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SCIENCE NEWS BY AGU

A Cataclysmic Start to Subduction

Antarctica's Disappearing Meteorites

Why Europa May Lack Life

The Career Issue

Find out how 14 scientists made it through a maze of opportunity.

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From the Editor

This month, *Eos* is shining a light on some already bright stars of science. In this year's career issue, we follow 14 Earth and space scientists through the trials, experiments, and restarts it took to get them where they are today.

Cate Larsen is a social media "rock" star, dropping groovy geological knowledge on audiences far and wide (p. 22). One of the few Black faculty members at her university, Adriana Alves is helping pave the way for others like herself (p. 18). Riley Black brings ancient fossils to life in her writing (p. 19). Alexander Farnsworth studies the climates of Earth's past and future and asks, Could Westeros winter really last for years? (p. 20)

Some of these individuals have been guided by a sense of duty, some by curiosity. Whatever their motivation, these folks have shown us how to get things done. Join us as we stand in awe of their hard work and achievements.

On the Cover

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Janice Lachance, Interim Executive Director/CEO

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Hawaiʻi Finally Gets Its Own Climate Divisions

Despite its small size, Hawaiʻi is climatically diverse. Shown here is Nāpali Coast State Wilderness Park on the island of Kauai. Credit: Roberto Nickson/Unsplash

From the barren 4,200-meter peak of Mauna Kea on the Big Island to the lush valleys nourished by meters of annual rainfall on Kauai, Hawaiʻi has no shortage of climatic extremes. But it wasn't until earlier this year that climate divisions were finally defined for the fiftieth state. This new data set—which establishes official maps of climatically similar regions across Hawaiʻi—will help ensure that the state is included in national climate analyses previously available to only the continental United States and Alaska.

Waiting in the Fiftieth State

From historic county boundaries to the Zone Improvement Plan (ZIP) codes developed by the U.S. Postal Service in the 1960s, individual U.S. states have been continuously subdivided and categorized.

Initial efforts to divide the 48 states in the contiguous United States into climatologically distinct regions began in the early 20th century. But some of those divisions appeared to have been based more on geography, agricultural land use, or even the ease of communicating via mail. It wasn't until the 1950s that state climatologists began incorporating climate data to create so-called climate divisions for each of the Lower 48 states.

These regions, which today number 1–10 per state, encompass areas that are climatically similar in key indicators such as precipitation and surface temperature. Alaska received its own climate divisions—a record-setting 13—in 2015. But one state was, until earlier this year, conspicuously untabulated.

"Hawaiʻi did not have official climate divisions," said Xiao Luo, an atmospheric scientist at the University of Hawaiʻi at Mānoa in Honolulu. Luo and her colleagues have now used precipitation data from 1990 to 2019 to define climate divisions for the fiftieth state.

Hawaiʻi is the final state to receive official climate divisions, said Thomas Giambelluca, a climate scientist at the University of Hawaiʻi at Mānoa and a member of the research team. The lack of climate divisions in Hawaiʻi till now has meant that the state has been omitted from analyses such as the U.S. Gridded Standardized Precipitation Index and the National Temperature Index.

"We are excluded from a huge percentage of the so-called national products related to weather and climate," Giambelluca said.

"We are excluded from a huge percentage of the so-called national products related to weather and climate."

From Stations to a Grid

To define climate divisions for Hawaiʻi, Luo and her colleagues mined monthly precipitation data from more than 600 rain gauges spread across seven of Hawaiʻi's eight major islands: the Big Island, Maui, Kahoolawe, Molokai, Lanai, Oahu, and Kauai. (Niihau, Hawaiʻi's westernmost island, was not represented because of a lack of data.)

The researchers then interpolated between those measurements to define a gridded data set of precipitation measurements with a resolution of 250 meters.

That was a critical step, said Chris Daly, a geospatial climatologist at Oregon State University in Corvallis who was not involved in the research. "You need spatially complete information, not just station data." And it's a challenging undertaking, said Daly, who helped to define the climate divisions for Alaska. "It takes a lot of data and a lot of expertise to be able to create these data sets."

Looking for Patterns

Luo and her colleagues next used an algorithm to group the gridded data into clusters.

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The goal was to group together regions that exhibit similar precipitation patterns, said Abby Frazier, a climatologist at Clark University in Worcester, Mass., and a member of the research team. "We tried to figure out which regions in Hawai'i have similar climates."

The team reran the analyses allowing for 8–16 clusters before settling on a dozen groups. "The 12 divisions capture the entire state's variability in rainfall," Luo said. As a sanity check on their results, the researchers verified that the 12 regions also reflected differences in surface temperature.

Twelve climate divisions might, at first glance, seem excessive for such a small state. After all, Idaho, Michigan, Mississippi, New York, Ohio, Pennsylvania, Texas, Washington State, and Wyoming each have only 10 climate divisions, and every one of those states is substantially larger than Hawai'i. The only state with more climate divisions is Alaska, but it's also more than 60 times larger than Hawai'i.

However, it's important to remember that Hawai'i is extremely diverse, climatically speaking, said Frazier, who completed her graduate studies at the University of Hawai'i at Mānoa. "We have these incredibly wet places, but we also have these extremely dry desert locations."

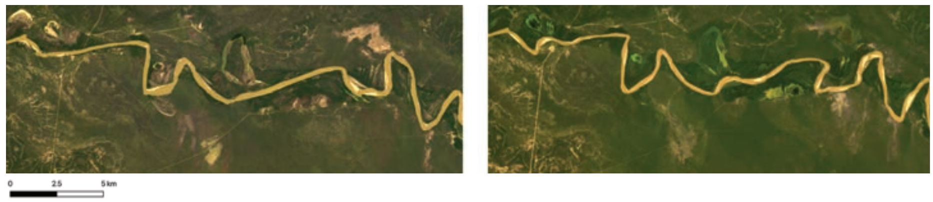
"We have these incredibly wet places, but we also have these extremely dry desert locations."

This investigation is long overdue, Daly said, and the findings make sense. "The people working on it know a lot about the climate of Hawai'i." These results were published in the *Bulletin of the American Meteorological Society* (bit.ly/HI-climate-divisions).

There's still more to do, Frazier pointed out. Climate division data sets that are billed as national aren't quite there yet, she said. "There's still nothing for Puerto Rico, Guam, and American Samoa."

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

Sand's Role in Rerouting Meandering Rivers Is Bigger Than We Thought



Landsat images of the Rio Bermejo in Argentina show how the path of the river migrated between 2013 (left) and 2022 (right). Credit: USGS

The paths of meandering rivers, which curve back and forth across landscapes the world over, can shift by dozens of meters per year. This movement affects both the livelihoods of millions of people living in floodplains and—because river ecosystems not only absorb carbon but also carry it from land to sea—the terrestrial carbon cycle.

"The migrations of these meandering rivers are the clocks that access that carbon or dictate the timescales at which a lot of that carbon is removed," said Evan Greenberg, a doctoral student in geography at the University of California, Santa Barbara (USCB) studying fluvial geomorphology.

Erosion along the outer edge of a river's curve, which can be mitigated by vegetation, and sediment deposition on the inner edge of a curve are two major factors that control how fast a river migrates.

Meandering rivers began developing hundreds of millions of years ago, around the same time that plants with roots did. In part because of this correlation, the leading paradigm has long been that vegetation is the most important variable in determining river migration rates.

But a new study by Greenberg and his adviser at UCSB, Vamsi Ganti, published in *Earth and Planetary Science Letters,* found that the amount of sediment a river carries plays a prominent role in river migration rates (bit.ly/meandering-river-sediment). Whereas previous studies have found this to be true in specific regions, such as the Amazon, Greenberg and Ganti examined 139 rivers of various sizes, climates, regions, and vegetation levels (bit.ly/meanders-pre-vegetation).

"Our goal was to really try and bring all of these ideas under the similar umbrella, because the vegetation hypothesis work ignored sediment flux, and the sediment flux work that was done at regional scale before ignored vegetation," said Ganti, a geomorphologist.

That Dam Sediment

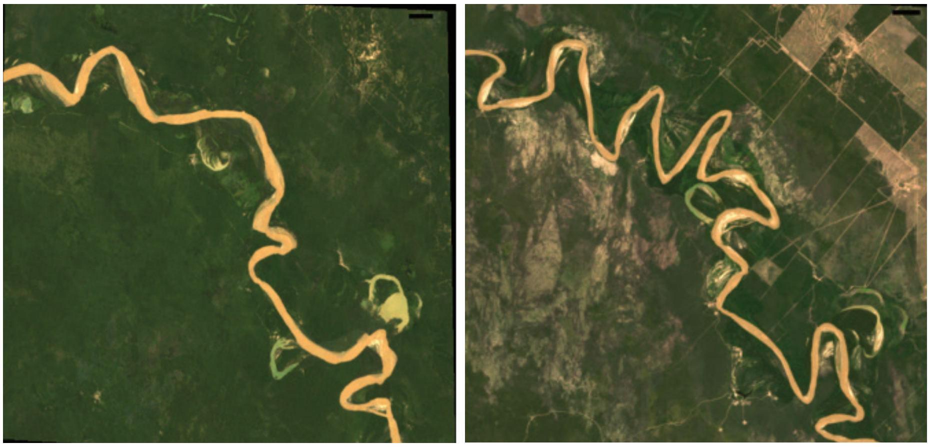
Ganti and Greenberg combined publicly available data on river migration, primarily from rivers in the Americas, with commercial satellite data for 60 smaller rivers in locations such as Central Asia and Papua New Guinea.

It's true, they found, that vegetated rivers, which are better shielded against erosion, tend to migrate more slowly than unvegetated rivers—but only about 4 times as slowly, not 10 times as slowly, as had been reported in a 2020 *Nature Geoscience* study (bit.ly/tenfold-slowdown).

Further, vegetated meandering rivers tend to be larger and carry less sediment than their unvegetated counterparts. This means that the rivers' slower migration rates could be attributed not to their vegetation but to their sizes or sediment loads. To untangle these effects, the researchers isolated the role of sediment supply by considering three dammed U.S. rivers.

"That kind of gives us this natural experiment of sediment being trapped in the reservoir, reducing the sediment supply to the downstream portion of the dam compared to the upstream portion" while vegetation levels remained the same in both portions, Ganti said.

"That kind of gives us this natural experiment."



The Rio Bermejo, a meandering river in Argentina, shifted significantly between 1986 (left) and 2023 (right). The scale bar at top right represents a distance of about 1 kilometer. Credit: USGS

In all three cases—the Red River and the Denison Dam, which straddles Oklahoma and Texas; the Iowa River and the Coralville Dam, in Iowa; and the Flint River and the Crisp County Power Dam, in Georgia—the researchers found that the rivers migrate more slowly downstream of dams, where there is less sediment in the water. This left them with a clear conclusion about sediment's key role in driving river migration.

A Matter of Methodology

Alessandro Ielpi, a geomorphologist at the University of British Columbia Okanagan Campus and first author of the *Nature Geoscience* paper suggesting that unvegetated rivers migrate 10 times as fast as unvegetated rivers, said the difference between the two groups'

The researchers found that the rivers migrate more slowly downstream of dams.

findings is a matter of methodology: His group had calculated the movement of rivers using the apex of river curves, or the part that migrated the most, whereas the new study averaged migration rates for rivers based on their centerlines.

"What we should have stated, really, was 'as much as 10 times,'" Ielpi said, adding that he

The global nature of this new study makes it "more important, from a statistical significance point of view," than previous regionally focused research.

and his colleagues have since replicated Ganti and Greenberg's findings about differences in migration rates. He also said the global nature of this new study makes it "more important, from a statistical significance point of view," than previous regionally focused research.

The researchers plan to expand their work by creating a global database of large sediment-laden river dams, as well as measuring the migration levels of all types of rivers, not just meandering ones.

After all, river migration can affect more than the terrestrial carbon cycle and riverside human communities.

By **Emily Dieckman** (@emfurd), Associate Editor

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A Step Closer to Solving the Fermi Paradox

"Don't you ever wonder where everybody is?" That question, famously posed in the mid-20th century by physicist Enrico Fermi, spotlights that precisely zero extraterrestrial civilizations have been found in the Milky Way, although by some calculations, our galaxy ought to be teeming with communicative life.

Researchers have now suggested that the lack of evidence of complex extraterrestrial life—the so-called Fermi paradox—is due to the scarcity of planets hosting long-lived plate tectonics and an amalgam of watery and dry environments. These results were published in *Scientific Reports* (bit.ly/finding-ET-factors).

Intelligent life elsewhere in the Milky Way might require plate tectonics, oceans, and landmasses. Credit: iStock.com/Darryl Fonseka

A Framework for Intelligent Life

In 1961, Frank Drake, an American astronomer then at the National Radio Astronomy Observatory in Green Bank, W.Va., proposed an equation to estimate the number of extraterrestrial civilizations in the Milky Way capable of transmitting electromagnetic signals such as radio waves. That equation consisted of seven terms, including the fraction of stars with planetary systems and the average length of time that a civilization broadcasts its presence out into space. This expression, which is still in use today, has come to be known as the Drake equation. (Drake died in 2022.)

"It gives us a framework for understanding all the planetary and astrophysical processes that might lead to a civilization," said Michael Wong, a planetary scientist at the Carnegie Institution for Science in Washington, D.C., who was not involved in the research.

Drake himself estimated that perhaps 10,000 communicative extraterrestrial civilizations might exist in the Milky Way. But other people's estimates using the same equation have been wildly different. Some scientists have proposed that there's just one communicative civilization in the Milky Way: ours. But others have postulated that millions might be out there.

Those discrepancies are expected, Wong said, because scientists haven't pinned down the values of all of the terms that go into the Drake equation. "Some of the terms we know, thanks to advances in astronomy and astrophysics. Some of the terms, we have literally no idea what their numerical value should be," he said.

