
# Eos

SCIENCE NEWS BY AGU

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OCTOBER 2020


This Ice Smells Like Us

Larger Waves in Our Future

Brazil's Birds Are Losing Land

# THE CRITICAL ZONE

**This study of where rock meets life is ready for new growth.**

AGU
ADVANCING EARTH AND SPACE SCIENCE

# Next Steps for the Critical Zone

During a phone call to discuss article ideas back in January, Andrew Wilcox told me: We really should do some coverage of the critical zone. Wilcox is *Eos*'s science adviser representing AGU's Earth and Planetary Surface Processes section, as well as a professor of geomorphology at the University of Montana and, yes, a critical zone scientist.

The motivation wasn't any single research project—though, of course, there is a ton of fascinating work in this field, as you'll see inside this issue—it was more a matter of recognition. The term critical zone is still new. Most geoscience programs don't offer a critical zone focus or even a class on the topic. The critical zone is, in simplest terms, the area of our planet stretching from the treetops down to the bottom of the groundwater. Critical zone scientists study everything and every interaction within it. (Read more in our introductory article on page 18.) "Framing Earth processes in the context of critical zone science is a way to underscore multiple dimensions of connectivity in terms of how water, sediment, nutrients, and biota move across landscapes; between scientific disciplines; and between humans and the environment," said Wilcox.

Our first step in planning the issue was a call with Adam Ward, one of our science advisers representing AGU's Hydrology section and an associate professor at Indiana University, who pointed us to the Critical Zone Research Coordination Network. This National Science Foundation (NSF)–funded project aims to bridge the gap between scientists working in the varied fields across the critical zone by creating inclusive language, reaching out to minoritized geoscientist networks, and coaching senior scientists on how to reach out. "If we are to do our research successfully, diverse alliances are important," write Kamini Singha and her coauthors on page 15.

If you've heard the term critical zone, it's likely due to NSF's Critical Zone Observatories. The nine remaining observatories, launched over the past 13 years, will reach the end of their successful run next year, when program funding expires. Research initiated at those facilities now stretches far past them—there are critical zone sites around the world, and NSF recently announced funding for nine new critical zone collaborative networks to take the baton, as well as a hub to coordinate critical zone research. Check out our features on pages 24 and 30, and read more in our exclusive digital coverage at eos.org/critical-zone.

Speaking of handing off projects to the next generation, flip to page 36 to read about the teams that are figuring out how to plan a space mission knowing it will have to be passed down to, quite literally, the next generation. With the Voyager spacecraft traveling beyond our solar system, the stars seem perhaps within our reach, but not on any time frame a single career would allow. People behind the proposed Interstellar Probe are creating a model for the kind of long-lasting spacefaring missions that may not even launch until their own grandkids are retiring.

One last piece of exciting news! As we look forward to hosting you virtually during #AGU20 Fall Meeting this December, *Eos* wanted to contribute something unique to the event. Watch for our **combined November–December special double issue,** packed with news and features looking at how the geoscience community adapted to the major challenges of 2020. Check your mailboxes in mid-November for this exciting issue of *Eos.*

**Heather Goss,** Editor in Chief



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Randy Fiser, Executive Director/CEO

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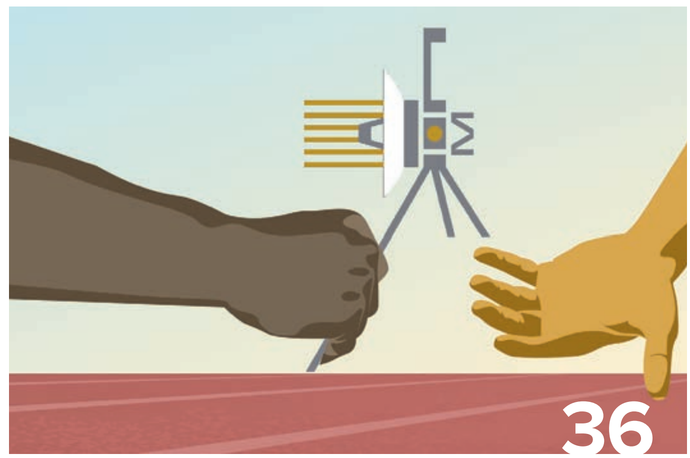


## Features



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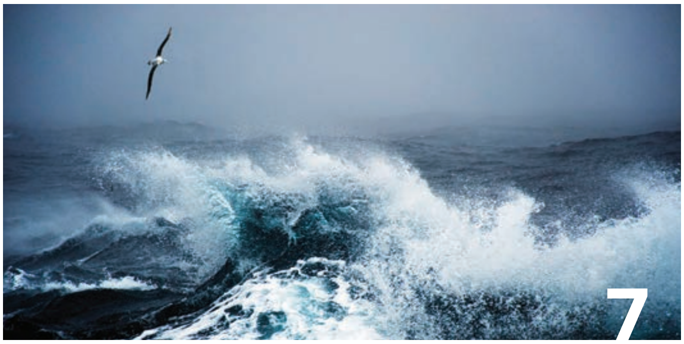





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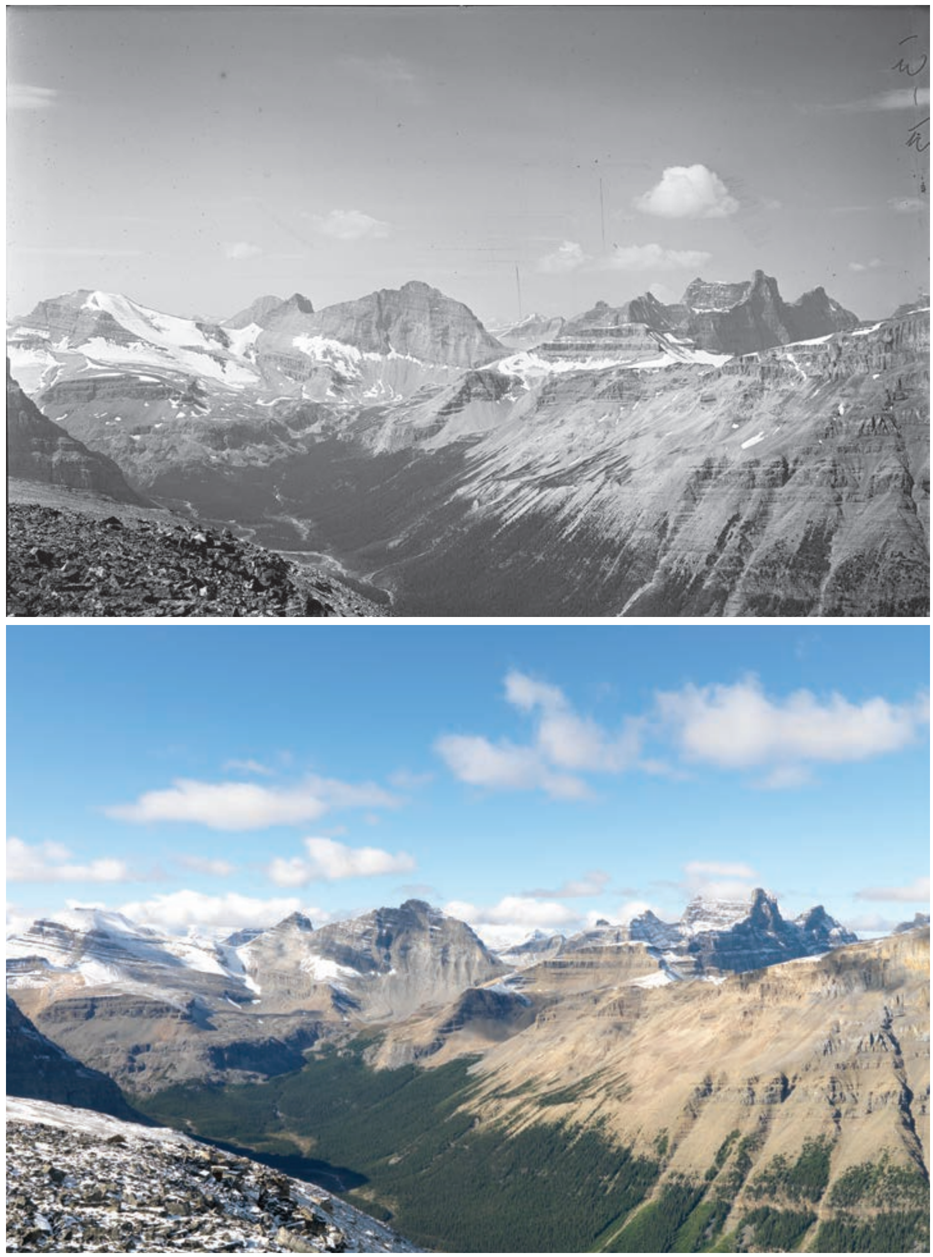
# Canada's Rocky Mountain Forests Are on the Move

On an overcast day in 1927, surveyors Morrison Parsons Bridgland and Arthur Oliver Wheeler trekked up from the Owen Creek drainage in what is now Banff National Park to take a series of photos of the mountains along the North Saskatchewan River. They aimed to make the first accurate topographical maps of the region but in the process created something much more robust than they could have imagined.

Outwardly, the black-and-white photographs Bridgland and Wheeler took look like timeless shots of the Canadian Rockies. But new research using these old images is allowing a group of scientists with the Mountain Legacy Project to quantify nearly a century of change in the landscape. Across the Canadian Rockies, forests are on the march.

The most recent results, published in the journal *Scientific Reports,* found tree lines extending higher and thicker than at the turn of the 20th century (bit.ly/mountain-changes). These changes are helping scientists understand how ecosystems will continue to shift in a warming world.



*Mountains in the Siffleur Wilderness Area in Alberta, Canada, show changes in snow and tree line between 1927 (top) and 2009 (bottom). Credit: Mountain Legacy Project, CC BY-NC 4.0 (bit.ly/ccbync4-0)*

### Onward and Upward

In the late 1990s, scientists rediscovered Bridgland and Wheeler's glass plate survey images at Library and Archives Canada in Ottawa. The 140,000-plus high-resolution negatives were taken in the late 1800s and early 1900s to precisely map the Canadian Rockies. A century later, they are a unique time capsule for understanding ecological change.

They "immediately recognized what a gold mine this was for science and for ecology, because you have this systematic coverage, during a period of time that we have really few data points," said Andrew Trant, lead author of the new paper and an ecologist at the University of Waterloo.

On a sunny summer day 89 years after Bridgland and Wheeler lugged their surveying equipment into the mountains along the North Saskatchewan, scientists returned—except this time they reached the 2,590-meter ridgeline by helicopter and brought a modern, high-resolution digital camera. Stepping in the surveyors' exact footprints, they carefully aligned and shot new photos that precisely replicated the originals.

Using this technique, known as repeat photography, scientists trekked to summits and vantage points across the Canadian Rockies. They've now replicated 8,000 of these images, and comparisons with their counterparts taken a century ago are showing an evolving landscape. Notably, they're showing a steady upward creep in tree line and forest density.

Tree lines—the limit in elevation or altitude above which trees cannot grow because of weather conditions—serve as visual

*This photo of a hilltop in the Crowsnest Forest Reserve in Alberta, Canada, taken in 2008 (right) shows noticeably more trees than its counterpart image from 1931 (left). Credit: Mountain Legacy Project, CC BY-NC 4.0 (bit.ly/ccbync4-0)*

boundaries of climate. Because tree lines evolve with shifts in weather patterns, they are useful in identifying how species are vulnerable to climate change.

**They "immediately recognized what a gold mine this was for science and for ecology, because you have this systematic coverage, during a period of time that we have really few data points."**

"Tree lines have long been considered the canary in the coal mine for climate change," said Melanie Harsch, a research affiliate at NOAA Fisheries who was not involved with the new work. "It is clear from the number of sites where trees have shifted from a shrub form to tree form, and tree density has increased, that climate change is impacting the Canadian Rockies."

In addition to higher tree lines, the forests were also denser and contained fewer stunted, windswept trees known as krummholz.

### Marching to the Beat of Climate Change

The new results agree with previous research documenting how a changing climate will dramatically redistribute the world's forests. Previous studies have found that climate change will induce forest-thinning droughts in the tropics. Models also predict that heat waves at the poles will increase the zone of subalpine forests. Other field studies have found a piecemeal response around the world, with half of the sites surveyed showing advances in tree lines.

"Going into it, we sort of expected something similar, where we find some areas that would have been responding and some areas not," Trant said. "And what we saw was a fairly uniform response."

The scientists think the difference might stem from the fact that this study, although covering a vast area of the Canadian Rockies, isn't a global analysis that covers diverse ecosystems. However, the difference might also be due to the usage of a longer timeline than other studies.

Although rising tree lines can be good for some forest species, they come at a price for others. The encroachment of subalpine ecosystems threatens species that have lived in formerly alpine habitats for thousands of years, including such trees as whitebark pine, flowers such as moss campion, and birds such as Clark's nutcracker.

"There are a lot of species, big charismatic species that we know and love, that depend on the alpine," Trant said. "Grizzly bears do a lot of their denning in the alpine area, and caribou spend time there in the winter."

**"Tree lines have long been considered the canary in the coal mine for climate change."**

With tens of thousands of images yet to reproduce, the Mountain Legacy Project hopes to continue documenting change across the Rockies in the years to come. Scientists are also using the data set to assess changes due to glacial recession, fire, and human activity. The possible projects that can be done with the images, Trant said, "are endless."

By **Mara Johnson-Groh** (marakjg@gmail.com), Science Writer

# Fragrances in an Ice Core Tell a Story of Human Activity

*Mount Elbrus in Russia is Europe's highest peak and recently provided information on 7 decades of perfume use starting in 1934. Credit: JukoFF, Public Domain*

Scented chemicals do more than perfume bodies. They often show up in sundry items such as soaps and other cleaning products to add a pleasant scent or mask unwelcome odors. A new study finds that these fragrant molecules can catch a ride on the wind to pile up in the ice of high, remote places.

Scientists have analyzed an ice core from Mount Elbrus in Russia for fragrances that settled on its snow during the 71 years from 1934 to 2005. Concentrations of fragrances in the later years were about 10 times greater than in the earliest years analyzed, according to research published in *Scientific Reports* (bit.ly/fragrances). Trends in these scent molecules also carried a whiff of economic trends and crises.

The study makes a shift from "just checking if some place is polluted…to reconstructing the story of this pollution," said Marco Vecchiato, an analytical chemist at the Institute of Polar Sciences in Venice, Italy. Vecchiato and his team analyzed the ice core for 17 fragrances and 17 polycyclic aromatic hydrocarbons, called PAHs for short. Released by combustion and industrial manufacturing, PAHs can provide an indication of human activity. Over the 7 decades analyzed, total concentrations of both PAHs and fragrances followed roughly the same pattern.

In the samples from the 1930s and 1940s, fragrance concentrations hovered around the lowest detected levels, which the scientists interpreted as background levels. Although this time period corresponds to World War II (a time when fragrance use may have dropped in Europe), these low levels may occur naturally, as flowers and plants make some of these fragrance molecules. Starting in the 1950s, the fragrance concentrations in samples began to grow and increased drastically starting around the year 2000.

That's "clearly the Great Acceleration," Vecchiato said, referring to the drastic increase in human impacts across Earth beginning in 1950.

Mount Elbrus, Europe's highest peak, receives regular deposits from not only nearby central Europe and Russia but also the Middle East and the Mediterranean, Vecchiato said. The perfume haul may reflect the Anthropocene, a term that describes our current geologic era, dominated by human activity, the authors suggested.

## As the Wind Blows

The scientists extracted the fragrances and PAHs from the ice core using a method that separates chemicals on the basis of their tendency to vaporize.

In all of the samples, upward of 80% of the perfume belonged to one of three salicylates, chemicals that provide sweet, floral aromas. Humans use a lot of these chemicals for products such as soaps, shampoos, and fabric softeners. They're fairly inexpensive to produce, Vecchiato noted. He said his team chose to analyze fragrances with a strong smell that can last for weeks or months.

But environmental chemist Staci Simonich, who was not involved with the work, suggests there were fragrances that last longer in the environment the team could have monitored. "There were some fragrance materials I'm surprised they didn't look for," she said, pointing to polycyclic musks, a class of fragrances used in personal care products, air fresheners, and detergents that would persist longer in the environment. Simonich works at Oregon State University in Corvallis.

The fragrances used in the study have relatively short lifetimes in the atmosphere, Simonich said. If you look at the trajectories of air masses around Elbrus, these fragrances likely come more from regional than global sources, she noted.

## Taking the Pulse of Pollution

Still, the Elbrus ice core may present a decades-long diary of fragrance use for the region, mirroring the ups and downs of what was once the Soviet Union.

"It's unusual to see such a clear indication of human output," said Kimberley Miner, a climate scientist who has studied pollutants and chemicals in the Arctic and in snow. Miner, a scientist at NASA's Jet Propulsion Laboratory in Pasadena, Calif., and a professor at the University of Maine in Orono, was not part of this study.

Between 1964 and 1982, the Union of Soviet Socialist Republics (USSR) experienced what was called the Era of Stagnation. Economic growth didn't stall entirely but was very slow. Perfume concentrations increased slightly from the 1930s baseline, but levels dipped during the economic slowdown.

Later, between 1989 and 1991, the Soviet Union collapsed, sending many into poverty. Lean times continued through the 1990s in former Soviet republics, including Russia. Both fragrance and PAH levels in the Elbrus ice core mirror those hard years before taking off in the 2000s. "You see this abrupt development…after the fall of the USSR," Miner said, "so it provides a really beautiful case study."

Miner wondered whether other contaminants, such as microplastics and certain flame retardants, follow this pattern in the region. This study provides yet another example, she said, "that everything that we use in our daily lives, everything that we use in our industrial processes, finds its way into the wider environment."

By **Carolyn Wilke** (@CarolynMWilke), Science Writer

# Larger Waves in Store as the Planet Warms

Mike Hill/Stone/Getty Images

Life-sustaining. Beautiful. Destructive. Ocean waves are all of these—they transport nutrients that nourish marine life, but they also damage ships and batter coastlines, triggering erosion that can send homes and infrastructure tumbling. Now scientists have used climate models to show that some parts of the globe, including the Southern Ocean, are likely to experience larger waves by the end of the 21st century. That's potentially bad news for coastal residents, the researchers suggested, because large waves could generate increased flooding and erosion.

### Generated by Wind

Ocean waves are kicked up by the wind, and warmer conditions promote stronger winds. Larger waves might therefore be a hallmark of our planet's future, Alberto Meucci, an oceanographer at the University of Melbourne in Australia, and his colleagues hypothesized. They set out to test that idea using climate models.

> **"If you want to be able to predict changes in extremes, having enough data to do so is important."**

The researchers focused on a metric known as significant wave height. Defined as the average of the highest one third of waves, it's a commonly used parameter in oceanography. (Waves more than twice the significant wave height are called rogue waves. These watery monsters, which can top 25 meters, were dismissed as sailors' tall tales for years before they were finally recorded using modern instruments.)

### Many Climate Models

Meucci and his collaborators relied on two very different greenhouse gas emissions scenarios. One, RCP 8.5 (the "business-as-usual" scenario), which assumes that carbon emissions will remain largely uncurbed, yields 8.5 watts per square meter of additional warming by the end of the 21st century (about 4.3°C). The other, RCP 4.5, assumes that some emissions mitigation policies are enacted and yields about 2.4°C of warming by 2100.

The researchers input both scenarios into seven different climate models. Meucci and his colleagues used multiple climate models to beat down statistical uncertainties. "The point of using seven global climate models instead of a single model was to be able to reduce the uncertainties connected with the representation of extremes," said Meucci.

The novelty of this study is its use of multiple climate models, said Laure Zanna, a physical oceanographer at New York University not involved in the study. "If you want to be able to predict changes in extremes, having enough data to do so is important."

Meucci and his collaborators fed the surface wind outputs of the climate models into wave generation models. The scientists determined the 1-in-100-year significant wave height—corresponding to a wave that has a 1% probability of occurring each year—for both the RCP 8.5 and RCP 4.5 scenarios for two time periods: 1979–2005 and 2081–2100.

