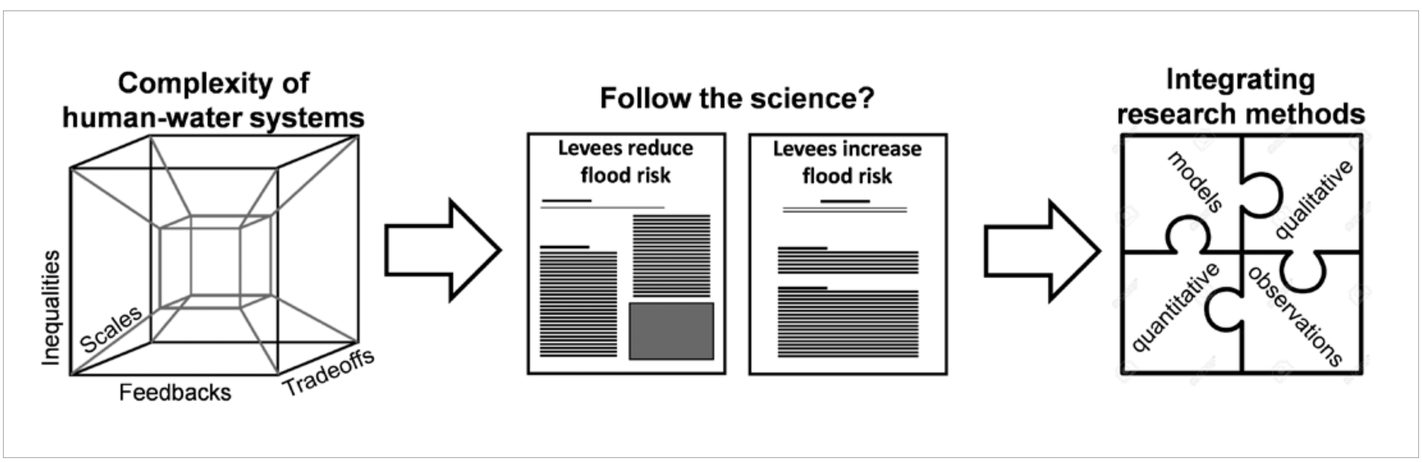
Is Earth's Albedo Symmetric Between the Hemispheres?

Earth's planetary albedo, the portion of insolation (sunlight) reflected by the planet back into space, is fundamentally important in setting how much the planet will warm or cool. An intriguing feature of the albedo, noted in previous literature, is that it appears to be essentially identical, on average, in the two hemispheres, despite their very different surface properties. *Datseris and Stevens* further support observations of hemispheric albedo symmetry using advanced time series analysis techniques applied to the latest release of data sets from the Clouds and the Earth's Radiant Energy System (CERES) project. Because of land-sea fraction differences, the clear-sky albedo is greater in the Northern Hemisphere than in the Southern. However, this difference in clear-sky albedo is countered by increased cloudiness in the Southern Hemisphere, especially over the extratropical ocean. In search of a symmetry-establishing mechanism, the authors analyzed temporal variability in the CERES data sets and found substantial decadal trends in hemispheric albedo that are identical for both hemispheres. The results hint at a symmetry-enforcing mechanism that operates on large spatiotemporal scales. (https://doi.org/10.1029/2021AV000440, 2021) **—Sarah Kang**



Temporally and zonally averaged cloudiness (solid) and cloud area fraction (dashed) over four equal-area latitude zones are shown here. The hemispheric asymmetry in cloudiness largely results from the southern extratropics being much cloudier than the northern extratropics. Credit: Datseris and Stevens

The Need for Rational Thinking About Human-Water Systems



The complexity of human-water systems means there are no simple, universal ways to address risks associated with these systems, such as floods and drought. Instead, integrated and interdisciplinary research is needed to deal with uncertainty and help create effective policy. Credit: Di Baldassarre et al.

Natural hazards such as floods and droughts have affected Earth and shaped human activities throughout our planet's long geologic and more recent human history. The stakes of managing risks associated with human-water systems are high because of floods' economic and social costs on large population centers and the drastic effects of droughts on global food security. These problems have become more urgent because of rapid urban population growth and climate change affecting regional and local weather. Advances in scientific knowledge can help find solutions to many such problems, but it is not clear whether just following the science helps in policymaking.

Di Baldassarre et al. postulate that there are no simple answers and recommend that as multiple disciplines in both the physical and social sciences contribute policy-relevant information, we need integrated interdisciplinary research and methods to cope with uncertainty and complexity in human-water systems. How to encourage politicians to make policy through rational thinking based on such integrated work remains a challenge. (https://doi.org/10.1029/2021AV000473, 2021) **—Tissa Illangasekare**

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ASSISTANT PROFESSOR (TENURE TRACK) IN METAMORPHIC PROCESSES

The Faculty of Geosciences and the Environment of the University of Lausanne invites applications for a tenure-track **Assistant Professor** position in Metamorphic processes, to be based at the Institute of Earth Sciences.