Bring in the Earth Science

A pair of researchers has now suggested replacing one of the terms of the Drake equation with two Earth science–related terms. Plate tectonics and the presence of both oceans and continents are critical to the development of complex life, the team argued, and the likelihood of a planet having those attributes should be incorporated into the Drake equation. Doing so reduces the number of predicted communicative life-forms in the Milky Way by several orders of magnitude, the team showed, which is a step toward reconciling the Fermi paradox.

"Some of the terms, we have literally no idea what their numerical value should be."

In its original incarnation, the Drake equation included a term known as f_i, which pertains to the fraction of life-bearing planets on which intelligent life emerges. Drake originally assumed that f_i was 1—that is, 100% of planets that developed life also went on to host intelligent life.

But that's likely a gross overestimate, new work suggests. Robert Stern, an Earth scientist at the University of Texas at Dallas, and Taras Gerya, a geoscientist at ETH Zürich in Switzerland, have proposed that f_i is at least 500 times smaller. To arrive at that estimate, they assumed that intelligent life will develop only on planets that have long-lived plate tectonics and both continents and oceans.

Plate tectonics is critical for several reasons, according to the researchers. For starters, the process makes tall mountains. Those peaks undergo erosion, which moves sediment around. "That contributes huge amounts of nutrients to the oceans and stimulates life," Stern said. Plate tectonics also regularly sculpts new terrain, essentially creating unique niches for life, he said. "That allows for multiple evolutionary pathways."

More primitive forms of tectonics, such as so-called single-lid tectonics, occurred on early Earth. But it wasn't until roughly 1 billion years ago that plate tectonics likely started in earnest. At the same time, the planet witnessed a rise in complex life.

Wet or Dry? Take Both

The presence of continents and oceans is also critical to the emergence of intelligent life, Stern and Gerya proposed. On Earth, the earliest life-forms developed in the ocean. Gerya explained that a watery environment literally bathes organisms in nutrients and provides structural support for life-forms that lack skeletons. "For early life, the ocean seems to be necessary," he said.

But complex life capable of communicating across interstellar space also needs dry land. That's because advanced technologies such as those that control fire or harness electricity are most easily achievable on land, Stern said. "Technological civilizations aren't possible purely in the ocean."

Stern and Gerya estimated that the fraction of planets with plate tectonics lasting for more than 500 million years multiplied by the fraction of planets with a mixture of watery and dry environments is no larger than 0.002. "That number is very hard to pin down," however, Stern said, because quite a few assumptions are folded into that calculation.

"Technological civilizations aren't possible purely in the ocean."

It makes sense to incorporate Earth science–related terms into the Drake equation, Wong said. "It seems like, at least for the evolution of life on Earth, it was crucial for there to be oceans and continents as well as plate tectonics." But the fractions of planets hosting long-lived plate tectonics, oceans, and continents that Stern and Gerya proposed are highly uncertain, he said. "I don't know how, honestly, to try even to get at these numbers."

That might change in the future, however, Wong said. Astronomers are exploring the concept of a space telescope devoted to finding and characterizing habitable planets beyond our solar system. Such a telescope, currently known as the Habitable Worlds Observatory, could potentially identify oceans and landmasses on extrasolar planets. That would be game-changing for the field of planetary science, he said. "We're in a data-starved field."

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

Carbon Offset Programs May Underestimate Hurricanes

A forest like this one in Maine could lose some carbon storage capacity to a hurricane. Credit: Chris Turgeon, Unsplash

New England is one of the most heavily forested areas in America: Roughly 15 million metric tons of carbon are stored there every year. Many carbon offset programs reforest in the region.

However, a new study published in *Global Change Biology* suggests that carbon offset programs may underestimate the destructive power of hurricanes (bit.ly/hurricanes-carbon-stocks). A single hurricane in New England could release at least 121 million metric tons of carbon from downed trees, the study showed, the equivalent of the energy use of almost 16 million homes in 1 year.

"I wanted to use this case study of New England and its risk from hurricanes to outline the broader issue," said Shersingh Joseph Tumber-Dávila, a forest ecologist at Dartmouth College and first author of the study. "We're not really adequately accounting for risks when we're relying on forest carbon as a nature-based climate solution."

Carbon Credits

When a company buys a carbon credit to offset its operations, it buys a slight surplus, allowing offset programs to plant slightly more trees. In theory, such offsets allow the program to remain carbon neutral even if trees are lost to drought, fire, disease, or other disasters.

However, these "buffer pools" are relatively small. The largest carbon offset program in the United States, California's Cap-and-Trade Program, designates only 8%–12% of its trees as a buffer, and only 3% of trees for storm damage specifically.

Earlier studies have questioned these buffer pools, claiming they don't adequately assess the threats that forests face in a changing climate. This is the first study to analyze the potential effect hurricanes could have on carbon offset forests.

To account for the forests of New England accurately, Tumber-Dávila and his colleagues worked with the U.S. Forest Service to create a map of different tree heights and types across New England. They also created a simulation of likely hurricane paths using the wind speed and direction of the 10 hurricanes that reached New England in the 20th century. By combining these models, the group could calculate the number of trees likely to be downed in a typical hurricane and the amount of carbon that would be released.

"Each storm that hits the region has a capacity to wipe out anywhere from 5% to 10% of aboveground forest carbon," Tumber-Dávila said. Percentages like these effectively reset the clock, taking out carbon sequestered over as many as 10 years.

On top of this massive carbon loss potential, the researchers also factored in the potential for hurricanes to get stronger over time. Climate simulations suggest that though hurricanes may not become more frequent, their wind speeds will likely increase, and in New England specifically, they may move farther inland without losing steam. Taking these changes into account, the group estimated that in 30–60 years, up to 250 million metric tons of carbon could be released by a single storm in New England.

All that carbon would not go into the atmosphere right away, however. Decaying wood from felled trees releases carbon more slowly than other types of disturbances, such as fire. Around 25% of fallen trees in New England are harvested to be used in wood products, which can delay their carbon release. Researchers estimated that the slow release of carbon from a single hurricane could take 100 years.

Make It Meaningful

As of 2020, 7% of California's Cap-and-Trade Program carbon was stored in New England forests, and 3% of that carbon was set aside for storm damage. A single storm could take out that buffer pool.

"We need studies like this, and we need studies that are broader, national, global in scale to actually quantify the risks," said Wil-

A hurricane hits New England only about once every 10 years, but it brings high damage potential. Here, Hurricane Irene nears New York City in 2011. Credit: NASA/NOAA GOES Project/Flickr, CC BY 2.0 (bit.ly/ccby2-0)

liam Anderegg, an Earth scientist at the University of Utah who was not involved with the study. When asked whether any carbon offset programs have a large enough buffer pool, Anderegg said, "Honestly, the short answer is no."

Carbon offset programs are still important, Tumber-Dávila noted, but they lose their effectiveness if we underestimate the threats they face. "I think setting aside more of an offset project's carbon to insure against risks is definitely worth doing."

By **Sierra Bouchér,** Science Writer

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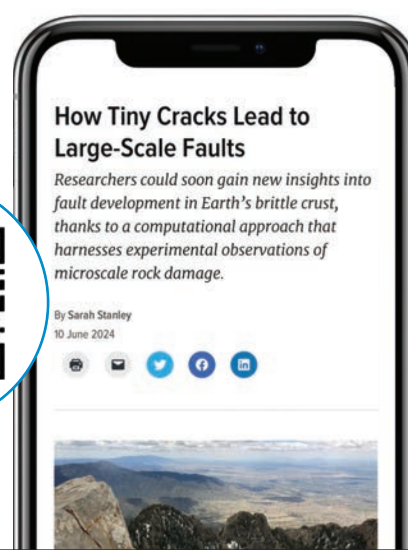


How Tungurahua Dropped Heavy Metals into Ecuador's Food Supply

Luis Egas works the land below Tungurahua in central Ecuador; the mountain's mineral-rich soils are good for the corn and fruit he grows on his farm. But the volcano has been restless, erupting ash frequently between 1999 and 2016. An eruption in 2006 was particularly destructive, depositing up to 20 millimeters of ash. "We lost practically everything: crops, animals, and homes; the ash collapsed the roofs," Egas said.

After the eruptions mostly subsided in 2016, Egas and his neighbors breathed a sigh of relief and continued rebuilding their farms. But they were worried about the longer-term effects of the ash.

Working with the farmers, researchers discovered that Tungurahua had brought hazardous levels of heavy metals such as nickel and cadmium to the soils below, contaminating wild plants and crops. These findings were recently published in a paper in *Ecotoxicology and Environmental Safety* (bit.ly/Tungurahua-metals).

Ashfall from Tungurahua covers nearby farms in Ecuador in 2006. Credit: P. Ramon, USGS

Contamination in the Fields

The effort began when Egas and others were put in contact with researchers from the Escuela Superior Politécnica de Chimborazo (ESPOCH) in Riobamba, Ecuador. "The farmers themselves took us to the sample sites, and then we returned to report our results to them," said the paper's first author, Lourdes Cumandá Carrera Beltrán, a chemist at ESPOCH.

Student Erika Lisbeth Erazo Macas samples agricultural fields below Tungurahua to identify heavy metal pollution. Credit: Lourdes Cumandá Carrera Beltrán/GAIBAQ

The ESPOCH team sampled agricultural fields, livestock pastures, and wildlife areas near the volcano in 2020, targeting vegetables and plants in both cultivated and uncultivated plots to account for potential chemical differences related to pesticide and fertilizer use. They also sampled soil and ash in cultivated and uncultivated plots.

The researchers dried, sieved, and ground up the samples, then analyzed each one for a range of heavy metals, including cadmium.

The analysis showed that cadmium concentrations averaged 1.76 milligrams per kilogram in potatoes and 1.38 milligrams per kilogram in corn, vastly exceeding internationally recognized limits. Cadmium and lead levels in small reed grass and kikuyu grass outside the cultivated plots were even higher than levels previously found in plants growing in mine tailings in central Peru, the researchers noted.

Environmental pollution of the kind found near Tungurahua is "of concern for vulnerable populations," said study coauthor Antonio Jose Signes-Pastor, a researcher from Universidad Miguel Hernández de Elche in Spain who specializes in the health impacts of contamination. "Contaminants like cadmium can lead to major metabolic changes, as well as major impacts on health in the future," he said.

"Contaminants like cadmium can lead to major metabolic changes, as well as major impacts on health in the future."

The researchers have not yet conclusively analyzed heavy metal levels in cow's milk or human urine from the region, explained coauthor and food scientist Angel Antonio Carbonell Barrachina, also from Universidad Miguel Hernández de Elche. In the future, these analyses could help the group understand the reach of the pollution in the area. Some from the group plan to return to Ecuador later this year to continue the work.

Future for Farmers

Farmers in volcanic regions face "unique challenges," said Octavio Pérez Luzardo, a toxicologist at the Universidad de Las Palmas de Gran Canaria in Spain who was not involved with the new research. "Although soils can become enriched with beneficial minerals thanks to volcanoes, there's a risk of heavy metal contamination, especially in the short term, that can be hazardous to both human health and ecosystem health," he said. Pérez Luzardo noted that the Tungurahua study was similar to a 2022 study he coauthored on the effect of volcanic ash on bananas in the Canary Islands (bit.ly/La-Palma-ash).

"Not all volcanic materials are the same," said Budiman Minasny, a soil scientist at the University of Sydney in Australia, who has studied volcanic ash and soil from recent volcanic eruptions in Indonesia but was not involved in the Tungurahua work. "The study in Ecuador is valid," he said, adding that given that some volcanic materials have elevated heavy metal levels, precautionary monitoring such as that done at Tungurahua, as well as establishing a baseline of these metals in the soil, is important.

"Happily, we were all very satisfied with the results of the study."

International studies have shown that compost can help clean up pollution, said study coauthor and project leader Irene Gavilanes-Terán, a chemist at ESPOCH. "Compost has a large cocktail of microorganisms with the ability to remove heavy metals," Gavilanes-Terán said. Researchers are studying bioremediation in the area using compost.

"Happily, we were all very satisfied with the results of the study," Egas said.

By **Andrew J. Wight,** Science Writer

Antarctic Meteorites Are Going, Going, May Soon Be Gone

Researchers collect a meteorite in Antarctica's Miller Range. Credit: NASA/JSC/ANSMET

For decades, scientists hunting for meteorites have known exactly where to go: the bottom of the world. Antarctica is a veritable treasure trove of space rocks, thanks to its shifting ice and relatively pristine surface. More than half of the meteorites ever found have been plucked from the frozen continent. But that may not hold for long.

A new study published in *Nature Climate Change* estimates that hundreds of thousands of meteorites could sink through the Antarctic ice and be out of reach by 2100 as the climate warms (bit.ly/Antarctic-meteorites). Already, some 5,000 meteorites are likely being lost each year, the study authors estimate, a trend that could persist after 2050 should we fail to get global warming under control. Once in the ice, the meteorites are unlikely ever to be recovered.

"We estimate that the meteorites are being lost much quicker than we can find them at the moment," said Veronica Tollenaar, a glaciologist and doctoral candidate at Université libre de Bruxelles and a coauthor of the study.

Tollenaar and her colleagues estimate that for every one tenth of a degree of warming, another 1%–2% of Antarctic meteorites will be lost. It should be a wake-up call to scientists and their funders, they argue.

"It's not a future problem," said Harry Zekollari, a glaciologist at Vrije Universiteit Brussel and a study coauthor. "We need to act rapidly to save this unique archive."

"It's not a future problem."

A Gold (or Rock) Mine for Meteorites

One of the most pristine places on Earth, Antarctica sees very little of the natural processes such as rain, snowfall, and erosion that quickly bury or degrade meteorites that fall elsewhere. In rare patches of bare "blue ice" in Antarctica, thousands of meteorites have accumulated over thousands or even millions of years because of ice flows. They are simply sitting on the ice, waiting to be picked up.

