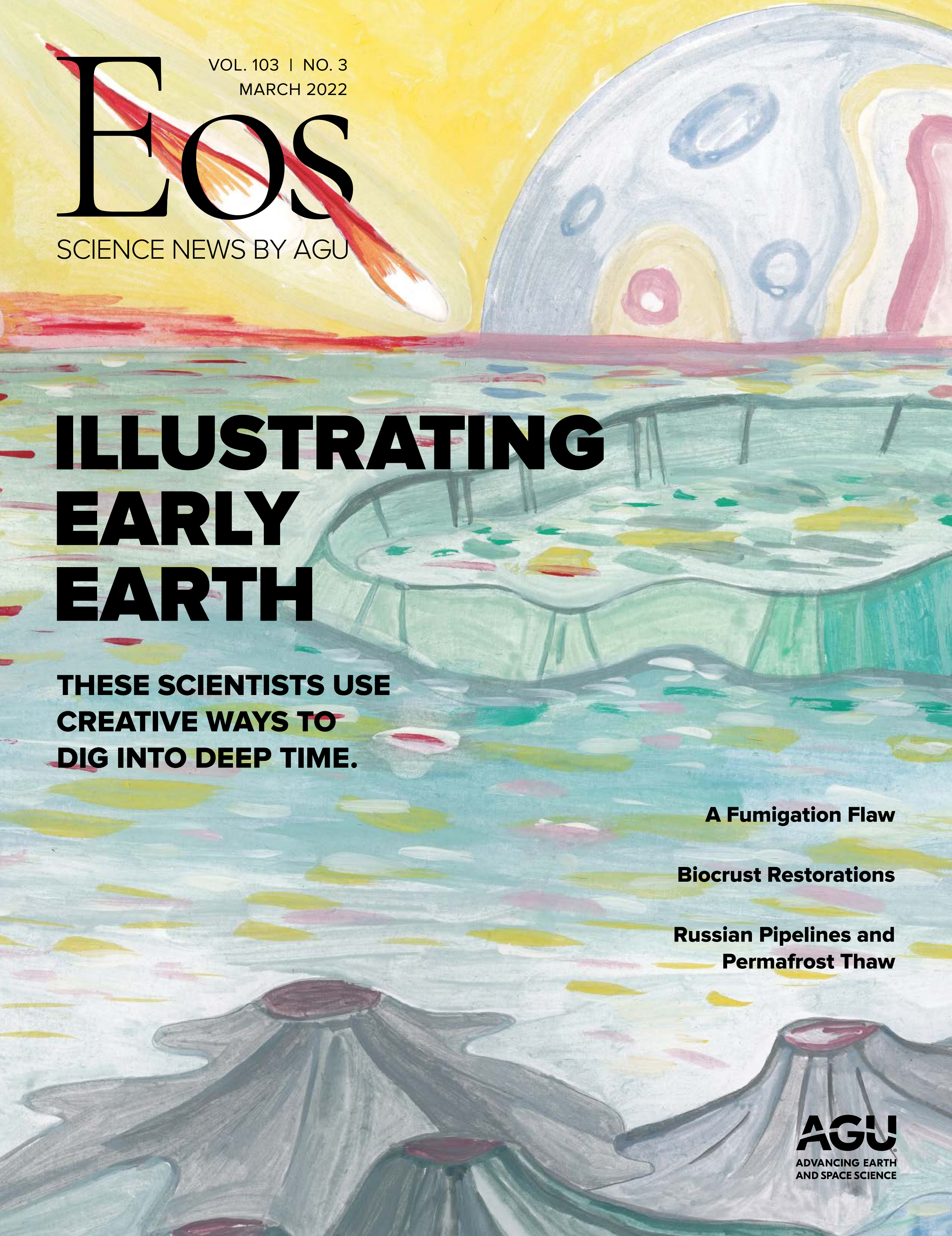

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Eos

SCIENCE NEWS BY AGU

ILLUSTRATING EARLY EARTH

THESE SCIENTISTS USE CREATIVE WAYS TO DIG INTO DEEP TIME.

A Fumigation Flaw

Biocrust Restorations

Russian Pipelines and Permafrost Thaw

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How to Work in the Dark on Deep Time

"In the almost complete absence of early crustal rocks, scientists have thus had to piece together their hypotheses from indirect evidence," write Anastassia Y. Borisova and Anne Nédélec in their research update featured in this issue. Much like those investigating exoplanets millions of light years away, scientists who study the interior of Earth and how it formed are working largely in the dark.

Our March issue highlights the work of these scientists. Borisova and Nédélec offer "A Simple Recipe for Making the First Continental Crust" on page 22, describing the creative approaches they've taken to develop a model that explains its origins—and potentially Mars's crust as well.

"The Young Earth Under the Cool Sun" on page 28 looks at another problem of Earth formation—how to explain why the planet didn't freeze before solar fusion was kicking into high gear. Researchers are looking all over the universe for an answer—from exoplanet cousins with their own faint young stars, to our Mars and Venus neighbors, and even to Moon rocks that Apollo astronauts collected and brought home. One thing we *can* tell you: Don't call it a paradox.

Research on deep-time questions often requires very specialized labs with very expensive equipment. So what happens when the head of the lab retires or moves on to other opportunities? It's an issue that most institutions across all disciplines deal with, but we look specifically at the case of argon-argon labs and how they're handling questions of succession and avoiding the loss of productive labs in a relatively small field. See what you might take away on page 34 in "Long-Term Planning for Deep-Time Labs."

Finally, we want to thank Anastassia Y. Borisova for the beautiful artwork on the cover and featured with her article. An innovative scientific thinker who can share her research eloquently in writing *and* painting? *Eos* is the place for you!

Would you like to share your research in *Eos*, too? Submit a brief proposal telling us what you'd like to write about at eos.org/submit. When we accept proposals, writers work with our editors, who are experts in science communication techniques that will help you compose an informative article for colleagues, as well as an engaging lesson for the broader public who come to Eos.org every day to learn about the wide world of Earth and space science from you.

See you next month!

Heather Goss, Editor in Chief

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Randy Fiser, Executive Director/CEO

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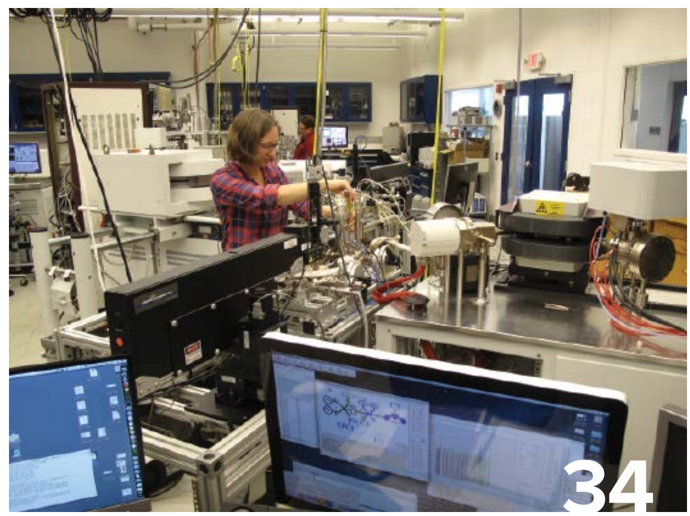


Features

On the Cover

During the Hadean, more than 4 billion years ago, a liquid water ocean, volcanic activity, and meteorite impacts acted together to fashion the surface of early Earth. Credit: Anastassia Borisova

Columns

How Much Did the Moon Heat Young Earth?

The Moon used to orbit Earth 10–15 times closer than it does today. Orbiting even closer than geosynchronous satellites, our only natural satellite exerted a strong gravitational pull on our planet, deformed it, and heated its interior.

A recent study published in *Paläontologische Zeitschrift* suggested that considerable tidal heating was generated for about a hundred million years after the formation of the Moon (bit.ly/tidal-heating). The heat could have directly increased the surface temperature of early Earth by several degrees. Indirectly, the process may have further heated the surface by triggering global volcanic activity and thus enriched the atmosphere with greenhouse gases.

A young Moon looms over Earth in this artist's rendering. Credit: Dan Durda

Never-Ending Dance of a Planet and Its Moon

About 4.5 billion years ago, a Mars-sized body likely collided with Earth. The collision propelled molten debris into orbit around Earth, and over time the wreckage coalesced into the Moon. Although scientists have largely accepted the giant impact theory of lunar origin, debates about the timing of the impact and the mechanisms that led to the formation of the Moon are ongoing. What is clear is that the Moon formed much closer to Earth than it is now, and it has been drifting away ever since.

Paradoxically, the Moon and Earth are growing apart due to gravity. The Moon's gravity exerts a stronger pull on the part of Earth that faces it (as opposed to the antipodes), stretching the planet into a slightly oblong, bulged shape. These tidal forces are the primary cause of tides on Earth. That would be the end of the story were it not for the fact that Earth rotates on its axis faster than the Moon orbits the planet. As a result of this discrepancy, the planet puts on the brakes while the Moon speeds up in its orbit, slowly drifting away.

Tidal forces contribute to heating in Earth's interior. "The tides generate friction, and friction leads to heat," explained René Heller, a scientist at the Max Planck Institute for Solar System Research and a lecturer at the University of Göttingen in Germany.

Tidal heating is not a significant phenomenon on Earth now, but conditions were different billions of years ago. Previous works found that tidal heating was relevant for a few million years after the formation of the Moon (bit.ly/tidal-heating-history). Heller and colleagues have suggested that the period of significant heating lasted about a hundred million years.

"The energy that would have been dissipated in the Earth, according to the authors, is of the order of magnitude of the heat content of the Earth," said Tilman Spohn, a professor and executive director of the International Space Science Institute in Switzerland. Spohn was not involved in the study. "If you release it at once, you would double [Earth's] internal temperature." (Both Spohn and the researchers noted that such a release would not be sudden.)

Warming Up Early Earth

The new research contributes to one of the most famous problems in astrophysics. Tidal heating could have raised the temperature of early Earth by a few degrees and therefore played a minor but not irrelevant role in solving the so-called faint young Sun paradox. (Read more on p. 28.) Evidence has suggested that Earth harbored liquid water as far back as 4.4 billion years ago. That observation is difficult to reconcile with our understanding of the evolution of the Sun, whose energy output at the time was about 30% lower than it is today. For decades, scientists have been trying to model various atmospheric conditions that would have kept early Earth from becoming a snowball. "There are theories that try to solve the faint young Sun paradox which ignore tidal heating entirely and just focus on the Earth's atmosphere," said Heller. "The truth will need to combine all these effects."

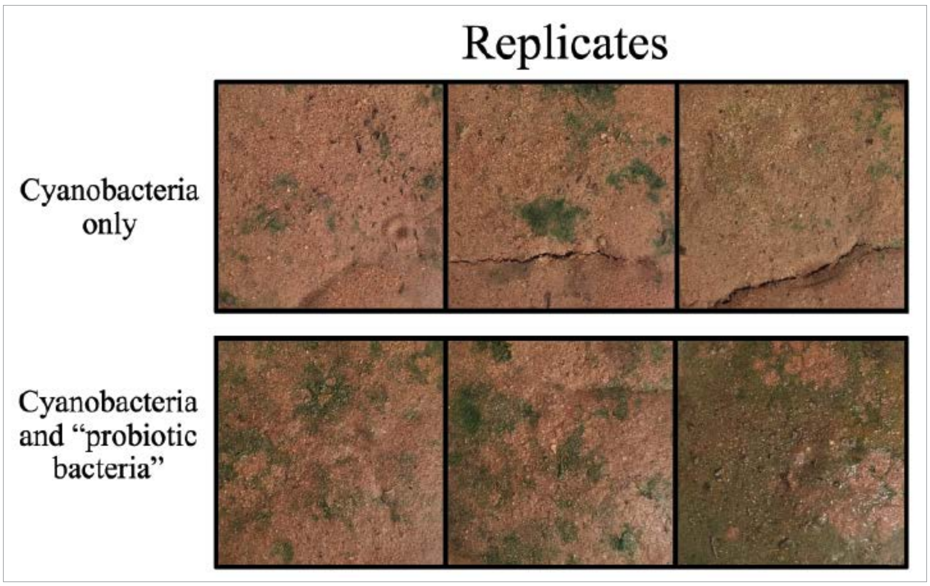
Furthermore, tidal heating likely triggered global volcanism. We need only to look at Jupiter's moon Io to see the effect playing out in real time. Thanks to enormous tidal stresses that melt the moon's interior, Io is the most volcanically active body in the solar system. Similar volcanic activity on early Earth would have released greenhouse gases into the atmosphere.