We seek candidates who conduct innovative, interdisciplinary, and quantitative investigations of metamorphic processes by combining field observations with geological and/or geochemical data. Research topics of interest include, but are not limited to, fluid-rock interaction, rates of metamorphic processes, coupling of reactions with rock deformation, ab initio calculations, mass- and heat transport, linking metamorphic processes to orogenic systems. This position offers numerous opportunities for internal collaborations in neighbouring fields such as geodynamics, geophysics, hydrology, (bio-) geochemistry and igneous petrology. The position involves teaching, mainly in metamorphic petrology and field-based courses at the bachelor and master level.

Appointment will be at the Assistant Professor level (tenure track). However, we will consider outstanding candidates for direct appointment at the Associate Professor level, particularly if this corresponds with our equal opportunity objectives.

Starting date: 1st of August, 2023 (or to be agreed upon)

Contract length: 2 years renewable twice (6 years). Tenure and promotion to the rank of Associate Professor expected after 5-6 years, leading to further contracts renewable every 6 years.

Activity rate: 100% (or to be agreed upon)

The successful candidate is expected to develop a competitive, externally funded research program within the Institute of Earth Sciences, teach courses and conduct field trips at the BSc and MSc levels, and supervise bachelor, master, and doctoral students.

A PhD in Earth Sciences at the date of appointment is required and postdoctoral experience is expected. Candidates must demonstrate a capacity to undertake high quality research, to obtain research funding, and to publish in peer-reviewed international research journals. A demonstrated potential for teaching and for supervising master and doctoral theses is required.

For further information, contact the Chair of the selection committee: Niklas Linde, Dean of the FGSE (niklas.linde@unil.ch). You can also consult the Unil website: **https://www.unil.ch/carrieres/en/home.html**

Application deadline: August 31, 2022 (23:59 Swiss time GMT+1)

The PDF application in English must be split into several files not larger than 9.9 MB and can only be submitted through the university website https://bit.ly/3FVfUVW and should include:
A cover letter explaining the reasons for applying (max. 1 p); a CV, the date and title of the doctoral thesis (max. 2 p); list of publications; a research statement, describing past major achievements and the research the candidate intends to develop (max. 4 p); a teaching statement, describing the candidate's teaching approach, intentions for teaching and his or her potential contribution to our teaching programs (max. 2 p); EDI (equity, diversity, and inclusion) statement (max. 1 p.); list and links to the three most significant publications and a statement on the personal contribution to each; the names and contact information of three to five referees.

HEAD OF THE SNOW AND ATMOSPHERE RESEARCH UNIT

Employer: WSL Institut für Schnee- und Lawinenforschung SLF
Location: Switzerland (CH), Davos
Salary: We pay salaries commensurate with the function and experience in accordance with the ETH Domain.
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Career Level: Experienced
Education Level: PhD
Desired Certifications: Professional Geologist, Professional Hydrologist, Certified Environmental Professional
Relocation Cost: No Relocation
Sector Type: Government

The **WSL Institute for Snow and Avalanche Research SLF** is part of the Swiss Federal Institute for Forest, Snow and Landscape Research WSL and thus of the ETH Domain. WSL focuses on the sustainable use and protection of the environment and on the handling of natural hazards. WSL employs approximately 600 people, of whom 140 work at SLF in Davos.

The Snow and Atmosphere Research Unit focuses on snow physics, snow processes, winter sports and climate as well as snow hydrology and climate impact. It investigates the physical properties of snow and the exchange processes between soil/snow and the atmosphere. The aim is to acquire a deeper understanding of the interactions between the cryosphere and climate change as they affect the formation of alpine natural hazards and global processes. From **1 October 2022** or another date to be agreed, WSL is looking to appoint a Head of the Snow and Atmosphere Research Unit.

As an internationally recognised research professional, you will lead the research unit and its 40 or so employees, together with the group leaders. This varied and highly responsible role will include coordinating and promoting research by the entire unit as well as leading projects of your own. You will foster the targeted practical implementation of scientific results and nurture close cooperation with relevant stakeholders. You will also be responsible for securing third-party funding for research projects and for maintaining cooperation with authorities and organisations at national and international level.

You are at an advanced stage of your academic career, have many years of research experience, as well as an outstanding scientific track record on the cryosphere and its interactions with the environment. You have extensive experience leading research groups and managing interdisciplinary research projects and possess a motivational and team-oriented management style. You are also inclusive, have excellent negotiating skills, and speak at least one of Switzerland's national languages, as well as being fluent in spoken and written English.

Please send your complete application to Clemens Güdel, Human Resources SLF, by uploading the requested documents through our webpage. Applications via email will not be considered. For questions about the position, please contact **Prof. Dr Beate Jessel, WSL Director (tel. +41 44 739 2224)**. For administrative queries, contact **Ms. Susanne Jost, Head of HR (tel. +41 44 739 2370)**. The WSL strives to increase the proportion of women in its employment, which is why qualified women are particularly called upon to apply for this position.