To date, around 50,000 meteorites have been gathered from Antarctica, representing around 60% of all meteorites ever found. The tally includes the first meteorite identified as coming from Mars, as well as the first lunar meteorites.

Scientists already knew that meteorites, which are dark, absorb far more radiation from the Sun than the ice on which they sit does. Even at temperatures well below freezing, a meteorite can melt the ice beneath it and sink into a puddle of its own making, eventually becoming locked invisibly beneath the surface.

The magic temperature, the researchers found, is about −10°C (14°F). "If temperatures go above this, even if it's not often…you're very unlikely to find meteorites," Zekollari said.

The researchers started with a database of Antarctic meteorite locations that Tollenaar had built as part of her Ph.D. research.

To create that data set, she used machine learning to combine estimates of ice flow speeds, snow levels, and temperatures and information on the ice surface to determine where meteorites are most likely to be found in Antarctica. For the more recent study, the researchers did much the same thing, this time using different temperatures drawn from climate models to simulate where meteorites might disappear in the future. The result considers how multiple variables interact, Tollenaar said.

"It's not simply setting a [temperature] threshold," she said. "It's really integrating all the observations that we know are important."

Areas of blue ice like this are a treasure trove of meteorites, with many simply lying on the ice. Credit: José Jorquera (Antarctica.cl), University of Santiago, Chile

The number of meteorites Antarctica stands to lose varies depending on how much global temperatures warm. Under current policies, which would create an estimated 2.7°C (4.8°F) of warming by 2100, 28%–30% of Antarctic meteorites could disappear. That number rises to 55% and 76% with 4°C and 6°C (7.2°F and 10.8°F) of warming, respectively. No matter the scenario, those numbers amount to hundreds of thousands of meteorites being lost.

"I don't think that I realized or recognized just how significant it could be," said Meenakshi Wadhwa, a planetary scientist at Arizona State University who wasn't affiliated with the research. "It will be a significant loss if we're not able to access many of these materials."

Scientific Funders, Take Heed

In addition to being easy to find, most Antarctic meteorites are largely untouched by Earth's environment, thanks to the continent's ice. That lack of contamination means that these space rocks can give scientists far more information on planets and asteroids in the solar system than meteorites found elsewhere. Antarctic meteorites, though not easy to get to, are relatively cheap to acquire.

They're "a poor person's space probe," Wadhwa said. Instead of sending a mission to space, "for a fraction of the cost, you can actually do a lot of science on these materials."

Indeed, this research may matter more to funding agencies than to scientists themselves, said Geoffrey Evatt, an applied mathematician who works with the United Kingdom's Lost Meteorites of Antarctica project.

"It will be a significant loss if we're not able to access many of these materials."

"It really helps answer a question and poses this challenge to funders," Evatt said. "We globally need to work together and actually have a concerted effort to collect these meteorites before many, many of them sink into the ice."

By **Nathaniel Scharping** (@nathanielscharp), Science Writer

Europa's Ocean Might Lack the Ingredients for Life

Jupiter's moon Europa has long been considered one of the most promising candidates to host extraterrestrial life in our solar system. Under kilometers of ice lies a liquid ocean where living organisms could potentially eke out an existence by exploiting chemical reactions similar to what happens near hydrothermal vents in the dark depths of Earth's oceans.

Two new studies presented at the 2024 Lunar and Planetary Science Conference, however, pour cold water on these expectations.

Researchers have found that the small moon likely lacks the necessary geothermal energy to produce volcanism with enough oomph to reach the surface, and tidal stresses induced by Jupiter and its other moons aren't enough to crack Europa's rocky crust.

Without the interaction between water and newly exposed rock, the oceans are chemically inert, leading to what's been called a "thermodynamics-driven extinction."

Hard to Break

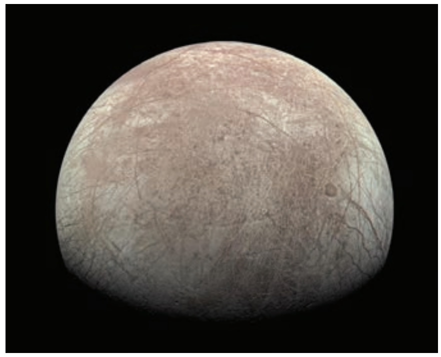
Though many studies have focused on the icy crust of Europa and the interactions between the ice and the ocean below, few have systematically looked into the crust and mantle. "When we think of icy worlds, generally, we should be thinking of them as rocky worlds as well, because the vast majority of Europa by volume and mass is rock," said Paul Byrne, a planetary geologist at Washington University in St. Louis who presented one of the studies (bit.ly/Europan-seafloor-geology).

Byrne and his coauthors investigated the strength of Europa's lithosphere and the forces that could fracture it.

They modeled its strength with two possible scenarios: a hard-to-break lithosphere, where the rock is unaltered and doesn't have any preexisting cracks, and an easier-to-break one, where the rock has been chemically weakened and previous geological processes have already produced faults and cracks. They also considered different seafloor depths, because a large water column increases pressure and makes the ocean floor more difficult to break.

In the second scenario, relatively weak forces could cause preexisting faults to slip, exposing fresh rock that could chemically react with the ocean.

The researchers looked at the strength of the mechanisms that could break the rock.



Europa may be dead after all, according to two new studies. Credit: NASA

They considered the tides produced by Jupiter and its other moons, as well as the compression produced by the cooling of the crust over time, and found that they don't come anywhere near the strength needed to break rock or cause preexisting faults to slip.

"I would say there's not much going on there," Byrne said, and if life on Europa depends on chemical reactions, "that becomes an issue."

Not Enough Magma

Another way fresh material could reach the top of Europa's lithosphere is through volcanism. Not only eruptions but also hydrothermal vents could supply chemical reactants, such as hydrogen sulfide, diatomic hydrogen, and methane, to the ocean. Hydrothermal activity doesn't require the magma to reach the seafloor, but it must be close enough to the surface to interact directly with the ocean.

Though the effect of tides and radiogenic elements trapped in the mantle can likely produce magma in the deep interior of Europa, that magma must travel up through the thick lithosphere. To see whether that's possible, the researchers combined existing estimates of Europa's mantle thickness and magma generation with newly developed simulations of the movement of that magma.

The team found that Europa does not produce enough molten rock to break through the lithosphere. In addition, the low gravity on the moon reduces the buoyancy of the magma, making it difficult for dikes to push all the way to the seafloor. The simulations showed that dikes are unlikely to travel beyond 3%–5% of the total lithosphere before cooling down and stopping their ascent.

"This makes present-day volcanism on the seafloor highly unlikely," said Austin Green, a planetary scientist at NASA's Jet Propulsion Laboratory who presented the second study (bit.ly/Europan-seafloor-volcanism). "If this volcanism is necessary for habitability, Europa's ocean is uninhabitable."

On the other hand, if heat builds up in Europa's interior, there must be a way for it to escape eventually, said planetary scientist Gabriel Tobie from Nantes Université in France, who wasn't involved in either study. "Maybe at some point it would lead to episodic volcanism," Tobie said. "If we look at other examples in the solar system, we can see that the Moon has evidence of prolonged volcanism and the tidal heat production inside the Moon is smaller than on Europa."

We must also consider, Tobie said, that the orbit of Europa has likely changed over millions of years, which could have led to periods of extreme heat and magma generation that could have produced volcanism. "It's something we need to model," he said.

Upcoming Exploration

In October 2024, NASA aims to launch the Europa Clipper mission, with the goal of determining whether the small moon harbors conditions suitable for life. The mission will study the composition and properties of Europa's icy crust and the composition of its ocean. The spacecraft might even sample the ocean if plumes of water spew into space, like on Saturn's moon Enceladus.

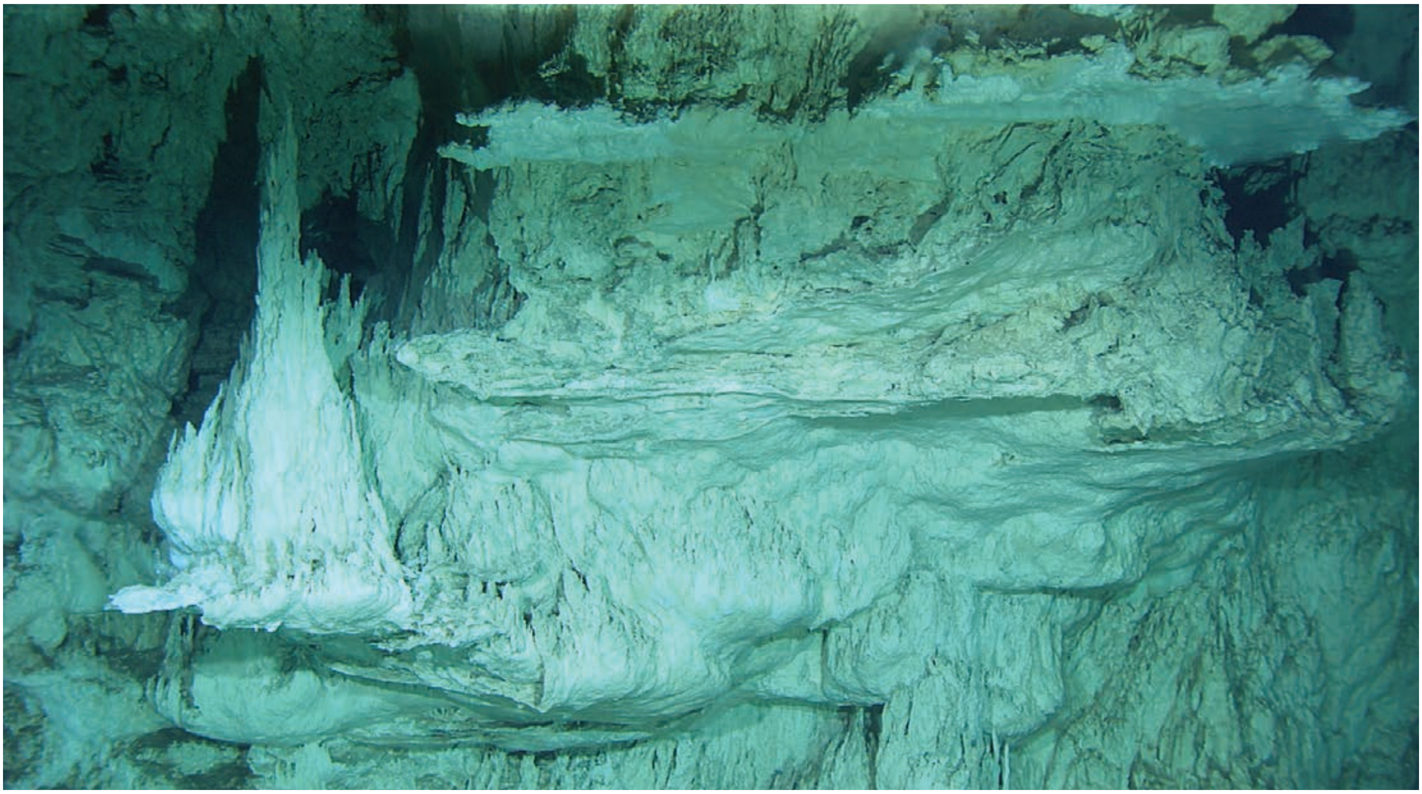
However, the Clipper mission isn't designed to look into the seafloor, so it's unlikely that it will answer questions about hydrothermal activity or seafloor tectonics.

There are some ways it could do so indirectly, Tobie said, such as by detecting gravitational anomalies that could point to variations in the thickness of the rocky crust. The thickness of the ice cover could also reveal the level of volcanic activity in the interior of the planet, because a warmer interior would lead to a thinner icy crust.

To test their hypothesis, Byrne said, "the only reliable way I can think of is getting down into the ocean and to the ocean floor, and I just don't see that happening for 150 years or so."

By **Javier Barbuzano** (@javibarbuzano), Science Writer

A Transformative Carbon Sink in the Ocean?



Mixing of naturally vented high-pH fluids and seawater at the Lost City hydrothermal field (LCHF) results in the precipitation of dissolved carbonate to form spectacular rock features at the seafloor. Seen here is the base of the three-story-tall, actively venting "IMAX" carbonate tower as it was photographed during an expedition to the LCHF in 2005. Credit: Institute for Exploration, University of Rhode Island, University of Washington, Lost City Science Party 2005, and NOAA

Several decades ago, when the concentration of carbon dioxide (CO_2) in Earth's atmosphere was much lower than it is today, climate scientists began warning of the negative effects of burning fossil fuels. From those early warnings, a consensus emerged that carbon emissions would need to be lowered (and eventually zeroed out) to avoid dangerous consequences of global warming such as extreme heat, stronger storms, and more intense floods and droughts.

Today the atmospheric CO_2 concentration is well over 400 parts per million and rising, and a plethora of research and severe weather events signal that these dangerous consequences are already happening.

Read the article at Eos.org

Governments have set ambitious goals to curb emissions, and some progress is being made, but serious questions and concerns about the slow pace of this progress abound.

Effectively lowering atmospheric carbon levels will require a range of actions, from making hard decisions about individual lifestyle changes to cooperating internationally in the pursuit of solutions.

Among the options under consideration are methods for deliberate carbon dioxide removal (CDR) from the atmosphere, once considered a last resort. Many approaches to CDR, both on land and at sea, are in various stages of testing and development. The financial, environmental, and safety costs of each approach, as well as their ability to draw down and store atmospheric carbon, are being evaluated.

Here we outline an alternative CDR approach, one inspired by a natural carbon-sequestering process at the seafloor, that in theory could remove substantial amounts of atmospheric carbon. Significant questions and concerns would need to be answered about this approach, too, but considering its vast potential, we think it is worth investigating.