All studies addressing the faint young Sun paradox have to contend with sparse geological records of early Earth, however. "The mineral zircon is almost the only record we have for early Earth," warned Junjie Dong, a graduate student at Harvard University who was not involved with the recent study. "The evidence for liquid water on the surface is based on isotopic records in zircons, and there are still people who dispute that interpretation."

Regardless, the researchers said the concept of tidal heating of early Earth should not be brushed aside. "I would take [the study] as a reminder or suggestion that maybe we should reconsider the early evolution of the Earth-Moon system," said Spohn. The next step would be to construct a more detailed model by considering the evolution of the Moon's orbit, tidal heating of the Moon itself, and a thorough treatment of Earth's internal structure.

By **Jure Japelj** (@JureJapelj), Science Writer

Biocrust "Probiotics" Can Aid Dryland Restoration Efforts



A comparison of nursery biocrust yields in desert soils illustrates the difference between soils inoculated with cyanobacteria alone and those with cyanobacteria and heterotrophic bacteria. Credit: Ferran Garcia-Pichel

In drylands around the world, human activity has harmed soil quality, in part by damaging biological soil crusts (biocrusts) composed of photosynthetic organisms like cyanobacteria, algae, mosses, and lichens that grow as biofilms. Biocrusts make up a "living skin" that covers around 12% of Earth's surface and provide essential ecosystem services to drylands. Trampling by livestock and off-road traffic damages established biocrusts, which grow only after rare rain events that moisten the soil. The loss of biocrusts can result in degraded ecosystems.

Enlisting the help of beneficial bacteria may give biocrusts their second wind.

Scientists are working to restore these damaged biological communities by planting biocrust-forming organisms in disturbed areas. The challenge lies in biocrusts' slow growth; natural recovery can take years to decades depending on the environment and frequency of disturbance. However, recent research published in *Applied and Environmental Microbiology* suggests that enlisting the help of beneficial bacteria may give biocrusts their second wind (bit.ly/bacteria-biocrusts).

The research, led by Ferran Garcia-Pichel, a professor at Arizona State University, aims to restore damaged biocrusts in the southwestern United States by growing cyanobacteria in nurseries and lab cultures. Garcia-Pichel's team then plants the cultivated biomass in disturbed ecosystems.

To produce microbial material suitable for biocrust restoration (inocula), biologists create environments conducive to faster cyanobacteria growth. Shading, increased frequency of watering, and soil stabilizers at on-site nurseries can create Goldilocks conditions. However, it can still take up to 3 months to obtain sufficient biomass for inocula. Now Garcia-Pichel's research suggests that growing heterotrophic bacteria with cyanobacteria can further improve growth in biocrust nurseries.

"[The time investment is] nothing—it's overnight cultures."

Soil contains many different heterotrophic bacteria (those that consume organic matter), but the bacteria that Garcia-Pichel's team use are special. They physically attach to the cyanobacteria, establishing a mutualistic relationship. The heterotrophic bacteria provide the cyanobacteria with essential nutrients, while the cyanobacteria feed the heterotrophic bacteria with carbon produced during photosynthesis.

Low Investment, High Returns

Can restoration biologists use such bacterial partnerships to aid biocrust restoration? Garcia-Pichel and his team tested this idea by adding cyanobacteria to desert soils in the lab and in outdoor nurseries. Then they compared the amount and speed of cyanobacteria growth with and without the heterotrophic bacteria.

The heterotrophic bacteria from dryland biocrusts improved the speed and amount of cyanobacteria growth under laboratory and nursery conditions, acting as a probiotic of sorts. In some soils, adding the heterotrophic bacteria alone was sufficient to increase biocrust growth.

The research findings suggest that adding these probiotic bacteria alone may help remnant cyanobacteria in disturbed biocrusts recover in some cases. This could benefit biocrust restoration, because the heterotrophic

Biocrusts composed of mosses, lichens, and cyanobacteria help restore degraded dryland ecosystems. Credit: Anita Antoninka

bacteria require much less time and effort to grow than cyanobacteria. According to Garcia-Pichel, "[the time investment is] nothing—it's overnight cultures." And, although not always effective in restoring biocrusts alone, adding the probiotic bacteria with cyanobacteria inocula could give the cyanobacteria an easier time in more degraded areas.

"For sure, I think this is beneficial," said Anita Antoninka, a biocrust ecologist at Northern Arizona University who was not involved in the research. "[The study shows that] you can increase the growth of [individual] strains more quickly by adding heterotrophic bacteria."

So far, biocrust probiotics have been used only under nursery conditions, so further assessment of their effectiveness on restoration in nature will be an important next step. According to Antoninka, whole biocrust inocula obtained from more pristine sites could already have sufficient heterotrophic bacteria present. So the effectiveness of probiotics in biocrust restoration is likely dependent on the inoculum and the extent of degradation.

By **Derek Smith** (@djsmitty156), Science Writer

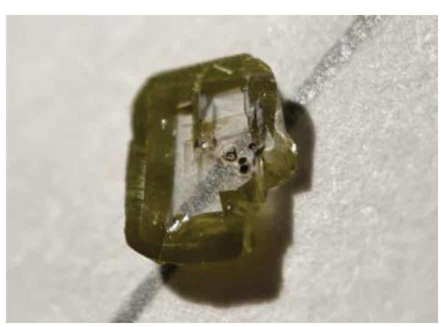
Diamond Discovery Unearths Secrets of the Deep

For decades, geologists have thought that Earth's deep mantle is composed largely of silicate minerals with a perovskite crystal structure. But mineralogical evidence has been very difficult to obtain.

The elusive calcium and magnesium silicate perovskites, although synthesized in the laboratory decades ago, are not stable below pressures of 20 gigapascals. That makes them nearly impossible to find in the lithosphere and rare even in the upper mantle. The high pressure of the lower mantle starts at about 660 kilometers underground and extends to about 2,000 kilometers below that.

Now, in a new report published in *Science,* researchers identified the presence of a natural calcium silicate ($CaSiO_3$) perovskite from the deep mantle (bit.ly/perovskite-mantle). Found in the inclusion of a deep-Earth diamond sourced from Botswana, the perovskite was officially confirmed as a new mineral by the International Mineralogical Association and called davemaoite. The mineral was named for geologist Ho-Kwang "Dave" Mao, in honor of his prolific contributions to deep-mantle geophysics and petrology. Mao, who was himself not involved in the research, responded by remarking on the rarity of the diamond: "The diamond not only preserved a high-pressure mineral inclusion but also preserved the 'pressure' itself," he said in an email. "The inclusion that normally spoils the clarity of an otherwise perfect gem diamond here makes the diamond uniquely invaluable with the scientific message it carries."

As Mao indicated, the inclusion reduces the diamond's value to a jeweler but for a geoscientist makes it priceless. Oliver Tschauner of the University of Nevada, Las Vegas and his team were not fully aware of the diamond's scientific value until they analyzed it with micro X-ray fluorescence and diffraction techniques as part of a larger analysis of inclusions in deep-Earth diamonds. "The discovery was quite a surprise—we did not expect that this mineral could be conserved, even in a diamond," said Tschauner in an email.



This deep-Earth diamond found in Botswana carries an inclusion of a new mineral, named davemaoite. Credit: Aaron Celestian, Natural History Museum of Los Angeles

"We did not expect that this mineral could be conserved."

Unearthing Secrets of the Lower Mantle

The discovery helps reveal the composition of the lower mantle, where davemaoite, along with bridgmanite and ferropericlase, is a major component, making up about 5%–7%, according to Tschauner. The newly identified mineral also plays a role in regulating the heat budget of our planet. During the team's investigation, structural and chemical analysis showed that davemaoite can host various elements (such as potassium, thorium, and uranium) whose isotopes generate heat in the lower mantle but are not stable in the upper mantle. These heat fluctuations help drive processes such as plate tectonics.

Davemaoite also tells us more about how diamonds form at depth, Tschauner explained: "The identification of davemaoite in a diamond proves that diamond formation (and the recycling of carbon in the mantle) extends to that depth. This had been proposed by some scientists, but here is the evidence."

Tschauner said the discovery is an encouraging sign that more deep-mantle minerals are waiting to be found. "Already, a few have been discovered, including breyite, jeffbenite, and ringwoodite. Diamonds from the deep mantle are quite uncommon, but it seems only a matter of time until we hit an inclusion of bridgmanite," he added.

By **Clarissa Wright** (@ClarissaWrights), Science Writer

Termite Fumigation in California Is Fueling the Rise of a Rare Greenhouse Gas

New research has suggested that the nationwide rise of the potent greenhouse gas sulfuryl fluoride comes almost entirely from termite fumigations in the greater Los Angeles area.

Sulfuryl fluoride is a common treatment for drywood termites, bedbugs, cockroaches, and other pests. Dow Chemical Company developed the gas, also known by its brand name Vikane, in 1959.

Concentrations of sulfuryl fluoride have grown exponentially worldwide: In 1978, it was 0.3 part per trillion. Today it's more than 2.5 parts per trillion.

The latest research has found that one hot spot in the United States—the greater Los Angeles area—has the highest emissions of sulfuryl fluoride. In the region, sulfuryl fluoride concentrations have topped 400 parts per trillion at times between 2015 and 2017, said graduate student Dylan Gaeta of Johns Hopkins University. The second-highest emissions came from California's Bay Area. The rest of the country releases barely any emissions.

According to the state's Department of Pesticide Regulation, the source of emissions in California is clear: Structural fumigations account for 99% of sulfuryl fluoride use.

The study analyzed the concentration of sulfuryl fluoride in the air between 2015 and 2017 measured by NOAA's Global Monitoring Laboratory. The agency's scientists regularly gather flasks of air from across the country using aircraft, towers, and surface collectors. NOAA scientists in Boulder, Colo., then test the flasks for minute traces of gas.

Gaeta and his collaborators used these measurements to estimate the rate of emissions nationwide. They fed a statistical model sulfuryl fluoride concentration measurements at different sites, along with other relevant data, and asked the model to infer where the emissions came from.

A multicolored tent in Los Angeles covers a residential building for fumigation. Credit: Matthew Field, CC BY-SA 3.0 (bit.ly/ccbysa3-0)

"We expected to see little splotches of emissions throughout at least some other parts of the country," Gaeta said. "The fact that we are seeing almost all of it from California? That was the shocking part."

NOAA's monitoring network does not extend to Florida, however, and the state does not track sulfuryl fluoride use. "It is possible that Florida is also emitting, and then it's just not being detected by the NOAA network," said Gaeta. He presented the research, which had not yet been peer reviewed, at AGU's Fall Meeting 2021 (bit.ly/sulfuryl-fluoride).