The scientists found an increase in the 1-in-100-year significant wave height at the end of the 21st century in the Southern Ocean for both greenhouse gas emissions scenarios. The largest difference, roughly 15%, was observed in the Southern Ocean for the RCP 8.5 scenario.

Larger waves might spell bad news for this region, which is already routinely battered by waves topping 20 meters, the team concluded. Large swells could very well roll up on the coasts of South Africa, South America, and Australia, said Meucci, where they might contribute to flooding and coastal erosion. Their impact could also be more far-reaching, he said. "Changes may be felt up to the North Pacific."

But not all ocean basins will experience larger waves, the team found. In portions of the North Atlantic, wave heights might even decrease by the end of the 21st century, Meucci and his collaborators noted.

The researchers next investigated changes in the frequency of extreme waves. Again, the Southern Ocean stood out. That basin was more likely to experience larger waves at the end of the 21st century compared with 1979–2005, the team found.

These findings are believable, but it's important to pinpoint what's driving the changes in the Southern Ocean, said New York University's Zanna. "An understanding of the physical mechanisms would help strengthen even further their results."

These results were published in *Science Advances* (bit.ly/larger-waves).

In the future, Meucci and his colleagues plan to conduct similar analyses using a new ocean wave model with finer resolution. They're also looking forward to using a revised suite of global climate models (CMIP6) that includes new versions of greenhouse gas emissions scenarios.

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

# Deep-Sea Mining May Have Deep Economic, Environmental Impacts

Advocates of deep-sea mining claim that the process is important for providing metals for renewable energy technologies. One of the strongest arguments against offshore mining is that the environmental risks are too high, given that deep-sea ecosystems are among the most undiscovered places on Earth.

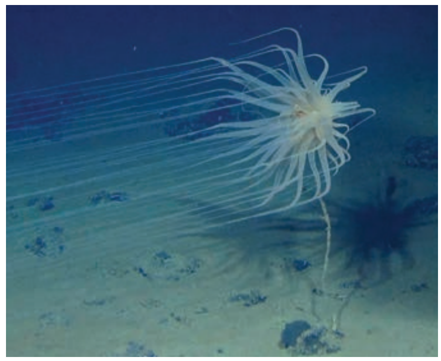
A less reported issue is the impact that deep-sea mining would have on developing economies that rely on land-based mining of those same metals. That is the subject of a recent report commissioned by the International Seabed Authority (ISA) (bit.ly/ISA-report).

The global seabed area is beyond any national jurisdiction, but ISA regulates mining. To carry out exploratory missions, state-backed companies must obtain an ISA license, which grants exclusive access to seabed areas of up to 150,000 square kilometers. To date, 30 licenses have been issued, with China holding the most, at five. The United States is not eligible for licenses, as it is not an ISA member state, but U.S. defense firm Lockheed Martin has a license through its U.K. subsidiary.

The report names 13 nations, the majority in Africa, as being most vulnerable to additional metal supplies entering the market. Each identified country currently generates at least 10% of its export earnings from one or more of the key metals targeted by deep-sea mining: copper, cobalt, nickel, and manganese.

The report identifies Chile, Democratic Republic of Congo, Eritrea, Lao People's Democratic Republic, Mongolia, Peru, and Zambia as vulnerable to a market influx of offshore copper supplies. Copper plays an important role in renewables due to its ability to conduct electricity and heat. Almost all cobalt (used in batteries) is a by-product of copper production, so it could also affect these countries.

The economies of Madagascar and Zimbabwe will be affected by new supplies of nickel, which is expected to play a key role in electric vehicles and high-capacity batteries. Gabon will be affected by new manganese supplies, used in the production of high-grade steel. Mauritania, Namibia, and Papua New Guinea are at risk because of the cumulative effect of all of the specified metals.



*Relicanthus*, a relative of sea anemones, are reliant on polymetallic nodules in the Clarion–Clipperton Zone, a target of deep-sea mining. Credit: Craig Smith and Diva Amon, ABYSSLINE Project, CC BY 3.0 (bit.ly/ccby3-0)

> **"This support will be in the form of an economic assistance fund created from a portion of the proceeds from deep-sea mining."**

### Assistance Fund

One of ISA's key recommendations is that these nations should be compensated if deep-sea mining does commence, which the report predicts will happen in 2027. The requirement for this economic support is linked with the United Nations Convention on the Law of the Sea, which became effective in 1994.

"This support will be in the form of an economic assistance fund created from a portion of the proceeds from deep-sea mining," said Michael Lodge, ISA secretary-general. Lodge said that the report is based on long-term economic projections and so should be unaffected by the COVID-19 pandemic.

But the proposal already has its critics. Among them is Bramley Murton, who leads the marine mineral research team at the National Oceanography Centre in the United Kingdom. He argues that deep-sea mining will be viable only if the commodity price is high enough as a result of increasing demand. "[Offshore] production costs are always likely to be greater than a well-resourced and efficient on-land mine," he said.

As the global seabed is not a part of any one nation's exclusive economic zone, Murton thinks it is unfair that only selected countries should benefit from ocean-mining royalties.

Andy Whitmore of the Deep Sea Mining Campaign is in favor of economic support for developing nations that rely on mining, but questions the quantity of money that would be available. "The amounts that are likely to be paid would likely be very low, unless the scale of deep-sea mining was so widespread, with so many exploitation licenses issued, that there would be significant impact on the seabed in international waters."

### Environmental Threats

Sediment plumes are considered the greatest ecological threat posed by deep-sea mining, appearing to cause lasting damage to microbial life. If mining operations scale up, noise could increasingly affect whales and other animals that rely on echolocation, while light pollution could affect animals that use bioluminescence.

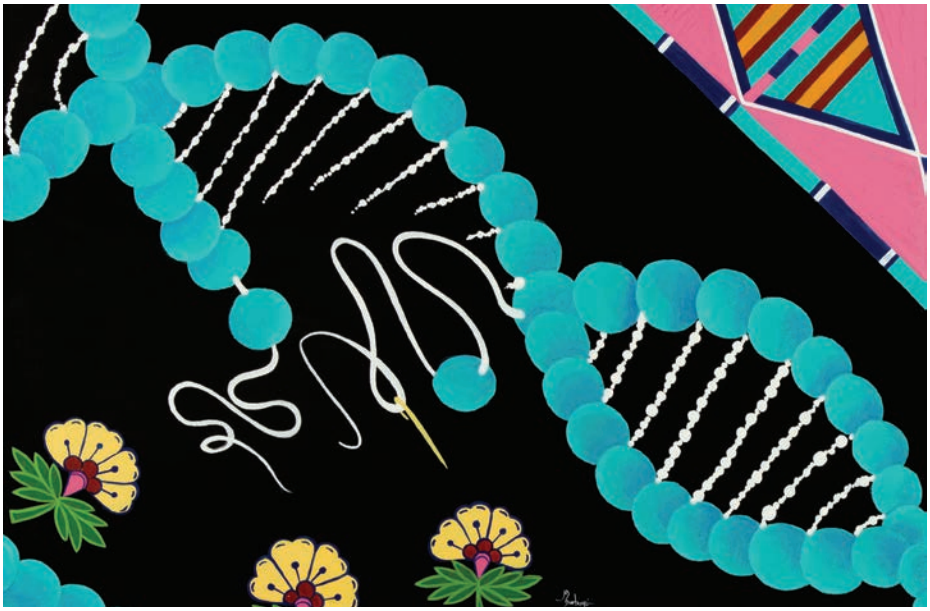
The short- and long-term effects on specific regions are unknown. More than half of the current licenses for deep-sea mining, for instance, relate to the Clarion-Clipperton Zone (CCZ), a fracture region in the Pacific Ocean covering 4.5 million square kilometers. For the CCZ, the greatest commercial interest is polymetallic nodules, compacted mineral-rich cements resembling blackened cauliflower florets.

Surveys of the CCZ have revealed that it also contains an abundance and diversity of life. Some species, including sponges and anemones, attach themselves to the nodules for feeding. Other species rely on the nodules indirectly, such as the recently discovered octopus nicknamed "Casper" that attaches its eggs to the stalks of dead sponges. A 2016 study published in *Scientific Reports* suggested that roughly half of the megafauna in the CCZ depend on the nodules as a hard substrate habitat (bit.ly/CCZ-megafauna).

"We're only beginning to scratch the surface of what's down there. The loss of biodiversity due to mining activities will be inevitable and permanent on a human scale," said Matthew Gianni, cofounder of the Deep Sea Conservation Coalition.

By **James Dacey** (@JamesDacey), Science Writer

# Thinking Zinc: Mitigating Uranium Exposure on Navajo Land



*Mallery Quetawki's paintings use an Indigenous lens to communicate scientific findings to Native communities. Here her artwork depicts DNA damage through the Indigenous perspective of a broken strand of turquoise beads. Credit: Mallery Quetawki*

After World War II, the U.S. government announced it would purchase all uranium ore mined in the United States. This announcement fueled a mining boom throughout the country, particularly in the Southwest.

As uranium production soared on and near Navajo lands, many Navajo people worked in the mines with no knowledge of the adverse effects of uranium exposure, even though the association with lung cancer was known at the time. "They thought it was ordinary digging," said Esther Yazzie-Lewis, coeditor of *The Navajo People and Uranium Mining.* "[The miners'] wives would do laundry…their clothes got exposed to uranium."

Despite passage of the 1990 Radiation Exposure Compensation Act, which acknowledged this historical neglect, risks of contamination at many abandoned mines have still not been properly addressed. For instance, according to Yazzie-Lewis, materials like wood from abandoned mines have been used to build houses, making cleanup a formidable project. Kidney failure and cancer, conditions associated with uranium contamination, continue to affect Navajo people. Filing for compensation can also prove arduous. For people married in traditional Navajo ceremonies, for example, reparative payments can often be difficult to obtain because of the difficulty of proving marital status.

Five federal agencies have been tasked with cleanup at the mines, but the process is slow and riddled with setbacks. In early June 2020, President Donald Trump signed an executive order rolling back environmental reviews. The same month, a federal court ruled against the Havasupai Tribe and environmental groups by allowing a uranium mine to operate near the Grand Canyon.

## Thinking Zinc

Despite environmental rollbacks, the scientific community is responding aggressively to the health crisis posed by uranium mining. An ongoing clinical trial at the University of New Mexico called Thinking Zinc seeks to test whether dietary zinc supplements could mitigate the adverse health effects of metal exposure. According to Johnnye Lewis, a professor at the Community Environmental Health Program at the University of New Mexico, long-standing relationships with colleagues from Navajo Nation made the trial possible.

"It is exciting to see [that] what our team learns in the laboratory can actually have meaning for communities by helping to reduce risk," said Lewis. "There has to be two-way participation."

Scientific findings and terminology can be inaccessible to many of the people who would be most affected by the study. Mallery Quetawki, artist in residence at the University of New Mexico College of Pharmacy, serves as a cultural liaison on the project to translate findings in a culturally relatable way. Emphasizing the importance of dialogue and cultural sensitivity, Quetawki said it would be a mistake to simply regurgitate data results to the community and expect comprehensive progress to follow. Research is a vital, but insufficient, step in delivering justice to Indigenous communities, she said.

By using a strand of turquoise beads to represent proteins and visually demonstrating how such proteins deteriorate when coming into contact with foreign metals such as uranium, Quetawki frames scientific findings through the lens of Indigenous ways of knowing. "This has allowed people to start dialogues and ask more questions," Quetawki said, describing her artwork as a "bidirectional communication tool for the community and for the researchers."

Quetawki's methodology indicates the paramount importance of trust building and cooperation throughout the research process. This process has the potential, she said, to achieve long-lasting impacts much more than a top-down experiment ever could.

"We need to stop looking at community members as subject matter," said Quetawki.

## Moving Forward

The COVID-19 crisis has introduced new ways for Thinking Zinc researchers to evaluate the effects of uranium mining on public health. According to Lewis, COVID-19 has had a huge impact on the production of a class of proteins called cytokines, as does exposure to metals like uranium. To researchers, this relationship indicates the need to evaluate the interaction between the disease and metal exposure.

The research may ultimately benefit communities beyond those affected by zinc exposure. The coronavirus pandemic, for instance, has disproportionately harmed Navajo communities, and the approaches embraced by Thinking Zinc may provide vital scientific insights on how to improve public health outcomes in that sphere.

By **Ria Mazumdar** (@riamaz), Science Writer

# India's Food Bowl Heads Toward Desertification

Punjab, a landlocked state in northern India, has a predominantly agriculture-based economy that earns it the nickname "the food bowl of India." However, experts worry that if the region continues to extract groundwater at current rates, there may not be enough water to grow crops, and the state could be economically and ecologically devastated.

Punjab is slowly starting to adopt measures to control water mining, but the losses are set to continue without more aggressive initiatives.

*Gurjap Singh, a farmer in the village of Harigarh in Punjab, cannot grow rice this year. His tube well, dug about 30 meters deep, no longer reaches the groundwater. Credit: Gurpreet Singh*

### How the Groundwater Dropped

In the mid-1960s, Punjab's agricultural sector blossomed, owing in part to federal subsidies for fertilizers and pesticides. In the 1970s, the state government established a corporation to access the region's abundant groundwater by constructing thousands of wells.

Today at least 40% of India's surplus food stocks are harvested in Punjab. By May of this year, during peak growing season, the Food Corporation of India reported it had collected nearly 13 million metric tons of wheat in the region, despite the coronavirus lockdown (bit.ly/India-wheat). Last year, it collected 11 million metric tons of rice from Punjab.

In the pursuit of growing more rice and wheat, more than 1.4 million agriculture tube wells have been dug in Punjab over the past 60 years. On average, groundwater levels have sunk by 51 centimeters every year.

**In the 1960s, "groundwater was available at 3 meters. Now tube wells are dug as deep as 150 meters."**

Last year, groundwater levels fell by more than 60 centimeters, said Gopal Krishan, a hydrology and soil scientist at India's National Institute of Hydrology. "This is alarming," he said.

More than 3.35 cubic meters of water are needed to grow 1 kilogram of rice, according to India's Commission for Agricultural Costs and Prices. Cultivated over 2.7 million hectares, an estimated 11 billion kilograms of rice grow in Punjab every season. The water demanded by these rice crops (nearly 36 billion cubic meters) amounts to 27 times more than the yearly household consumption (1.3 billion cubic meters) of the 28 million people living in the state.

### Deeper Waters

Farmers' worries have been mounting since Punjab's 2020 rice growing season for started in June.

Nek Singh, a 75-year-old farmer in the region, has witnessed dropping water levels over the past half century. In the 1960s, he said, "groundwater was available at 3 meters. Now tube wells are dug as deep as 150 meters" to reach the rapidly receding groundwater level. "Even if water is available deeper, it would not be economic, and we may have to shut our farms," Singh said.

Geographically, Punjab is divided into 138 administrative blocks; only 22 of these blocks have sufficient groundwater supplies, according to the 2017 assessment by India's Central Ground Water Board. The rest are at critical levels. "Loss of water is severest—more than 1 meter in a year—in 40 blocks," said Punjab state hydrogeologist Rajesh Vashisht. Districts in which these blocks are located have been notified that they cannot allow new irrigation tube wells.

"We can't go deeper, as it would be unviable to pull out water from aquifers at such a depth," said Vashisht. "The aquifers may not dry completely, but how deep can we go? A day will come when extracting water at a certain depth will be bad economics." This year, the Punjab government will pay a projected 65 billion rupees (approximately U.S.$879 million) for electricity to run the wells, a major portion of the state's annual budget.

### Confirmed Losses

"It will be a desert here if we continue to exploit our only natural resource," said agricultural economist Sardara Singh Johl, currently the chancellor of Central University of Punjab in Bathinda. When he was the chancellor of Punjabi University in the mid-1980s, Johl (now 93) sounded an alarm in a report submitted to the government asking farmers and the government to stop the depletion of groundwater by diversifying crops and halting rice production. "No one listened," he said.

In 2009, researchers reported a "mind-boggling rate" of groundwater decreases over the previous near decade in the northern Indian states of Punjab, Haryana, and Rajasthan (http://bit.ly/India-groundwater, http://bit.ly/Indian-well). More than 109 cubic kilometers of water had been pulled out of the region's aquifers, according to data collected by NASA's twin Gravity Recovery and Climate Experiment (GRACE) satellites, launched in 2002.

In its 2017 report, the Central Ground Water Board concluded that at current rates of extraction, Punjab's groundwater resources may be exhausted in 20–25 years.

Referring to the latest groundwater estimates, jointly prepared annually by Punjab's Department of Agriculture, Department of Water Resources, and the Central Ground Water Board, Vashisht said that "Punjab is consuming 166% groundwater for irrigation."

**"Punjab is consuming 166% groundwater for irrigation."**

### Digging Deeper

Alarmed over the radical changes in groundwater levels, the state government engaged Israel's national water company Mekorot Development and Enterprise Ltd. to find solutions. Mekorot will assess the scale of the problem, and the company has started gathering data across Punjab.

Earlier this year, the state also created a water regulatory body, the Punjab Water Regulation and Development Authority. Punjab's government also may ban digging of new tube wells and make registration of all existing tube wells mandatory.

In the end, however, the problem may be more political than hydrological. In 1997, Punjab's governing party decided to pay electricity costs to operate all tube wells in the state. With strong opposition from farmers, Punjab's government may have a hard time revoking that subsidy, even as the state's groundwater disappears.

By **Gurpreet Singh** (@JournoGurpreet), Science Writer

# Scientists Tune In to Krill

Antarctic krill are individually small but collectively mighty. Each one is only a few centimeters long, but they gather in groups so large that during certain times of year, the swarms can be seen from space.

But these tiny shrimp-like creatures may not be so numerous forever. In at least some areas of the Southern Ocean, krill populations appear to be in a period of long-term decline. And a loss of this keystone species would be devastating for the Antarctic's marine ecosystem.

Fortunately, emerging technologies are helping scientists monitor krill more effectively. One example is the Signature100, a device that combines an acoustic Doppler current profiler (which measures ocean currents) and a scientific echo sounder (which measures krill biomass).

David Velasco, lead author of a paper describing the technology (bit.ly/krill-biomass), said that because krill generally move with ocean currents, measuring currents and krill biomass at the same time can tell scientists not only how many krill there are but also where they're going.

The devices can also operate autonomously—scientists can attach them to stationary moorings or slow moving underwater robots called gliders, where they will quietly collect data for several months. This autonomous data collection, said Velasco, could provide substantial cost savings compared with ship-based research as well as allow for longer-term observations.

**Antarctic krill are "a key food item for almost all of the biodiversity that is visible to us as visitors to the Southern Ocean."**

### The Impact of the Krill Fishery

The krill fishery is important to both the Antarctic ecosystem and the human economy, so monitoring and sustainably maintaining its health has taken on increased importance. Leopard seals, blue whales, albatrosses, penguins, squid, and many species of fish all consume vast quantities of krill.

*Individual krill are just a few centimeters long, but collectively they help support the entire Antarctic food web. Credit: Antarctic Ecosystem Research Division, NOAA*

"Antarctic krill are central to the Antarctic food web," said Simeon Hill, a senior scientist with the British Antarctic Survey who studies the ecosystem of the Southern Ocean. "A wide variety of species covering a whole range of different sizes, from things that are about the same size as krill themselves, right up to the baleen whales, all feed on Antarctic krill. So it's a key food item for almost all of the biodiversity that is visible to us as visitors to the Southern Ocean."

Since the 1990s, the amount of krill harvested by the fishing industry has been on the rise. By the late 2010s, more than 300,000 tons of krill were being harvested from the Southern Ocean each year. Once harvested, krill can be used as a food source in aquaculture or to make krill oil, a popular dietary supplement high in omega-3 fatty acids.

"The fishery for Antarctic krill is the most important fishery in the Southern Ocean," said Hill. "And yet unlike most fisheries that have advanced management in the world, [the krill] fishery is managed without a clear idea about how the population size changes from year to year."

By **Hannah Thomasy** (@HannahThomasy), Science Writer

# Experiments Reveal How Permafrost Carbon Becomes Carbon Dioxide

Dig just about anywhere at far northern latitudes, and you're bound to hit permafrost.