The Current Menu of Carbon Dioxide Removal Options

The field of CDR is exploding as demand for cost-effective strategies grows. The most familiar approaches aim to store organic carbon in biomass on land and in the ocean. Efforts to restore natural habitats with capacity for carbon storage are laudable. However, this organic carbon is vulnerable to oxidation and rerelease into the atmosphere, most notably through combustion in wildfires and decay of drought-stricken vegetation. At sea, such efforts are pursued through seaweed cultivation and nutrient fertilization, for example, although it is unclear how much of the new biomass created is ultimately stored away or for how long.

Carbon dioxide can also be captured using acid-base chemistry, and then sequestered in rock (e.g., depleted oil reservoir formations) or in the ocean. However, such approaches also face the challenge of achieving permanent storage, raising questions about the security and potential for rerelease of sequestered carbon to the atmosphere.

Converting CO_2 into mineral carbonate affords a mechanism for permanent storage [*Kelemen and Matter*, 2008]. Natural reactions known as the Ebelmen-Urey reactions [*Pierrehumbert*, 2010]—in which silicate minerals such as forsterite (Mg_2SiO_4; a form of olivine) react with CO_2 to yield carbonate minerals and silica (e.g., $Mg_2SiO_4 + 2CO_2 \rightarrow 2MgCO_3 + SiO_2$)—are considered to have acted as a planetary thermostat over most of Earth's history because of their dependence on temperature and related feedbacks. These reactions have, in the past, gradually pulled Earth out of warm greenhouse climates by lowering atmospheric CO_2, and they will eventually erase the anthropogenic carbon spike, although not on a timescale relevant to human civilization.

In the meantime, humanity may need to implement CDR on a vast scale to compensate for the extraction and combustion of fossil fuels over the past century.

Ocean alkalinity enhancement (OAE), in which the addition of ions like Mg^{2+} and Ca^{2+} (sourced from materials such as olivine or lime) to the ocean drives more dissolution of atmospheric CO_2 to form bicarbonate (HCO^{3-}), holds considerable promise, because the ocean's capacity for storing bicarbonate is ample on the relevant time frame [*Renforth and Henderson*, 2017]. Indeed, OAE approaches—often involving materials dispersed at the ocean surface—are being studied, though they, too, face questions about their large-scale feasibility. Are there other marine settings where OAE could be pursued on a broad scale and with durable results?

Ocean alkalinity enhancement holds considerable promise because the ocean's capacity for storing bicarbonate is ample on the relevant time frame.

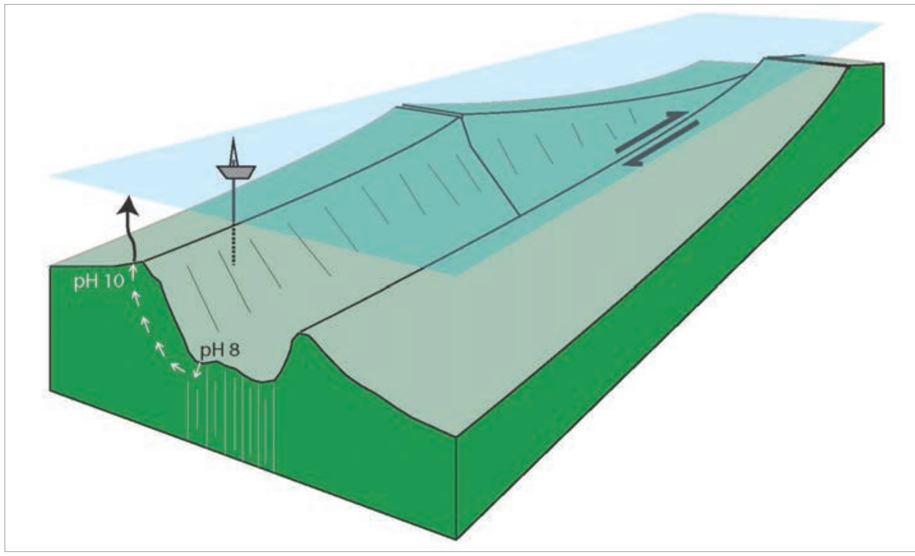


Fig. 1. Oceanic transform faults and their fracture zone extensions (vertical white lines) may be settings where a natural carbon dioxide (CO_2) removal process could be enhanced. In these settings, seawater (pH ~ 8) infiltrates fractured rock below the seafloor, where it can react with rock (e.g., peridotite), releasing thermal and mechanical energy and creating alkaline hydrothermal fluids (pH ~ 10) that buoyantly rise (small white arrows) and precipitate mineral carbonate when they mix with seawater back at the seafloor. The drilling ship shown on the ocean surface suggests how this process might be enhanced by creating additional fractures around the fault to drive more hydrothermal circulation. The resulting hydrothermal fluids might be piped (black vertical arrow) to the surface ocean mixed layer where they would counter ocean acidification and remove CO_2 from the atmosphere.

Transform Faults Offer a Transformative Approach

Earth's mantle, constituting more than 80% of the planet's volume, is a vast reservoir of ultramafic (low-silica) rock. In concept, a small fraction of this rock—minimally about 600 cubic kilometers if completely converted to carbonate—could neutralize the entire slug of fossil carbon released to the atmosphere since the beginning of the Industrial Revolution.

Oceanic transform faults and their fracture zone extensions present tectonic settings where such reactive mantle rocks, which are typically buried under kilometers of crust, are exposed at Earth's surface. The discovery of transform faults—which connect the divergent plate boundaries located at mid-ocean spreading centers—was key to unleashing the plate tectonic revolution in the 1960s [*Karson*, 2020]. And today, the co-occurrence of the right rocks and high-relief bathymetry presents an optimal combination of chemical and gravitational disequilibria, suggesting a potential for large-scale CDR found nowhere else on Earth (Figure 1).

Especially at magma-poor slow spreading (<4 centimeters per year) plate boundaries, transform fault settings feature relatively fast reacting magnesium silicate minerals in abundance [*Kelemen et al.*, 2020]. The scale of transform fault valleys dwarfs that of terrestrial erosional features such as the Grand Canyon. Submarine valley walls are prone to mass wasting, which exposes fresh surfaces of reactive silicate minerals. Locally, the motion of almost-horizontal detachment faults results in portions of crust sliding off the underlying mantle, further exposing ultramafic rock on the seafloor.

Active fracturing, needed for water-rock reactions to yield alkaline solutions, is widespread. Slow velocities of seismic waves observed along oceanic transform faults imply that water penetrates to depths of more than 30 kilometers [*Wang et al.*, 2022]. Because of differential cooling in the seafloor rock in these settings, the fracture zone extensions of transform plate boundaries also continue to experience differential vertical movement and fresh fracturing. In addition, active faults exposing reactive mantle rock are locally present along ridge crests and along trench walls.

Suburbanize Lost City?

Oceanic transform fault settings are known to host low-temperature hydrothermal systems that sequester dissolved CO_2 by precipitating mineral carbonate [*Kelley et al.*, 2007]. A prime example, the Lost City hydrothermal field (LCHF), sits at about 30°N latitude approximately 15 kilometers west of the Mid-Atlantic Ridge on the Atlantis Massif. Here, seafloor vents release high-pH, alkaline fluids that react with seawater to precipitate towers over 60 meters tall made of carbonate (e.g., $CaCO_3$) and brucite ($Mg[OH]_2$).

Low-temperature hydrothermal circulation at the LCHF is linked to heat-releasing hydration of olivine and related minerals by water percolating beneath the seafloor (e.g., $2Mg_2SiO_4 + H_2O + 2H^+ \rightarrow Mg_3Si_2O_5(OH)_4 + Mg^{2+}$). This reaction forms serpentine-group minerals (e.g., $Mg_3Si_2O_5(OH)_4$), the primary minerals in serpentinite rock. The hydrothermal fluids then rise through a permeable system of fractured rock. Mixing of the warm, alkaline vent fluids (pH > 10) with seawater shifts the carbonate equilibria locally to favor carbonate precipitation.

Imagine if it were feasible to enhance this process by deliberately expanding low-temperature hydrothermal systems such as Lost City and delivering the alkaline fluids to the ocean surface to reverse anthropogenic ocean acidification and draw down atmospheric CO_2 simultaneously. It may seem an audacious and technically demanding feat, but the core technologies needed are already available.

Alkaline hydrothermal fluids vent from a structure in the LCHF as seen during a 2003 expedition. The red laser spots are 10 centimeters apart. Credit: University of Washington, CC BY-NC-ND 3.0 (bit.ly/ccbyncnd3-0)

Drilling and hydrofracturing at sites of active mass wasting would create fresh reactive mineral surfaces and promote serpentinization, further cracking, and the production of greater volumes of alkaline, high-pH hydrothermal fluids. Then the fluids could be either pumped or directed to rise buoyantly through insulated pipelines to raise the alkalinity of the surface ocean mixed layer. By comparison with the existing fossil fuel infrastructure that crisscrosses the continents and the seafloor, piping these fluids to the surface should be eminently doable. As for surface infrastructure, mothballed fleets of aircraft carriers—presumably powered by nonfossil sources of energy such as nuclear or wind—might serve as drilling platforms. Earth's transform fault scarps cover on the order of 100,000 square kilometers, an area likely more than sufficient for this approach to CDR [e.g., *Kelemen et al.*, 2020].

Even if the fundamental technology and scale of exposed mantle material were available, however, practical scientific questions would need to be addressed. For example, additional research would be needed to understand the relative importance of negative and positive feedbacks in low-temperature hydrothermal settings [*Kelemen et al.*, 2020]. Negative feedbacks might include "clogging," where the precipitation of secondary minerals inhibits permeability and the production of alkaline fluids. Positive feedbacks that keep these systems going, meanwhile, are evidenced by both the long lives of vents and the pervasiveness of fractured and altered rock.

Kinetic issues might also need to be contended with—although the chemistry favors increased consumption of CO_2 in the ocean, the pace of the reactions may be too slow to matter on human timelines. Several options have been explored to accelerate rates of CO_2-consuming reactions. *Kelemen and Matter* [2008], for example, showed that the rate of olivine carbonation increases a millionfold above typical rates at the optimal reaction temperature of 185°C (365°F) and high partial pressures of CO_2. Electrochemical strategies to accelerate the process have also been explored [e.g., *Rau et al.*, 2013].

The Trouble with Methane

Beyond questions of its technical feasibility, the notion of intentionally expanding hydrothermal systems and piping fluids to the ocean surface raises distinct concerns. High on the list is that methane, a potent greenhouse gas, is a ubiquitous product of serpentinization.

What role do carbon-free minerals play in the formation of carbon-rich methane?

In serpentinization reactions, mantle olivine, a solid solution of typically 90% forsterite (Mg_2SiO_4) and 10% fayalite (Fe_2SiO_4), releases reduced iron (Fe^{2+}), which is the culprit. Water oxidizes the reduced iron, forming molecular hydrogen (H_2) in the process (i.e., $3Fe_2SiO_4 + 2H_2O \rightarrow 2Fe_3O_4 + 3SiO_2 + 2H_2$). This hydrogen then converts any oxidized carbon present (e.g., CO_2) into methane (i.e., $4H_2 + CO_2 \rightarrow CH_4 + 2H_2O$). It clearly would be undesirable to create or enlarge methane sources and have the gas end up in the atmosphere.

The notion of intentionally expanding hydrothermal systems and piping fluids to the ocean surface raises distinct concerns. High on the list is methane.

The news might not be all bad, however. Both hydrogen and methane gases are energy sources—the former a clean energy source. Harvesting the gases could help to meet continuing demand for conventional energy and growing demand for clean energy while also helping to finance drilling and CDR infrastructure. In an alternate, economically focused framing, the main goal for expanding hydrothermal vent systems as described could even be to produce and market income-generating sources of hydrogen gas, with CDR as a beneficial by-product.

Harvesting these gases in the deep ocean could prove challenging. At Lost City, the carbonate cap rock at the seafloor helps to focus the flows of venting fluids. Whether an artificial infrastructure would similarly focus the gases produced without excessive leakage is an open question.

What Else Could Go Wrong?

Other concerns—apart from the potential escape of excess methane—exist as well.

Low-temperature hydrothermal systems such as Lost City stand in sharp contrast to high-temperature hydrothermal systems, which are common along mid-ocean ridges. These high-temperature systems, in which dissolved magnesium is in effect traded for protons (i.e., $Mg^{2+} \rightarrow 2H^{+}$), vent acidic solutions that subtract from the ocean's alkalinity budget, so inadvertently increasing fluid fluxes from these systems would be counterproductive. Clearly, proximity to sites of high heat flow is to be avoided.

Drilling above fault scarps could also conceivably trigger mass wasting events and tsunamis, a potential hazard that has been studied in tectonically active regions such as the Puerto Rico Trench.

Activities associated with the proposed CDR approach could also disrupt seafloor and ocean surface habitats. Such disruption is a major concern with seafloor mining efforts, and substantial care would be required to avoid damaging seafloor ecosystems for the sake of CDR. To minimize disruptions in surface ocean habitats, a delivery system could be engineered to remove problematic solutes and dilute the alkaline vent fluids before they mix with surface waters.

The results of natural CO_2 removal are evident in the white veins of mineralized carbonate occurring amid green serpentinite in this rock specimen. Credit: James St. John/Flickr, CC BY 2.0 (bit.ly/ccby2-0)

Dispelling a Wicked Problem

The "wicked problem" of climate change has no simple or single solution [*Incropera*, 2015]. The transition away from fossil energy sources is underway, but even if carbon emissions disappeared tomorrow, an excess of CO_2 would long remain in our skies.

No perfect options for removing excess carbon exist—all methods face questions about safety, durability, and efficacy at large scale. The natural CDR process that occurs at oceanic transform fault settings, if it could be harnessed to draw down atmospheric CO_2 and raise surface ocean pH, represents a potentially transformative solution. These settings combine optimal chemical and gravitational disequilibria at the scale needed—the right rocks ready to fracture are present in effectively unlimited quantity. If reduced gases like hydrogen and methane could be harvested for energy without fear of leakage, the approach could be financially sustainable.