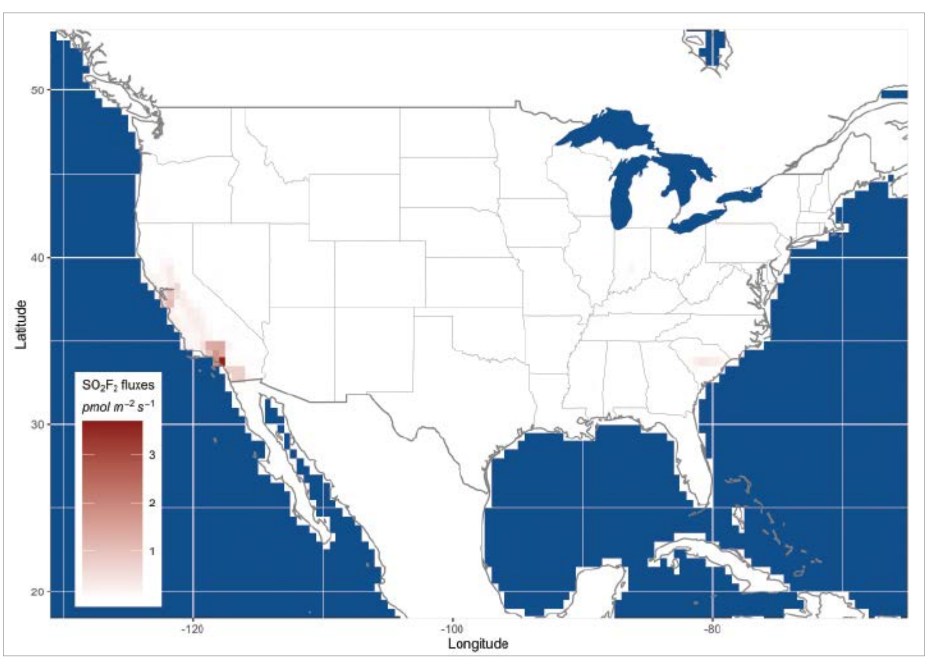
A Surprise Greenhouse Gas

For years, the insecticide was thought to be relatively harmless when it came to global warming.

To use the substance, fumigators first cover a building with an airtight tent. They fill the building with gas and let it do its work. Afterward, workers open windows to air out the building, releasing the gas to the atmosphere, where it was believed to break down relatively quickly.

The method rose in popularity after the Montreal Protocol phased out another common fumigant, methyl bromide, that was found to erode the ozone layer.

But research in 2008 and 2009 revealed that sulfuryl fluoride has a relatively high global warming potential and sticks around longer than initially thought. The gas has a global warming potential of more than 4,000 times that of carbon dioxide over 100 years



Compared with other states, California has unusually high rates of sulfuryl fluoride (SO_2F_2) emissions. Credit: Dylan Gaeta and remains in the atmosphere for about 36 years.

"When something stays in the atmosphere this long, you cannot lessen the climate effects overnight by just turning off the emissions," said atmospheric chemist Mads Sulbaek Andersen of California State University Northridge, who has studied the gas's characteristics but was not involved in the new research.

The California Air Resources Board (CARB) recently added the insecticide to its list of short-lived climate pollutants. California is the only state to track its use, with records stretching back to the 1990s. Yet the state's progressive emissions goals don't include sulfuryl fluoride because the rules were written before scientists knew it was a greenhouse gas.

"CARB staff continue to monitor the scientific literature to better understand the greenhouse gas emissions and effects of sulfuryl fluoride and other pesticides," said CARB public information officer Dave Clegern.

Fumigation Alternatives

A house can be rid of pests without fumigation, but other methods may not work as well, said urban pest researcher Andrew Sutherland at University of California Agriculture and Natural Resources (UC ANR). Other techniques to target drywood termites, bedbugs, and wood-boring beetles include heat treatments and local insecticide application. Both require advanced monitoring, detection, and delimitation methods, said Sutherland.

But when infestations are widespread, nothing can equal sulfuryl fluoride's "efficacy and cost-effectiveness," Sutherland said.

Los Angeles County integrated pest management adviser Siavash Taravati of UC ANR said that sulfuryl fluoride comes in handy when an infestation is inaccessible to technicians. "If [sulfuryl fluoride is] banned, pest control operators will have to switch to local treatment methods."

The change could reverberate around the world: According to recent work from the Massachusetts Institute of Technology, structural fumigation in North America was the leading global source of sulfuryl fluoride emissions in 2019.

If California fumigations stopped, said Gaeta, "almost all the emissions coming from the U.S. would go away."

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

Clever Wood Use Could Mitigate Wildfires and Climate Change

Innovative products made from wood harvested during forest thinning treatments in California could displace materials that are less carbon friendly. Credit: Daniel Sanchez

Wildfire risk reduction in California is a climate conundrum.

In early 2021, the state set a goal of reducing wildfire risk on 1 million acres (405,000 hectares) of forest per year through prescribed burning and forest thinning. However, thinning treatments lower a forest's capacity to remove carbon dioxide from the atmosphere, and the harvested smaller, low-value trees are typically burned or left to decay, which releases even more carbon.

"There's this unique role of emerging and innovative wood products in achieving forest management that reduces wildfire risk and also preserves forests as carbon sinks."

In a study published in the *Proceedings of the National Academy of Sciences of the United States of America*, researchers from the University of California, Berkeley provide a possible path to limiting both carbon emissions and wildfires by turning the low-value wood harvested during forest thinning into new products (bit.ly/innovative-wood).

"There's this unique role of emerging and innovative wood products in achieving forest management that reduces wildfire risk and also preserves forests as carbon sinks," said the study's senior author, Daniel Sanchez.

Modeling Forest Management

For the analysis, Sanchez and his colleagues used forest inventory data from the U.S. Forest Service for more than 33 million acres (13.4 million hectares) of California forests and applied several forest management models to simulate forest growth, forest treatments, wildfire risks, and revenue potential over the next 40 years.

They ran simulations of three scenarios and then estimated the carbon impacts of each scenario. Two scenarios modeled business-as-usual forest management in California with variations in how much wood is sold. The third introduced a value to the low-value wood generated from forest thinning, allowing it to be used for new products. Smaller trees can be turned into a construction-grade wood product called oriented strand board, which retains the wood as a carbon store. A mixture of forest residues, including leaves and bark, can be used to make low-carbon fuels, such as hydrogen.

Benefits of Innovative Wood Products

The study found that the "innovative wood product" scenario lowered both the wildfire risk and carbon emissions from wildfires and postfire decay compared with the other two scenarios. On top of that, turning low-value wood into low-carbon fuels and wood products displaced products that are less carbon friendly, like gasoline or steel and concrete. So even though the amount of carbon stored in living trees decreased, the new wood market prevented the equivalent of as much as 16 million metric tons of carbon dioxide per year from entering the atmosphere when compared with the other two scenarios. The researchers estimated that the climate benefit could be improved even further with state incentives to build affordable housing with innovative wood products.

"We find that in these innovative wood product scenarios, we do reduce the amount of net carbon. Then by putting it into products, we get all these other benefits," said Sanchez. Another benefit is that the new wood products market could generate enough money to treat 12 million acres (4.9 million hectares) of additional forest over the next 40 years.

> **"I think that [this paper] does point in the direction where there are real opportunities for California."**

"It's a really interesting paper," said Chris Field, director of the Stanford Woods Institute for the Environment, who has worked with Sanchez in the past but was not involved in the new study. "I think that it does point in the direction where there are real opportunities for California."

He added that in addition to the forest and climate benefits, the innovative wood products industry could also help rural economies in California. "We've lost thousands of jobs in the forest products industry over the last 15 years. The industry that you would get this result from [would be] very different, but it would still be based in those communities."

Can California Make It Happen?

Sanchez acknowledged that unforeseen challenges could arise from variables they didn't include in the simulations. For example, the models did not predict the potential impacts of innovative wood products on forest soils or belowground forest biomass and economic considerations such as the impact of biofuel prices on the demand for petroleum products. "There are second- and third- and fourth-order effects that we probably don't count," Sanchez said.

Field sees potential issues getting forest sector professionals and conservationists on the same page to move forest management toward innovative wood products. "I think it's a direction that we can go, but it's not entirely straightforward," he said.

But the markets for fuel and wood products are already large in California, Sanchez said, and several existing state policies incentivize industries to use products that are more climate friendly, which might make these wood products enticing. Sanchez is eager to determine which technologies have viable business opportunities.

"I think that in a lot of ways, this provides the motivation for what people are going to have to do within California, which is not only ramp up things on the forest management side but also ramp up things on the wood products infrastructure side to get this done," said Sanchez.

By **Andrew Chapman** (@Andrew7Chapman), Science Writer

Projection: $110 Billion in Repairs for Russian Pipelines on Permafrost

One of the world's biggest producers of oil and gas may face billions in upgrades as permafrost thaw destabilizes pipelines in the Arctic, according to new research.

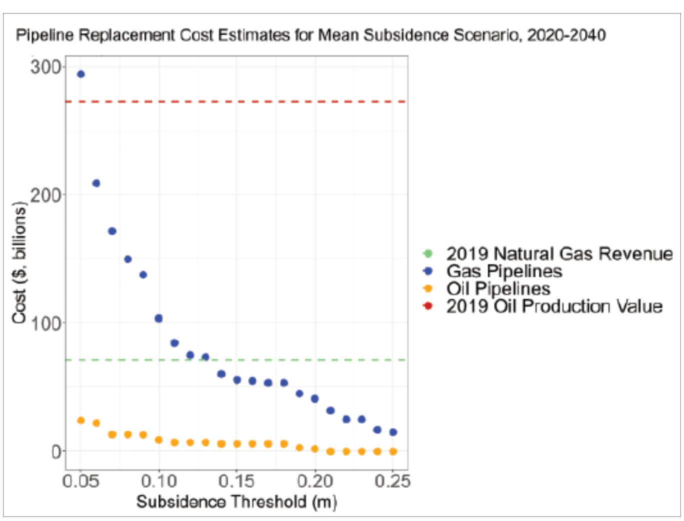
Russia produces 80% of its natural gas in the Arctic, where rising temperatures are thawing ground that has been frozen for tens of thousands and even hundreds of thousands of years.

"Natural gas pipelines appear to be particularly vulnerable," said Meredydd Evans, an Earth scientist with the Pacific Northwest National Laboratory, because natural gas extraction occurs a little farther north—and more into permafrost territory—than oil extraction.

Evans and a team of scientists at national laboratories in the United States compared Russian oil and gas pipeline routes with projected ground subsidence from permafrost thaw. When permafrost melts, the ground level sinks, sometimes by several centimeters per year and sometimes by more than a dozen.

Most Russian pipelines are underground, making them particularly vulnerable to shifting soil. Soil settling unevenly deflects and deforms pipelines, and water pooling around the pipes corrodes them.

Russia produces 80% of its natural gas in the Arctic, including the Zapolyarnoye. Credit: Russian Federation Government, CC BY 3.0 (bit.ly/ccby3-0)



This graph shows the relationship between repair costs and the revenue from oil and gas. The subsidence threshold (horizontal axis) represents the amount of ground subsidence that triggers a repair (a smaller number means that slight change to the soil height will require fixing pipelines). For natural gas, the repair costs over 20 years surpass 1 year of revenue for certain subsidence thresholds. Credit: Pacific Northwest National Laboratory

The ground beneath gas pipelines may subside up to half a meter in places over the next 20 years, according to the group's permafrost projections. A soil slump of even 10 centimeters can be enough to inflict damage on pipelines.

The costs add up: If emissions stay the same, cumulative costs will reach US$110 billion (8.1 trillion rubles) by 2040. Repairs to natural gas pipelines during that time could rival the revenue of natural gas gained in 1 year. "We were just struck by that," said Evans.

The Yamal Peninsula, which may hold 100 years' worth of natural gas reserves, is a hot spot for subsidence. The permafrost there contains more ice than in other areas, making the soil particularly vulnerable to warming, said Evans. She presented the work, which had not been peer reviewed, at AGU's Fall Meeting 2021 (bit.ly/arctic-pipelines).

A soil slump of even 10 centimeters can be enough to inflict damage.

Previous research found that permafrost thaw may cost the Russian Arctic $183 million–$365 million in annual road repair between 2020 and 2050 (bit.ly/russian-permafrost).

Oil and gas are key economic revenue sources for Russia, the world's third-largest producer of oil and second-largest producer of natural gas. Costly repairs could hamper economic development in the region, but state support may buoy the industries.