But this frozen soil is thawing as Arctic temperatures rise, and the carbon within it is escaping into the atmosphere in the form of carbon dioxide, a major greenhouse gas. Researchers have now experimentally studied how sunlight triggers carbon dioxide production from permafrost carbon that's been flushed to lakes and rivers, a process long ignored in climate models.

Current estimates of global warming from permafrost carbon feedback are biased low, the team concluded.

## No Longer Locked Up

Permafrost has been frozen for far longer than humans have been on the planet. That's a good thing, because permafrost contains over a trillion metric tons of organic carbon deposited by generations of plants, and all of that carbon remains locked up when it's frozen.

"But now, because of human activity, it's starting to thaw," said Collin P. Ward, an aquatic geochemist at the Woods Hole Oceanographic Institution in Woods Hole, Mass. "The big concern here is what's going to happen to all of that organic carbon."

The effects of thawing extend beyond climate change—buildings and roads in the Arctic are also apt to collapse when the permafrost beneath them thaws.

## Microbes and Sunlight

One way in which permafrost carbon gets converted to carbon dioxide is via microbes—some microscopic life-forms chow down on carbon and respire carbon dioxide.

Although this microbial process is generally taken into account in climate models, comparably little is known about the permafrost carbon that's flushed to lakes and rivers, where it's exposed to sunlight. "We've known for a while that sunlight converts organic carbon to carbon dioxide, but the governing control of this process has escaped us," said Ward.

It's been hypothesized that this photomineralization might be controlled by the presence of iron, which is abundant in Arctic fresh waters. "There have been lots of lab-based studies suggesting that iron is a key player, but this is the first to let nature tell us what controls this process," said Ward.

In 2018, Ward and his colleagues collected five samples of permafrost from northern Alaska. Back in the laboratory, they thawed the permafrost, filtered out the microbes, and isolated the dissolved organic carbon and other constituents, including iron. They then exposed the samples to different wavelengths of ultraviolet and visible light.

## Visible Light Wins

In nature, the highest rates of photomineralization occur in the presence of visible light, Ward and his colleagues calculated. Two factors contribute to this finding. First, Earth's surface receives significantly more visible light than ultraviolet light. Second, iron kick-starts reactions at longer wavelengths, the team showed. (Visible light is characterized by wavelengths longer than those of ultraviolet light.)

Photomineralization's wavelength dependence has important implications, said Ward. It means that permafrost carbon in deep lakes or rivers is still apt to be converted to carbon dioxide. "As you move deeper into the water column, there's less ultraviolet light available and more visible light," said Ward.

## Older and More Effective

The researchers also determined that the older carbon found in permafrost—several thousand years old—was roughly twice as effective at producing carbon dioxide as modern carbon. Modern carbon has more sunlight-absorbing compounds, said team member Jenny Bowen, a biogeochemist at the University of Michigan, but permafrost carbon is better at reaping the reaction-promoting benefits of iron.

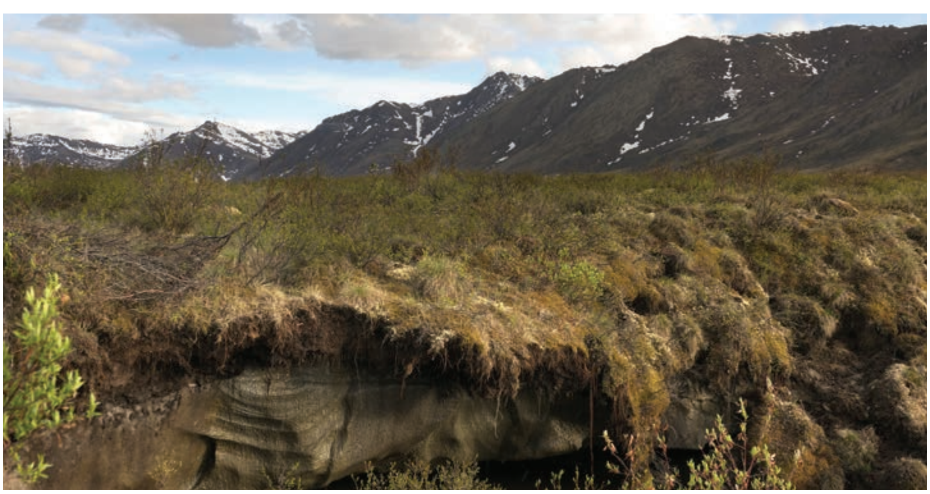
This unaccounted-for contribution from old carbon has the potential to fundamentally change the carbon cycle, said Ted Schuur, an ecosystem ecologist at Northern Arizona University in Flagstaff not involved in the research. "Stuff that wasn't part of the atmosphere is suddenly ending up in the atmosphere."

Because photomineralization of permafrost carbon isn't presently included in climate models, estimates of future global warming are biased low, the researchers concluded. "Sunlight increases the amount of carbon dioxide coming from thawing permafrost by 14%," said Bowen. "The planet will warm even more than expected."

These results were published in *Geophysical Research Letters* (bit.ly/permafrost-CO2).

In the future, Ward and his colleagues plan to study how sunlight-driven photomineralization and microbial degradation work in tandem to convert permafrost carbon into carbon dioxide. "Sunlight can facilitate microbial degradation," said Ward. "Sunlight breaks molecules into simpler ones that microbes can readily use."

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



*Many landforms in Tombstone Territorial Park in Canada are underlain by permafrost. Sunlight can trigger reactions that turn carbon in permafrost into climate-warming carbon dioxide. Credit: iStock.com/milehightraveler*

# The Seismic Hush of the Coronavirus

Seismic noise has dropped by half during coronavirus lockdown measures, giving scientists a rare lull in which to search for hidden signals usually drowned out by human activities.

Researchers measure seismic waves coming from natural sources, like earthquakes and volcanoes, as well as from human activities. Trucks, cars, factories, and even shopping can create high-frequency seismic waves radiating out from population centers, and most scientists filter out human noise to seek natural signals.

But seismic noise has been unusually quiet lately, in what scientists are calling the "anthropause."

"If it's quieter now and we can pick up some of the smaller signals, that improves our seismic risk analyses," said Paula Koelemeijer, lead author of a study published in the journal *Science* (bit.ly/seismic-hush).

Tracking smaller earthquakes can help scientists understand larger, more dangerous quakes and monitor how faults move. When a magnitude 5.0 earthquake struck Petatlán, Mexico, on 4 July, a station 380 kilometers away was able to detect the quake from raw data. Normally, the station would have missed the small quake without filtering out noise.

**Seismic noise has been unusually quiet lately, in what scientists are calling the "anthropause."**

"This is likely to become a landmark article in the fields of seismic monitoring and ambient noise tomography," said volcanologist Jan Lindsay at the University of Auckland who was not involved in the study. "The '2020 seismic noise quiet period' will likely become something that Earth science students of the future will learn about in textbooks."

Globally, seismic noise dropped by a median average of 50% during the coronavirus lockdowns from March through May. The measurement includes all seismic signals, but scientists attribute the drop to a decrease in human activity by comparing changes in seismic noise with mobility data from Google and Apple.

*A drop in seismic noise from humans could help scientists track tremors from volcanos such as Rangitoto in Auckland, New Zealand, seen here. Credit: Wikipedia/DXR, CC BY-SA 3.0 (bit.ly/ccbysa3-0)*

The drop in noise varied by location: It decreased by 33% in Brussels, Belgium; 50% in Sri Lanka; and 10% in Central Park, New York. Rural areas grew quieter too—noise at a station at Rundu, Namibia, dropped by over 25%. (Koelemeijer attributed the drop to decrease in tourists at a popular hippo-watching spot nearby.) The study pulled data from 185 seismic stations across the globe in both urban and rural locales and included information from professional instruments as well as from those on public platforms.

"This study impressively demonstrates just how much [human]-made noise there actually is," said research associate Carolin Böse at the GFZ German Research Centre for Geosciences who was not involved in the research. "Seismologists around the world now have a chance to make good use of the data presented in this study and hunt for otherwise 'hidden signals' in the seismic recordings."

One of those hidden signals could be volcanic tremors in Auckland, New Zealand. One and a half million people live in the area, which is affected by a volcanic field underlying the city. Comparing the seismic noise before and after lockdown could help scientists uncover volcanic earthquakes, said Lindsay. "In theory, this could provide critical extra warning time in the lead-up to a future eruption."

**Seismic noise has been unusually quiet lately, in what scientists are calling the "anthropause."**

This study builds on others tracking changes to Earth as a result of the coronavirus. Recent work revealed that emissions from common pollutants from fossil fuels, such as carbon dioxide and nitrogen dioxide,have plummeted during the lockdowns.

Koelemeijer expects follow-up studies on seismic noise, which some scientists can use to image the inner Earth, and a fresh appreciation for human-caused seismic noise. She also sees a global effort to stop the spread of the coronavirus.

"If you're just stuck in your house and your normal activities can't continue at the moment, it is comforting and motivating that we're seeing this all around the world," Koelemeijer said. "Everyone is in this together."

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

# Birds Are Getting Caged In at Brazil's Savanna

Poor land use combined with the onset of climate change is putting the Cerrado under severe strain. This tropical grassland in central Brazil is the world's most biologically diverse savanna, home to 5% of the planet's plants and animals, according to the World Wildlife Fund. It's also the world's most threatened savanna. Scientists recently studied how much refugia, or land available as habitat for species that are crowded out of their native areas, would be left in the Cerrado by 2050.

Brazilian researchers chose birds for their study, selecting 103 species out of the 856 the Cerrado harbors, focusing on those that rarely or never leave the savanna. They looked at how climate change factors—specifically, temperature and precipitation—would change in kilometer-square grid cells across the biome. The scientists then incorporated a factor that few do when studying long-term habitat changes: land use predictions. Using maps projecting out to 2050, the scientists categorized each grid cell as either "high native vegetation," meaning that an area is likely to stay untouched, or "low native vegetation," meaning that the location has been or will likely be transformed for urban or agricultural use.

Areas projected to have both high native vegetation and low impact from climate change amounted to only 13% of the Cerrado—a small area of possible refugia for these birds in the next 3 decades. And even that area is not guaranteed: "The bad news is, these are not protected areas," said coauthor of the study Rafael Loyola, scientific director of the Brazilian Foundation for Sustainable Development and a professor at the Federal University of Goiás. Only a little more than 10% of that potential refugia is within land that's legally protected from land use changes.

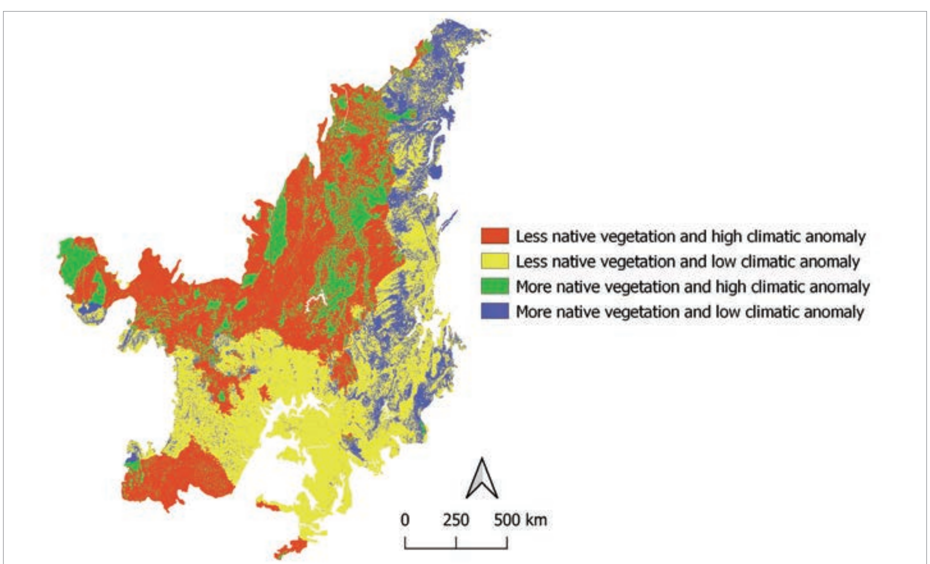
## Forced Migration

After evaluating possible refugia, Loyola and his colleague Fábio Borges looked specifically at how Cerrado birds would fare given these projections. Nearly three quarters of the birds in their study would be living largely within the highest-risk areas, those prone to the most changes due to both climate and land use—in fact, nearly 100% of the species would be in areas that had transformed to agricultural or urban use. Only four out of the 103 species studied currently live primarily in the potential refugia.

The paper identifies four bird species as being in the most danger. The crimson-fronted cardinal, the Araguaia spinetail, the Goiás parakeet, and the Bananal antbird—the last two of which are threatened species—are endemic to parts of the Cerrado outside the potential refugia and have shown low responsiveness to changes in their climate.

"The fact that a broad study like this was able to spot the vulnerability of these species is really alarming," said Renato Pinheiro, a professor of conservation biology at the Federal University of Tocantins in Brazil who was not involved with the study. He said the study is innovative in the sense that it crossed future climate and land use changes to build a predictive model, because studies of this kind usually work on one aspect or the other, rarely intersecting both.

Pinheiro's team studies the Orinoco goose, a species that lives in both the Cerrado and the Amazon basin and has been attempting to adapt to habitat changes. "The reduction of floodplain areas in the Cerrado has driven these birds to hibernate in rice culture areas since they end up having more nutrients," Pinheiro said. Such behavioral changes expose the birds to diseases and pesticides.




*Scientists recently calculated native vegetation and climate anomalies to determine the amount of refugia in the Cerrado in 2050. Credit: Fábio Júlio Alves Borges and Rafael Loyola*

## Protecting the Cerrado

"The Cerrado has a strong agricultural potential because of its fertile soil, many watersheds, and good rainfall regime. A considerable chunk of Brazil's gross domestic product comes from there," said Loyola.

Such richness attracts economic interests. According to the World Wildlife Fund–Brazil, 40% of the Cerrado is used for agribusiness, and roughly half the biome has been clear-cut for pastures and other agricultural uses. From August 2018 to July 2019, the Cerrado lost 648,400 hectares to development—4 times the size of the metropolitan area of London. According to the MapBiomas project, in 2019 alone there were more than 7,000 deforestation alerts in the Cerrado.

Conservationists are trying to work with farmers to make the land they're already using more productive, rather than increasing their crops by spreading out over more land. If those tactics aren't followed, the biome is at risk of losing another third of its area to soy production by 2050 in a business-as-usual scenario, said Loyola. More than 80% of the Cerrado might be lost by the middle of this century. "If this happens, we could lose over a thousand animal and plant species, 480 of them endemic to that area," said Loyola.

Borges and Loyola's study was published in *Perspectives in Ecology and Conservation* (bit.ly/cerrado-birds).

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

# Demystifying Critical Zone Science to Make It More Inclusive

*Students perform a dye test, which helps them to estimate groundwater–surface water exchange near the Susquehanna Shale Hills Critical Zone Observatory in Pennsylvania. Credit: Kamini Singha*

Each of us lives on this planet differently. The way in which we are affected by or have an effect on our surroundings changes from person to person, from community to state to nation. As critical zone scientists, perhaps we understand that more than many scientists. We study the layer of our planet from the treetops down to the base of groundwater, where the interactions between our natural habitat and all of Earth's living creatures are complex and constantly evolving.

If we are to do our research successfully, diverse alliances are important. This truth motivated our group to form the Critical Zone Research Coordination Network (CZ-RCN), launched in 2019 and funded by the National Science Foundation (NSF). Fifteen years ago, NSF established the Critical Zone Observatories, a group of diverse sites around the United States and Puerto Rico selected for intensive critical zone research, and today the observatories are preparing to evolve as critical zone science grows internationally. The data collected from these sites span ecology, hydrology, biogeochemistry, geology, atmospheric science, social science, and even more fields. Many key scientific problems—such as quantifying and predicting the architecture of the critical zone, and how the critical zone evolves and its role in myriad processes controlling ecosystems—remain difficult to tackle, in part because of the convergent perspectives required to think through them.

Unfortunately, because critical zone science is a new approach to transdisciplinary science, few universities offer courses or fieldwork in ways that incorporate related studies under this term. As a result, many early-career Earth scientists have not heard of the critical zone and do not understand how their work studying rivers or the carbon cycle—or any process occurring at Earth's surface—fits squarely within it. This is a shame, not just for progress in critical zone science but also for those researchers who may miss out on the many benefits the critical zone approach and community offer, including collaborating broadly on problems of societal importance, such as feeding a growing world population or sequestering carbon to mitigate climate change. People who interact with this community often say it has changed the lens through which they conduct science.

**Many early-career Earth scientists have not heard of the critical zone and do not understand how their work studying rivers or the carbon cycle fits squarely within it.**

More problematic is that because of its relative obscurity, some see critical zone science as an insider's club—one that touches a huge spectrum of research but excludes all but the few who have managed to get into the observatory clique. What the RCN strives to make clear is that the critical zone approach is open to everyone.

### Bringing Diverse Groups into the Zone

The RCN is addressing challenges in uniting disparate scientific disciplines that operate in the critical zone while also addressing the inequities experienced by underrepresented groups that may prevent them from participating fully in their areas of interest. These groups include ethnic and racial minorities, individuals with disabilities, the LGBTQ+ community, veterans, first-generation students, and women.

We know that including different social identities is key to making better science [e.g., *Medin and Lee,* 2012]. That means first having the demographics of our programs at least match those of the available talent pool and then working to increase the diversity of that pool. To achieve this, we are broadly advertising our efforts, including with groups organized by minoritized scientists such as

GeoLatinas, the American Indian Science and Engineering Society, the Earth Science Women's Network, and more.

The RCN encourages people from different backgrounds to work together and facilitates these relationships, easing the discomfort those experiences can bring. We do this in part by asking senior scientists to share their career paths and experiences in presentations at our meetings, including telling stories about setbacks and other challenges; providing structured opportunities for participants to network broadly; and leveling the playing field by talking about skills that not all trainees are taught, such as navigating the NSF proposal system and managing imposter syndrome.

We are also offering financial support for conference travel to scientists from programs lacking significant resources. We integrate career development and networking opportunities into our scientific workshops on an equal footing with scientific talks.

For example, at the RCN event Bringing the Science Home! A Cybersymposium for Earth Surface Scientists, held in June 2020, a professor shared their nonlinear path from being a high school student who wanted to pursue physics, to finding work as a bartender and drywaller, to eventually becoming a professor of geophysics. Although traditional, direct paths are usually more valued by academia, such divergence resonates much more with the broader community of scientists who have had varied experiences and struggles. We argue that it is crucial to integrate these perspectives into the traditionally elite table of academia. Diverse experiences and collaborations broaden our definition of societally important problems and contribute to more innovative solutions to solve them.

**We integrate career development and networking opportunities into our scientific workshops on an equal footing with scientific talks.**

Every individual has unique experiences on this thin layer of Earth where the critical zone is defined, which in turn defines our worldviews and what we think is meaningful.

*Students (left to right) Stefan Klingler, Ian Gambill, Jackie Randell, and Anna Marshall mix salt into water for an in-stream tracer test at Little Beaver Creek, a tributary of the Cache la Poudre River in northern Colorado. The tracer allows scientists to study the role of logjams in controlling surface water movement. Credit: Kamini Singha*

For example, some Native Americans consider water an ancestor rather than a resource to be used at will [e.g., *Fox et al.*, 2017]. These differences in values deepen the conflicts around such issues as building the Dakota Access and Keystone XL pipelines [*Fernández-Llamazares et al.*, 2020]. This relationship with nature, called kincentric ecology by *Salmón* [2000], views different parts of natural systems as a whole and resembles the interdisciplinary and systems approaches that critical zone science undertakes.

## Accessibility Means Including the Community

The RCN also aims to develop an inclusive vocabulary within the field of critical zone science. By making our work more accessible, we include in the conversation people with different expertise who may help crack some of the difficult problems we face in critical zone research. These problems require working not just across scientific disciplines and with diverse scientists but also with nonscientists: understanding how resilient our water supplies are to changing climatic conditions, how the critical zone feeds back to control climatic conditions, and how changes in anthropogenic atmospheric emissions affect the viability of the critical zone.