The process of expanding hydrothermal systems, like all geoengineering solutions, can have unintended consequences, so a cautious approach is in order. We suggest that more research is needed to investigate the technical feasibility of the CDR approach outlined here and identify possible test sites along transform faults for pilot drilling experiments. A system of governance to monitor and regulate research, testing, and development of marine CDR is needed as well.

So is this a potentially planet-saving idea worth exploring or an intriguing but distracting one? We welcome input from the Earth sciences community and beyond. Regardless of one's take, it's becoming more and more clear that ambitious ideas are needed to speed progress toward mitigating the effects of global warming and dispel the wicked problem we're facing.

The natural CDR process that occurs at oceanic transform fault settings, if it could be harnessed, represents a potentially transformative solution.

Acknowledgments

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References

Incropera, F. P. (2015), *Climate Change: A Wicked Problem—Complexity and Uncertainty at the Intersection of Science, Economics, Politics, and Human Behavior*, 337 pp., Cambridge Univ. Press, Cambridge, U.K., https://doi.org/10.1017/CBO9781316266274.

Karson, J. A. (2020), Oceanic transform faults, in *Encyclopedia of Geology*, 2nd ed., vol. 3, edited by D. Alderton and S. A. Elias, pp. 930–946, Elsevier, Amsterdam, https://doi.org/10.1016/B978-0-12-409548-9.12490-X.

Kelemen, P. B., and J. Matter (2008), In situ carbonation of peridotite for CO_2 storage, *Proc. Natl. Acad. Science U. S. A., 105*(45), 17,295–17,300, https://doi.org/10.1073/pnas.0805794105.

Kelemen, P. B., et al. (2020), Engineered carbon mineralization in ultramafic rocks for CO_2 removal from air: Review and new insights, *Chem. Geol., 550*, 119628, https://doi.org/10.1016/j.chemgeo.2020.119628.

Kelley, D. S., et al. (2007), The Lost City hydrothermal field revisited, *Oceanography, 20*(4), 90–99, https://doi.org/10.5670/oceanog.2007.09.

Pierrehumbert, R. T. (2010), *Principles of Planetary Climate*, 674 pp., Cambridge Univ. Press, Cambridge, U.K., https://doi.org/10.1017/CBO9780511780783.

Rau, G. H., et al. (2013), Direct electrolytic dissolution of silicate minerals for air CO_2 mitigation and carbon-negative H_2 production, *Proc. Natl. Acad. Sci. U. S. A., 110*(25), 10,095–10,100, https://doi.org/10.1073/pnas.1222358110.

Renforth, P., and G. Henderson (2017), Assessing ocean alkalinity for carbon sequestration, *Rev. Geophys., 55*(3), 636–674, https://doi.org/10.1002/2016RG000533.

Wang, Z., et al. (2022), Deep hydration and lithospheric thinning at oceanic transform plate boundaries, *Nat. Geosci., 15*, 741–746, https://doi.org/10.1038/s41561-022-01003-3.

By **Doug Reusch** (reusch@maine.edu), **Kayleigh Brisard, Gil Hamilton,** and **Carson Theriault,** University of Maine at Farmington

A Guide Through the Maze

Surrounding yourself with support can get you far.

The 14 individuals who grace these pages come from many places in the geosciences. From the chilliest corners of Earth to the particle-spewing corona of the Sun, you'll find them discovering, creating, illustrating, and engineering.

Though they are each finding their own way, they aren't navigating the maze alone. Friends, family, audiences, mentors, and colleagues were key to building their successful careers and are important to keeping them. Flip through these profiles to learn how these scientists made it through and take in a bit of their hard-earned wisdom.

Read about how collaboration helps a seismologist unriddle one of Earth's greatest puzzles, how one scientist is trying to make sure people actually understand one another, how a meteorologist is ensuring early warnings for all, and how a chief is using his geological knowledge to guide his tribe. Get advice on building a network, helping others, and being true to yourself.

We are excited to share these stories highlighting the many ways to be an Earth or space scientist and hope they inspire you to find your network and your niche.

—The Editors


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Adriana Alves

Creating an Inclusive Academy

One of few Black professors at an elite university in Brazil advocates for a more diverse and inclusive academic environment.

Geologist Adriana Alves worked through roadblocks to become a faculty member at the University of São Paulo in Brazil. Credit: Bel Junqueira/Instituto Serrapilheira

OF MORE THAN 5,100 PROFESSORS at the Universidade de São Paulo (USP) in Brazil, 28 are Black. Geologist Adriana Alves is one of them.

An associate professor at the university's Institute of Geosciences, Alves studies how volatile material spewed by ancient volcanoes might have influenced Brazil's climate in the past.

The road to that research had many barriers.

> *"It is exhausting always having to show you're good enough and prove skeptics are wrong about you."*

As a child, Alves inherited a love of reading from her mother, a housekeeper who always got books from her employers. "In school, I was always at the top of my class," she recalled. But at the beginning of her undergraduate studies at USP, geology "sounded like Mandarin."

The public schools she had attended all her life had not prepared her for the challenging course load at the elite university. She worked twice as hard to catch up with her peers. "Then I fell in love with fundamental crystallography, and it all started making sense," she said.

Her university years were tough. Challenges at home and a long commute made Alves decide to live on campus, unofficially sharing a dorm with other students..

"The undergraduate scholarship I got from a research project did not cover all living expenses, so I gave tutoring classes, which was great because I learned and taught at the same time."

Alves also had to deal with another issue: race. "I remember in sixth grade my mathematics teacher was sure I always cheated in exams," she said, "because it didn't make any sense that I got such high grades." Her non-Black peers received no such skepticism.

"It is exhausting always having to show you're good enough and prove skeptics are wrong about you," Alves said. Now, as a professor, she is involved in human rights commissions within the university to help make the path for students today easier than hers was. "For many years I kept my distance from racial issues because that hurt. It still hurts," she said. "But now, the academic environment is becoming more inclusive, and debate is possible."

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

Tanja Amerstorfer

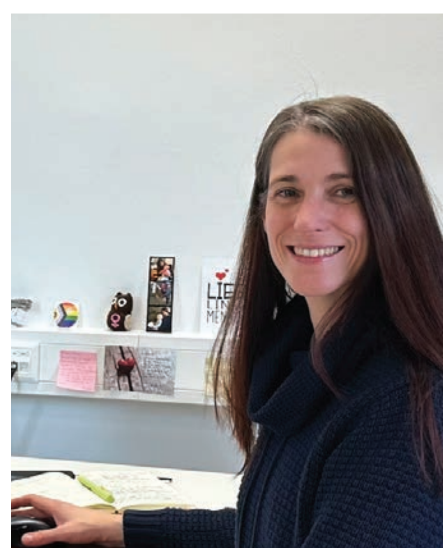
Forecasting Space Weather

The deputy head of the Austrian Space Weather Office built a supportive network.

EVERY FEW DAYS OR SO, a magnetic field somewhere in the Sun's corona snaps, flinging plasma out into space in enormous arcs. These solar events, called coronal mass ejections, can hit Earth's magnetic field, creating beautiful auroras at the poles—and potentially wreaking havoc on spacecraft and power grids.

Heliophysicist Tanja Amerstorfer is using machine learning to better predict this kind of dramatic space weather. She's the deputy head of the freshly founded Austrian Space Weather Office at GeoSphere Austria in Graz, where she and her colleagues are practitioners as well as theorists.

"It's a combination of doing research and also forecasting," Amerstorfer said. "We can really use the research we do for improving our models, improving something that has value for society. So I really like that."



Heliophysicist Tanja Amerstorfer keeps a close eye on the Sun. Credit: Tanja Amerstorfer

At first, Amerstorfer was more interested in Earth weather than space weather. She studied physics at the University of Graz and wanted to go into meteorology. That changed when a professor she admired offered her a master's project on space weather. "Space weather was a rather small field when I started," Amerstorfer said.

> *"You always try to build up a group, to not be a lonely fighter."*

Since then, Amerstorfer has spent her entire career in Graz—a choice she has made for her family but one that hasn't always been easy, she said. In Europe, scientists are often expected to go abroad for at least part of their career, Amerstorfer said. A former boss even told her that it would be impossible to get a permanent position at their institute without having left home.

Cultivating a network of colleagues who support each other through the tougher points of a scientific career was key to landing her current role, said Amerstorfer.

For anyone considering a scientific career, "My message would be that you always try to build up a group, to not be a lonely fighter," she said. "I think that's a very important thing."

By **Elise Cutts** (@elisecutts), Science Writer

Riley Black

Bringing Fossils to Life

A fossil hunter paints visceral pictures with words about the lives of dinosaurs and other prehistoric creatures.

IN 2022, SCIENCE WRITER and paleontologist Riley Black was on a fossil-finding expedition in southeastern Utah. Scrambling up to peek at an outcrop of distinctive orange rocks, she discovered what looked like an aquarium of fossilized fish, every scale still in place. As her hollers of joy echoed off the canyon walls, her eyes adjusted, seeing even more delicately preserved details.

Unearthing exquisite fossils, she said, is "like getting the best news that you didn't expect."

Black (who uses she/they pronouns) grew up during the late 1980s' dinomania—when many children wore dinosaur pajamas as they snuggled into dinosaur sheets, hugging dinosaur toys. Black donned dino costumes while wondering how the reptiles might have moved and sounded.

While studying ecology and evolution at Rutgers University in the early 2000s, Black dove into academic literature. At a time when the creationism versus evolution debate was taking center stage in schools, "I wanted to know more about what the fossil record [said] about evolution," they said.

Black started translating information from journal articles by blogging. Their knack for communicating with the public led to a blog hosted by *Smithsonian Magazine*. "Publications had an interest in bringing in voices of people outside traditional academia and journalism," they said.

> *"Just because you're not getting your master's or Ph.D. doesn't mean that you can't be involved in some way."*

Blogging also became a way for Black to process their thoughts as they wrote books. They have authored numerous news stories, blog posts, and academic journal articles, as well as nearly a dozen books about fossils for both children and adults.

Black came out publicly as a transgender woman in 2019. "Before I came out," she said, "I was trying too hard to fit into the mold of people that I admired." Now, she said, she brings her entire self to her work. That's allowed readers access to her imagination—rooted in the latest science—letting her make now fossilized creatures come alive on the page. "Being able to enthuse about these animals—as I think about them—[has] opened up my writing so much more," she said.

Black, who once considered pursuing academia, also volunteers with researchers from museums and universities who rely on dedicated amateurs. Anyone can learn from the experts while making discoveries, they said. Black has found numerous fossils that are housed in museums around the United States.

Riley Black hikes Utah's Cleveland-Lloyd Dinosaur Quarry in summer 2023. Credit: Riley Black

"Just because you're not getting your master's or Ph.D. doesn't mean that you can't be involved in some way," they said.

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

Lina Ceballos-Bonilla

Living in the Clouds

A meteorologist puts her training into action to coordinate an early-warning system for flooding around Medellín, Colombia.

LINA CEBALLOS-BONILLA'S MOTHER always joked that her daughter had her head in the clouds. And she wasn't wrong.

Ceballos-Bonilla earned bachelor's and master's degrees in engineering from the Universidad Nacional de Colombia at Medellín. Then an interest in atmospheric and numerical modeling took her to the United States, where she earned a second master's degree in atmospheric sciences from the Georgia Institute of Technology (Georgia Tech) in the United States.

"Then I started pursuing a career in the clouds," Ceballos-Bonilla said laughing.

Her coadviser at Georgia Tech, Colombian atmospheric scientist Carlos D. Hoyos, talked about setting up a group in Medellín to reduce the effects of natural disasters and asked Ceballos-Bonilla to consider working with him. "I always thought that I would like to go back to Colombia and apply all the things that I have learned," Ceballos-Bonilla said. After graduating, she returned to Medellín.

So began the Early Warning System of Medellín and the Aburrá Valley (SIATA) project, aimed at providing early warnings of flash floods. Ceballos-Bonilla's initial role was to determine the hazard, and that started with looking at what atmospheric conditions might lead to flooding.

Coordinating the project's ever growing scope has required Ceballos-Bonilla to draw on her science and engineering background and be flexible and adaptable. She has continued to do scientific research, but the real reward for her now is seeing the direct effects of the project.

"When I see the result of our work on communities, that's when I realize that this really matters and is what I want to do."

"I'm a technical girl. I like the science still," Ceballos-Bonilla said. "But when I see the result of our work on communities, that's when I realize that this really matters and is what I want to do."

Ceballos-Bonilla hopes that SIATA's system can serve as a model for early-warning systems in other Colombian cities and elsewhere.

Although she still studies clouds, even her mother sees that her work has real, down-to-Earth effects. "It is exciting, as it is science in action," Ceballos-Bonilla said. "And you get to see the results."

By **Jane Palmer** (@TJPalmerWrites), Science Writer

Meteorologist Lina Ceballos-Bonilla works on the Early Warning System of Medellín and the Aburrá Valley in Colombia. Credit: Fredy Amariles Garcia

Alexander Farnsworth

Finding Fact in Climate Fiction

A paleoclimatologist uses his modeling skills for both science and sci-fi.

GROWING UP, paleoclimatologist Alexander Farnsworth was fascinated by TV shows and movies about hurricanes, volcanoes, tornadoes—anything destructive. "I just wanted to know more about why these things happen," he said.

In college, Farnsworth gravitated toward meteorology. Researching phenomena such as tropical cyclones allowed him to learn as well as travel while working on his master's degree. As a Ph.D. candidate, Farnsworth spent several months in Ghana studying monsoon systems and exploring climate modeling.

Though his academic career has mostly focused on modern and future climates, as a senior research associate at the University of Bristol today, Farnsworth examines the climates of the past.

"I jokingly say that paleoclimate is more interesting than what's going on now or in the future," he said. "All these interesting things were happening that we want to try and understand."