High costs could change how oil and gas are transported in the future, said Evans. Rather than building more pipeline, the country could ship reserves. Shipping in the Arctic gives off soot, or black carbon, that darkens snow and quickens melting.

"Sixty-five percent of Russia's territory is located in the permafrost zone, but this is not mentioned in a single federal program document, despite the fact that the permafrost area

"Sixty-five percent of Russia's territory is located in the permafrost zone, but this is not mentioned in a single federal program document."

is a vital component in the natural environment, of which the landscape, vegetation and coastline is dependent," Aleksander Kozlov, Russian minister of natural resources and the environment, said in a statement (translated by the *Barents Observer*). More than 40% of Russia's northern buildings are starting to collapse, he said (bit.ly/minister-statement).

Kozlov announced that the country is launching a new state system for monitoring permafrost. Regional initiatives are picking up steam, too: A lab dedicated to permafrost studies—the first of its kind in Russia—will open in the Yamalo-Nenets region in 2022.

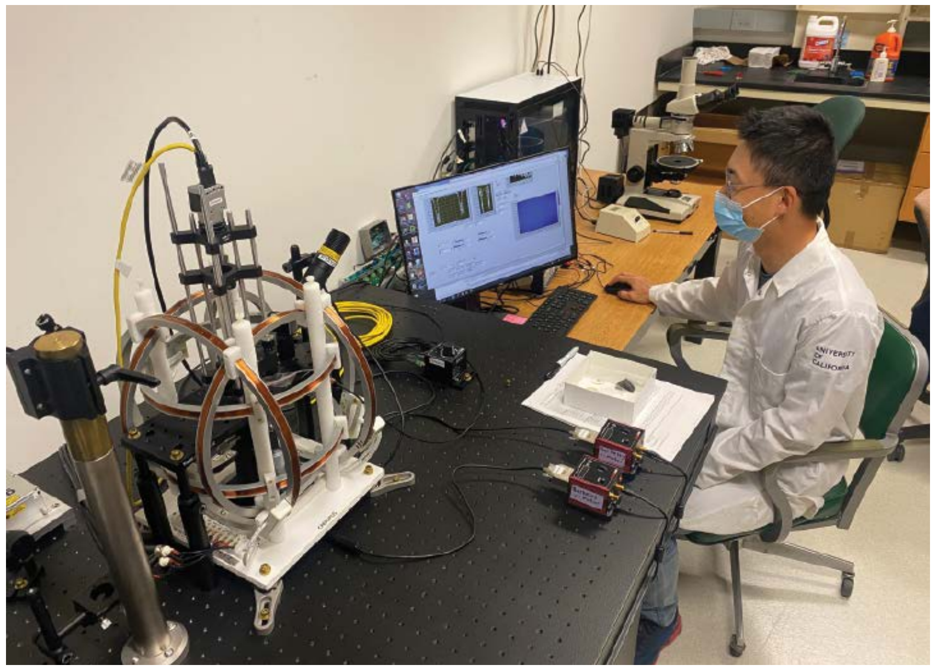
Newly constructed pipelines in Russia have more modern features, such as thermal siphons around the pilings that hold the pipes aboveground. In one state-owned gas field, pipes circulating refrigerant cool the soil underground.

But these interventions are expensive, said Evans.

Because permafrost is likely subsiding earlier in Russia than in other Arctic areas (such as Alaska), pipeline damage may be a bellwether for other regions, she said. "Just understanding what's happening in Russia could be helpful and informative."

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

Diamonds Are a Paleomagnetist's Best Friend



Yiming Zhang, a doctoral student at the University of California, Berkeley, works at a computer to examine data collected by the quantum diamond microscope, on the table to his left. Credit: John Grimsich

The Earth's geodynamo—the magnetic field created by the roiling inner core—protects our planet from solar radiation and may be integral to Earth's habitability. The magnetic field leaves its mark in the rock record by forcing iron-bearing minerals to align their magnetic fields, for example, as they precipitate in the pore space of a sedimentary rock or as igneous rocks solidify. These often minuscule magnets, which find north no matter where it might have been, have helped scientists discover seafloor spreading, trace the path of continents past, and explore just how old the geodynamo is.

Bulk rock paleomagnetic measurements, typically collected from samples the size of a soda bottle cap, should tell scientists the direction and intensity of Earth's magnetic field when the rock formed, said Sonia Tikoo, an assistant professor at Stanford University. But some rocks have heterogeneous magnetic signatures at fine scales, and others may no longer record the original magnetic imprint because of weathering, erosion, or some other alteration, she explained. The relatively nascent quantum diamond microscope, or QDM, helps scientists like

The quantum diamond microscope helps scientists read the complicated chapters of a rock's history.

Tikoo read these complicated chapters of a rock's history.

Originally developed to image magnetic fields at high resolution, these instruments enable micrometer-scale imaging of either thin sections—slivers of rock mounted on glass—or individual crystals that contain magnetic inclusions. By discerning exactly which part of a sample is magnetic, said Tikoo, scientists have used this tool to address a host of questions, from the Hadean to the Holocene.

Lasers, Diamonds, and Microwaves

"This is our QDM lab," said University of California, Berkeley doctoral student Yiming Zhang as he unlocked a door posted with a laser hazard warning sign. Upon entrance to the laboratory, a list of safety protocols greeted Zhang, along with a floor-to-ceiling black curtain shielding the makeshift foyer from the rest of the room. The curtain, said Zhang, protects people as they don red-tinted safety goggles designed to protect their eyes from a laser that produces green light.

Zhang ducked behind the curtain and headed to a long table with a microscope in the middle. The microscope was surrounded by small copper-colored circles that look like hula hoops designed for dolls. These, he said, are Helmholtz coils, arranged in different orientations in part to cancel Earth's magnetic field in the region where the sample sits.

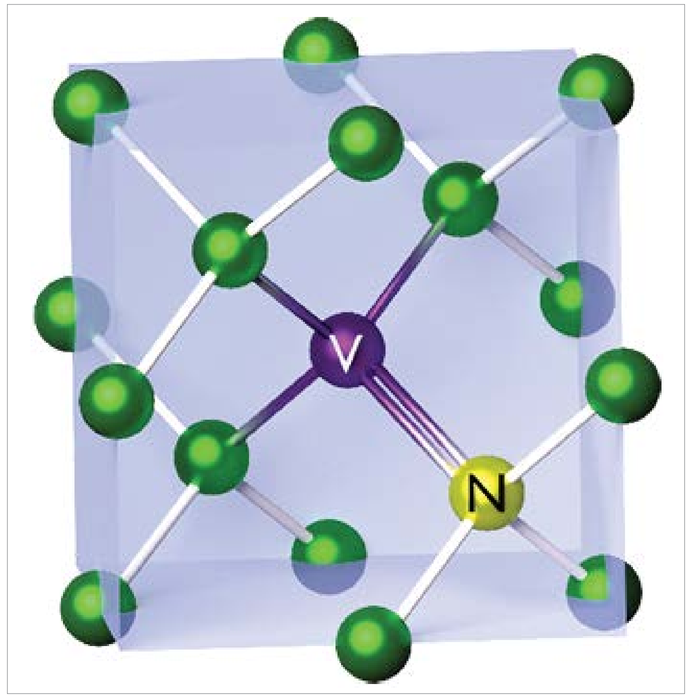
A square-shaped diamond, machined to have a flat face, is mounted on the microscope lens. Zhang must load his thin section onto the microscope's stage, ensuring that the diamond and sample sit flush. Too close, and the diamond could scratch or crack the carefully polished thin section. Too far, and the magnetic signal dies away.

The synthetic diamond is designed with a specific defect comprising a nitrogen atom and a void space, or vacancy, in the crystal structure. Each nitrogen-vacancy center swaps out two carbon atoms, said Roger Fu, an assistant professor at Harvard University and a progenitor of using the quantum diamond microscope for paleomagnetic work.

Once the sample is properly positioned, analysis begins by shining the green laser's light on the diamond as a horseshoe-shaped loop emits microwaves near the sample. The diamond will fluoresce, emitting a reddish light. The intensity of that fluorescence changes as the microwave energy changes. "By looking at how the intensity of the fluorescence changes with the microwave you put in, you can convert that to the magnetic field," said Fu.

A camera mounted atop the microscope captures this fluorescence information across the entire viewing area, which is about 2 square millimeters, said Fu. Each 1- × 1-micrometer pixel is a single measurement of that field, he said, which means the camera captures 2 million separate measurements of the magnetic field at once.

Accumulating sufficient information from a single field of view can take anywhere from 20 minutes to several hours, depending on the sample. Software designed by Fu converts these measurements into a magnetic field map, which can be interrogated for where north was when each magnetic carrier or group of carriers internalized its signature.



A ball-and-stick model within a transparent blue cube shows the atomic structure of a diamond. Green balls indicate carbon atoms. The yellow nitrogen ball, labeled N, and the purple vacancy ball, labeled V, show a nitrogen-vacancy center. Credit: National Institute of Standards and Technology

Solar System to Rainstorms

When magnetic minerals document differing north directions within a sample, interpretations can be tricky. Meteorites in particular record multiple magnetic directions at the scale of millimeters, said Fu, in part because they're amalgams of disparate parts of the early solar system. Dating each magnetic event with geochronological methods can help detangle the first 5 million years of our solar system's history, he said.

In zircon, magnetism ideally comes from inclusions like magnetite, said Tikoo, and this method is "a good way to test whether your magnetic carriers could be secondary."

Paleomagnetic studies of zircons older than about 3 billion years hinted that the geodynamo could have formed with the zircons themselves. However, using the quantum diamond microscope, Fu and his colleagues found that when similarly old zircons contained magnetic minerals, those paleomagnetic indicators formed later. Any original magnetic signature from when the zircons crystallized, he said, appears to be lost. The debate is ongoing.

At the opposite end of the age spectrum, said Fu, are actively forming cave deposits. Each layer—as thin as a single sheet of paper—has a distinct magnetic signature as floods, winds, and drip waters bring different material into the cave, said Fu. In some environments, extreme rainfall events tend to mobilize magnetite, whereas in others, dry spells bring more soil in, he explained. These fine-scale changes in magnetite, identified using the quantum diamond microscope, help scientists track rainfall and reconstruct paleoclimate, he said.

"It's a powerful tool for looking at very small things."

With an eye toward extraterrestrial craters that could have harbored life, Tikoo is using Berkeley's quantum diamond microscope to explore the longevity of hydrothermal systems in the Chicxulub impact crater, associated with the demise of the dinosaurs. The rocks in question—made from broken bits of other rock—have complex magnetic signatures. With the quantum diamond microscope, Tikoo can pinpoint from where the dominant magnetic signal comes. "It's a powerful tool for looking at very small things."

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

WAMPUM: An Indigenous-Designed Path to Sea Level Rise Adaptation

For centuries, Indigenous Peoples living along the North Atlantic coast have carved wampum beads from quahog or whelk shells and strung them together to create belts and ceremonial gifts. As European settlers arrived, tribal nations used the beads to form treaty relationships, and over time, the wampum bead came to represent sustainability for these communities, which have long-standing experiences of adapting to environmental changes and colonization.

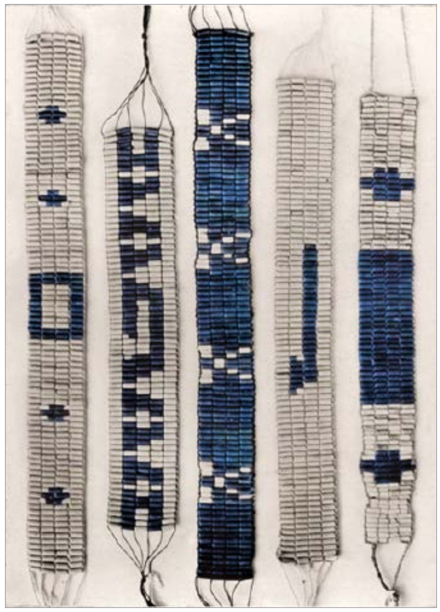
Consequently, when it came to designing a framework to help coastal communities adapt to sea level rise in the Northeast and Mid-Atlantic coastal regions, Kelsey Leonard, an assistant professor in the Faculty of Environment at the University of Waterloo in Canada and an enrolled citizen of the Shinnecock Nation, named her strategy after the small but mighty wampum bead. Leonard was an invited speaker at "Native Science to Action: How Indigenous Worldviews Inform, Diversify, and Build Capacity in Environmental Science and Policy" at AGU's Fall Meeting 2021 (bit.ly/native-science-action).