One presentation from our recent cybersymposium, for instance, highlighted working with farmers who want to grow healthy and hardy crops while also conserving water and minimizing water pollution. Scientists on the project listened to the farmers' experiences and integrated that knowledge into their models, which the farmers were able to learn from and integrate into their practices. This communication could not have happened without an inclusive vocabulary.

We can't do any of this, however, if we don't have diverse viewpoints at the table. We must value and measure the effort put in by those recruiting new participants in the same way we value traditional scientific output, such as publishing. It is critical that this effort not be relegated only to minoritized scientists. Everyone should be trained in fostering inclusion, giving and receiving constructive criticism and feedback, learning from mistakes, and coming to the realization that as we improve our approaches, no single approach will fit all scenarios.

## Critical Heavy Lifting

Scientists who have already experienced success in their careers—those who have gained tenure and are leading research—must do the heavy lifting to make critical zone science

*Claudia Shuman (left) and Stephanie Troutman prepare an optical televiewer for deployment. They use the instrument to image fractures in the subsurface geology and estimate the fractures' orientation. Credit: Kamini Singha*

more inclusive. This task should especially be taken on by the many white scientists who have gained success through privilege, which may leave them with a limited view of Earth systems problems. Senior scientists need to change their view of mentoring the next generation from a one-way learning experience to a rich partnership. Veteran scientists can learn a lot from early-career scientists, who may be in different critical zone research fields and who also have experience in communicating with a broader demographic and in different ways (e.g., by social media).

Enhancing diversity throughout the science, technology, engineering, and mathematics (STEM) fields means learning some cultural humility. Everyone comes to the table with their past experiences; the question is how to support the sharing of those experiences so that everyone feels included and valued. What feel like intractable problems in the critical zone may remain that way unless we can bring in new people interested in transdisciplinary science along with their new ideas and enable communication across disciplinary, methodological, racial, economic, and religious boundaries.

By bringing new groups of individuals together, we stimulate creative and diverse ways of conceptualizing problems and synthesizing solutions that will only improve critical zone research. The RCN is collecting the resources we have found helpful for others to use in their efforts to expand inclusion in their disciplines, even outside critical zone science (see bit.ly/RCN-resources). We look forward to working with our broader geosciences community to grow diversity, inclusion, and access in critical zone science and STEM fields writ large.

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# CRITICAL ZONE SCIENCE COMES OF AGE

BY PATRICIA WALDRON

**THE DEVELOPING FIELD, WHICH UNITES EARTH SCIENTISTS TO EXAMINE THE PLANET'S SURFACE AS A SINGLE, UNIFIED ENTITY, IS UNRAVELING THE COMPLEX, INTERCONNECTED PROCESSES THAT SUPPORT LIFE ON EARTH.**

It's time for a critical zone coming out party.

The critical zone—Earth's thin living skin, which spans from the top of the canopy to the bottom of the groundwater—is still unfamiliar to many scientists.

More than a concept, it's an interdisciplinary endeavor that draws on multiple fields to piece together the complicated interactions between water, air, life, rock, and soil that support terrestrial life. By understanding and modeling these relationships and how they evolve, scientists can predict how human activities threaten these necessary, life-sustaining systems.

Critical zone science began almost 2 decades ago and developed in the United States through a network of observatories funded by the National Science Foundation (NSF). Now, as a new generation is applying critical zone science to novel questions and sites, the discipline has finally come of age.

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## The Birth of a New Field

Gail Ashley, a professor emerita at Rutgers University, first coined the term critical zone in a prophetically titled 1998 abstract for the Geological Society of America meeting, "Where Are We Headed?" "I called it the critical zone because it's critical for life," she said. "Also, it's critical to know more about it because of the potential for damaging it."

A sedimentary geologist, Ashley spent most of her career reconstructing the ancient paleo–critical zone of Olduvai Gorge in Tanzania, one of the richest paleoanthropology sites in the world. Her team uncovered evidence of wetlands and freshwater springs that likely supported hominins living at the site more than a million years ago.

The concept of critical zone science gained traction through a 2001 National Academies report, to which Ashley contributed, that recommended the creation of natural observatories for studying the critical zone.

Susan Brantley, a geochemist at Pennsylvania State University, was a driving force in developing critical zone research in the United States. "In the early 2000s, hydrology was funded separately from geochemistry, was funded separately from geomorphology," said Brantley. "A lot of us were starting to talk about how we…should be looking at the Earth's surface as one thing and bringing all those subdisciplines together." In 2003, Brantley led a team that hosted workshops, wrote white papers, and held town halls at national and international meetings to recruit Earth scientists interested in how biological, physical, and chemical processes shape Earth's surface.

Brantley and her colleagues proposed various sites for laboratories dedicated to the study of the critical zone, and in 2006, NSF put out the call for interdisciplinary watershed-scale projects that would "advance our understanding of the integration and coupling of Earth surface processes as mediated by the presence and flux of fresh water." The Critical Zone Observatories (CZOs), the first long-term sites supported by NSF's Directorate for Geosciences, were born.

## Data: The Language of Science

In 2007, NSF awarded 5-year grants to establish three CZOs, all, coincidentally, in forest watersheds. Brantley was a co-principal investigator at the Susquehanna Shale Hills site, an eastern forest on weathering shale bedrock in central Pennsylvania. Sites in California's southern Sierra Nevada and one in the Colorado Rockies also received funding. The American Recovery and Reinvestment Act of 2009 provided funding for three more observatories, with a wider variety of river basins. Finally, in 2013, the number of CZOs grew to nine, with the closure of one site and four additions. Long-term funding was critical for understanding how the critical zone functions normally and how it responds to disturbances, like fires or floods.

"One of the challenges early on was just finding a vocabulary," said Timothy White, a geologist at Penn State University and the national office director of the CZOs. It took a few years, he said, for collaborators from different fields to understand each other's science enough that they could help each other out, "and then we really began to be able to do truly interdisciplinary science."

"From the beginning, it was also about data, how to collect all of these data," said NSF program director Enriqueta Barrera, who nurtured the program from its infancy.

**It took a few years for collaborators from different fields to understand each other's science enough that they could help each other out, "and then we really began to be able to do truly interdisciplinary science."**

Ultimately, data and new technologies became common tongues in critical zone science. Advanced techniques in isotope geochemistry helped scientists track the movement of elements through the critical zone, estimate the size of fluxes, and calculate the speed of chemical processes on timescales ranging from minutes to millennia. Through remote sensors, researchers monitored weather, soil moisture and temperature, sap flow, and snow depths from the comfort of their labs. Using lidar, they mapped changes to the landscape from planes. The bounty of data were integrated into numerous geochemical, hydrological, and climate models.

Other countries began to replicate the CZO system. In collaboration with CZO scientists, researchers have established obser-

*Southern Sierra Critical Zone Observatory field manager Erin Stacy conducts measurements of water and carbon fluxes at the Providence Creek eddy covariance flux tower in 2015. Credit: Roger Bales*

vatories around the world, on every continent except Antarctica. In the United States, the Department of Energy modeled some long-term monitoring sites after CZOs, and many critical zone scientists worked independent of the observatories.

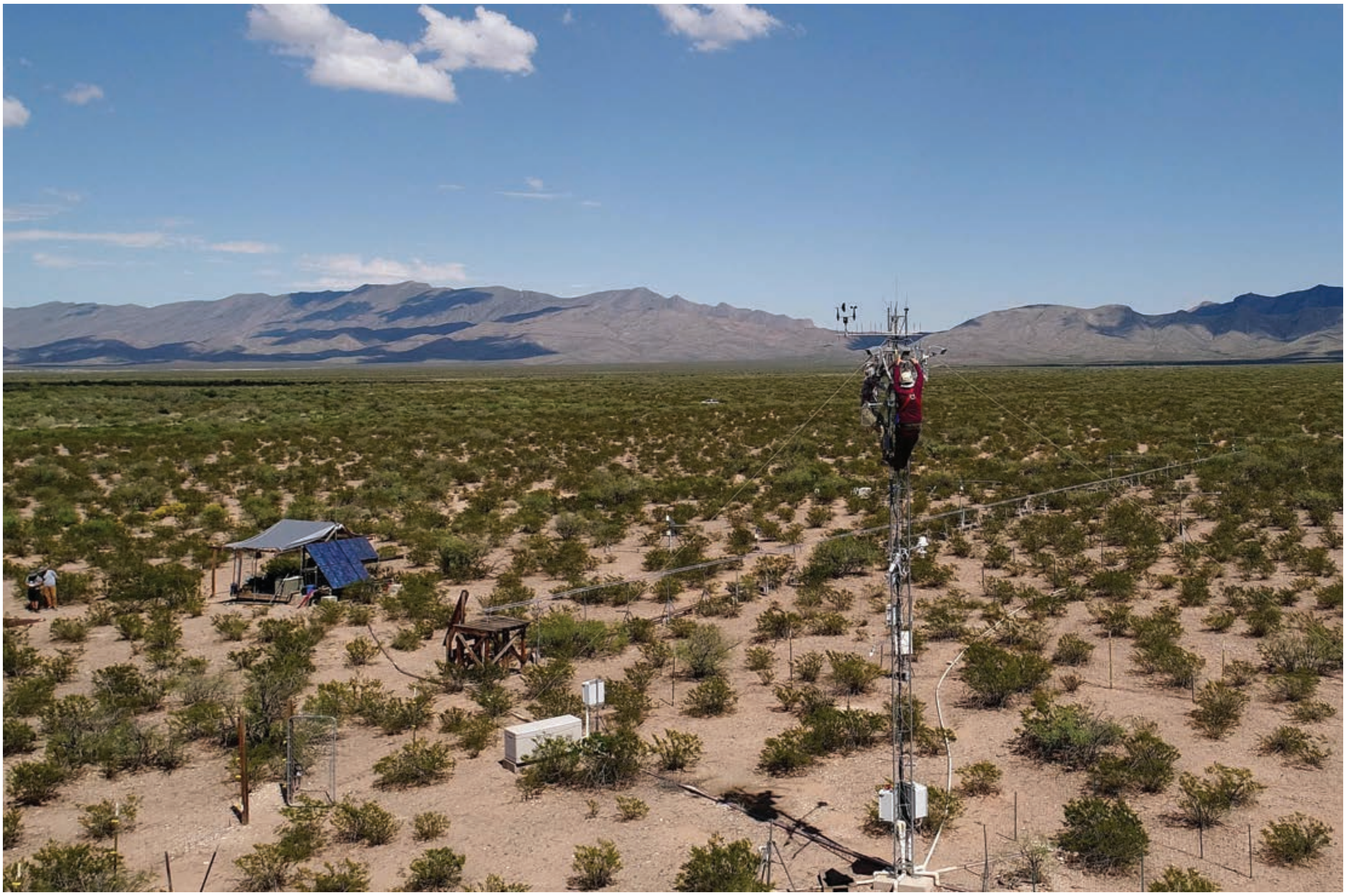
### How Far Can You Push the Critical Zone?

Since the field's inception, critical zone scientists have shown how altering Earth's surface and vegetation leads to subsurface impacts—changing water flow, minerals, and microbial life at surprising depths. Subsurface imaging and drilling have also shown considerable belowground variation and the ways in which that alteration influences surface conditions. These discoveries opened the door to more applied research and better land management practices.

For example, critical zone studies in California let researchers predict how much deep water, stored in pores in weathered bedrock, is available to forests during droughts. Scientists at the Southern Sierra and Eel River CZOs reported the amounts of root-accessible moisture available from year to year, which sustained plant life during the severe 2011–2015 drought. Nearly 150 million trees succumbed to the drought, mainly in the southern Sierra Nevada. These die-offs were a direct result of the gradual depletion of the root-accessible moisture by overstocked forests—caused by long-term fire suppression—according to research by Roger Bales, a hydrologist at the University of California, Merced, and colleagues at the Southern Sierra CZO.

Now Bales is making recommendations to the U.S. Forest Service and other land managers based on this work. "We can provide metrics that tell you where the forest is likely to suffer drought stress," said Bales, "based not just on precipitation and temperature, which is what traditional drought indices do, but also factoring in over-year storage provided by long-term bedrock weathering."

In the Midwest, at the trio of agricultural sites in the Intensively Managed Landscapes CZO in Illinois, Iowa, and Minnesota, researchers showed that industrial farming has changed the prairie landscape from one of transformation into one dominated by transport. The prairie ecosystem that evolved after glaciers from the last ice age receded functioned primarily by cycling nutrients in place and holding water in soil and groundwater (transformation). But with industrial farming, added fertilizer is par-



*In the Chihuahuan Desert, an eddy covariance tower measures the fluxes of water and carbon dioxide between the ecosystem and the atmosphere. Credit: Craig Tweedie*

tially taken up and harvested as grain, and the rest is transported away by water through altered surface pathways and subsurface drainage, ultimately fueling algal blooms in the Gulf of Mexico.

"There is a direct link between what we are finding from how these critical zones function and what we can do better in terms of ecosystem services," said Praveen Kumar, a hydrologist at the University of Illinois and head of the Intensively Managed Landscapes CZO.

**Growing the Critical Zone Community**

A crucial outcome from the development of the CZOs is a new generation of Earth scientists trained to think within a multidisciplinary framework. As of 2018, the CZOs had trained more than 300 graduate students and more than 100 postdocs. At least 40 have gone on to become assistant professors.

**Critical zone science is "this ability to get people to bring in different data sets and different mindsets and perspectives to really challenge the data about what we're seeing."**

One former trainee is Pamela Sullivan, an ecohydrologist at Oregon State University. As a postdoc at the Shale Hills CZO, she used monitoring wells to study a series of weathering processes that occurred as water flowed across the small catchment. Now she studies how factors like plant roots, bedrock fracture networks, or a shift from snow to rain alter soil structure and subsurface water flow, to better inform climate models. Working in a multidisciplinary team at the CZO was a "transformative experience," said Sullivan. "It's this ability to get people to bring in different data sets and different mindsets and perspectives to really challenge the data about what we're seeing."

Sullivan acknowledges, however, that some have felt left out of critical zone science because they were not affiliated with an observatory. To encourage collaboration, she serves as a co-principal investigator on a Critical Zone Research Coordination Network focused on synthesizing data and models to investigate the evolution of the critical zone and how it will respond to future human impacts (see p. 15). The group facilitates networking to advance research within the community.

As critical zone science expands, researchers say the field has finally matured, although "it's not an exaggeration to think of the critical zone as a new science," said William Dietrich, head of the Eel River CZO. "Once you see the thing, you can't walk away from it.... I think the critical zone is here to stay."

### The End of the Observatory Era?

Despite, or perhaps because of, the success of the CZO program, NSF will conclude its funding of the program in 2021. NSF program director Richard Yuretich is spearheading a new program that focuses on testing principles across a cluster of sites instead of comprehensive studies at a single observatory. Ideally, the data—aided by high-performance computing—will be integrated into comprehensive models of critical zone processes across diverse environments. The Consortium of Universities for the Advancement of Hydrologic Science Inc. (CUAHSI), a nonprofit that supports interdisciplinary water science, will serve as the critical zone hub. CUAHSI and collaborators will coordinate activities among the clusters, support training and synthesis activities, and provide cyberinfrastructure for collaborative modeling and for sharing and archiving data.

The shift was unwelcome news to some researchers. "I think it's going to be a great opportunity for the younger generation," said White, "but I think it was a shame that the literally tens of millions of dollars that were invested into the observatory network that we have is mostly being cast aside."

NSF has funded nine critical zone network clusters, which began in September 2020. Many clusters include locations at existing CZOs or long-term field sites with legacy data, but are led by a new wave of early-career scientists. "We have a whole new generation of scientific researchers who now have this in their DNA," said Yuretich. "The new thematic cluster and coordinating hub network is designed to capitalize on these individuals and bring them into the forefront of designing new research in the critical zone."

Now free from the constraints of the observatories, scientists can ask questions that transcend location. Teams are investigating how the coastal critical zone responds to rising sea levels and saltwater intrusion, what big data can reveal about how the critical zone recovers from disturbances, the limits of human interference, and the many functions of dust as it travels from its source in the Rocky Mountains to the deserts of southern Nevada.

### Forecasting the Future of Critical Zone Science

The new program will also help to deepen understanding of critical zone function beyond alpine watersheds. By graduating to a wider variety of environments, the ultimate goal is for researchers to construct more comprehensive models of critical zone processes worldwide.

One new critical zone network team will focus its operations in the Chihuahuan Desert, which receives about 20 centimeters of water each year, mostly during the July monsoon season. Dryland sites like this have been underrepresented in previous critical zone work. Lixin Jin, a geochemist at the University of Texas at El Paso and a former postdoc at the Shale Hills site, leads the project. She is fascinated by the desert environment, despite growing up in frigid Jilin Province, the Minnesota of China. What she discovers with her colleagues, including co-principal investigator and fellow University of Texas at El Paso geochemist Lin Ma, may have important implications for the future of the Chihuahuan and other dryland environments. These cover about 40% of Earth's landmass and support more than 2 billion people.

**The ultimate goal of this and other critical zone work is to develop models that transcend the boundaries of individual research sites so we can "Earthcast," or predict how Earth will respond to a changing climate and more intensive land use.**

Unlike tropical or temperate environments, where precipitation leaches minerals from rocks and soil, limited water in the desert concentrates minerals into a cement-like layer called caliche. This water-impermeable layer builds up over thousands of years. "If you poke it with your finger, it's as hard as rock," said Jin. "We're trying to understand how this unique architecture will govern how the ecosystem and water function in the critical zone."

To see whether precipitation reaches the subsurface, the team will drill wells more than 100 meters deep to access El Paso's freshwater source. Despite multiple hydrology studies, the city does not know the size of its reserves or whether surface water is refilling the aquifer. "To be honest, we don't know what happens to the loose water," said Ma. "But some of the water may make it all the way down."

For comparison, the team is looking at younger soils along the Rio Grande, where farmers grow pecans, chilis, and alfalfa. Irrigation from the river carries a lot of minerals, and in less than a century of agriculture, farmlands have already been shown to accumulate salt, which stresses crops. Critical zone researchers will examine how irrigation alters the fate of surface water—whether it enters plants, the atmosphere, or the subsurface—and whether irrigation contaminates drinkable groundwater by mobilizing salt, nutrients, and trace metals.

Jin and her collaborators are also excited to bring a dryland critical zone curriculum to local classrooms and to recruit students from the local Latino population. "Especially in the geology field, or Earth science in general, I just don't think we have good representation of the minority groups," said Jin. "We really want to prepare and train the next generation of scientists."

The ultimate goal of this and other critical zone work is to develop models that transcend the boundaries of individual research sites so we can "Earthcast," or predict how Earth will respond to a changing climate and more intensive land use.

"We have forecast the weather," said Jin. "But can we Earthcast the critical zone?"