Farnsworth sees a connection between his work and the fictional worlds of books and movies. "I've always been a sci-fi and

Alexander Farnsworth, seen here in Tibet, has traveled the world studying past climates. Credit: Alexander Farnsworth

fantasy fan, so I love looking at crazy dystopian futures," he said. "But there's a part of me that's always wondering, How realistic is that? Could that really happen? Is that feasible? And then I think, I've got a really cool climate model tool; I could use it to play a lot of what-if games to see if it's possible."

When the *Game of Thrones* series aired, Farnsworth and a colleague simulated the climate of the fictional world of Westeros to see how realistic it would be for a planet to have winters that last for years.

Farnsworth and colleagues also examined the climate of Arrakis, the inhospitable desert of the *Dune* universe, finding that the fictional planet would be habitable. The analysis may even suggest possibilities about life on desert exoplanets elsewhere in the galaxy.

"When our science becomes more relatable to things people have a relationship with already, it comes to life."

Farnsworth's models were used for the Apple TV+/BBC show Prehistoric Planet to give context about weather in the Cretaceous period. "How foggy was it off Antarctica on January 12, 66 million years ago?" he asked "That was an actual question they wanted to know!"

"When our science becomes more relatable to things people have a relationship with already, it comes to life," Farnsworth said.

By **Rebecca Owen** (@beccapox), Science Writer

Aliyah Griffith

Ocean Scientist, Explorer, Mermaid

A marine biologist is studying coral reefs and making ocean sciences more tenable for young explorers.

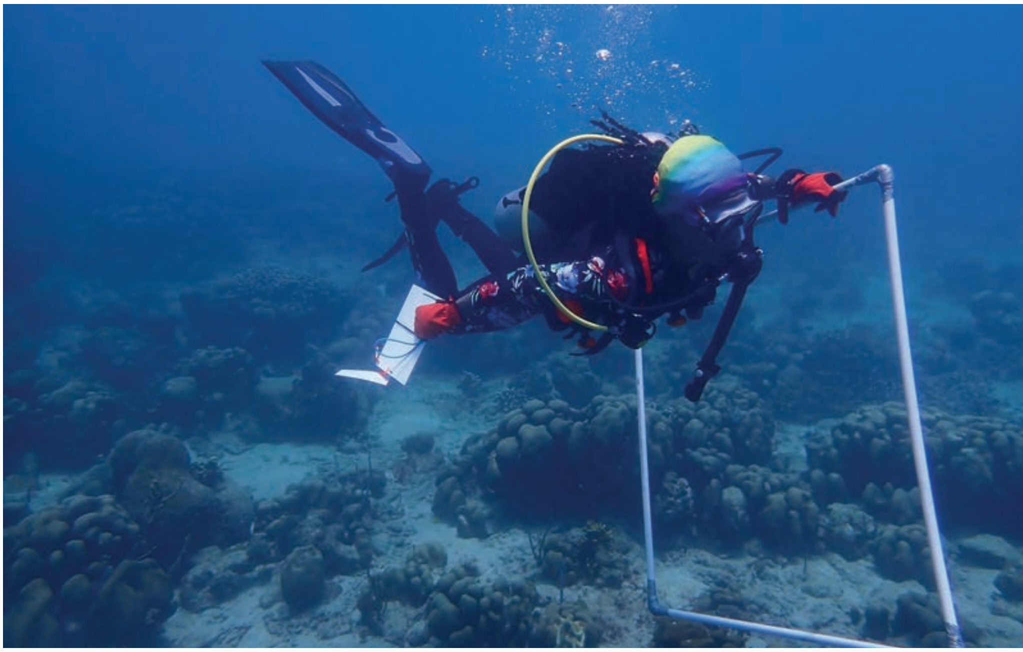
GROWING UP NEXT TO the Atlantic Ocean, Aliyah Griffith was endlessly fascinated by the mysteries of the deep. Then a chance encounter at SeaWorld sealed her future: Pressing a dolphin trainer on what her real title was introduced a young Griffith to the term marine biologist. Ever since, she knew that's what she would be.

Griffith followed her love of the ocean to an internship with Paul Barber's The Diversity Project at the University of California, Los Angeles, a summer research program for students from underrepresented groups. There she and a cohort of undergraduates earned full scuba certifications, then traveled to the coral reef paradise of Mo'orea in French Polynesia.

Today Griffith is completing a Ph.D. in marine biology at the University of North Carolina at Chapel Hill, where she studies degradation of reefs in Barbados and assesses how best to work with communities to manage coasts.

"Don't allow anyone else to change the way you feel about the field or about exploring the ocean."

As National Geographic Explorer, she worked with Disney to promote the live-action film *The Little Mermaid*. Prior to that experience, Griffith had founded a nonprofit called Mahogany Mermaids to show young people of color like herself that they too can explore the ocean. People have prejudices about where certain people should be and what they should be doing, Griffith



Aliyah Griffith surveys a reef in Barbados. Credit: Aliyah Griffith said. To counter that, Mahogany Mermaids' primary goal is to give kids exposure to aquatic sciences and let them know that "it's an option for our communities," she said.

Why mermaids? "They're the international mascot of curious explorers," she said.

Her advice for up-and-coming mermaids (and future ocean scientists) aligns with those words: "Don't allow anyone else to change the way you feel about the field or about exploring the ocean."

By **Nathaniel Scharping** (@nathanielscharp), Science Writer

Cate Larsen

Teaching About Rocks

A geocommunicator uses the connective power of social media to bring geology to the masses.

"I TALK ABOUT ROCKS for a living," said Cate Larsen.

Even through a screen, Larsen's enthusiasm for her work is contagious—viral, if you will. Hundreds of thousands of people follow the New York–based geocommunicator on TikTok, YouTube, and Instagram. For geologists, her posts hit the relatability-hilarity sweet spot. (Be honest: Who *hasn't* licked a rock?) For everyone else, they are an invitation to discover our planet in a new way.

"I put forward content that I think is going to really engage people in this science that is really overlooked," Larsen said.

It's hard to imagine Larsen, who works under a playful 1970s-inspired yellow-, orange-, and blue-striped personal brand as The Groovy Geologist, being anything but a geologist. But her heart didn't always beat for rocks. "I had no interest in Earth science. In high school, I was a space kid," she recalled. That changed in the first class of the planetary geology course she took as a last resort for her astronomy major. Two lectures later, she'd switched majors.

"I love what I do. I love what I study. I love geology. And I love to teach people about it."

Larsen earned her B.S. in geology at the State University of New York at Oneonta in 2020. Stuck in pandemic lockdown and unable to find an opportunity for grad school, she started making TikTok videos about geology. After a short clip about geologists' casual attitude toward hydrochloric acid went viral (bit.ly/hydrochloric-acid-tiktok), she started making more and more videos.

Today she teaches geology to an audience of more than 632,000 people. She's spoken at dozens of universities and libraries and even at Badlands National Park in South Dakota. She hosts a podcast, *The Schist of It*, that breaks down geology research papers, and a weekly livestream called "Rocks and Hops": casual geology lessons featuring a different craft beer each month. Larsen also founded a network of other geocommunicators called AllGneiss and works for Geologize, a company that trains geoscientists to communicate with the public.

Up next for Larsen is grad school. She's applying for master's and Ph.D. programs, with the goal of eventually becoming a professor. An educator at heart, she wants to inspire students the way her geology professors inspired her.

"I love what I do. I love what I study. I love geology. And I love to teach people about it," she proclaimed.

By **Elise Cutts** (@elisecutts), Science Writer

Cate Larsen speaks to a group at Anza-Borrego Desert State Park in Southern California. Credit: Cate Larsen

Samantha Montano

Helping Communities Recover

A disasterologist has a passion for making emergency management systems more just and equitable.

AS A HIGH SCHOOLER IN MAINE, Samantha Montano volunteered with fellow students to rebuild houses in New Orleans after Hurricane Katrina. It was her first real experience seeing the aftermath of a large natural disaster.

"I really had no concept of how complicated the recovery process was going to be and how much help was going to be needed," Montano said.

That experience motivated her to move to New Orleans and study sociology at Loyola University. There, she worked with disaster recovery nonprofits on Katrina recovery efforts and cleanup following the 2010 Deepwater Horizon oil spill. She trav-

Samantha Montano helps with disaster recovery after a tornado in Joplin, Mo., in 2011. Credit: Samantha Montano

eled to Joplin, Mo., in 2011 to help the town rebuild after an EF5 tornado killed more than 150 people and destroyed large swaths of the area, and she aided in recovery efforts after smaller disasters across the South.

"Everything from the building you're sitting in to the way the roads have been designed to how the different parts of our towns and our societies are structured have all been done around various types of hazards."

"As I went from disaster to disaster, I realized that the way in which we were approaching recovery across the country was very ineffective, very time-consuming, and inequitable," she said.

Nailing houses back together had an immediate effect on those displaced by disasters, but she felt that large-scale improvement needed to be made at the system level, too.

That work was the focus of Montano's doctorate degree in emergency management from North Dakota State University. While in grad school, she began blogging about her research into how to make disaster recovery more efficient and equitable. Her *Disasterology* blog was initially meant to help friends and family understand her research, but it helped her realize that there was much about disaster recovery research that was opaque to the public.

"Everything from the building you're sitting in to the way the roads have been designed to how the different parts of our towns and our societies are structured have all been done around various types of hazards," Montano said. "That's all part of emergency management. It is inescapable."

With climate change altering the strength, frequency, location, and types of hazards that every region experiences, emergency management and how it is communicated to the public are increasingly important, she said.

Montano is now an assistant professor of emergency management at Massachusetts Maritime Academy in Bourne. She teaches her students the ins and outs of the United States' emergency management system, conducts research, and advocates for better emergency management policy at the state and federal levels.

She also recently cofounded Disaster Researchers for Justice, which brings together disaster scholars and justice advocates to work on reforming preparedness and response. The group came together after Hurricane Maria struck Puerto Rico in 2017 and fully formed after COVID-19 spread around the world. She and her colleagues saw how inequitable the response and aid distribution were for each of these disasters.

"When we do have these major events happen and there is an opportunity for us to advocate on policy issues and other things that are a part of those responses and recoveries, we can better mobilize to do that," she said.

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

Sarah Minson

A Collaborative Quake Career

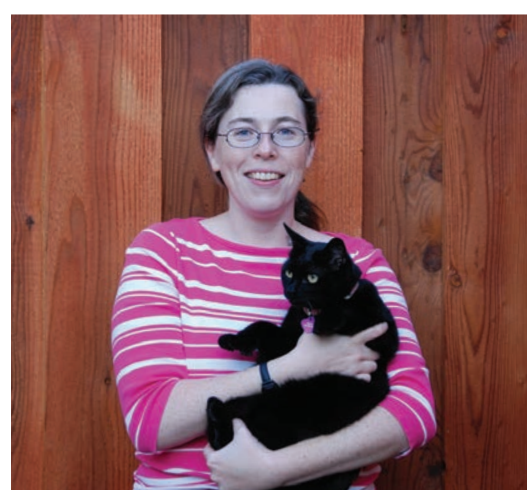
A geophysicist thrives on teamwork at the U.S. Geological Survey.

SARAH MINSON SPENDS HER DAYS at her computer modeling earthquakes and their sources as a U.S. Geological Survey (USGS) geophysicist. With no fieldwork and no lab experiments, it's not something that will make the agency's brochure, she joked. But she's been drawn to the field since she was an undergraduate.

"I really just wanted to do something fun with math and physics," she said. "And there just seemed like nothing more interesting and exciting than earthquakes and the amazing things that the Earth does."

"Everyone [at USGS] is on the same team, supports each other, and supports each other's science so that we can go farther together than we could go alone."

After earning a doctoral degree in geophysics from the California Institute of Technology, Minson started a 2-year Mendenhall Postdoctoral Fellowship with the



Sarah Minson studies big-picture questions about Earth's faults. Credit: Sarah Minson

Earthquake Hazards Program. She's been with USGS ever since, collaborating on earthquake source modeling, hazard mapping, and early-warning systems. In her first year on staff, she received the Presidential Early Career Award for Scientists and Engineers, the highest honor bestowed on young scientists by the U.S. government.

Minson has big questions about what can and can't be known about earthquakes. Geophysicists can only infer what's happening belowground when a fault slips, and big uncertainties limit our understanding of how quakes start and progress. "I find it extremely interesting and extremely important," she said of her big-picture research.

When discussing her career, Minson is quick to shout out her colleagues. One of her favorite quotes comes from Ivan Oransky and Adam Marcus, two Stat columnists who wrote that science is "the teamiest of team sports."

That's what Minson loves about her career. Many of her projects sprouted organically from questions and conversations with coworkers. She also volunteers as an earthquake scientific response coordinator for Northern California, coordinating between USGS scientists and emergency managers. Collaboration is an everyday element of her work.

"Everyone [at USGS] is on the same team, supports each other, and supports each other's science so that we can go farther together than we could go alone," she said.

By **J. Besl** (@J_Besl), Science Writer

Thanh Huong "Helen" Nguyen

Chasing Down Pathogens

An environmental engineer addresses some of public health's biggest problems.

Helen Nguyen (left) talks with farmers in Vietnam in January 2024. Credit: Mark Davis, Illinois Natural History Survey

THANH HUONG "HELEN" NGUYEN remembers her sewer-diving days, when she'd descend into cities' underbellies to collect wastewater. "You can learn a lot about community health without having to invade people's privacy," she said.

Today Nguyen is still passionate about how the stuff we flush can inform public health. But she and her colleagues now send remotely operated pumps into sewers to collect samples.

Nguyen is an environmental engineer at the University of Illinois Urbana-Champaign. She studies biological contaminants in the environment. Samples of drinking water, compost, soil, and wastewater routinely show up in her laboratory.