Leonard's goal in crafting the WAMPUM framework was to propose a culturally tailored approach to assist impacted tribal nations in adapting to sea level rise. Her guidelines also aim to highlight the adaptation strategies that Indigenous Peoples in Northeast communities are already deploying—strategies from which all concerned communities could learn. "Current strategies don't take into consideration the vast amounts of knowledge that we [as Indigenous Peoples] have and scientific practice that we have in adapting to sea level rise over millennia," Leonard said.

The Necessity of Indigenous Input

In the past century, sea level crept up more than a third of a meter along the northeastern coastline of the United States. Some predictions estimate that it could rise by the same amount again in the next 30 years, with severe consequences for coastal ecosystems and communities. For coastal tribal nations, the expected sea level rise will threaten water security and their ability to survive on lands where they have thrived since the glaciers receded.

Existing sea level rise adaptation strategies, which use militarized and combative language, represent the antithesis of the Indigenous approach of prioritizing the environment and ecosystem over human benefits and use, Leonard said. Western strategies "center on what humans need to adapt rather than the responsibility that humans have to nature to ensure that it can adapt, thrive, and flourish," Leonard said.



Before European contact, tribal nations used strings of wampum for exchange, storytelling, ceremonial gifts, and recording important treaties and historical events. Credit: Frank Speck, The Eastern Algonkian Wabanaki Confederacy

Current approaches neither include tribal nations' perspectives nor consider the cultural, social, political, or spiritual effects of sea level rise on Indigenous communities. As such, they often fail to accurately assess the effects on Indigenous communities and, consequently, fall short of outlining effective adaptation options, Leonard said.

"Moving forward, it's imperative to have new sea level rise adaptation strategies that are not only inclusive of Indigenous Peoples but designed by them," Leonard said.

Adaptation with Dignity

Leonard's WAMPUM framework presents a set of guidelines for sea level rise adaptation centered on Indigenous Knowledge systems and the historical experiences of northeastern and mid-Atlantic coastal tribal nations.

Each letter of WAMPUM highlights a different principle of the framework. The "witnessing" principle emphasizes the Indigenous Knowledges approach of careful observation and cooperation with natural systems for a sustainable future. "The natural world is really smart, keen, and adaptive," Leonard said. "The witness principle encourages us to be humble and learn how to adapt from the natural world."

The "acknowledge" principle stresses the need to acknowledge traditional teachings, conservation, and stewardship practices and empower tribal nations to restore these practices to care for the land and water. The related "mend" principle addresses the reality that humans have inflicted trauma on the environment since the advent of colonization and the necessity for adaptation measures to mend shoreline and coastal areas through cultural and ceremonial practices that promote healing and ecosystem rehabilitation.

Tribal nations, such as the Shinnecock, are working to protect their ancestors as rising ocean levels are encroaching on burial sites. The "protect" principle recognizes that the protection of such cultural sites advances Indigenous water justice and cultural and ceremonial practices for future generations.

Adapting to sea level rise and climate change will require communities to "unite," the fifth principle, Leonard said. "Planning for adaptation is something that can't happen in isolation, whether you're Indigenous or non-Indigenous," she continued. "We are small, but mighty together, and through scaling up collective resources, we can build adaptive capacity."

"Through scaling up collective resources, we can build adaptive capacity."

Historically, eastern coastal tribal nations had several village sites across large areas of land, allowing them to adapt to seasonal changes and move when needed. The final principle, "move," addresses how tribal nations can migrate to new places with cultural connections and rebuild their lives. "But right now, due to colonialism, that principle is impossible," Leonard said.

The answer to the move principle lies in federal legislation and funding that would support tribal nations moving to areas on the eastern Atlantic coast where they could preserve their cultural connection to the land and ocean and continue stewardship practices, Leonard said. "As a Shinnecock person, you can't just plop us in the middle of Arkansas and imagine that we'll be able to maintain our culture," Leonard said. "We are people of the shore, and if the shores cease to exist, we cease to exist."

A Sustainable Path

The WAMPUM framework provides a path forward for tribal nations to help guide them in adapting to sea level rise using cultural knowledge and skills. "Tribal governments and communities have to get on the same page in terms of what strategies are realistic and seem feasible," said geographer Casey Thornbrugh, a citizen of the Mashpee Wampanoag Tribe and the tribal climate science liaison at United South and Eastern Tribes. "The strategies laid out in the WAMPUM framework, with tribal nations and communities leading the way, offer a sustainable path to adaptation."

Existing adaptation strategies present humans as battling the coast, using militaristic terms such as "hardening the coastline" and "coastline defense," according to geoscientist Jon Woodruff of the University of Massachusetts Amherst, who is also the codirector of the Northeast Climate Adaptation Science Center. "But the WAMPUM framework brings the perspective of mending the shoreline, rather than taking a hard-line militant approach," Woodruff said. "And I think people are starting to appreciate the value of these long-term sustainable practices rather than the short-term fixes that set communities up for failure once the hard defenses are compromised."

For Leonard, the approach also serves as a call to action to reject oppressive adaptation strategies and develop frameworks that capture Indigenous Knowledges in building resilience to climate change. "If we're to build a sustainable future and ensure our shared planetary health, we have to mobilize our diverse knowledge systems together," Leonard said.

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

Drones and Crowdsourced Science Aid Great Lakes Data Collection

Cities along the shores of Lake Michigan are dealing with increasingly problematic shoreline erosion that has already caused millions of dollars in damage. Technologies including aerial photographs and bathymetric lidar have helped experts track coastal changes. Yet high-resolution data sets along the lakes' shores are lacking, and there is little understanding about how changes to the coastlines have lasting impacts. Gathering data and revealing changes can help with coastal monitoring and management.

Using drones and crowdsourced data, researchers are expanding studies to include ecological and physical changes to the lakes' shorelines. Data from two projects were presented at AGU's Fall Meeting 2021 (bit.ly/great-lakes-coast).

The first project focuses on collecting data on the Great Lakes during the winter so experts can better understand the physical features and chemical properties of sedimentary rock in the nearshore system. "The goal is to see what the cumulative impacts of ice-nearshore and ice-shoreline interactions are," said C. Robin Mattheus, a coastal geologist with the Illinois State Geological Survey. Once formed, ice affects beaches and sandbars, which interact with waves and sediment. This interplay can change the shape of a shoreline in as little as a year.

Community members were trained to monitor shoreline change and infrastructure damage.

Data were collected with drones flown over beaches. Images taken by the drones were then merged into one orthophoto, allowing the scale of the photographs to be uniform. Using the orthophotos, the team created topographic models illustrated in ArcGIS StoryMaps to document the dynamism of the shoreline. "This is at a very high resolution, counted at a centimeter scale," said J. Elmo Rawling III, a geomorphologist at the Wisconsin Geological and Natural History Survey.

Ice can be broken up by waves and can contribute to erosion, as seen here along the southwestern shores of Illinois Beach State Park on Lake Michigan. Credit: C. Robin Mattheus

Cue the Volunteers!

The second project—Interdisciplinary Citizen-based Coastal Remote Sensing for Adaptive Management (IC-CREAM)—involved the local community. Through the project, community members were trained to monitor shoreline change and infrastructure damage. This project is "the first of its kind within the region to put drones in the hands of people to collect coastal imagery," said Erin Bunting, an assistant professor of geography, environment, and spatial sciences at Michigan State University. IC-CREAM's crowdsourced data create "constant information with the high spatial resolution needed to better understand beach erosion, vegetation loss, and other physical changes happening along the lakes' coasts," said Bunting.

Dan Laskey, a volunteer involved with IC-CREAM who has been based in Manistee, Mich., for the past 40 years, said, "the development and movement of the shoreline is something that's pretty important to us, as we spend so much time here."

The research team members have incorporated themselves into local communities by attending town council meetings and speaking to city and project managers about what these data mean and their impact. "Given the large expanse of the Great Lakes, it's really hard to have a direct and constant connection within these communities, and that's something we're trying to establish with community science," said Bunting.

By **Iris Crawford** (@IrisMCrawford), Science Writer

Settlement of Rapa Nui May Have Been Doomed by a Dearth of Dust

Poor soil quality, due in part to a lack of fertilizing dust from Asia, may have contributed to the challenges faced by the ancient Rapa Nui, whose colossal moai are emblematic of the culture. Credit: iStock/Mlenny

Historians and archaeologists debate what led to the decline of Polynesian society on Rapa Nui. Although one popular narrative holds that the creation of the famous Easter Island statues depleted resources and led to environmental collapse, more recent research has suggested that collapse began when Europeans brought disease and conflict. Whatever the case, Polynesians on Rapa Nui never reached the levels of agricultural productivity seen on an archipelago settled around the same time: Hawai‘i.

According to new research, small size and isolation might have set up Rapa Nui for failure from the beginning. Researchers knew that by the time Polynesians arrived, Rapa Nui's soils were probably already less fertile than those on Hawai‘i. Now analysis of soil samples has shown that an important fertilizer—dust blown over from Asia—doesn't even reach the isolated island (now a part of Chile, more than 3,500 kilometers away on the South American mainland). This finding could help researchers better understand the environmental challenges faced by ancient Polynesians. Oliver Chadwick, a soil scientist at the University of California, Santa Barbara, presented his team's findings at AGU's Fall Meeting 2021 (bit.ly/rapa-nui-dust).

Rock gardens like these were a farming strategy used to help the poor quality soil on Rapa Nui retain moisture and grow crops like taro. Credit: Thegn Ladefoged

A Story Stored in Soil

"What archaeologists love about the Pacific is you get historically related people in a bunch of different settings," said Thegn Ladefoged, an archaeologist with the University of Auckland in New Zealand. "Hawai‘i has relatively big islands and a lot of environmental variation, and Rapa Nui is very much smaller and more isolated."

Polynesians who settled Hawai‘i at least a thousand years ago found rich soils near active volcanoes where they could easily grow crops such as taro and sweet potato. Hawaiian society flourished.

When Polynesians reached Rapa Nui around the same time, however, the story went differently. The soils on the island were poor, and the Rapa Nui people developed rock gardens: plots of land with piles of volcanic rock. The porous rocks, quarried from long-extinct volcanoes on the island, would have helped the soil retain moisture.

Chadwick, Ladefoged, and others determined that by the time humans arrived on Rapa Nui, heavy rains had already leached many nutrients from the soil. The new soil analysis showed that Rapa Nui also lacks traces of mica, quartz, and rare earth minerals that don't naturally occur in volcanic rock. Hawaiian soils contain these minerals, thanks to continental dust blown in from Asia. "The bottom line is that the results suggest that there is virtually no detectable dust in Rapa Nui," Chadwick said.

This new insight provides "a major contribution to the study of the island, both its history and for the future sustainability of current Rapa Nui communities," said Robert DiNapoli, an environmental archaeologist at Binghamton University, State University of New York who was not involved in the research.

Although the new analysis didn't turn up evidence of dust, the scientists did find some interesting isotopes present in the rock gardens but not in the surrounding soil. These isotopes of phosphorus (an important soil nutrient) were chemically similar to those found in ancient agricultural plots in Hawai‘i.

Perhaps, Chadwick said, Rapa Nui farmers broke up volcanic rocks and carried them to these gardens to act as a sort of fertilizer. This theory supports the idea that people on Rapa Nui found a way to make the most of the environment they had, for a time.