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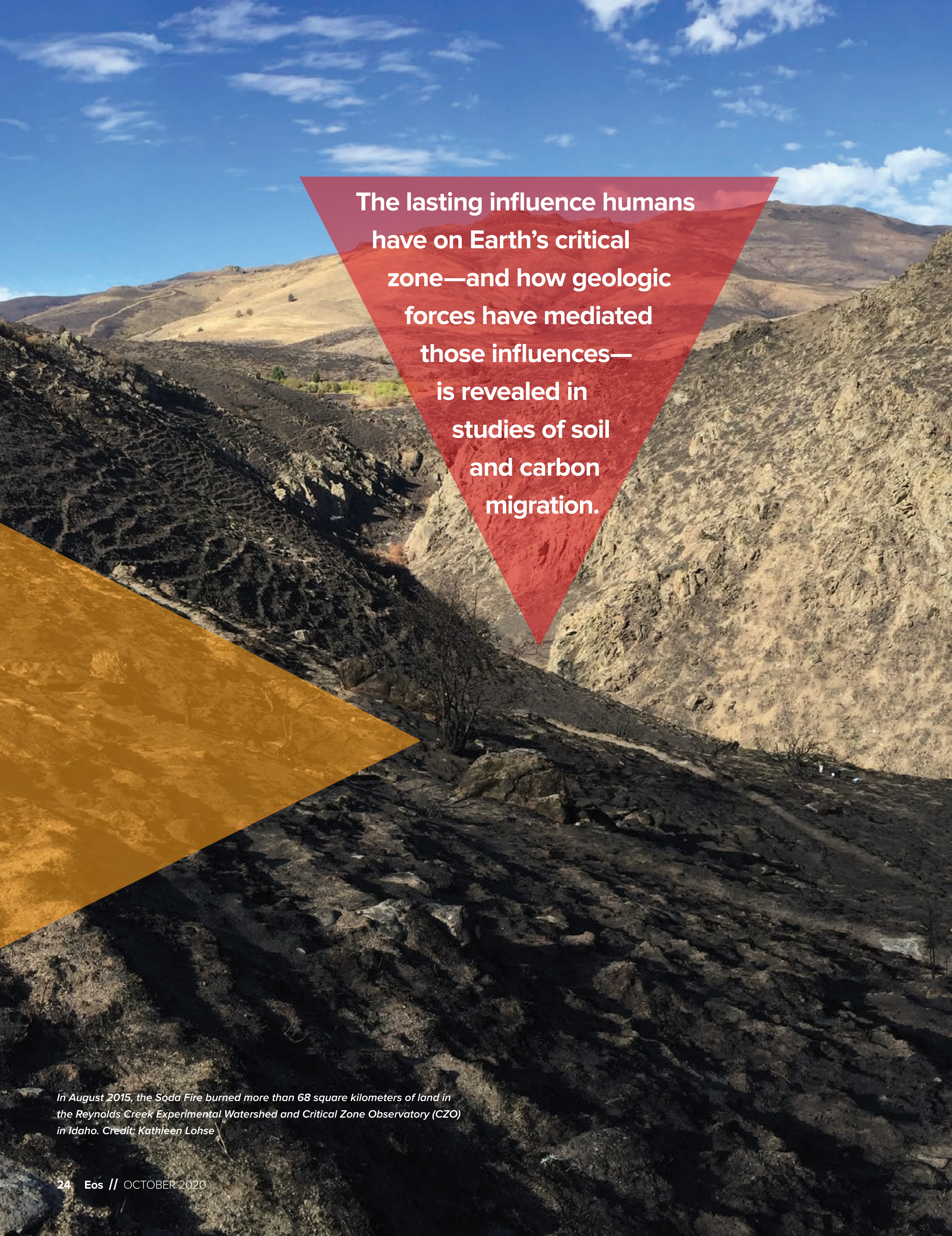
**The lasting influence humans have on Earth's critical zone—and how geologic forces have mediated those influences—is revealed in studies of soil and carbon migration.**



*In August 2015, the Soda Fire burned more than 68 square kilometers of land in the Reynolds Creek Experimental Watershed and Critical Zone Observatory (CZO) in Idaho. Credit: Kathleen Lohse*

# SOIL SIGNALS TELL OF LANDSCAPE DISTURBANCES

By Kathleen A. Lohse, Sharon A. Billings, Roman A. DiBiase, Praveen Kumar, Asmeret Asefaw Berhe, and Jason Kaye

We live in the Anthropocene, a time when the intensity and frequency of disturbances to Earth's ecosystems are increasing as humanity's footprint grows and the climate changes. The impacts of some disturbances, like land use changes for agriculture, can persist over decades to centuries and thus represent persistent, or press, disturbances. Some, like floods and fires, occur naturally as short-term pulses. Regardless of duration, all of these events can strongly affect Earth's critical zone, the thin layer of vegetation, soil, rock, and water in which nearly all the planet's terrestrial life lives.

The physical structure and chemical composition of the critical zone constrain its responses to extreme events and climate and land use change and are thus key to predicting these responses and to sustaining the ecosystem services from which society benefits [*Field et al.*, 2015]. Emerging research in critical zone science has shown that many Anthropocene disturbances are accelerating the lateral movement of topsoil and associated soil organic matter across landscapes and that some disturbances penetrate more deeply and persist longer than previously appreciated. These and related discoveries, developed from the National Science Foundation's Critical Zone Observatories (CZOs) and critical zone science more broadly, have profound implications for soil fertility and agriculture, natural climate regulation, ecosystem productivity, and ecosystem resiliency to anthropogenic influences.

Many Anthropocene disturbances are accelerating the lateral movement of topsoil and associated soil organic matter across landscapes.

## Restructuring Through Redistribution

Around the world, extreme pulse events like wildfires are happening more often and with greater intensity as a result of climate change and other human-mediated influences, such as the introduction of invasive grasses, historic fire suppression, woody encroachment, and power lines and houses built in wildlands. These processes are accelerating rates of sediment and organic matter erosion, thus removing soil nutrients and carbon. In many regions, soil is being lost to erosion more rapidly than it is replenished by natural soil formation, which occurs over millennia.

All five CZOs in the western United States have experienced wildfires within the past decade. For example, the Catalina-Jemez CZO in the Coronado National Forest in Arizona and Valles Caldera National Preserve in New Mexico (a CZO partner organization) experienced two human-caused fires, in 2011 and 2013, respectively. In a recently burned catchment at the New Mexico site, erosion rates were 3 orders of magnitude higher than baseline rates, as documented by measurements of suspended sediment loads in streams, repeat airborne and terrestrial lidar data, and cosmogenic isotopes that help estimate soil denudation rates [*Orem and Pelletier,* 2016]. Indeed, pulsed erosion following

*The Soda Fire sweeps through the Reynolds Creek CZO in 2015. Wildfires are an example of a pulse disturbance. Credit: Hugo Sindelar* fire represented more than 90% of the denudation at this site over long (thousand- to million-year) timescales.

These enhanced erosion rates were comparable to findings at the Reynolds Creek CZO in Idaho, where researchers measured losses of sediment and particulate organic carbon (POC) following a wildfire in 2015. Losses in the year after the fire were equivalent to roughly 20 years of export at baseline levels, or 1–2 orders of magnitude higher than 25-year averages established from sediment records and hindcasted POC. These studies, and research from other CZOs documenting floods and hurricanes, highlight the value of long-term monitoring to quantify and understand the magnitude of responses to pulsed disturbances. The work also reveals a tight coupling of geomorphic landscape features and biological processes in regulating these losses.

In addition to demonstrating accelerated lateral movement of soil, researchers have shown how the redistribution of carbon across a landscape by pulse disturbances can restructure the critical zone itself. At the Catalina-Jemez CZO, for example, soil horizons and watersheds that exhibited different spatial distributions of legacy pyrogenic carbon (PyC; soot or black carbon from earlier fires) were homogenized during the Thompson Ridge Fire in 2013 [*Galanter et al.,* 2018]. Near the Southern Sierra CZO in the Sierra Nevada of California, following the 2013 Rim Fire, the highest rates of postfire erosion and preferential enrichment of PyC in eroded sediments were measured in the most severely burned areas. The interactive effect of fire and erosion led to lateral transport of large amounts of soil, carbon, and PyC from soil, particularly from high-severity burn areas, illustrating how postfire erosion can be an important control on carbon dynamics in soil systems [*Abney and Berhe,* 2018]. Finally, researchers at the Reynolds Creek CZO identified that preferential loading of fine sediments into swale channels by wind-driven, or aeolian, processes in the immediate postfire period, followed by flushing of these sediments via runoff during snowmelt, can be a large source of stream sediment transport [*Vega et al.,* 2020].

These findings highlight the role of aeolian and hydrologic erosion processes in redistributing carbon and restructuring the critical zone after disturbances. Movement of soil organic matter to depositional environments dictates carbon balance and nutrient dynamics across landscapes. Studies in the Southern Sierra CZO show that climatically mediated transport of soil by water and wind can significantly affect plant nutrient redistribution within and into soils [*Stacy et al.,* 2015; *Aciego et al.,* 2017]. Further, modeling of soil carbon migration across landscapes and associated carbon fluxes to and from the atmosphere demonstrates that the depth to which carbon is buried can determine whether eroded soil organic carbon is mineralized to carbon dioxide or retained in the soil system, and whether eroded soil organic matter can promote ecosystem productivity downslope [*Billings et al.,* 2019].


*This satellite image shows agriculture as a repeated press disturbance in the vicinity of the Susquehanna Shale Hills CZO in Pennsylvania. Forested areas are present where sandstone bedrock dominates, whereas agriculture dominates on calcareous bedrock. Credit: Google Earth*

Anthropogenic press disturbances also restructure the critical zone. Long-term enhanced erosion due to agriculture can mobilize and redeposit surface soil from uplands to bottomlands, which alters carbon source and sink locations. By coupling models with experimental and observational data, scientists at the Intensively Managed Landscapes CZO, colocated in Illinois, Iowa, and Minnesota, have characterized the lateral and vertical redistribution of soil and carbon by industrial agricultural practices. At upland erosional sites in these landscapes, for example, the rate of soil organic carbon decomposition appears to be slower than the gain from plant residues, generating net sinks for atmospheric carbon dioxide, whereas lowland depositional sites appear to serve as net carbon sources [*Yan et al.,* 2018]. Meanwhile, tile drains, which remove excess water from the subsurface, cause vertical transport and further loss of dissolved organic carbon concurrent with water efflux into nearby waterways.

## Preconditioning and Resilience

Disturbances can leave legacies in critical zone processes over geological timescales. At the Susquehanna Shale Hills CZO, critical zone responses to Anthropocene disturbances vary across different types of sedimentary bedrock in the region and are preconditioned by periglacial (glacier-adjacent) processes that were active during cold periods over much of the past 2.6 million years (i.e., the Pleistocene). Indeed, Anthropocene land use is highly correlated with local geology [*Li et al.*, 2018]. For example, agriculture is never present where sandstone bedrock dominates in the region, but it is the dominant land use over calcareous substrates like limestone. Some areas underlain by noncalcareous shales, meanwhile, have cultivation histories, but agricultural productivity in those areas was so poor that most farms were abandoned in the 20th century and forests now dominate.

These observations extend the known depths to which human modification of natural biogeochemical cycles penetrates Earth's surface.

On all substrates, periglacial solifluction—the downslope movement of thawed permafrost—transported sediment from hillslopes to valley floors [*Del Vecchio et al.*, 2018], but the depth and composition of valley floor fill and its proximity to anthropogenic activities are distinct for each rock type. Overall, geologic legacies appear to shape ecosystem responses to Anthropocene disturbances. And at least in some cases, periglacial soil movement seems to have enhanced the resiliency of these systems to Anthropocene effects, such that despite roughly 200 years of cultivation, ecosystem productivity has not dramatically declined.

Pleistocene glacial-interglacial cycles also can have legacy effects on the vertical and lateral structure of the critical zone. At the Intensively Managed Landscapes CZO, aeolian activity toward the end of the last glacial cycle covered much of the Midwestern landscape with sediment layers of varying thickness, and ecosystem transitions resulting from simultaneous climate change culminated in prairie and wetland landscapes with organic-rich fertile soils that support modern industrial agriculture [*Kumar et al.*, 2018]. Today the resilience and continuing usefulness for farming of this naturally fertile land are maintained through continuous human intervention. Extensive deployment of tile drains amid these low-permeability and largely flat landscapes allows for early spring deployment of agricultural machinery, for example. Together with substantial nutrient inputs from fertilizers, such interventions result in high crop yields.

## The Deep Reach of the Anthropocene

After European settlers instituted row crop agriculture in North America, many more regions experienced soil erosion that far

*Researchers hike to the Macks Creek subcatchment in the Reynolds Creek CZO to instrument the area with soil respiration chambers in October 2015, 2 months after the Soda Fire. Credit: Kathleen Lohse* outpaced soil production, and many forested landscapes were transformed from closed-canopy, hardwood forests into fragmented patchworks of land uses dominated by agriculture. Research at CZOs has probed deep into the soil to understand the natural formation of soil profiles [*Bacon et al.,* 2012]; the nutrient and carbon dynamics produced through interactions among plants, microbes, and minerals; and the depths to which human-induced signals of land use change can propagate over human timescales.

Investigators at the Calhoun CZO in South Carolina have quantified lower root densities beneath long-term agricultural fields versus those beneath old-growth forests growing on never-plowed soils [*Billings et al.,* 2018]. Such differences are evident even after roughly 80 years of forest regeneration on former agricultural land. Deep roots perform many functions, such as nutrient uplift, generation of deep soil carbon stocks, deep soil weathering via carbon dioxide (i.e., carbonic acid) generation, and creation of preferential flow paths for water, dissolved solutes, and gases. Persistent modification of these deep soil processes means that many ecosystem services are unintentionally altered for many decades after land use change decisions are implemented.

This work also demonstrated that greater root abundances in old-growth forests versus agricultural land were linked to the greater availability of some forms of soil organic carbon well below the depths at which root abundance differences were observed. The consequences of these differences for soil organic carbon preservation are not yet known, but the result hints that old-growth forests are more effective contributors to deep stores of soil organic carbon than agricultural systems.

These observations extend the known depths to which human modification of natural biogeochemical cycles penetrates Earth's surface. They prompt compelling hypotheses about the depth of human fingerprints in other anthropogenically modified systems around the world. For example, we might hypothesize that the truncated rooting depths of most annual agricultural systems, compared with perennial systems, limit carbon input and root modification of soil porosity deep in soil profiles.

Critical zone science demonstrates the value of placing physical and biogeochemical ecosystem processes into the context of the Anthropocene by delving deeper in space and time to understand critical zone responses and resiliency to both pulse and press disturbances. The studies highlighted here document the acceleration in modern times of soil and soil carbon movement across landscapes and their redistribution both vertically and laterally. These processes directly influence how vulnerable soil carbon is to being lost back to the atmosphere, where it contributes to rising temperatures.

In many cases, these studies illuminate the powerful role of life in processes historically studied by geologists, as well as how geologic legacies continue to shape responses of the critical zone to human influences today. Discoveries from this work help us understand how ecosystems will function and inform landscape management in the Anthropocene.

*Kathleen Lohse collects sterile soil samples from a pit more than 2 meters deep dug near Upper Sheep Creek in the Reynolds Creek CZO while research assistant Mitch Price takes notes. The effort was part of a cross-CZO project investigating deep microbial life in soils. Credit: Nicholas Patton*

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# LIFE TEEMS BELOW THE S

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By Jon Chorover, Emma Aronson, Jennifer McIntosh, and Eric Roden

# URFACE

**SCIENTISTS ARE RESOLVING HOW PLANTS, MICROBES, AND LITHOLOGY SCULPT THE STRUCTURE OF THE CRITICAL ZONE.**

Earth has skin. Like our own, Earth's is a living, porous membrane with multiple layers and a complex structure that is vital for survival. Unlike ours, Earth's skin—also known as the critical zone—arises from biogeochemical interactions among rock, soil, plants, microbes, and fluids that continually reshape and rejuvenate it. The critical zone extends from the top of the vegetation canopy to tens or even hundreds of meters into the subsurface, supporting terrestrial ecosystems and regulating exchanges of water, dissolved solutes, and gases between the land, atmosphere, and hydrosphere. It also absorbs, stores, and releases carbon, water, and nutrients, with direct implications for climate and ecosystem health.

Along with the critical zone, Earth's capacity to support life has evolved as a direct result of complex interactions between organisms and Earth materials. And evidence of life's role in shaping Earth's surface has been recorded in the sedimentary record. The rise of molecular oxygen roughly 2.4 billion years ago in the Great Oxidation Event, which was mediated by the proliferation of early phototrophic organisms similar to cyanobacteria, changed Earth's atmosphere from a reducing to an oxidizing environment. This change caused many species to die out, but it also enabled the development of multicellular life, including, eventually, mammals. Meanwhile, oxidation of iron and manganese in Earth's crust altered the structure, mineralogy, and geochemistry of surface materials, as exemplified in banded iron formations.

A grand challenge for critical zone scientists is to resolve the interactions and feedbacks between biota and Earth materials that give rise to critical zone structure and its life-supporting functions, as well as how the structure and these functions change with time, climate, and rock type. Research over the past decade combining real-time field and laboratory measurements with modeling and experimentation has helped us address this challenge and reveal that the diverse ways that the biosphere "breathes" directly influence the function and evolution of Earth's living skin, even at great depths (Figure 1).

## Teleconnections Speed Soil Formation

Pore spaces in soils and layers of fragmented bedrock, called regolith, underlying forested hillslopes teem with roots, microbes, dead biomass, and metabolites. Because of limitations on how fast gas can diffuse from these pores, they become highly enriched in carbon dioxide ($CO_2$) resulting from plant and microbial respiration. It is generally thought that this $CO_2$ diffuses upward, returning carbon captured during photosynthesis back to the atmosphere. By pairing vertically distributed $CO_2$ and $O_2$ gas sensors at different hillslope locations in the Catalina-Jemez Critical Zone Observatory (CZO) in Arizona and New Mexico, *Sánchez-Cañete et al.* [2018] found, however, that more than half of the $CO_2$ produced by soil respiration is not returned directly to the atmosphere. Rather, this $CO_2$ is dissolved in soil pore waters, creating carbonic acid, which is then transported deeper or laterally in the critical zone.

Subsequent observations using CZO sensor networks revealed that when wetting fronts propagate into the $CO_2$-enriched subsurface, which happens during rainfall and snowmelt events, the fronts are "charged" with carbonic acid and promote pulsed episodes of silicate rock (mica-bearing schist, specifically) dissolution and clay mineral formation along hydrologic flow paths that extend deeper than the bioactive soil zone [*Olshansky et al.,* 2019]. In this way, the breathing of biota in near-surface soils is teleconnected to deep subsurface weathering processes, where it plays an important role in accelerating the transformation of bedrock to soil.

This work also highlighted that $CO_2$ transported along deep subsurface hydrologic flow paths can emerge outside the measurement footprint of eddy covariance towers, which are used to quantify ecosystem respiration. This $CO_2$ may return to the atmosphere only after $CO_2$-enriched groundwater is discharged into streams and rivers, thereby effectively evading detection by the sensor towers designed to measure it. The coupling of biota to rock weathering through such transport of acidified water is consistent with an analytical model from *Calabrese et al.* [2017] that suggested that the hydrologic transport of carbonic acid from the bioactive rooting zone into the bedrock weathering zone may be as important as reactions occurring at mineral surfaces in determining chemical weathering rates.

In some cases, teleconnections between surface-colonizing ecosystems and the deep critical zone are more direct. For example, in a study at the Susquehanna Shale Hills CZO in Pennsylvania, *Hasenmueller et al.* [2016] found that roots and associated microbes extended deep into shale bedrock fractures. These investigators also observed that fractures lined with bioactive root tissue accumulated the same kinds of secondary minerals found in conjunction with roots in the soil zone. These results suggest that the $CO_2$ production and microbial community proliferation stimulated locally by plant roots can also play active roles in the conversion of rock to regolith and soil.