She and her colleagues are currently looking for antibiotic-resistant bacteria in wastewater near hospitals. Because antibiotic resistance makes bacterial infections difficult to treat, "it has the potential to erase a lot of the progress we've made in medicine," she said. Nguyen and her colleagues believe it might be possible to detect antibiotic-resistant bacteria in wastewater before they start making hospital patients sick. "We want to inform medical doctors so that they can prepare," she said.

Nguyen grew up in Vietnam and won a scholarship to complete her undergraduate degree in Ukraine. She initially chose to study geology, inspired by her father's Ph.D. in the same field. But when Nguyen decided to pursue graduate studies, she applied to programs in the United States focused on Earth and environmental science and engineering. It was appealing to think about addressing environmental issues head-on, she said. "I actually wanted to solve problems, not study problems."

Earlier this year, Nguyen took over as editor in chief of the AGU journal *GeoHealth*. She said that she looks forward to spotlighting studies at the intersection of environmental science and public health, such as investigations of how green spaces in urban areas can benefit human health.

"I actually wanted to solve problems, not study problems."

When she's not working, Nguyen can often be found in a dance studio. She picked up ballet in graduate school and has stuck with it ever since. Her classmates tend to be several decades her junior, but Nguyen doesn't mind. She finds dancing rejuvenating and aims to practice 2 hours each day after which "I feel mentally and physically refreshed," she said.

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

Devon Parfait

Using Earth Science to Support Coastal Residents

At every step of his career, a coastal resilience expert has worked to protect his community.

GROWING UP, DEVON PARFAIT felt connected to Earth not through science but through experience. As a member of the Grand Caillou/Dulac Band of Biloxi-Chitimacha-Choctaw (GCDBCC) in southern Louisiana, he spent his childhood next to the bayou, fishing, shrimping, and enjoying the state's natural beauty and biodiversity.

Along with that beauty came natural hazards: Hurricanes Rita and Katrina threw the housing market into chaos, and by the time Parfait finished high school, his family had lived in four different towns across the state.

Despite his close relationship with the natural world and awareness of its far-reaching effects on coastal communities, Parfait wasn't aware that studying geosciences could be an interest of his, much less a career.

"I got so lucky to get to do work that is directly related to coastal restoration in Louisiana."

That changed in 2017, when he traveled to a Geological Society of America conference with Rónadh Cox, a geologist at Williams College. He'd connected with Cox through Williams-Mystic, a semester-long ocean studies program that had worked with the GCDBCC Tribe in the past.

Parfait enrolled at Williams College in 2019 to study geoscience. Working with Cox, he studied land loss in coastal Louisiana.

His research showed that much of the land designated for his GCDBCC ancestors in the 18th century is now open water, geographically scattering tribe members and compounding environmental injustices. Parfait hopes to use the results to petition the Bureau of Indian Affairs for federal acknowledgment of the GCDBCC Tribe, of which he is now chief.

Devon Parfait, pictured here with U.S. Army Corps of Engineers tribal liaison Brian Ostahowski, leads his coastal community using his geoscience expertise. Credit: Brendon Bourg

"I realized that this is a career path that I can take, and I'm also directly benefiting my community by doing this," he said. "Everything kind of clicked."

After graduating in 2022, Parfait moved to a position at the Environmental Defense Fund, where he is a coastal resilience analyst in a dual role with the Mississippi River Delta Coalition, a network of nonprofits dedicated to restoring Louisiana's coast. There, Parfait works on several different projects to advance coastal resilience, including determining the best way to backfill old oil and gas canals to halt land loss and restore the natural watershed.

His work fits perfectly with his responsibilities as chief: "I got so lucky to get to do work that is directly related to coastal restoration in Louisiana," he said.

Though he's keeping possibilities open for the future, he said one thing is certain: He'll continue to serve the people of coastal Louisiana. "That's where I'll be for the rest of my life," he declared.

By **Grace van Deelen** (@GVD__), Staff Writer

Britney Schmidt

Following the Ice

An Earth and planetary scientist is most at home in cold places that mimic the worlds of the outer solar system.

BRITNEY SCHMIDT GREW UP in southern Arizona, but she now seeks out decidedly chillier climes. She frequents such places as Antarctica, Greenland, and Canada's Northwest Territories to learn about the icy worlds of our outer solar system. Her work is an amalgam of engineering, planetary science, astrobiology, robotics, and polar oceanography.

Britney Schmidt isn't fazed by the cold. Credit: Peter Kimball

"I like to focus on everything," Schmidt said. "That multidisciplinary approach is, to me, really exciting."

Schmidt became a scientist almost by accident. "Nobody in my family is a scientist or an academic," she said. In college, Schmidt was having trouble deciding on a major and on a whim took an introductory astronomy class. It captivated her, and she remembered being astounded when she learned that some of the moons of Jupiter and Saturn contain oceans hidden under thick layers of ice. "I had my mind blown," she said.

"I had my mind blown."

Today Schmidt is an Earth and planetary scientist at Cornell University in Ithaca, N.Y. She's still fascinated by ice-covered oceans, and she builds instruments such as submersibles that she and her team use in polar regions. It's exciting to think that similar technology might one day be used to explore a distant world like Jupiter's moon Europa, she said.

There are closer-to-home motivations for her work, too, Schmidt said. The effects of climate change in polar regions are acute, and she and her colleagues are working to better understand some of those fragile landscapes before they disappear. "Being in these places that are so powerful and so delicate is really overwhelming," she said.

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

Pedro Val

River Science Runs in the Family

A researcher mixes geology and biology to make sense of river biodiversity.

Pedro Val investigates how geomorphology influences biodiversity in riparian habitats. Credit: Pedro Val

CAN CHANGES IN RIVER FLUX affect the diversity of fish species in estuarine environments? And how have massive rivers such as the Amazon rerouted over time—despite being far away from fault lines or tectonic activity?

These are some of the research questions that motivate Brazilian geologist Pedro Val. He became fascinated with tectonic geomorphology at the end of his undergraduate years at the Universidade Federal do Amazonas. "Geology disciplines were interesting, but when my adviser, Clauzionor Silva, first showed me the change in river flows due to tectonic activity, I didn't want to know about anything else," he said with a laugh.

"Geology disciplines were interesting, but when my adviser first showed me the change in river flows due to tectonic activity, I didn't want to know about anything else."

Now, Val is an assistant professor of Earth and environmental sciences at Queens College, City University of New York. Two of his research collaborators are his parents, both biologists at the Instituto Nacional de Pesquisas da Amazônia, Brazil's Amazonian research institute. "They definitely had an influence on my choice for a career in science," he said.

In his doctoral research, Val combined tools from environmental science, hydrology, and climate studies to advance the use of cosmogenic isotopes to study Earth's surface.

"As rocks get stashed between sandpiles, these isotopes, hidden in quartz, decay. And we look for them to see how old sediments are."

This helps researchers understand how basins such as the Amazon have changed through time. For instance, about 10 million years ago, the Amazon River ran toward the Pacific Ocean. With the rise of the Andes, it began flowing out to the Atlantic. This change, Val said, is also recorded in fish DNA—and could possibly explain the diversity of species in the tropical river.

"Fish populations that were together before might have been separated with this change in river flux and started taking different genetic paths," Val said. This is an area he will continue to research in the eastern Paraná Basin, using funds from a National Science Foundation CAREER Award he received in late 2023.

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

Brandon Whitehead

Unifying Data to Streamline Discovery

A data scientist coheres disparate data sets so that Earth scientists can get the most out of information.

BRANDON WHITEHEAD'S JOB is to "link data together coherently," as he put it. Take icebergs, for example: Those with steep sides and flat tops can be called tabular icebergs, tabular bergs, table icebergs, or barrier icebergs. One of Whitehead's projects involves linking data sets so that scientists won't be thrown off by inconsistent terminology.

Whitehead is an environmental data scientist at Manaaki Whenua–Landcare Research, a Crown Research Institute in Aotearoa New Zealand where scientists study how to sustainably support the environment and biodiversity. Part of his work involves finding ways to describe the commonality between different worldviews. That could be relevant in New Zealand, where the holistic view of the Māori people often differs from the general approach of Western science.

Whitehead's love of science goes back to his experience attending middle school outside Minneapolis, where one teacher in particular made science exciting with hands-on activities. Whitehead remembered a time when that teacher used a slingshot constructed from bicycle inner tubes to propel office chairs carrying students down a hallway to illustrate inertia and momentum.

As an undergraduate and then a master's student at Minnesota State University, Mankato, Whitehead discovered that he loved both Earth science and computing. He also learned that inconsistently reported data can be a huge stumbling block to research. For example, while studying how the water table had changed in two states (New Mexico and Texas), "the amount of gymnastics I had to do to get those two data sets…to play nicely together was ridiculous," he remembered.

Brandon Whitehead poses for a photo during a visit to the United Nations Educational, Scientific and Cultural Organization (UNESCO) World Heritage Sites of Pompei, Herculaneum and Torre Annunziata in Italy. Credit: Brandon Whitehead

After leaving Minnesota, Whitehead spent several years working for private companies in California—which also let him follow his passion for beach volleyball—before he moved to New Zealand and began making data accessibility a full-time job.

"In today's world, everything is data," Whitehead said. His goal is to help scientists squeeze as much information out of the data as possible.

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

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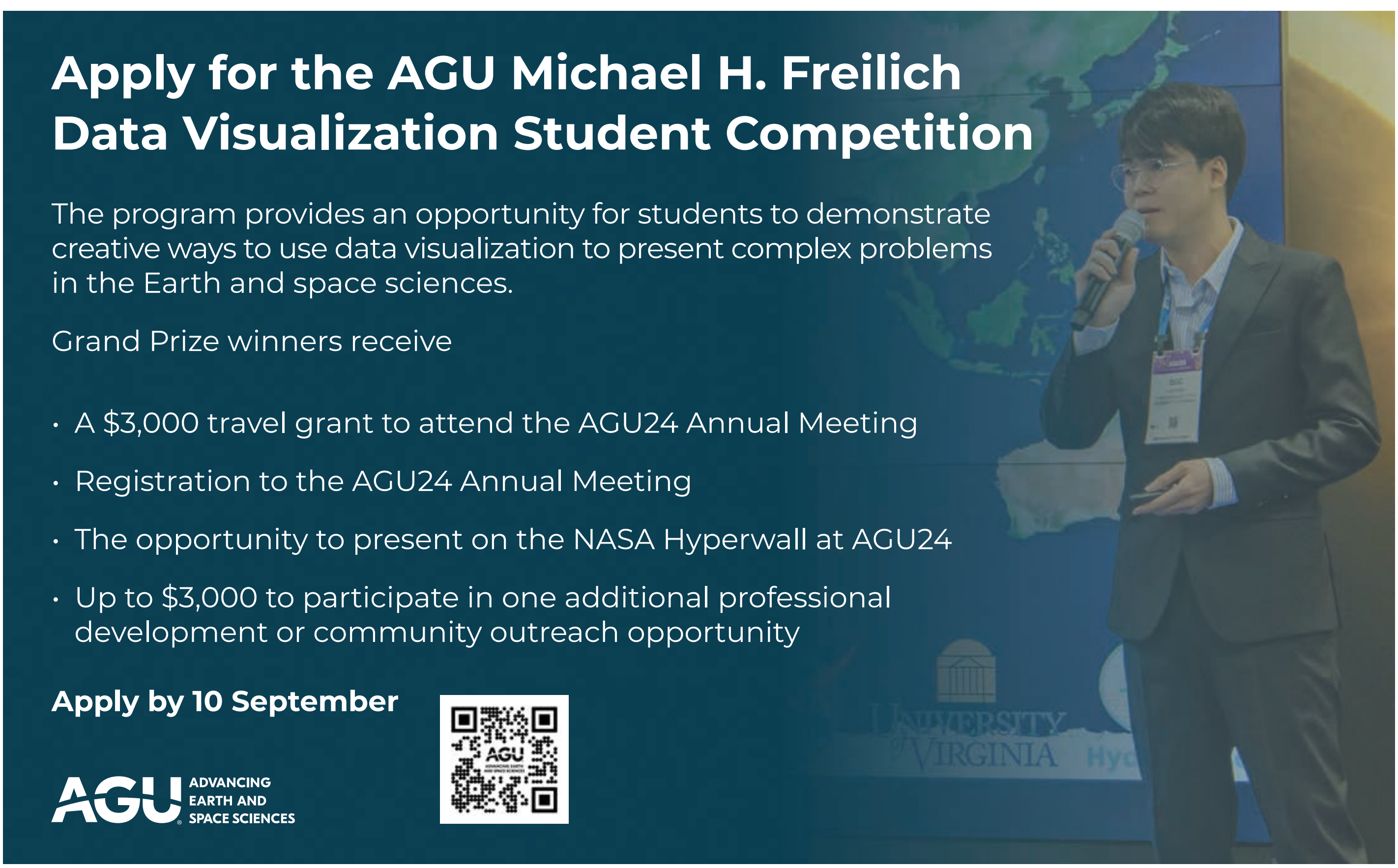


Measuring and Modeling Methane Emissions in Wetlands

Global atmospheric methane concentrations have risen steadily since 2006. Growth in agriculture, transportation, and industry are partly to blame, but so too is the rise in biogenic emissions, or emissions from natural sources.

Biogenic emissions are as varied and complex as the ecosystems from which they derive—recent work highlighted tree stems as one overlooked emitter—but wetlands stand out as the largest natural methane contributor. In fact, they account for about a third of total methane emissions, natural or otherwise.

But understanding wetland methane dynamics is complicated because these dynamics are affected by so many factors, ranging from salinity to temperature to vegetation types to water levels. Into these soggy reaches wade *Hill et al.*, with an approach to disentangle these variables.

The authors combined empirical dynamic modeling and convergent cross mapping to analyze 5 years' worth of methane flux measurements in a salt marsh in the St. Jones Reserve, part of the Delaware National Estuarine Research Reserve and the AmeriFlux network. The algorithms incorporated 18 environmental measurements, from wind speed to atmospheric pressure, to characterize how they interact to shape methane emissions.