By **Rachel Fritts** (@rachel_fritts), Science Writer

Training the Next Generation of Physical Data Scientists

Gerd Altmann, Pixabay License

Artificial intelligence (AI), machine learning (ML), and data science provide flexible, scalable, and interpretable approaches to harness the growing volume of available data that can help us improve the understanding and prediction of a wide variety of geoscience phenomena, including natural hazards, climate change, and severe weather events. As such, AI/ML and data science are gaining popularity throughout the geosciences. However, geoscience education has not kept up with this trend, leaving students and researchers with knowledge gaps that hinder their ability to innovate and grow through the development of new approaches to and applications of their research. To bridge these gaps, we need to train a new generation of data scientists to be prepared to address the unique needs of geoscience data and related phenomena.

AI/ML methods are domain agnostic and lack inherent physics-based understanding of natural processes. This characteristic of AI/ML methods can be advantageous in some situations, but applying AI/ML to geoscience phenomena and problems requires deep knowledge of the physics involved. And although superficial training may enable researchers to select existing AI/ML methods that could be useful in their work, creating new methods that can transform scientific understanding requires users to know the underlying characteristics of their data and their methods.

Physical data scientists thus need holistic preparation, including foundational training in their respective disciplines (atmospheric science, oceanography, geoscience, etc.) as well as in AI/ML, that will allow them to work and innovate with increasingly large and complex data sets.

Beyond Basic Mathematics and Programming

A strong grounding in mathematics is fundamental to understanding foundational geoscience processes as well as the principles of computer science. Some math courses already feature in geoscience programs nationwide. The background offered by these courses might be sufficient to develop a superficial understanding of AI/ML methods. However, innovating requires a deeper level of knowledge of the mathematics underlying AI/ML.

For example, adding physics-based constraints to existing AI/ML methods requires understanding partial derivatives and how changing loss functions affects machine learning. Thus, for the next generation of graduates, we must expand core training in mathematics, up to and including courses on partial differential equations and statistics.

Many geoscience disciplines have added introductory computer programming to their curricula, but physical data scientists will also need training in computer science fundamentals such as high-performance computing, efficient data structures, and parallel programming to implement and test ideas using AI/ML. Introductory courses typically teach students about concepts like variables and simple loops and functions but not about more advanced concepts such as object-oriented programming and data structures. We argue that understanding how to use and create data structures like trees, hash maps, and sets is critical for efficiently and reproducibly handling large geoscience data sets.

Applying artificial intelligence (AI) and machine learning (ML) to geoscience phenomena and problems requires deep knowledge of the physics involved.

Efficient high-performance computing also requires a grasp of how today's modern supercomputers, including graphical processing units (GPUs), work. GPUs first came into widespread use in arcade games and

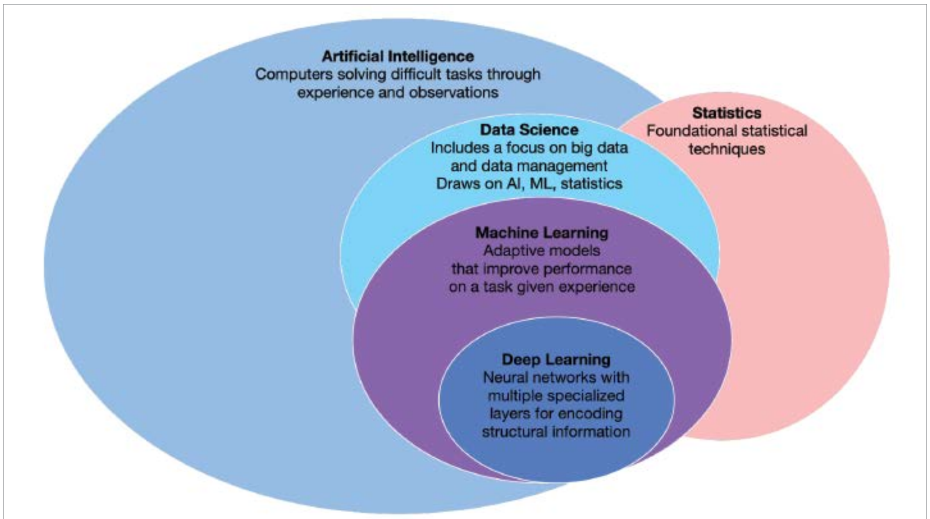


Fig. 1. Artificial intelligence is a broad field that encompasses and overlaps with other fields, including data science, machine learning, and statistics. Tools from these fields are applied in a wide variety of scientific endeavors.

were later used for desktop gaming, but their ability to perform parallel operations on multiple data sets has greatly expanded their range of applications. Used appropriately, GPUs can provide orders-of-magnitude faster processing of multidimensional geoscience data. Many data libraries already use GPUs, although creating specialized code (which often requires linear algebra) may be required to use these processors for novel purposes.

Foundational Training in AI/ML and Data Science

Ensuring that the next generation of physical data scientists will be well prepared may require training that diverges from traditional approaches to training scientists in data science and AI/ML research.

Within the geosciences, AI, ML, statistics, and data science all overlap and so are often conflated or misunderstood, thus it helps to clarify their meanings. We define AI to include all categories of methods that act intelligently to solve problems (Figure 1). Such methods include intelligent search techniques such as A*, the method used in most map search apps. They also include multiagent systems that enable AI methods to coordinate actions among diverse agents, such as teams of humans and robots completing a search and rescue operation.

Within AI, ML focuses on models that adapt over time, given experience or data. ML methods draw in part on traditional statistical methods, like regression or Kullback-Leibler divergence, and thus are not entirely independent of statistics. New techniques involve hybrid statistical and ML approaches. For example, data science methods tend to focus on analysis of big data and on data management and draw from AI, ML, and statistical methods. Deep learning is a type of ML focused on the use of specialized neural networks, and it is currently one of the most popular ML methods in use in the geosciences.

Ensuring that the next generation of physical data scientists will be well prepared may require training that diverges from traditional approaches to training scientists in data science and AI/ML research.

Traditional training for data scientists typically includes separate classes on each of the topics mentioned above. We suggest that training for physical data scientists could instead focus on foundational methods relevant to all these topics, with strong and synergistic involvement of mathematics and computer science. This approach would be more efficient and likely require a shorter series of classes.

For example, instead of taking a longer series of discipline-focused classes in AI/ML, we propose an interdisciplinary three-course sequence. This sequence would cover the mathematical foundations of ML methods while focusing on applications to facilitate understanding of which methods are best suited for which types of phenomena. The course sequence would include a class on more traditional ML methods, an advanced class focused on deep learning, and a class that brings together methods from data science and statistics to facilitate efficient exploration of and experimentation with large data sets, including empirical and statistical analysis and validation of AI/ML methods as applied to different scientific domains.

Workforce Development and Diversity

In addition to reshaping curricula for student education as AI/ML methods gain popularity, it is critically important that we also provide existing geoscience researchers, forecasters, and practitioners with avenues for continuing education and development. Given career constraints, expecting current members of the workforce to attend multiple semester-long classes, as degree-seeking students do, is not realistic. Hence, other paths must be developed.

Several efficient concepts for retraining working atmospheric scientists already exist and might serve as models for similar programs related to AI/ML and data science. These concepts include the following five:

1. Summer schools are intended to get people up to speed quickly on a broad topic but with less depth. Because of COVID-19, the National Center for Atmospheric Research (NCAR) adapted its traditional in-person summer school format for an online audience, expanding attendance in summer 2020 to more than 2,000 people. Last year, NCAR and the National Science Foundation–funded AI Institute for Research on Trustworthy AI in Weather, Climate, and Coastal Oceanography (AI2ES) ran a 4-day joint summer school on developing trustworthy AI for environmental sciences that included lectures, tutorials, and group discussions. The summer school was offered both live and asynchronously, so people can access it at any time, which should increase its impact.

2. Short courses cover more focused topics in depth. For example, the Cooperative Institute for Research in the Atmosphere taught a short course on using AI/ML in weather and climate research. AI2ES taught a short course on explainable AI and will be teaching additional courses over the next few years. As with the recent summer school, these short courses were held live, albeit with smaller audiences to facilitate participant interaction, and were recorded and later provided online to the public. Sample AI/ML codes provided by instructors have proven critical in the success of these courses—with the codes, participants are able to see quickly how the methods work and apply them to phenomena and problems in their own domains.

3. **Tutorials** are generally full- or half-day events at which researchers jump into a topic while attending a larger conference. The American Meteorological Society (AMS) AI Committee, for example, has been providing in-depth tutorials on AI for weather research at the AMS annual meeting for several years.

4. **Full-length online courses** developed and taught through AI2ES are, like traditional semester-long, in-person courses, offered for university students; they are also being provided online for free. Rather than signing up for the full course, members of the workforce can view specific modules as needed and at their own pace—an approach that facilitates targeted and efficient retraining.

5. **Community college certificates** in AI are a recent development. Del Mar College in Corpus Christi, Texas, a partner in AI2ES, has developed one of the first such community college certificates in AI for environmental sciences. This five-course sequence, and others like it, could be used for workforce retraining and for broadening participation in the geosciences.

We emphasize that such efforts to strengthen and streamline workforce retraining should be broadly available to everyone in the geoscience community to help improve the diversity of the workforce.

Research has demonstrated that women and those in marginalized communities become more interested in science, technology, engineering, and mathematics (STEM) fields if they can see the real-world applications of the work. However, classes focused on foundations of programming, or even about specific AI/ML methods, rarely offer opportunities to appreciate tangible applications. Ensuring that the training for future physical data scientists includes relevant and frequent demonstrations of the applicability of foundational computer science and mathematical principles may thus improve diversity both in the geosciences and in computer science, which could also improve innovation.

Evolving and Adapting Instruction

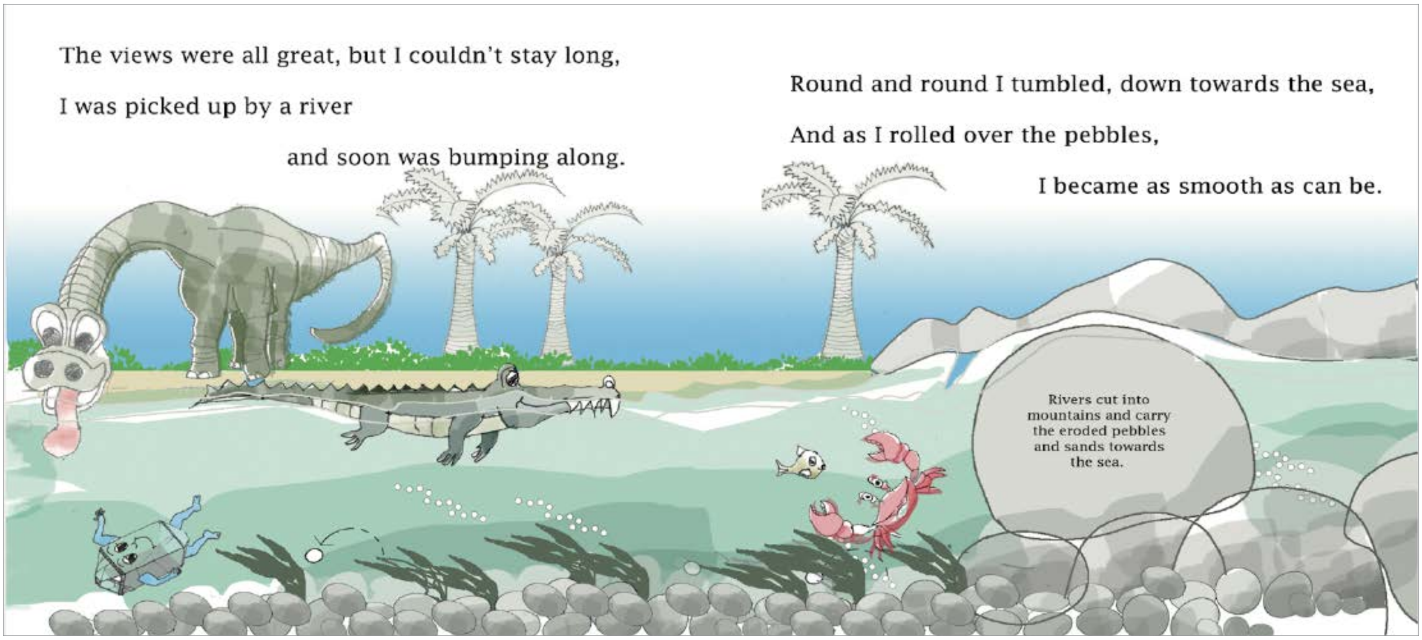
The need to evolve and innovate in training and education reflects trends in the broader research community. For example, the European Centre for Medium-Range Weather Forecasts' recently released 10-year road map for AI/ML states, "We anticipate that it will be increasingly difficult to distinguish between scientists working on machine learning and domain scientists in the future."