## Plant–Microbe Mediation

Plants transform solar energy into chemicals like carbohydrates, proteins, lignin, and low-molecular weight organic acids that are injected into the critical zone through root networks and that fuel diverse heterotrophic (organic matter–metabolizing) microbial communities. Microbes are found throughout the critical zone, but their functional roles and species biodiversity change with depth because of variations in habitat, including in the moisture dynamics and the availability of energy and carbon sources for growth [*Akob and Küsel,* 2011]. Key questions posed by critical zone scientists include, How deep do signals from surface plants extend into the critical zone, and how does this extension create depth-dependent

**A GRAND CHALLENGE FOR CRITICAL ZONE SCIENTISTS IS TO RESOLVE THE INTERACTIONS AND FEEDBACKS BETWEEN BIOTA AND EARTH MATERIALS THAT GIVE RISE TO CRITICAL ZONE STRUCTURE AND ITS LIFE-SUPPORTING FUNCTIONS.**

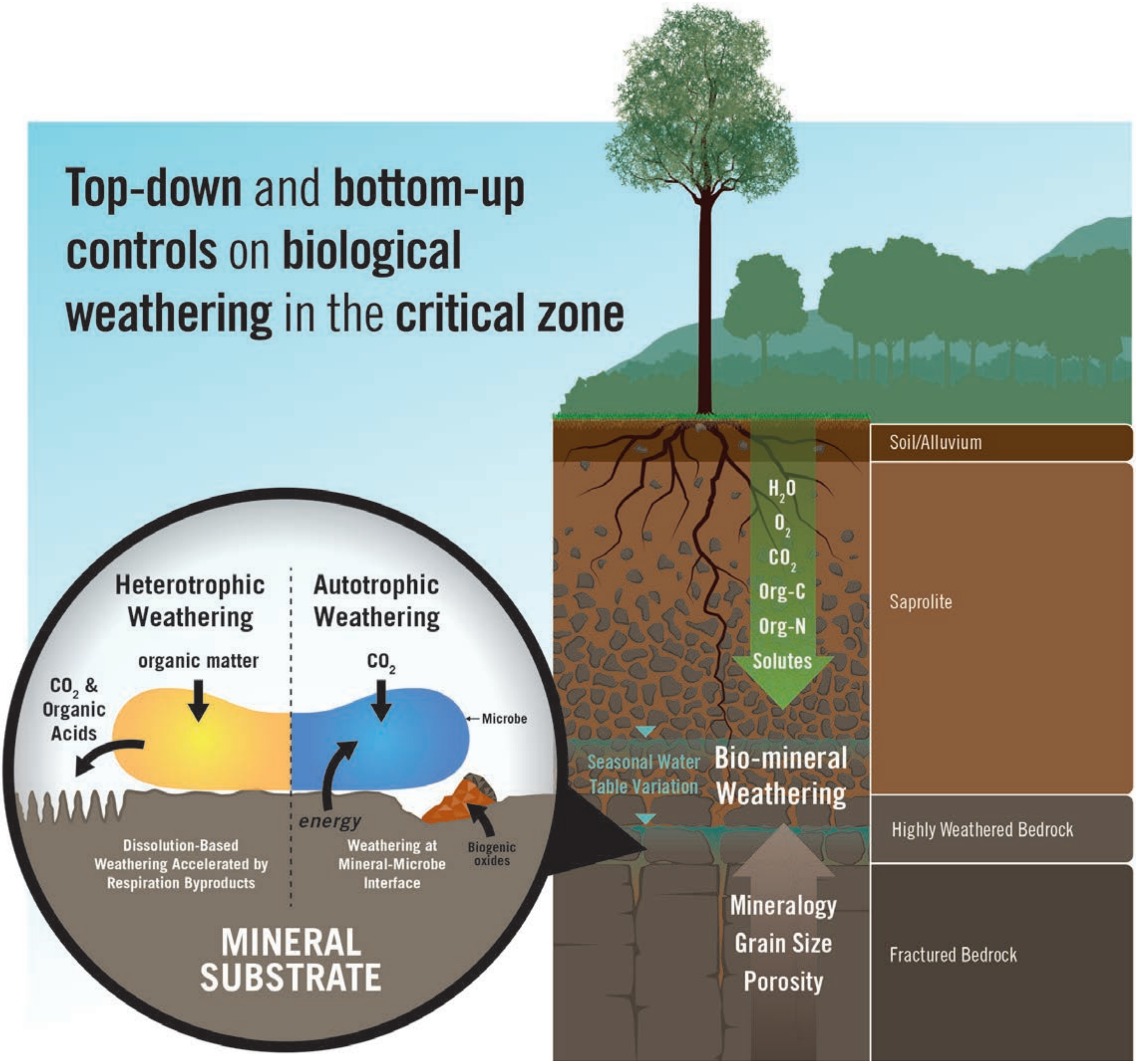


*Fig. 1. Both top-down controls, such as plant roots, water, and dissolved gases and solutes, and bottom-up controls, such as the mineralogy, grain sizes, and porosity in local bedrock, influence biological weathering in the critical zone. The inset depicts how microbes interacting with mineral grains contribute to weathering, either by way of heterotrophic respiration by-products like carbon dioxide and organic acids or by autotrophic metabolic pathways like metal (e.g., iron or manganese) oxidation. $H_2O$ = water; $O_2$ = oxygen; $CO_2$ = carbon dioxide; Org-C = organic carbon; Org-N = organic nitrogen.*

trends in microbial communities? Addressing these questions is essential because microbes drive many biogeochemical cycles—not only of carbon and nitrogen but also of iron, manganese, silicon, and aluminum, for example—throughout the critical zone depth profile.

Whereas prior studies of soil microbial ecology have focused on near-surface soil horizons, predominantly in the top 10 centimeters, critical zone scientists have delved much deeper to examine how microbial community composition and function change with depth and at different locations in complex hillslope terrain. Studying bacterial and archaeal composition as a function of depth in several excavated pits in the Boulder Creek CZO in Colorado, *Eilers et al.* [2012] found that microbial diversity decreased by 20%–40% between the surface and 2-meter depth, tracking exponential decreases in both microbial biomass and soil organic matter. Large variations in microbial composition were observed in different surface horizons across the Gordon Gulch watershed, but this lateral variation decreased significantly below the surface, such that deeper communities were much more similar irrespective of location.

# THE EVOLUTION OF CRITICAL ZONE ARCHITECTURE ULTIMATELY FEEDS BACK TO SUPPORT PRODUCTIVE ECOSYSTEMS AND THE SERVICES THEY PROVIDE TO SOCIETY.

The team found that the changes in microbial community composition that occurred between the surface and 2-meter depth at the Boulder Creek CZO exceeded those observed across a wide range of biome types sampled globally by the same team. That is, the microbial communities living just a meter or two below the surface were composed of very different strains than those living in the surface soils, and this difference was larger than those seen elsewhere worldwide. This observation highlights the heterogeneous nature of the critical zone profile, in which environmental conditions for life can change dramatically over very short vertical distances.

To determine whether these trends hold beyond Boulder Creek, *Brewer et al.* [2019] examined depth-dependent trends in bacterial and archaeal taxa to 1-meter depth in 20 soil profiles excavated in sites spanning the full national network of CZOs. This team also reported an average decrease in microbial diversity with depth and the associated shift from carbon- and nutrient-rich to carbon- and nutrient-poor conditions. However, several strains consistently increased in relative abundance with depth across multiple locations, especially Dormibacteraeota, whose genome provides the capacity to synthesize and store carbohydrates and the potential to use carbon monoxide as a supplemental energy source. Such capabilities are likely key to survival in the nutrient-deficient deep critical zone.

Deeper in the critical zone, the availability of organic matter as an energy and carbon source for heterotrophic microbial growth becomes progressively more limited. As a result, chemolithoautotrophy is expected to become increasingly important—as seen, for example, in fractured bedrock at much greater depths (kilometers) [*Osburn et al.,* 2014]—but direct evidence of such an increase has been lacking. Chemolithoautotrophic organisms obtain their energy from reduced inorganic compounds (as opposed to organic matter) and their carbon for growth from $CO_2$. Both heterotrophic and chemolithoautotrophic metabolisms affect mineral transformations and hence critical zone evolution, albeit differently.

Examining the previously hypothesized existence of a subsurface chemolithoautotrophic, iron-oxidizing microbial community at the bedrock interface tens of meters below the surface at the Luquillo CZO in Puerto Rico [*Buss et al.,* 2005], researchers recently showed that bacteria can, indeed, obtain energy directly from the oxidation of ferrous iron ($Fe^{2+}$) in granitic bedrock [*Napieralski et al.,* 2019]. This iron-silicate bio-oxidation process resulted in precipitation of ferric ($Fe^{3+}$) oxide nanoparticles, which accumulated within pores near the weathering front, where fresh bedrock is transformed into regolith. The microbially oxidized rock was then more susceptible to acid-promoted dissolution, like that which occurs when $CO_2$-charged waters enter the deep critical zone (as discussed above). The results of this and an ongoing companion study suggest potential positive feedbacks between $CO_2$ production mediated by interactions between plant roots and heterotrophic microbes in the near surface and chemolithotrophic mechanisms of mineral oxidation at greater depths.

## Revealing Critical Zone Complexities

Altogether, these and other results from CZOs have begun to reveal complex interactions among plants, microbes, and minerals that drive the weathering and structure of the critical zone. The evolution of critical zone architecture, particularly the biologically mediated transformation of bedrock to soil, ultimately feeds back to support productive ecosystems and the services they provide to society, like carbon and water storage, ecosystem nutrition, and the provision of food and fiber.

Further explorations of interactions between top-down and bottom-up controls on bedrock weathering, soil formation, and critical zone structure should address important outstanding questions such as how deep into the critical zone the weathering effects of plants extend and what influences rock type has on microbial colonization of the deep critical zone and associated bioweathering reactions. Such efforts will continue to uncover vital insights into how Earth's remarkable skin works and how it affects those of us living on it.

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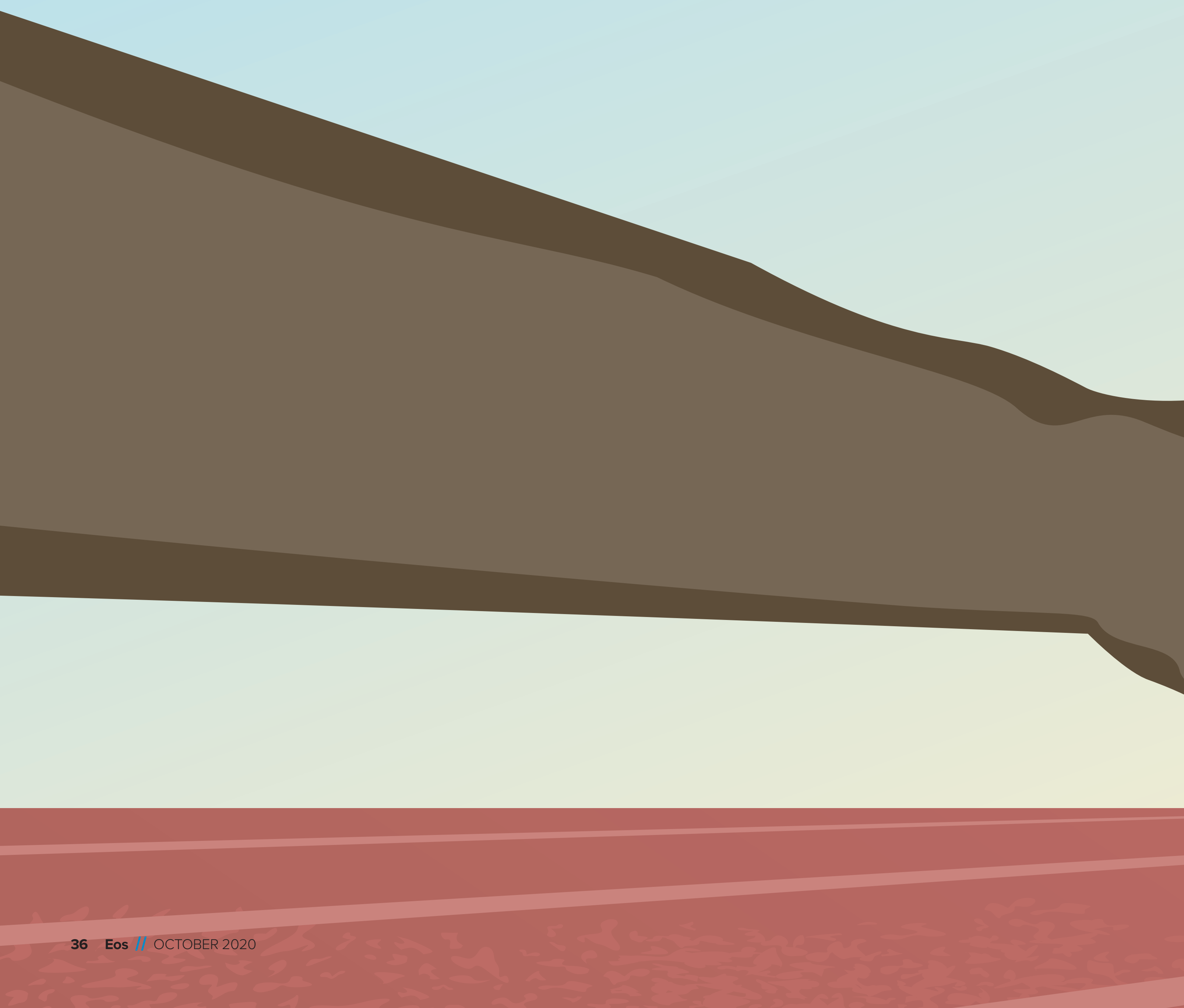
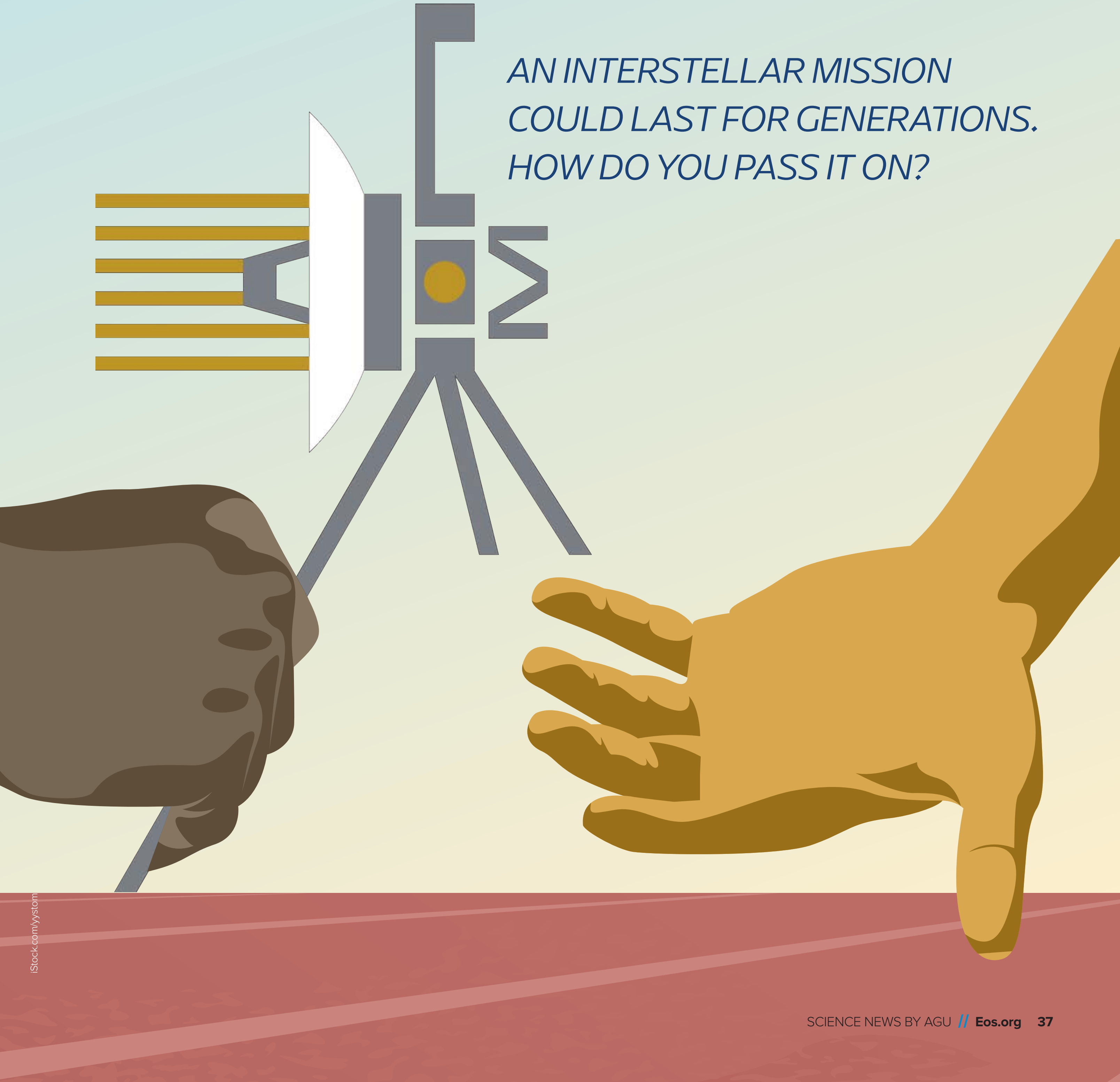
# PREPARING HANDOFF



# FOR A

By Damond Benningfield

*AN INTERSTELLAR MISSION COULD LAST FOR GENERATIONS. HOW DO YOU PASS IT ON?*



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Scientists and engineers preparing Interstellar Probe, a mission to explore the environment between the stars, face an unsettling truth. "They're trying to design a spacecraft to launch around 2030 and get a thousand AU [astronomical units] from Earth in 50 years," said Janet Vertesi, an associate professor of sociology at Princeton University and an adviser to the Interstellar Probe study team. "The problem is, by then they'll all be dead."

Most space science missions have an expected life span of less than a decade—well within the careers of most participants. Some missions last longer than planned, of course. The Opportunity rover trundled across Mars for more than a decade beyond its primary mission, for example, while the twin Voyagers have logged almost 4 extra decades in space.

Interstellar Probe, though, is one of several proposed projects (including the Solar Gravitational Lens mission concept and Breakthrough Starshot) with planned lifetimes of several decades or even longer. Most of the scientists and engineers who design and build the spacecraft and send them on their way will retire or pass on long before the missions end. Such projects will require a management structure different from that of typical missions of exploration.

"This isn't something that people typically think about when they're planning a mission," said Ralph McNutt, principal investigator for the Interstellar Probe study and chief scientist for the space exploration sector at the Johns Hopkins University Applied Physics Laboratory (JHUAPL).

So the Interstellar Probe team reached out to Vertesi, who studies the management of space exploration projects, for help in structuring a multigenerational approach to the mission.

Through workshops and other interactions, Vertesi has outlined several possible steps for the Interstellar Probe project:

- It should plan for a multigenerational approach from the beginning, with all participants understanding that their time on the project will be limited.
- It should nurture mentorships and apprenticeships, making sure that the next generations are well prepared to assume control when their time comes.
- It should develop its own ways of recording knowledge about the mission for future generations.
- It should develop its own rituals to help build continued enthusiasm for the mission.

### Creating a Multigenerational Culture

"One analogy I often hear about these projects is that it's like building the great cathedrals of Europe," said Geoff Landis, a researcher at NASA's John H. Glenn Research Center in Cleveland, Ohio, and an adviser to Breakthrough Starshot, an effort to develop the technology to send tiny probes to Proxima Centauri in the coming decades. "Those were enormous undertakings for the time, and it took many generations to put them together. You need an organizational structure that can continue to keep people involved in the project."

Interstellar Probe was conceived decades ago as a mission to study the interstellar medium (ISM), the cosmic rays, wisps of gas and dust, and magnetic fields that fill the space between stars. It also would look back at the solar heliosphere, a "bubble" dominated by the Sun's magnetic field and the solar wind, and monitor the interaction between the heliosphere and the ISM.

A half century after launch, Interstellar Probe would reach a distance of 1,000 astronomical units from the Sun. (An astronomical unit is the average Earth–Sun distance, equal to almost 150 million kilometers.) It would continue to study the ISM until its nuclear-powered generator could no longer supply enough energy to operate its instruments or remain in contact with Earth.

The mission concept "sounds like Voyager on steroids," said McNutt, but the current study team isn't designing the actual spacecraft or selecting its specific science goals. Instead, "we're trying to put together a menu of options for a future science definition team," McNutt explained. "What science would make sense? What instruments would you need, what measurements would you need?... Do you need a couple of miracles, or can you do it with standard engineering?"

The team realized early on that engineering a probe to last for 50 years or longer isn't the only challenge the mission will face. Another is building a project team—a problem not faced by prior missions.

"It's a fascinating challenge," said Vertesi. "There's no tradition of handing off to the next generation—there was no model for doing that."

"The big lesson from the rovers and Cassini is that the way you choose and organize your science team is really important," said Vertesi, who spent 2 years observing the Mars Exploration Rover team as an ethnographer. "People don't typically consider that. Teams just kind of happen depending on the way a mission is funded.... If you're going to be multigenerational, you may need to be more bureaucratic. No scientist loves bureaucracy—they hate it. But you can't have a charismatic [principal investigator] who doesn't want to pass on the baton."