The results showed that methane levels' response to environmental shifts can lag by up to 35 days. During the day, emissions changes were most closely tied to the ebb and flow of water levels. But seasonal patterns of emission rates were most influenced by fluctuations in temperature, dissolved oxygen levels, and gross primary production.

As methane emissions continue to climb, they could trigger a positive feedback loop in which rising atmospheric methane concentrations instigate greater ecosystem releases. By revealing the mechanics of methane dynamics in the salt marsh, the study offers a framework for improving wetland emission estimates and may help clarify a strategy for mitigating the rise in global methane concentrations. (*Journal of Geophysical Research: Biogeosciences*, https://doi.org/10.1029/2023JG007630, 2024) **—Aaron Sidder**, *Science Writer*

Looking for Life Looking for life on Enceladus: What Questions Should We Ask?

Geysers of ocean water—potentially containing clues to the origin of life—erupt through ice fractures on Saturn's moon Enceladus in this illustration. Credit: NASA Goddard Space Flight Center

Does life exist beyond Earth? One of the most compelling places to consider the possibility is Enceladus, a moon of Saturn with a liquid water ocean encased in a frozen shell. There, plumes of water spray from ice fractures into space, and spacecraft observations of these geysers suggest that Enceladus has all the chemical building blocks necessary for life.

It is no surprise that robotic missions to search for life on Enceladus are in development.

On the brink of this new era of space exploration, *Davila and Eigenbrode* propose a strategic research framework for studying Enceladus and similar ocean worlds.

The framework is based on the theory of organic chemical evolution, the idea that life results from a series of chemical steps that began with the Big Bang. As stars and planets formed, simple molecules interacted to form increasingly complex molecules and, eventually, the first cell.

Scientists are still working out the exact steps that led to life on Earth, given that well-preserved records from before life originated are sparse. Icy ocean worlds like Enceladus could hold new clues about how life begins—or doesn't.

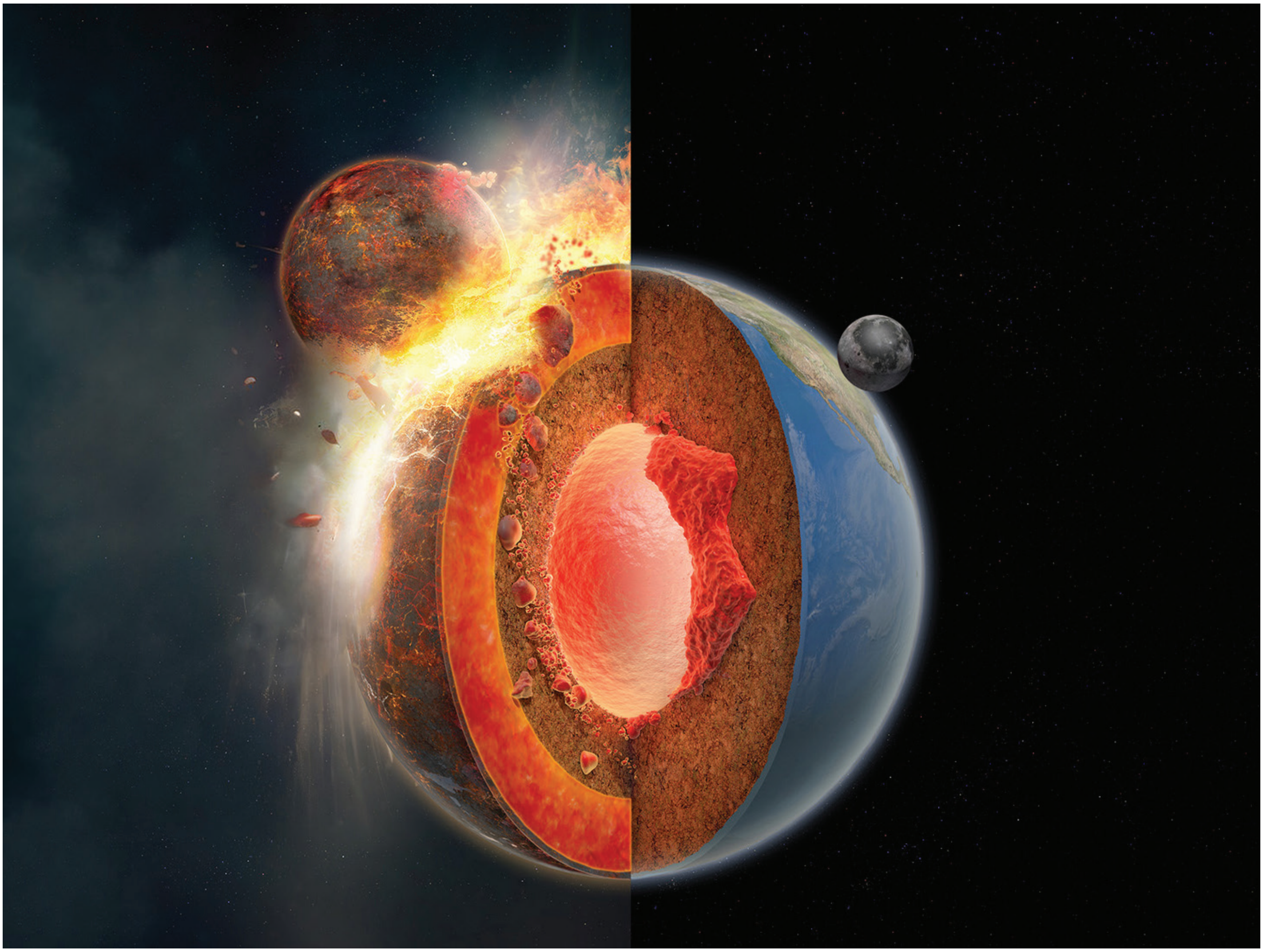
Therefore, instead of asking whether Enceladus is inhabited, the researchers propose asking, What is the extent of organic chemical evolution in Enceladus's ocean? This shift in focus could allow for deep learning regardless of whether Enceladus is currently inhabited, on its way to developing life, past a time when it held life, or unlikely ever to host life.

With this approach, missions to Enceladus would not search only for direct evidence of life. They would first seek to determine the molecular and structural properties of the complex carbon-containing molecules we already suspect are in the moon's ocean. Supplemental studies could search for more complex organic compounds with biochemical properties, cell-like objects, and any evidence of evolutionary adaptation.

Structuring missions in this way, the researchers say, is a lower-risk strategy that could provide high-reward insights into life in the universe.

In other words, if life exists on Enceladus and other ocean worlds, this approach would help us find it. If not, we'd learn far more than if we'd looked just for life. (*Journal of Geophysical Research: Biogeosciences*, https://doi.org/10.1029/2023JG007677, 2024) **—Sarah Stanley**, *Science Writer*

Earth's Subduction May Have Been Triggered by the Same Event That Formed the Moon



A collision that formed the Moon also may have led to our planet's first subduction event, according to new research. Credit: Hernán Cañellas

By 4.3 billion years ago, Earth's crust already may have looked much like it does today. This is the earliest time some researchers think that pieces of the planet's lithosphere began to slide against, over, and under each other in a process known as plate tectonics. How the very first instance of subduction—a key part of plate tectonics—occurred is still debated.

In a new study, *Yuan et al.* find evidence tracing the first subduction event to the same impact that created our Moon. The giant impact hypothesis theorizes that early in its history, Earth was struck by another planetary body about the size of Mars, sending a large chunk of rock—the Moon—into orbit.

But this giant impact might have been even more consequential to future life on our planet—within 200 million years, Earth's outer layer had gone from a static casing to a dynamic system of plates unique in our solar system, according to analyses of ancient zircons.

The researchers explored postimpact mantle convection using both 2D and 3D thermomechanical modeling. They found that the increase in temperature at the core-mantle boundary after the giant impact could have led, over time, to strong mantle plumes—phenomena still seen today that can sometimes lead to volcanic activity far from plate boundaries.

Over the course of 200 million years, extrastrong plumes could have formed from remnants of the impactor embedded in the mantle, weakened the lithosphere, and initiated the planet's first subduction event. (*Geophysical Research Letters*, https://doi.org/10.1029/2023GL106723, 2024) **—Rachel Fritts,** *Science Writer*

Animals Should Be Included in Global Carbon Cycle Models

Models of the global carbon cycle typically include plants, microbes, soil, and the atmosphere. But they may be leaving out an important variable: Animals, from earthworms to elephants, can have a significant, though heretofore little-studied, influence on how carbon is captured and stored in ecosystems.

A new theoretical framework from *Rizzuto et al.* offers a road map for including animals in carbon cycle models. Their work shows that adding herbivores and predators to such models significantly alters both the amount and the dynamics of carbon cycling. Future modeling of carbon dynamics, important for understanding climate change and designing nature-based carbon sequestration projects, should take animals into consideration as well, the researchers argue.

Animals affect carbon cycling directly by eating plants or by eating other animals that eat plants. By producing waste, respiring, and even trampling leaves on the forest floor, they also indirectly speed up the rate at which nutrients—including carbon—are recycled. The authors found, on average, a twofold increase in ecosystem carbon sequestration when animals were included in their carbon cycle model.

By pairing an ecosystem compartment model (which considers plant, animal, and soil microbial trophic compartments) with a traditional carbon modeling approach, the authors found noteworthy increases in both plant growth and carbon sequestration, as well as changes to carbon cycle dynamics, when animals are included in carbon models. It is important to note that these effects can be complex and are mediated by feedback loops that are still not completely understood. For example, a scenario that includes herbivores but not predators showed the highest levels of carbon sequestration. Adding in predators decreased overall carbon sequestration, though it remained higher than a scenario with no animals.

Adding animals to carbon cycle models leads to a significant "rewiring" of the carbon cycle that will require further study to better understand, the authors conclude. Distinguishing between herbivore and predator types, as well as adding in ecosystem-specific animal behavior dynamics, could help refine models in the future.

This kind of work could inform future nature-based carbon sequestration proposals and highlights the importance of animals' contributions to the carbon cycle. (*Journal of Geophysical Research: Biogeosciences*, https://doi.org/10.1029/2024JG008026, 2024) **—Nathaniel Scharping,** *Science Writer*

Warming Experiment Explores Consequences of Diminished Snow Cover

The SPRUCE ecosystem warming experiment is located in the Marcell Experimental Forest in northern Minnesota. Credit: Paul Hanson

Snow plays a vital role in northern and high-elevation ecosystems. It protects soil and vegetation from extreme cold and keeps the land surface cool by reflecting incoming solar energy. In the spring, snowmelt feeds rivers and replenishes groundwater.

Yet springtime snow cover across the Northern Hemisphere has decreased by about 2% each decade since the 1960s. This slow but steady loss threatens the ecology, hydrology, and economies of many historically snowed-in locales.

One such place is the Marcell Experimental Forest in north central Minnesota. Situated at the southern margin of a boreal peatland forest, the ecosystem is considered especially vulnerable to climate change. It is therefore a strategic location for the Spruce and Peatland Responses Under Changing Environments (SPRUCE) whole-ecosystem experiment, operated by Oak Ridge National Laboratory. This experiment subjects environments to a range of elevated temperature and carbon dioxide conditions to elicit biogeochemical responses.

SPRUCE comprises 10 open-topped octagonal enclosures in a forested bog dominated by black spruce. Each hydrologically isolated enclosure stands 40 feet wide × 26 feet tall. The enclosures feature forced-air blowers that warm plot temperatures to between 4.05°F (2.25°C) and 16.2°F (9°C) above ambient air temperatures. In each plot, digital cameras continuously monitor vegetation and watch as snow piles up and disappears throughout the seasons.

Using SPRUCE imagery from 2015 to 2021, *Richardson et al.* researched the relationship between warming temperatures and changes to snow duration, depth, and cover. The study evaluated the snow's response to experimental warming treatments in the enclosures, which were superimposed on natural climate fluctuations.

The results showed that snow presence, depth, and coverage were extremely sensitive to warming, especially as temperatures crested at 8°F (4.5°C) higher than the ambient air temperature. But even warming of 3.6°F (2°C) cut in half the number of days with at least 2 inches (5 centimeters) of snow cover. The reduction in snow cover resulted in higher surface temperatures, as shrub-covered ground reflected less solar energy than snow cover. The plots also experienced more frequent freeze-thaw cycles.

The findings indicated that at best, climate change will have a negative but linear effect: Warmer temperatures will, of course, lead to less snow and its accompanying consequences. However, the results revealed other plausible scenarios in which snow will behave nonlinearly, with steep and immediate loss of snow cover in response to any warming beyond current conditions. (*Journal of Geophysical Research: Biogeosciences*, https://doi.org/10.1029/2023JG007833, 2024) **—Aaron Sidder,** *Science Writer*

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Opposite: Elizabeth S. Forbes

Hello from Utqiagvik, Alaska!

This picture was taken in late February 2024 during the research expedition portion of my yearlong Arctic geophysics undergraduate research class.

In this course, students choose their own research question dealing with the sea ice, and I work with them to build—to MacGyver—their own microcontroller-based sensors to collect data. Then we head to Alaska to deploy the sensors on Arctic sea ice.

One evening during the trip, the aurorae put on a particularly spectacular display. One of my students—Garrett O'Hara—stood atop a pile of snow and ice, caught up in the phenomenon. He had no idea I was behind him, and I captured this photo of him holding his rock hammer overhead, howling in a "hammer of the gods" moment. His unbridled joy is apparent at seeing hazardous particles from the Sun causing harmless and beautiful high-atmosphere light displays by a happy conspiracy of Earth's magnetic field and its atmosphere.

In addition to experiencing these bucket list auroral marvels, my students get to do research under difficult conditions in an extreme environment, often surprising themselves at what they could accomplish. Many of them refer to this experience—both the research and living in that beautiful area—as life-changing, and I can honestly say the same thing myself.

—**Rhett Herman,** Department of Physics, Radford University, Radford, Va.

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