Dear AGU,

In a scene reminiscent of the mat world that prevailed during the first few billion years of life on Earth, photosynthetic (purple) and chemosynthetic (white) microbial mats flourishing today create a dynamic mosaic in groundwater containing high sulfur and low oxygen at the Middle Island Sinkhole in the Thunder Bay National Marine Sanctuary on Lake Huron. Daytime dive photos (as shown here in a midday image) and nighttime dive photos reveal a diel vertical shift in the workforce of the mat ecosystem—purple cyanobacteria dominate the mat surface during the day, and white sulfur-oxidizing bacteria take over at night. Indeed, these diel submillimeter journeys turn the underwater mat scape mostly purple by dusk and white by dawn!

Might similar vertical mass movements of life have occurred daily in the benthic mats of the Precambrian seas and continued all the way to the present? Could modern-day microbial mats such as these, wherein photosynthetic cyanobacteria use diel vertical movements to optimize photosynthesis at the surface during the daytime, have shaped the early biosphere by gradually producing net oxygen each day?

—**Bopi Biddanda, Ian Stone, Tony Weinke, Janie Cook, Nate Dugener, Davis Fray, and Sarah Hamsher,** Annis Water Resources Institute, Grand Valley State University; **Phil Hartmeyer, Stephanie Gandulla, John Bright, and Russ Green,** Thunder Bay National Marine Sanctuary, NOAA; and **Travis Smith and Steve Ruberg,** Great Lakes Environmental Research Lab, NOAA

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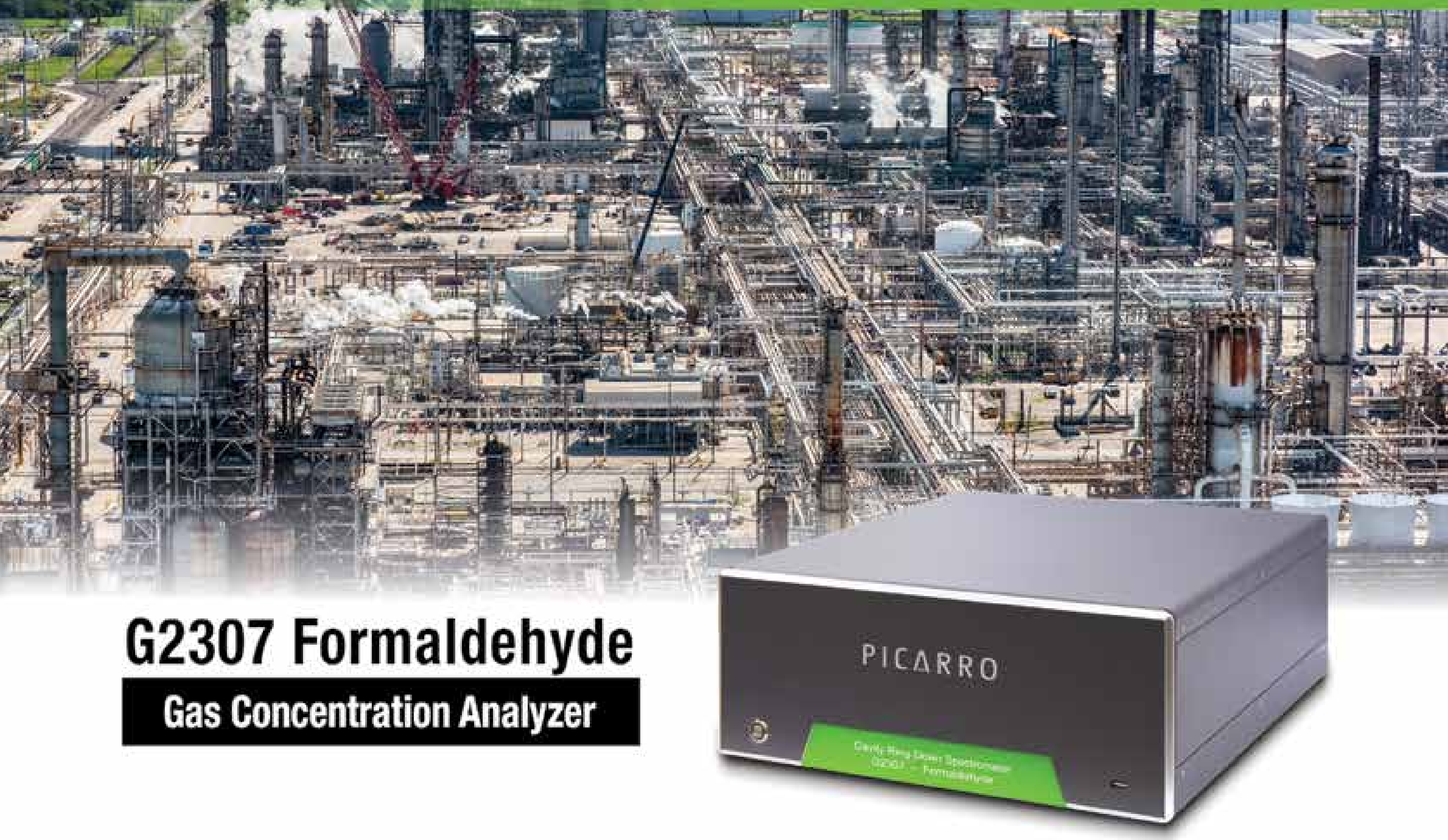

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