Quickly adapting training and education to leverage new and emerging technologies has traditionally not been a strength of academic communities. Yet with the rapid growth of AI/ML and data science methods and with the range of pressing geoscience questions to which they can be applied, we argue that it is worth the time and investment to recast instructional approaches to train students in physical data science and to better prepare them for the workforce of the future.

By **Amy McGovern** (amcgovern@ou.edu), School of Computer Science and School of Meteorology, University of Oklahoma, Norman; also at NSF AI Institute for Research on Trustworthy AI in Weather, Climate, and Coastal Oceanography; and **John Allen,** Department of Earth and Atmospheric Sciences and Earth and Ecosystem Science Ph.D. Program, Central Michigan University, Mount Pleasant

▶Read the article at bit.ly/Eos-physical-data

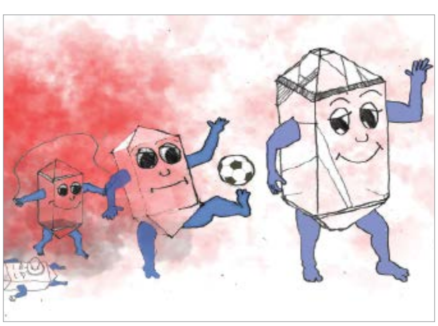
Meet Jane the Zircon Grain—Geochronology's New Mascot



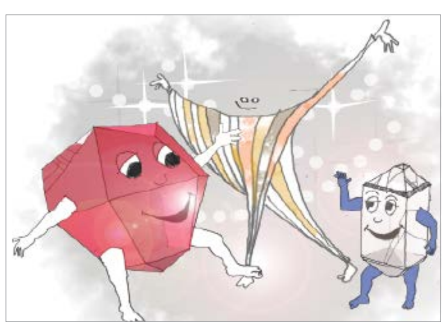
In this excerpt from Jane's Geological Adventure, *Jane the zircon bumps along the riverbed as animals appropriate to the Cretaceous swim and play. Credit: Matthew Fox and Martin Fox*

There is no "once upon a time" in the children's book *Jane's Geological Adventure,* but if there were, that time was 400 million years ago, in a world replete with creepy-crawly creatures threading their way through a lush verdure of unfamiliar plants. As a volcano's magma chamber seethed, a zircon grain named Jane was born, growing until she erupted onto Earth for a full life of metamorphism, multiple mountain-building adventures, sundry erosion styles, and her most recent phase: display at a museum.

As part of his outreach efforts, author and geochronologist Matthew Fox, a lecturer at University College London, created Jane the zircon grain, modeling her life after rocks similar to the Jura Mountains in Switzerland. "That we can actually understand this much information from a single grain of sand is really incredible," said Fox, "and I wanted to try to describe how we can do that."



Jane's birth and maturation into an "adult" zircon crystal occur within a volcano's magma chamber. Credit: Martin Fox



As Jane metamorphoses, other minerals marking the rock's transformation grow, including Mitesh the mica (center) and Gary the garnet. Credit: Martin Fox

Jane's Geological History

"You can think about this as a children's book," Fox said, or "you can think about it in terms of how you could actually extract that information from a crystal, which might require different analytical methods." As nature's time capsules, zircons like Jane can retain evidence of multiple high-temperature events, like the timing of crystallization or metamorphism. "That's why we use them for geochronology," he said.

As Jane metamorphoses, she is joined by Gary the garnet and Mitesh the mica. Although the characters are anthropomorphized, the metamorphic mineral assemblage is real. "You can look at trace element concentration within different zones to see what other minerals might have been growing at these different time intervals," explained Fox.

The shapes of the crystal itself provide additional clues, said Fox. For example, Jane's distinct points erode away as she bumps along a river bottom.

After this tumultuous travel, the sediments in which she lands eventually lithify and rise skyward as mountains. From this vantage, Jane watches glaciers carve the land before she is plucked from an outcrop by a geochronologist who wrings history from Jane's lattice.

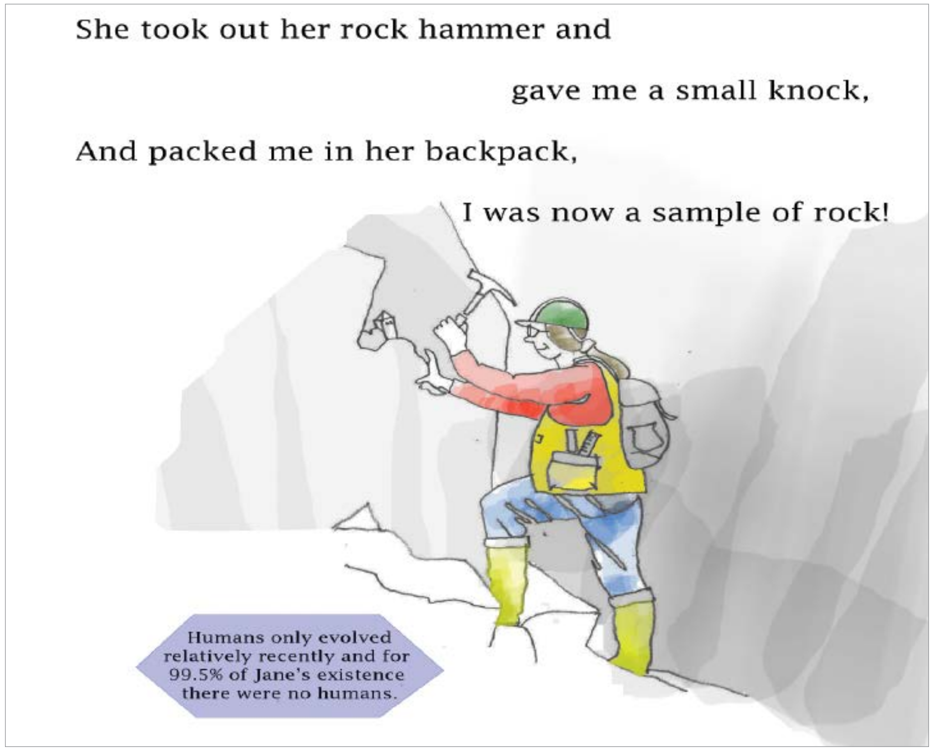
By describing the many geological processes that Jane (and, by extension, mountains like the Swiss Jura) experiences, Fox said, "you can get a sense of how much can fit into such a long period of time."

A Family Project

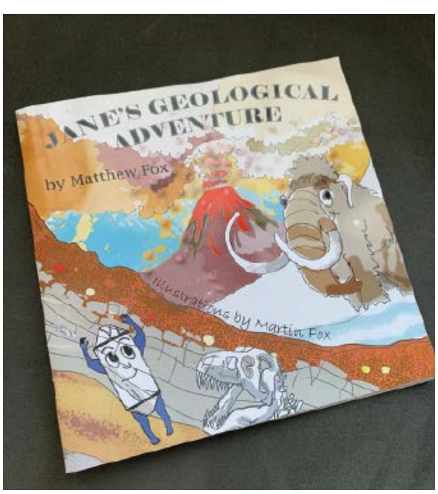
Although Jane's geological tale spans 400 million years, the book itself has a much younger provenance. After years of scribbling short geology-themed poems during field trips, Fox began to toy with writing a longer poem for children. In 2018, shortly after joining University College London as a Natural Environment Research Council Independent Research Fellow, he began to compose Jane's story on his phone during his commute.

As Fox refined the rhyme, he reached out to several friends and colleagues, many of whom (including the author of this article) worked on zircon-related quandaries. With the support of his community, Fox became convinced that a children's book was worth pursuing. However, without funds to pay for an illustrator, he was stuck.

At this point, the project became a true family affair. Fox's mother contributed indirectly to the story because Jane is her namesake. Fox proposed a collaboration to his father, Martin, an architect and occasional painter, who agreed to help. Fox the elder created a playfully anthropomorphic, but scientifically precise, depiction of Jane's journey, while Fox the younger ensured that the details were correct—for example, that only dinosaurs from the same era feature in Jane's story.



A geologist collects Jane from an outcrop. Credit: Matthew Fox and Martin Fox



Jane's Geological Adventure *was written by Matthew Fox and illustrated by Martin Fox. Credit: Alka Tripathy-Lang*

Connecting with Kids and Parents

As the Fox family worked to illustrate Jane's exploits, Matthew began looking forward to fatherhood himself. His daughter was born soon after he finished the book and just as the COVID-19 pandemic began in spring 2020.

The pandemic thwarted Fox's plan to sell the book at conferences to eschew postage. He opted to sell the book via his website instead, publishing the first 200 copies during parental leave. "[Fatherhood] made me appreciate how important children's books are and how important that time is where you actually interact with children," said Fox. "My partner says it's one of [my daughter's] favorite books."

Structural engineer Jan Moore of Salt Lake City said that Jane's appeal is not limited to children. "[My kids] really got the idea [that] the dinosaurs existed at one time and not another, which I thought was an advanced idea that kids don't always grasp," she said. "I don't think I really grasped what the age [of a rock] really meant until there was a children's book to explain it."

Creative Public Outreach

When it comes to public outreach, said Fox, "everyone's got different skills." For example, although he's spoken at schools around London, he acknowledged that public speaking sometimes makes him nervous.

He had a different approach to the book. "This was something that I quite enjoyed doing…and I thought I could contribute to outreach in a way that might be potentially more far-reaching," Fox said. He plans to donate any profits made from the sales of *Jane's Geological Adventure* to GeoBus, an outreach activity funded by the U.K. Natural Environment Research Council wherein a van brimming with activities designed to engage children in geology travels to different schools.

To other researchers trying expand their outreach, Fox offered some tried-and-true advice: "Try and do outreach activities that you enjoy doing." If the outreach you're doing is something you're excited about, he said, people will respond to that.

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

▶Read the article at bit.ly/Eos-Jane

LABORATORY EXPERIMENTS SERENDIPITOUSLY REVEALED A ROCK-FORMING PROCESS THAT MIGHT EXPLAIN HOW THE FIRST CONTINENTAL CRUST FORMED ON EARTH— AND POSSIBLY ON MARS.

A Simple Recipe *for* Making *the* First Continental Crust

By **ANASTASSIA Y. BORISOVA**
and **ANNE NÉDÉLEC**

During the Hadean, more than 4 billion years ago, a liquid water ocean, volcanic activity, and meteorite impacts acted together to fashion the surface of early Earth. Credit: Anastassia Borisova

Earth's continental crust, on which billions of people and countless land animals and plants spend their lives, is distinguished by its predominantly felsic composition. That is, this crust contains large proportions of silicon, oxygen, aluminum, and alkali metals like sodium and potassium, and it is made up largely of quartz and feldspar minerals. Felsic continental crust as old as 4 billion years has been recognized on Earth's surface, and we know it was associated with basaltic oceanic crust made of minerals rich in calcium, magnesium, and iron, such as plagioclase feldspar, olivine, and pyroxenes. But the planet's earliest rigid outer shell—its primordial crust, which crystallized from the magma ocean covering the nascent Earth about 4.5 billion years ago—probably looked very different.