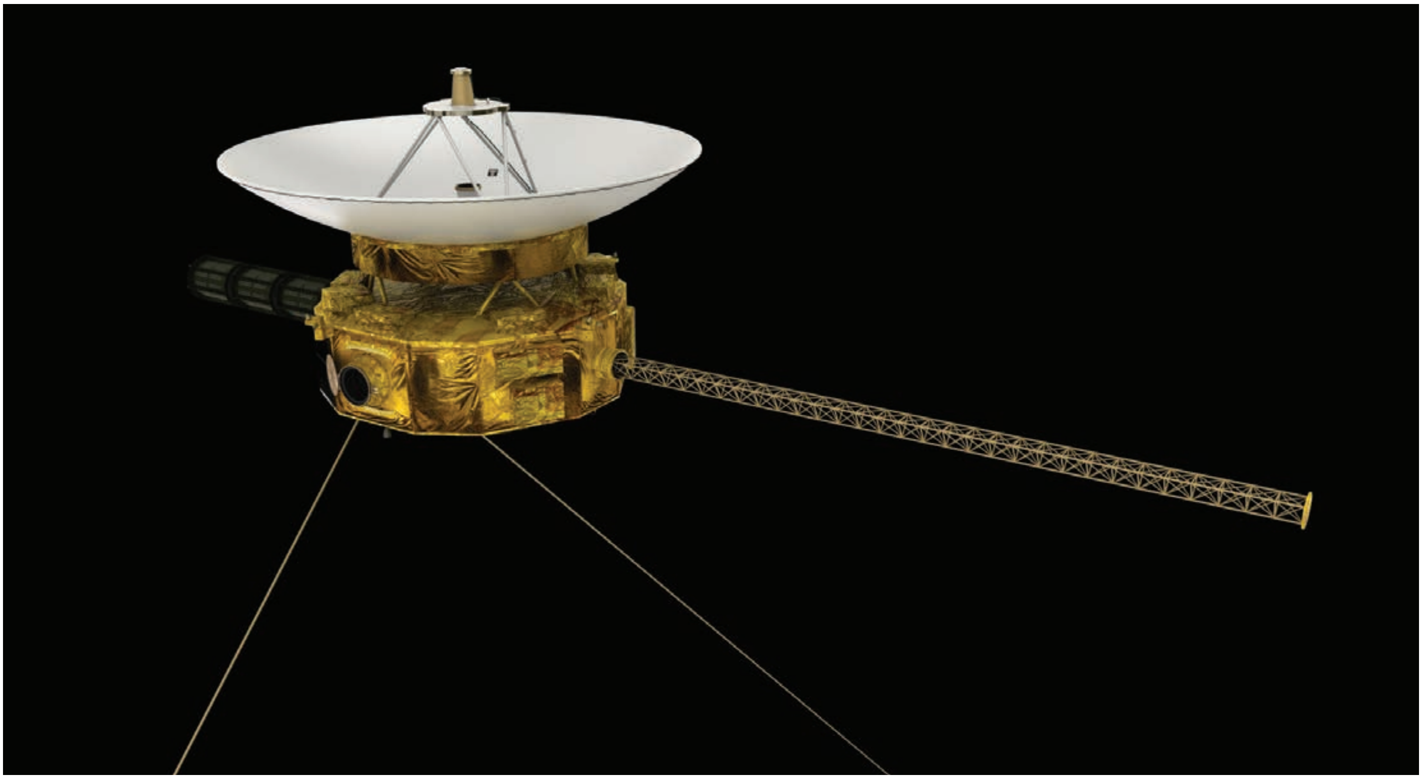
"The ideal thing I would suggest is to make sure it's very clear there are term limits," said Vertesi. "You might turn over [key positions] every 7–10 years. It would be predictable, built in as part of the project."

> **"NO SCIENTIST LOVES BUREAUCRACY—THEY HATE IT. BUT YOU CAN'T HAVE A CHARISMATIC [PRINCIPAL INVESTIGATOR] WHO DOESN'T WANT TO PASS ON THE BATON."**

Younger scientists with the project said they accept that concept and even look forward to bringing in new members in the decades ahead.

"I'm a little sad that I might not live long enough to get to the interstellar medium," said Elena Provornikova, who recently joined JHUAPL's professional staff after 3 years as a postdoctoral researcher. "But at some point, I will pass along my knowledge and expertise to the next generation of scientists, and I'll be happy to see their success and the discoveries they will make."

Kathleen Mandt, a member of the study team and chief scientist for exoplanets at JHUAPL, notes that she would be roughly 100 years old by the time Interstellar Probe reaches its target distance. "I may or may not still be alive, and I don't know if I'll still be working," she said with a chuckle. "But I sure don't want the mission to bail because I'm not there."



*This preliminary concept for Interstellar Probe shows a strong resemblance to the Voyager spacecraft. The design is likely to change significantly during the study, says Ralph McNutt. Credit: Johns Hopkins University Applied Physics Laboratory*

### Preparing for the Next Generation

Ensuring that transitions are smooth would require a program of mentorships or apprenticeships, McNutt said. "You'd need to bring people up to speed so that at some point, you could give them the keys to the car with some confidence that they won't wreck it the first time they take it out of the driveway."

Such programs are common in large, long-lasting organizations. Mandt, for example, said it is expected in the U.S. Navy, where she served before turning to academia and space missions. "If somebody is in a leadership role [in the Navy], they have an expected responsibility to train the next generation to take their place," she said. "If not, the military will fail and your mission will fail. That was ingrained from day one.... There's a feeling of accomplishment in that, but you don't see it often in the space community."

Handing off from one generation to the next doesn't mean that earlier team members should vanish, however.

"I highly recommend keeping retirees in close communication with the project, because you will want to call them in when something goes wrong and you have a question," said Suzanne Dodd, manager of the Voyager Interstellar Mission since 2010.

Voyager launched two spacecraft in 1977 that have since entered interstellar space. Voyager 1 left the heliosphere in 2012, and Voyager 2 followed in 2018. Both are projected to continue operating until around 2025.

Neither was intended to study such a distant realm, though, and because of that, no one anticipated that so much of the original knowledge of the spacecraft systems would be lost during their long trek. Although much of that knowledge is preserved in documents, the background details were locked in the minds of the original scientists and engineers—many of whom are gone.

"We built a pretty good Rolodex of retired people we could ask questions of," said Dodd. "Now, at 43 years and counting [since the Voyagers launched], a lot of those people have passed away. So you might be able to get ahold of them when they retire, but you can't have séances with them when they're gone."

"One of the things we've learned is that knowledge capture is important," Dodd said. "People document the decisions that are made, but they don't document the thought processes behind them.... So you have to decide what's the right information to get about how a system operates, and how you capture it—in written form or in a video format or something else."

Vertesi, in fact, recommends "all of the above"—both formal knowledge capture through technical reports, diagrams, and other formats, and informal knowledge capture through institutional storytelling.

"If you talk to people, you find out that every spacecraft develops a personality," Vertesi said. "People know just how and why an instrument has a special flutter, for example. Those kinds of stories help.... But you need to decide what kinds of storytelling are necessary, what kinds of cultural elements [the team needs] to have in place to make sure that stories are passed down from generation to generation."

At a workshop last year, the Interstellar Probe team was split into small multigenerational groups to discuss how team members can talk to each other, how one generation can mentor others, and what kinds of narrative structures they might create.

The exercise wasn’t always easy. A younger member of Mandt’s group, for example, suggested podcasts as a way to preserve informal knowledge about the mission. “I thought that was great because I’m getting into podcasts and my son even makes them for a living,” Mandt said. “But somebody from the boomer generation just wasn’t happy about that. He’s not into them—he prefers videos. So it was interesting seeing that generational dynamic.”

Good records, both formal and informal, will help scientists and engineers maintain and update equipment that while state of the art when the spacecraft was designed and built, will seem antiquated by the time it reaches its target distance from the Sun.

Keeping up with evolving technology isn’t easy, though, especially because no one knows what technology will look like decades after a mission is launched. Data from early missions were stored on magnetic tapes, for example, and in many cases the technology no longer exists to play them. So long-term missions must build as much flexibility into their spacecraft’s hardware and software as technology will allow.

“We’re told to refresh the operating system on our desktop computers every 3 years, but once your spacecraft is launched, it’s the spacecraft you have,” Dodd said. “The Voyagers were never designed to update or repurpose the software to get to a more recent operating system. So that’s another concern—you can’t update a spacecraft very much after it’s launched.”

“WE’RE TOLD TO REFRESH THE OPERATING SYSTEM ON OUR DESKTOP COMPUTERS EVERY 3 YEARS, BUT ONCE YOUR SPACECRAFT IS LAUNCHED, IT’S THE SPACECRAFT YOU HAVE”

“You have to keep in mind that these are evolving projects,” said Slava Turyshev, a scientist at NASA’s Jet Propulsion Laboratory and principal investigator for the Solar Gravitational Lens mission concept, which aims to send a solar sail–powered spacecraft to at least 550 astronomical units from the Sun to use its gravity to image exoplanets. “We need to evolve the project every time we get together. We rely on people who are excited and are united by a common goal. We need to allow human genius to contribute to the project objective. And we need to be flexible—we don’t want to constrain ourselves with too rigid a structure.”

### Rituals Large and Small

The Interstellar Probe team planned a workshop at the historic Explorers Club in New York to begin fulfilling another of Vertesi’s recommendations: Establish rituals.

Meeting at the headquarters of a group whose members included the first people to reach the North Pole, the South Pole, the deepest spot in the oceans, and the surface of the Moon would emphasize the historic nature of Interstellar Probe. The meetings grew so large, though, that the club had to be abandoned.

Rituals can be as small as establishing seating charts for team meetings, working on a certain problem at the same time in each meeting, or allowing junior team members to ask the first questions. Graphics that depict a mission’s path might have the ritualistic impact of showing the generation that will navigate it through each milestone, Vertesi said.

Other missions have established more extensive rituals. Because Europa played a key role in Arthur C. Clarke’s *2001: A Space Odyssey* series, for example, a Europa Clipper mission team built a large monolith that it rolls out at meetings. “They ‘pass the baton’ between different work group leads every year by handing over a large bone in front of the monolith,” Vertesi said. “They play the music from the movie and everyone laughs, but it’s a part of their culture—a part of the way you know you’re doing that mission.”

“What kind of rituals can [the Interstellar Probe mission] build that will be meaningful over multiple generations? You want continuity that involves new people as they come in and really gets them involved in the wonder of the mission,” she said.

Yet Vertesi and others involved with Interstellar Probe acknowledge that despite all the planning, no one can know how the mission will play out or how technology and society will change.

“If there’s anything this particular moment in time is teaching us, it’s that we really don’t know what’s going to happen, even in the next few weeks,” Vertesi said. “But we do know that things will change, so you plan for change and do the best job you can.”

### Author Information

**Damond Benningfield,** Science Writer

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# "Mushballs" May Drive Ammonia Transport on Jupiter

Observations made by NASA's Jupiter-orbiting Juno spacecraft have revealed substantial and unexpected depletions of ammonia in the planet's atmosphere. Although some evidence for this anomaly can be seen from telescopes on Earth, Juno's close-up microwave measurements show that the depletion of ammonia—a trace but important cloud-forming component in Jupiter's skies—extends far deeper than previously known, down to a hundred kilometers below the clouds, and exhibits a striking dependence on latitude.

Radial profiles produced near Jupiter's equator show ammonia levels of about 360 parts per million regardless of depth in the atmosphere, whereas profiles made at Jupiter's midlatitudes reveal upper atmospheric abundances as low as 120 parts per million that increase only slowly with depth. Previously proposed mechanisms, such as direct transport of ammonia by updrafts and circulation in Jupiter's famous atmospheric bands, do not explain this variance.

In a pair of new papers, *Guillot et al.* postulate a new transport mechanism—water-ammonia hail—and show that it explains Juno's microwave data and is linked to the presence of large storms. Water is relatively scarce near Jupiter's cloud tops, but previous research has suggested that powerful storms can uplift substantial amounts in the form of micrometer-sized ice crystals. The authors calculate that as these crystals rise, they absorb gaseous ammonia, increasing in mass and density and partially liquefying to become the slush-like cores of hail particles. (In an accompanying study of Juno data in *Nature*, Becker et al. report detections of lightning—and thus confirm the presence of liquid—in the region of the atmosphere where these slushy "mushballs" are thought to form (bit.ly/Jupiter-lightning).)

Continuing their ascent, the mushball cores can accumulate additional layers of ice, growing to millimeter and centimeter sizes. Once they become too heavy to remain aloft, the hail balls—now up to 10 centimeters in diameter—reverse course, losing outer layers to evaporation as they fall. But the cores, now denser and cooler than when they first formed, can penetrate far deeper into the atmosphere than where the ice crystals and ammonia gas originated. Because fully grown hail balls can contain up to 30% ammonia, the result is efficient transport of ammonia that may explain Juno's observations.

Unlike Earth, Jupiter has no solid surface, so these hail particles continue falling until they either fully evaporate or reach neutral buoyancy in the surrounding gas. The combination of the cores' composition and the depth they ultimately reach may thus help scientists untangle details of Jupiter's internal structure. (*Journal of Geophysical Research: Planets*, https://doi.org/10.1029/2020JE006403 and https://doi.org/10.1029/2020JE006404, 2020) **—Morgan Rehnberg,** *Science Writer*

# In Vegetation Growth Studies, What You Measure Matters

Plant growth is an important indicator for diagnosing environmental health as well as shifts in climate. Large-scale monitoring of vegetation patterns relies on several proxy measurements derived from satellite observations. Although these proxies all correspond roughly to the amount of plant material observed, each one depends on a different aspect of plant biology.

The normalized difference vegetation index (NDVI) exploits the fact that chlorophyll is highly absorbent of red light (hence plants' distinctive green color) and highly reflective of near-infrared light. Thus, it acts as a measure of total photosynthesis capability. Another proxy, vegetation optical depth (VOD), gauges water stored within plant matter through the use of microwaves, offering an estimate of total vegetation mass. And solar-induced chlorophyll fluorescence (SIF) measures the light emitted during photosynthesis, making it a proxy for active photosynthesis.

*Image of a forest in Puerto Rico taken in 2017 by Goddard's Lidar, Hyperspectral and Thermal Imager (G-LiHT), a portable, airborne imaging system. Combining multiple vegetation metrics that each relate to different aspects of plant biology offers a fuller picture of plant growth cycles and may better indicate vegetation responses to changes in climate. Credit: NASA Goddard Space Flight Center*

Using data collected from multiple instruments between 2007 and 2015, *Wang et al.* compare these metrics over the course of the growing season to evaluate how closely they track the yearly cycle. They observe that the three indices indicate similar timing for the start of vegetation growth in a given region. After that, however, the indices begin diverging, such that the timing of the peak SIF signal occurs roughly 10 days before that from NDVI, which in turn is about 10 days before the peak signal from VOD. The end of the growing season indicated by the three proxies varies by more than a month.

These differences appear to be consistent with the biological property traced by each metric. For instance, the end of the season as measured by NDVI lags that of SIF. This lag corresponds to a known reduction in photosynthesis activity that precedes the actual loss of chlorophyll indicated by changing leaf colors. The end of the season indicated by both of those proxies precedes that indicated by VOD, which is sensitive to an overall reduction in plant mass. VOD levels, which depend on the availability of water, also vary on the basis of local climate.

The authors conclude that obtaining a full picture of large-scale plant growth cycles requires considering all three metrics together, and they suggest that the metrics' relative variation could offer key insights into how plants respond to local climate changes. (*Journal of Geophysical Research: Biogeosciences*, https://doi.org/10.1029/2020JG005732, 2020) **—Morgan Rehnberg,** *Science Writer*

# Corals Make Reliable Recorders of El Niño Fluctuations

The El Niño–Southern Oscillation (ENSO), a climate pattern in the tropical Pacific Ocean that recurs about every 2–7 years, can lead to disruptive heat waves, droughts, and floods around the world. Observations from the past few decades suggest that the frequency and magnitude of ENSO events may be accelerating, but instrument records of the phenomenon are not yet long enough to confirm the full range of natural ENSO variability.

To better characterize ENSO fluctuations during the preinstrument period, scientists rely on global climate model simulations as well as proxy data derived from tropical Pacific corals. But several sources of uncertainty, including year-to-year variations in how coral skeletons record sea surface temperatures and other climate signals, make it challenging to directly compare the results.

Now *Lawman et al.* have developed a new proxy system model, a tool that helps reconcile climate modeling with paleoclimate reconstructions, to evaluate potential sources of interannual variability in coral geochemistry. The proxy system model builds on earlier research by adding submodels to an existing framework to quantify year-to-year impacts of nonclimatic processes on the coral archives.

Results from using the new tool indicate that calibration and analytical errors generally increase estimates of ENSO interannual variability from coral geochemistry, whereas variations in growth rates, when combined with certain age assumptions, systematically decrease estimates. The findings suggest that such factors can measurably affect interpretations of coral archives and that the factors' relative importance is specific to each individual site. Despite these additional uncertainties, the authors conclude that corals from locations around the Pacific do capture broad changes in ENSO variability over decadal or even longer timescales.

The study helps evaluate whether researchers can use proxies to establish whether changes in ENSO variability can be linked with anthropogenic warming. The results foster confidence that tropical Pacific coral archives are high-fidelity recorders of ENSO variability, according to the authors, and suggest that such tools could be used to constrain projections of how the ENSO climate pattern may fluctuate in the future. (*Paleoceanography and Paleoclimatology*, https://doi.org/10.1029/2019PA003836, 2020) **—Terri Cook**, *Science Writer*

*Corals such as these* Porites *and* Acropora *in reef flat pools in the National Park of American Samoa preserve geochemical information that can be used to reconstruct year-to-year climate fluctuations. Credit: Curt Storlazzi, Pacific Coastal and Marine Science Center, U.S. Geological Survey*

# Modeling Water Stress for Shared Water Resources

A third of the world's population is living with high levels of water stress, according to the World Resources Institute. Reservoirs in major cities in India, South Africa, and elsewhere have nearly run dry because of ever increasing water demand, and climate change is expected to make these arid regions even drier.

Researchers typically evaluate such factors as local climate, population, and resource management decisions to predict a region's future water stress. But such predictions are especially complex in transboundary basins, where populations separated by national borders share the same water resources. Current hydrological and climate models don't account for the fact that water stress in transboundary basins is driven both by local factors and by upstream water availability and consumption. Consider the Colorado River: The waterway flows across the U.S. Southwest, serving 35 million Americans, before flowing into Mexico. It used to carry 1,200 cubic meters of water per second across the border, but increasing demand in the United States and drought conditions have left the riverbed nearly dry in Mexico. Previous research has indicated that upward of 2 billion people worldwide experience water stress for at least part of the year because of upstream water use.

To investigate what future water stress might look like in these areas, *Munia et al.* used data on water availability, consumption, and population from global hydrological models run under various future greenhouse gas emission and socioeconomic scenarios. They found that under the best-case scenario, with low emissions and slow population growth, water stress in transboundary basins will increase by half by 2050, relative to stress in 2010. Under the business-as-usual scenario, with high emissions and population growth, water stress will double over the same time frame.

The team identified 246 transboundary basins and 886 subbasin areas that rely on transboundary water resources, and the modeling revealed that water stress will increase in all areas already experiencing moderate to extreme water scarcity, including parts of Asia, the Middle East, and North Africa. The specific effects of water availability and consumption depended on the level of water stress that a basin was already experiencing. Increased local water consumption generally had a larger effect on changes in stress in areas with low water stress levels, whereas changes in upstream availability had a larger effect in areas already experiencing high water stress.

The takeaway, the authors note, is that local water management decisions will have a substantial impact on future water stress. But changes upstream can influence downstream water availability, and the number of people living in areas dependent on upstream water is expected to grow. (*Earth's Future*, https://doi.org/10.1029/2019EF001321, 2020) **—Kate Wheeling**, *Science Writer*

# Glacial Contributions to 21st-Century Sea Level Rise

The world's glaciers are retreating. Temperatures in the Arctic and in mountainous regions where glaciers form are rising faster than anywhere else on Earth. Many glaciers are now the smallest they've been in tens of thousands of years.

Although glaciers account for only a fraction of global ice mass—the Greenland and Antarctic ice sheets make up the bulk—their meltwaters still contribute significantly to sea level rise. However, there are several sources of uncertainty in projections of glacier mass change and related sea level rise: inherent uncertainty in glacier and climate models, unknown future emissions, natural climate variability, and ambiguity in the size and volume of glaciers today. All of these factors contribute to variable sea level rise predictions.

In a new study, *Marzeion et al.* compared 11 glacier models, 10 global climate models, and 4 Representative Concentration Pathways (RCP) to estimate the contribution of glaciers to sea level rise throughout the 21st century and to identify the main drivers of uncertainty over that time period.

The study found that glacier area will decrease throughout the 21st century in every region and across all four emissions scenarios, but the scale of ice loss varied drastically. Under the RCP2.6 scenario, which imagines stringent mitigation efforts to reduce emissions, glaciers will lose about 18% of their mass and begin to stabilize in some regions by 2100. Under RCP8.5, a high-emissions scenario, glaciers will lose 36% of their mass, and many regions will experience complete glacier loss. Estimates of sea level rise ranged from about 79 millimeters of sea level equivalent (SLE) by the end of the century under the low-emissions scenario to about 159 millimeters of SLE under the high-emissions scenario. Both projections are slightly lower than, but within the uncertainty ranges of, previous median projections.

The team found that the dominant source of uncertainty until midcentury is in ice mass loss projected by glacier models. This glacier model uncertainty grows modestly throughout the century but is eclipsed in the second half of the century by uncertainty associated with emissions scenarios. (*Earth's Future*, https://doi.org/10.1029/2019EF001470, 2020) **—Kate Wheeling,** *Science Writer*

# Great Plains Plants Bounce Back After Large Wildfires

Wildfires provide important benefits to ecosystems, nourishing soils, clearing brush and making room for new plants, and sometimes killing off damaging pests or disease. But as climate change progresses, large grassland wildfires are becoming more frequent, raising concerns about their long-term effects on vegetation.

In new research, however, *Donovan et al.* suggest that at large spatial scales, vegetation in the U.S. Great Plains is largely resilient to major wildfires. Building on previous field studies, the researchers analyzed 18 years' worth of recently released high-resolution, satellite-derived data on plant cover across the Great Plains. They combined this information with data on drought severity and the locations and sizes of 1,390 Great Plains wildfires that occurred during 1984–2017.

At the biome level, the analysis showed rapid recovery to prefire conditions across varying Great Plains ecosystems for all forms of vegetation studied: shrubs, trees, and annual and perennial forbs and grasses. The only exception was a persistent postwildfire decline in tree cover in the northwestern Great Plains.

Severe drought intensified the short-term responses of vegetation to wildfire, but subsequent recovery still occurred. On smaller scales, some areas did experience persistent postfire changes in plant cover, but these appeared to be extreme local cases within larger wildfires.

*Smoke from a smoldering fire rises above trees and brush south of Bismarck, N.D., in April 2015. Credit: National Guard photo by Chief Warrant Officer 4 Kiel Skager, North Dakota National Guard Joint Force Headquarters*

The new findings add to a growing body of research that suggests that certain postfire management techniques used to help rehabilitate grassland ecosystems, such as reseeding, may not actually be needed. Still, the authors note, as wildfire and drought patterns change with global warming, continued research and advancements in techniques for monitoring vegetation and wildfires will be needed. (*Earth's Future*, https://doi.org/10.1029/2020EF001487, 2020) **—Sarah Stanley,** *Science Writer*

# Land Motion Offers Insights into Cascadia Earthquake Cycle

The western edge of North America is one of the most seismically active areas on Earth. In the Cascadia Subduction Zone, which spans from northern Vancouver Island in British Columbia to Northern California, strain has been building since a massive earthquake, thought to have been about magnitude 9, occurred in 1700. When a large quake strikes this megathrust fault again, the toll on infrastructure and human life could be catastrophic, so scientists are continually trying to understand better how energy builds up on the fault.

In new research, *Yousefi et al.* study vertical land motion (VLM) on the western coast of North America, comparing GPS data with a 4,000-year record of land motion from sea level data. By subtracting recent trends in land motion from the longer record, the scientists show which part of the observed surface deformation is due to plate locking along the megathrust as part of the Cascadia earthquake cycle and which part is more likely caused by other processes, such as groundwater extraction and glacier retreat.

Late afternoon comes to Ecola State Park along the Oregon coast. By comparing vertical land motion observations over different timescales along the western coast of North America, researchers isolated the land motion signal related to plate locking along the Cascadia Subduction Zone megathrust from other signals, for example, those due to groundwater extraction and glacier retreat. Credit: Lidija Kamansky/Moment/Getty Images

Overall, the VLM data in the new study show widespread uplift and a landward tilt in the Cascadia region related to fault locking. Uplift is dominant along most of the western Canadian and American coasts, except for the San Diego Bay area, where subsidence is occurring. The researchers found that their refined VLM data compared well with an existing model of Cascadia megathrust locking tuned to match horizontal land motion rates, especially for the case in which complete locking occurs at shallow depths (less than 30 kilometers).

The scientists conclude that this sort of VLM data analysis, which allows the contribution to land motion from deformation between major earthquakes to be isolated, will be useful in better constraining locking models of the Cascadia and other subduction zones, especially where only horizontal land motion data have been used previously. (*Journal of Geophysical Research: Solid Earth*, https://doi.org/10.1029/2019JB018248, 2020) **—David Shultz,** *Science Writer*

# Electron Density near Enceladus Shows Orbital Variation

The icy moon Enceladus is among the most dynamic objects in the Saturnian system. Observations by NASA's Cassini spacecraft revealed a plume of nearly pure water erupting from fissures in the moon's south polar region. The resulting ice particles form one of Saturn's largest rings, the E ring. Ionization of particles in the plume also provides most of the plasma in Saturn's magnetosphere.

Cassini measurements show that the activity and brightness of the plume are variable, peaking when Enceladus is farthest from Saturn (apoapsis) and reaching a minimum when the moon is nearest its host planet (periapsis). This occurs because tidal stresses on the south pole cause the fissures through which the icy plume particles emanate to expand near apoapsis and compress near periapsis.

*Persoon et al.* searched for a similar pattern in the electron density near Enceladus. They analyzed data collected by Cassini's Radio and Plasma Wave Science instrument during 13 equatorial flybys of the moon when the spacecraft passed through the plume, as well as from one flyby when the moon was at periapsis. The researchers determined the magnitude of Enceladus's position-based electron density enhancement and found a consistent peak in the density after the moon passes apoapsis. This post-apoapsis enhancement differs notably from the near-apoapsis peak in plume activity.

The authors suggest that the lag in the electron density enhancement stems from the time needed for the enhanced plume particles to become ionized. However, none of the ionization processes previously observed at Enceladus account for the magnitude and timing of the electron density peak. Previous theory and computer modeling have indicated that interactions between the water plume and Saturn's existing plasma environment may lead to increased ionization, but these processes may also be too slow to account for the observed density enhancement.

These discrepancies suggest that one or more ionization processes not previously considered may drive the variation. A future mission to Enceladus, advocated by some planetary scientists, could provide an opportunity to resolve this question. (*Journal of Geophysical Research: Space Physics*, https://doi.org/10.1029/2019JA027768, 2020) **—Morgan Rehnberg,** *Science Writer*

### Atmospheric Sciences

**The National Science Foundation is seeking qualified candidate for a Physical Scientist (Program Director) position for the Geospace Facilities (GF) program in the Division of Atmospheric and Geospace Sciences (AGS) within the Directorate for Geosciences (GEO), Alexandria, VA.**

AGS supports fundamental research into the physical, chemical, and biological processes that impact the composition and physical phenomena and behavior of matter between the sun and the surface of the Earth. This includes a wide variety of important processes that impact humans and society, such as weather, climate, air quality and space weather. Specific programs include studies of the physics, chemistry, and dynamics of earth's upper and lower atmosphere and its space environment, and research on climate processes and variations.

The Geospace Section (GS) funds research and facilities to add new understanding to how the geospace system responds to driving from the Sun. Specific research areas and activities supported by GS include:

• Studies of physics and chemistry of mesosphere through the outer thermosphere and ionosphere,

• Investigations of the plasma environment of magnetosphere,

• Explorations of the Sun and how its energy output is transported to the Earth,

• Examinations into origins and nature of space weather.

The Geospace Facilities Program promotes basic research on the structure and dynamics of the Earth's upper atmosphere through the support of several large incoherent-scatter radar facilities. The radars are located at widely distributed sites throughout North and South America, including Alaska, Northern Canada, Puerto Rico, and Peru. Each of the incoherent scatter facilities is also equipped with powerful optical and electromagnetic diagnostics instruments. Research efforts utilizing these facilities have strong links to the Geospace Section science programs: Aeronomy, Magnetospheric Physics, Solar-terrestrial Research, and Space Weather Research.

Duties

Working closely with colleagues in the Geospace Section, AGS, and throughout NSF, the incumbent will have primary responsibility for the programmatic oversight, award management and lifecycle planning of the AGS-funded geospace observing facilities. Specific duties will include:

• Manage solicitations, programs and budgets for operating geospace observing facilities.

• Conduct program reviews and other evaluations.

• Work with NSF science program officers to ensure that the utilization of the geospace observing facilities is well-coordinated, technically feasible and equitable.

• Working with colleagues, the scientific community and facility managers, lead the development of long-range plans for the AGS geospace observing facilities.

• Serve on intra-agency, inter-agency and international committees involving geospace observing facilities.

• Undertake other program officer responsibilities as needed. Develop solicitations and Dear Colleague Letters. Manage proposal review, ensuring a rigorous and fair process with appropriate participation by members of underrepresented groups.

• Proactively support NSF's strategic goals in the area of broadening participation.

### Geodesy

**Tenure Track Scientist–Geology & Geophysics**

Woods Hole, Massachusetts

Job Summary

The Geology & Geophysics Department at Woods Hole Oceanographic Institution (WHOI) invites exceptional candidates to apply to one or more of our full-time exempt tenure track positions on our scientific staff. We seek to hire at the Assistant Scientist level; however, extraordinary candidates may be considered at Associate Scientist without Tenure, Associate Scientist with Tenure, or Senior Scientist levels.

The successful candidate would ideally have expertise in Seismology or Geodesy (marine or terrestrial), and an interest in the use and/or development of marine instrumentation and novel techniques for analyzing seafloor data. WHOI currently houses the Ocean Bottom Seismometer Instrument Center (OBSIC) (https://obsic.whoi.edu/) which provides seafloor instrumentation for the US seismic community. Individuals who are able to develop synergies and collaborations with OBSIC would be desirable.

However, candidates from other geophysical fields, whose expertise complements and strengthens that of the department may also be considered and are encouraged to apply. Existing departmental strengths and interests include geophysics (active and passive seismology, electromagnetic methods, and magnetics), tectonics, ice-sheet dynamics, volcanology and fluid dynamics, geochemistry, coastal processes, past and present climate dynamics and biogeochemistry.

WHOI is the largest private, non-profit oceanographic institution in the world, with staff, postdocs, and graduate students numbering approximately

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**ASSISTANT PROFESSOR/ASSOCIATE PROFESSOR/PROFESSOR**
Thrust of Earth, Ocean and Atmospheric Sciences (EOAS), HKUST (GZ)
Job ID 5478

The Hong Kong University of Science and Technology (HKUST) has positioned itself as an international university which emphasizes on both teaching and research. Over the years, HKUST has been making strides progressively in education, research, knowledge transfer, and community services. Leveraging on the academic leadership in higher education and impending development of China's innovation-driven Greater Bay Area (GBA), HKUST welcomes the opportunity to establish a new campus in Guangzhou (GZ), the Mainland China (**http://gz.ust.hk/**). The new campus will synergize with and maintain the same academic standard as that of its Clear Water Bay (CWB) counterpart. The Hong Kong University of Science and Technology (Guangzhou) (HKUST(GZ)) will nurture talent and facilitate collaboration amongst Hong Kong, the Greater Bay Area (GBA) and beyond on education, research and commercialization, while strengthening knowledge transfer to bridge Hong Kong's gap in high-tech manufacturing.

Thrust of Earth, Ocean and Atmospheric Sciences (EOAS) is a Department of HKUST (GZ). The aim of the EOAS is to become a leading educational and research entity in the areas of earth surface process, oceanography, atmospheric science, which focuses on interdisciplinary studies of ocean-atmosphere-land interaction in the earth system for the regional sustainable environment and climate change. It covers multidisciplinary study of physical, biogeochemical, watershed hydrological and earth surface sciences in the coupled system of land-sea, sea-ocean and atmosphere-ocean. Appointees are expected to engage in the cutting-edge and innovative scientific research; undertake national-level scientific research projects; and lead the development of disciplines.

*Applicants should have a PhD degree in Earth Surface Science, Oceanography, Atmospheric Science, or related field with relevant research and teaching experience in Earth Surface Physical and/or Biogeochemical Science, Hydrology, other disciplines in Oceanography and Atmospheric Sciences.*

- *For the post of **Assistant Professor**, applicants should have at least 2 years of post-doctoral experience and strong research track records.*
- *For post of **Associate Professor**, applicants should have a strong record of teaching, student supervision and strong record of research and publication.*
- *For post of **Full Professor**, applicants should have world-class academic achievements, strong academic leadership and reputation, and an excellent record of research and publication.*

*Good command of written and spoken English and ability to teach effectively in English are required.*

English is the medium of instruction and administration at HKUST(GZ) campus. HKUST(GZ) is committed to diversity in recruitment and equal opportunity employment and we strongly encourage suitable candidates of diverse backgrounds to submit their applications.

**REMUNERATION AND CONDITIONS OF SERVICE**
Salary is highly competitive of international standard and will be commensurate with qualifications and experience. Generous research funds, ample laboratory space and excellent research equipment and support will be provided.

All posts are tenure-track Mainland China appointments to be offered by the HKUST Mainland entity in accordance with the local employment laws and regulations. Appointment to Professor rank and some Associate Professor rank will be made on substantive basis while initial appointment to other tenure-track faculty ranks will be made on a fixed-term contract of up to three years commencing the earliest in **July/August 2020**. Re-appointment thereafter will be subject to performance, mutual agreement and funding availability.

**APPLICATION PROCEDURE**
Applications should be sent to **gzrecruitFUN@ust.hk** and cc to Prof. Jianping Gan at **eoast@ust.hk** together with **(i)** full CV (including education, publications, teaching experience, honor and award, and projects); **(ii)** a statement of research and teaching, and the career plan for the future; **(iii)** at least 5 representative academic publications all in PDF formats (in the last 5 years); **(iv)** record of teaching performance; **(v)** the names and contact information of three referees; and **(vi)** three letters of reference. Review of applications will continue until the positions are filled.

For more information, please visit **https://hrmsxprod.psft.ust.hk:8044/psp/hrmsxprod/EMPLOYEE/HRMS/c/HRS_HRAM.HRS_CE.GBL**

1,000. Its mission is to advance our understanding of the ocean and its interaction with the Earth system, and to communicate this understanding for the benefit of society. The Institution is located in Woods Hole, Massachusetts, a world-renowned center of excellence in marine, biomedical, and environmental science. An additional 500 affiliates are associated with the scientific endeavors of the Institution, many of whom are foreign nationals from the international community.

WHOI is committed to supporting a diverse and inclusive environment and is proud to be an equal opportunity employer. All qualified applicants will receive consideration for employment without regard to race, color, religion, gender, gender identity or expression, sexual orientation, national origin, genetics, disability, age, or veteran status. WHOI believes diversity, equity, and inclusion are essential components that support our academic excellence. We strive for a diverse and inclusive workforce, and encourage women, minorities, veterans and those with disabilities to apply.

WHOI offers a comprehensive benefit package that includes medical and dental plans, short-term and long-term disability and life insurance programs, medical and dependent care pre-tax Flexible Spending Accounts in addition to our own child care subsidy reimbursement program, paid parental leave, a generous employer contribution retirement plan, vacation, occasional illness, and family illness time as well as flexible work arrangements. WHOI also provides dual career services for assisting your spouse or partner should they be impacted by your career decision. We have a dedicated team who will work with applicants to identify and explore available options within WHOI or the broader community.

Essential Functions

Opportunities for interdisciplinary research exist and are highly encouraged, through collaborations with colleagues in our other science departments, centers, and labs as well as with researchers in the broader Woods Hole scientific community. WHOI's Scientific Staff members are expected to provide for their salaries and those staff members who work in support of their research from grants and contracts that they have been awarded. The Institution provides salary support when no other funding is available. There are also opportunities for significant internal funding to develop innovative research projects. Candidates hired at the junior non-tenure level will receive an initial appointment for four years.

Education & Experience

Applicants should have a doctoral degree, postdoctoral experience, and a record of scientific research publications in scholarly journals. Scientific staff members are expected to develop independent, externally-funded, and internationally-recognized research programs. They also have the option of advising graduate students and teaching courses through the MIT/WHOI Joint Program in Oceanography and Oceanographic Engineering.

Special Requirements

Applicants should upload, in the designated areas of the application, the following documents. Please include the title of the position that you are applying for in the name of your files: A cover letter; curriculum vitae (CV); three-page research statement; names of four references; and copies of up to three relevant publications. In addition to the online application, please email the documents directly to the chair of the Geology & Geophysics Department at gg-chair@whoi.edu with the subject "Geology & Geophysics Scientist Application". Interviews will be conducted virtually.

Physical Requirements

Further details of the physical requirements of established essential functions for this position will be addressed/discussed during the interview process.

## ASSISTANT PROFESSOR

The Department of Geosciences at Princeton University seeks a **global geophysicist** to join its Faculty at the **Assistant Professor** level.

We are looking for applicants with expertise, research and teaching interests in Earth and planetary geophysics, seismology, geodynamics, or mineral physics. The Department is especially interested in candidates who will contribute to the diversity and excellence of our academic community.

The successful candidate will complement our existing strengths and areas of concentration, and enjoy cross-disciplinary ties with University Programs such as the Program in Applied and Computational Mathematics (PACM), Princeton Center for Complex Materials (PCCM), the Princeton Institute for Computational Science and Engineering (PICSciE), the Princeton Institute for the Science and Technology of Materials (PRISM), and other Science Departments.

Applicants should send a curriculum vitae, including a publication list, a statement of research and teaching interests, a separate statement outlining how they see themselves contributing to our mission of building a diverse and inclusive discipline with a strong department, and contact information for three references to: **https://www.princeton.edu/acad-positions/position/17221**. Evaluation of applications will begin as they arrive; for fullest consideration, apply by **December 21, 2020**, but applications will be accepted until the position is filled.

Diversity and inclusion are central to Princeton University's educational mission and its desire to serve society. Members of the Geosciences department have a deep commitment to being inclusive. We believe that commitment to principles of fairness and respect for all is favorable to the free and open exchange of ideas, so we seek to reach out as widely as possible in order to attract the ablest individuals as students, faculty, and staff. In applying this policy, we are committed to nondiscrimination on the basis of personal beliefs or characteristics such as political views, religion, national or ethnic origin, race, color, sex, sexual orientation, gender identity or expression, pregnancy, age, marital or domestic partnership status, veteran status, disability, genetic information and/or other characteristics protected by applicable law in any phase of its education or employment programs or activities.

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

*Princeton University is an Equal Opportunity/Affirmative Action Employer and all qualified applicants will receive consideration for employment without regard to age, race, color, religion, sex, sexual orientation, gender identity or expression, national origin, disability status, protected veteran status, or any other characteristic protected by law. EEO IS THE LAW*

Ciao e benvenuto to the glorious views from the critical zone summer school at Gran Paradiso National Park in Italy during July 2019.

This unique event brought together graduate students from across disciplines and across the globe to learn about relationships between critical zone science and ecosystem services. In addition to learning about local interactions between geology and biology at the Nivolet Critical Zone, many of the students became great friends over 2 weeks.

The photo features two of my friends—Maria Teresa Tancredi from the University of Georgia and Corey Palmer from the University of Massachusetts Amherst—crossing a cold, wide river. Our class ventured to the edge of the valley to sample water near the ice. When it was time to head back, everyone had a little more trouble getting across the river than they did on the way up. I made sure to go early because I get timid crossing rivers like this, but it gave me time to look back at my friends, enjoy the view, and snap a few pictures.

This area is very close to the border with France on the Gran Paradiso massif. The dip of the metamorphic rock pictured here seemed the same in every direction, giving a clue to the complex tectonics of the region.

Grazie mille!

—**Mackenzie Vecchio,** Florida Atlantic University, Boca Raton

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