When and how the first felsic crust formed are questions researchers have pondered for decades. Unfortunately, a handful of microscopic zircons, accessory minerals commonly found in felsic rocks, from a few places around the world are the only remnants from the Hadean, the first 500 million years of Earth's existence. In the almost complete absence of early crustal rocks, scientists have thus had to piece together their hypotheses from indirect evidence.

Recently, our research group completed laboratory experiments and numerical modeling that revealed evidence of a felsic rock-forming reaction that may have occurred on Hadean Earth and may have been responsible for creating the planet's first continental crust.

The nature and genesis of continental crust in Earth's most remote past—during the Hadean, more than 4 billion years ago—are a mystery.

Continental Crust Through the Ages

Present-day continental crust is formed by magmatism at volcanic arcs above subduction zones, like the Aleutian Arc off Alaska, the Izu-Bonin-Mariana Arc in the western Pacific, and the Andes in South America. As water in a subducting oceanic slab (crust and mantle) is driven off by the high heat at depth (50–100 kilometers below the surface), the water promotes partial melting of overlying mantle rocks (e.g., peridotites). The buoyant melt then rises to the surface, where it interacts with existing crust, cools, and solidifies underground or erupts from volcanoes. The result is new continental crust of dioritic to tonalitic composition. This process has operated efficiently for at least the past 2.5 billion years.

Before that, in the Archean (starting 4 billion years ago), when Earth was hotter, continental crust formed directly from partial melting of hydrated oceanic crust in "vertical drips" of basaltic crust before the beginning of plate tectonics around 3.2 billion years ago or in warm subduction zones afterward [e.g., *Shirey and Richardson*, 2011; *Gerya*, 2019]. Archean continental crust is made of tonalites, trondhjemites, and granodiorites (TTG): felsic rocks with a higher sodium content than modern continental crust. However, the nature and genesis of continental crust in Earth's most remote past—during the Hadean, more than 4 billion years ago—are a mystery.

Many hypotheses have been suggested to explain the formation of felsic, zircon-bearing crust in the Hadean, although so far none have been sufficiently convincing. Some researchers favor a Hadean context in which felsic crust formation was very similar to that on modern Earth [*Harrison*, 2020], whereas others think that it resembled processes occurring in the Archean. All of these researchers have assumed that the parental magmas of the Hadean zircons formed at depths of 30–50 kilometers from protolith (sediments or a basaltic protocrust) that had previously interacted with liquid water [e.g., *Drabon et al.*, 2021].

Faltys and Wielicki [2020] suggested a crucial role of meteorite impact–induced magmatism in the formation of the first felsic continental crust. However, in most cases, a role for early plate tectonics is assumed, even though evidence from geochemical and geodynamic modeling studies suggests that modern-style plate tectonics did not begin until about 3.2 billion years ago.

An Unintended Discovery

Our research group did not set out to establish how the first continental crust formed. Instead, we were studying interactions among solid rock, magma, and fluids under the ocean to explain the origin of the oceanic mantle-crust transition boundary and adjacent upper mantle rocks (chromitite, dunite, and hydrated peridotites (i.e., serpentinite)). This transition boundary plays a crucial role in controlling the chemical composition and physical properties of oceanic magmatism and crust.

Nail Zagrtdenov, a doctoral student in the Géosciences Environnement Toulouse laboratory at the University of Toulouse III in France, was leading laboratory experiments under the supervision of Anastassia Y. Borisova and Michael J. Toplis. These experiments were designed to replicate the shallow conditions and processes happening at the mantle-crust boundary about 6 kilometers beneath present-day oceanic spreading centers.

In these experiments, we examined interactions between basaltic melts and different proportions of serpentinite rock at temperatures of 1,250°C–1,300°C and pressures of 0.1–0.2 gigapascal [*Borisova et al.*, 2021a, 2021b]. Serpentinite, which commonly forms at oceanic ridges, is formed by hydrothermal alteration of peridotite, an ultramafic rock that makes up most of Earth's upper mantle.

Our experimental results surprised us. As expected, we saw chromitite and dunite form at 0.2 gigapascal. However, we also observed felsic melts—the starting material for continental crust—forming amid the dense, dark, olivine-rich serpentinized peridotite. Production of felsic melts from hydrated peridotites at such shallow conditions was a novel observation, and we began to think that we had unintentionally reproduced conditions that were prevalent more than 4 billion years ago. Perhaps we had stumbled onto the explanation for the formation of early felsic crust.

To investigate further, we followed up our experiments by simulating the same conditions using thermodynamic numerical modeling. This modeling confirmed that felsic melts could be produced from the same starting materials and remain stable at pressures of 0.1–0.2 gigapascal (3-6 kilometers deep). With the combined laboratory and modeling results, our multidisciplinary team of researchers from France, Germany, Russia, and the United States became convinced we had established the ingredients and the physical and chemical conditions necessary to form the very first felsic crust on Earth—and possibly on Mars [*Borisova et al.*, 2021a].

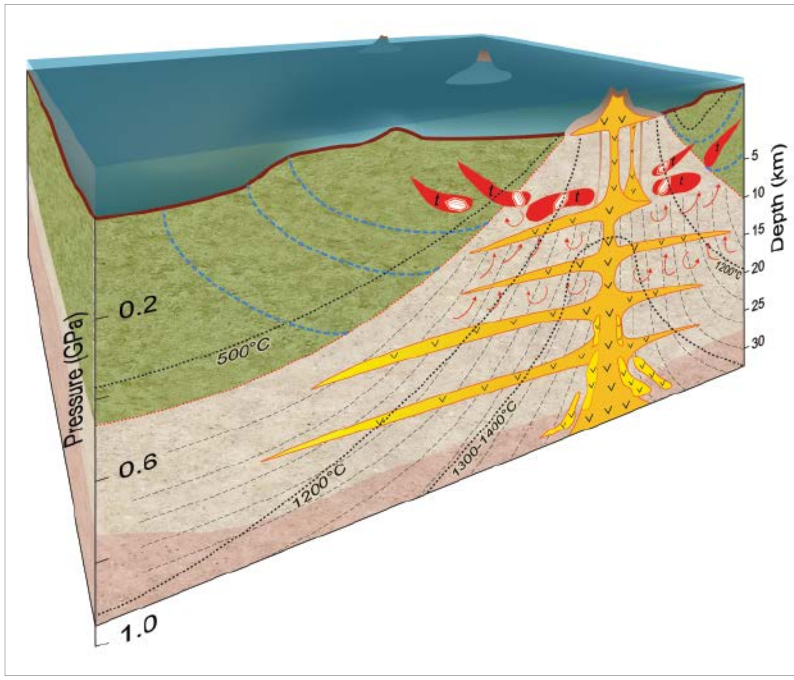


Fig. 1. In a new model for the production of Hadean felsic crust, serpentinite (green) submerged under water (blue) comes into contact with basaltic magma (yellow). This interaction produces felsic magmas (red) with accessory zircon crystals (white crystals) in association with olivine-rich peridotite (beige). Frequent meteorite impacts in the Hadean could have aided in the mixing and interaction between the hydrated peridotite and basalt in the presence of water, triggering the production of the first zircon-bearing continental crust.

A New Model for Early Crust

Publishing our data and interpretations was rather difficult. Indeed, these results were entirely new, and some researchers were skeptical. Most previous hypotheses had proposed that the first continental crust resembled either present-day continental crust or Archean continental crust in terms of its formation processes and conditions. The conditions and ingredients of our experiments, and the felsic melts they produced, suggest a completely different scenario.

Our model posits that liquid water existed on early Earth's surface [*Valley et al.*, 2002]. The idea that the protolith of the magmas from which Hadean zircons crystallized had previously interacted with liquid water is accepted on the basis of oxygen isotope data from these zircons [*Mojzsis et al.*, 2001]. However, considering hydrated peridotite as a possible protolith is a novel suggestion (Figure 1).

The young planet's magma ocean would have had the same peridotitic composition as the mantle. As the magma ocean cooled and crystallized, a thin peridotite crust could have quenched atop the ocean while gases, including water vapor, were expelled from the magma. These gases would have built a primitive atmosphere, from which liquid water would have condensed to the hydrosphere. The primitive peridotitic crust would have rapidly interacted with the liquid water, yielding serpentinites [*Albarède and Blichert-Toft*, 2007]. This possibility has not received much consideration from researchers, who typically assume that the Hadean protocrust was basaltic, comparable to the present-day surfaces of asteroids and protoplanets.

In our model, basaltic magmas would have formed as the last differentiate liquids remaining at the very end of the crystallization of the magma ocean, and then they would have locally intruded and mixed into the uppermost serpentinized crust. Interaction between magma and protocrust material would have caused dehydration of the serpentinized peridotite. Afterward, the peridotite would have partially melted to produce felsic melts at shallow depth—as we observed in our experiments. These melts would have then cooled to form the first felsic crust (Figure 1). Frequent meteorite impacts in the Hadean could have aided in this mixing and interaction by fracturing, heating, and promoting water convection through partial melting of the protocrust.

We see evidence of such felsic rock formation in the field. For example, felsic (plagiogranitic) rocks are exposed now amid hydrated peridotitic mantle rocks in the Semail ophiolite in Oman, which formed at less than 10 kilometers below the surface.

Perhaps we had stumbled onto the explanation for the formation of early felsic crust.

Further Explorations

The scenario of interacting serpentinized rocks and basaltic magmas offers a simple and efficient recipe that we believe well explains the origin of Hadean felsic crust for several reasons. First, it requires the existence of shallow liquid water on the early terrestrial surface (Figure 1). Second, it involves plausible shallow interactions between hydrated peridotite and basaltic melts resulting from shallow magmatism or impact-induced melting. Third, in agreement with existing geodynamic models

Plagiogranite veins and intrusions from Earth's mantle appear as white streaks amid brown serpentinized peridotite in a section of the Wadi Fizh, Semail ophiolite in Oman. Credit: Georges Ceuleneer

for the Hadean, it does not require plate tectonics. Furthermore, our experimental felsic melts can crystallize low-temperature zircons very similar to observed detrital Hadean zircons [*Borisova et al.*, 2021b].

The scenario offers a simple and efficient recipe that we believe well explains the origin of Hadean felsic crust.

To further develop this model and understand the origins of the first planetary continental crust, we plan to conduct further experiments involving pressure gradients and shock process modeling. This work is necessary to explore mineral dehydration and melt channelization happening during shock processes, melt percolation, and reequilibration of the percolating melt with the hydrated peridotite. Such work should increase the applicability of our experimental results to phenomena occurring throughout the Hadean and will help develop our new model of primordial processes happening on early Earth and Mars.

We are also planning new experiments to reproduce conditions on Mars and study whether our new results could relate to processes that happened on the neighboring planet. Like Earth, early Mars had water on its surface sometime after the crystallization of a primordial crust from a magma ocean. It is important to note that the composition of our experimental felsic melts is similar to that of felsic rocks that Curiosity discovered on Mars [*Sautter et al.*, 2015]. Thus, it seems worthwhile to compare conditions on the two planets.

Current explorations of Mars may help validate and complement our hypothesis regarding the early evolution of water-bearing rocky planets. New seismic data from the InSight (Interior Exploration using Seismic Investigations, Geodesy and Heat Transport) lander, coupled with crustal and thermal modeling based on InSight data, have provided new information on the depth and structure of the Martian crust [e.g., *Knapmeyer-Endrun et al.*, 2021]. Analysis so far, considering that Mars's gravitational field is only about 40% as strong as Earth's, suggests that early felsic crust on the planet could have been located deeper than it was on Earth—at depths of 25–30 kilometers compared with the corresponding Hadean felsic crust generated less than 10 kilometers deep on Earth.

There is much more to learn about early crust-forming processes and conditions on Earth—and on Mars. But the mechanism described here may represent the most plausible idea yet of how large volumes of the first felsic crust were made, answering a decades-old question in Earth science.

Acknowledgments

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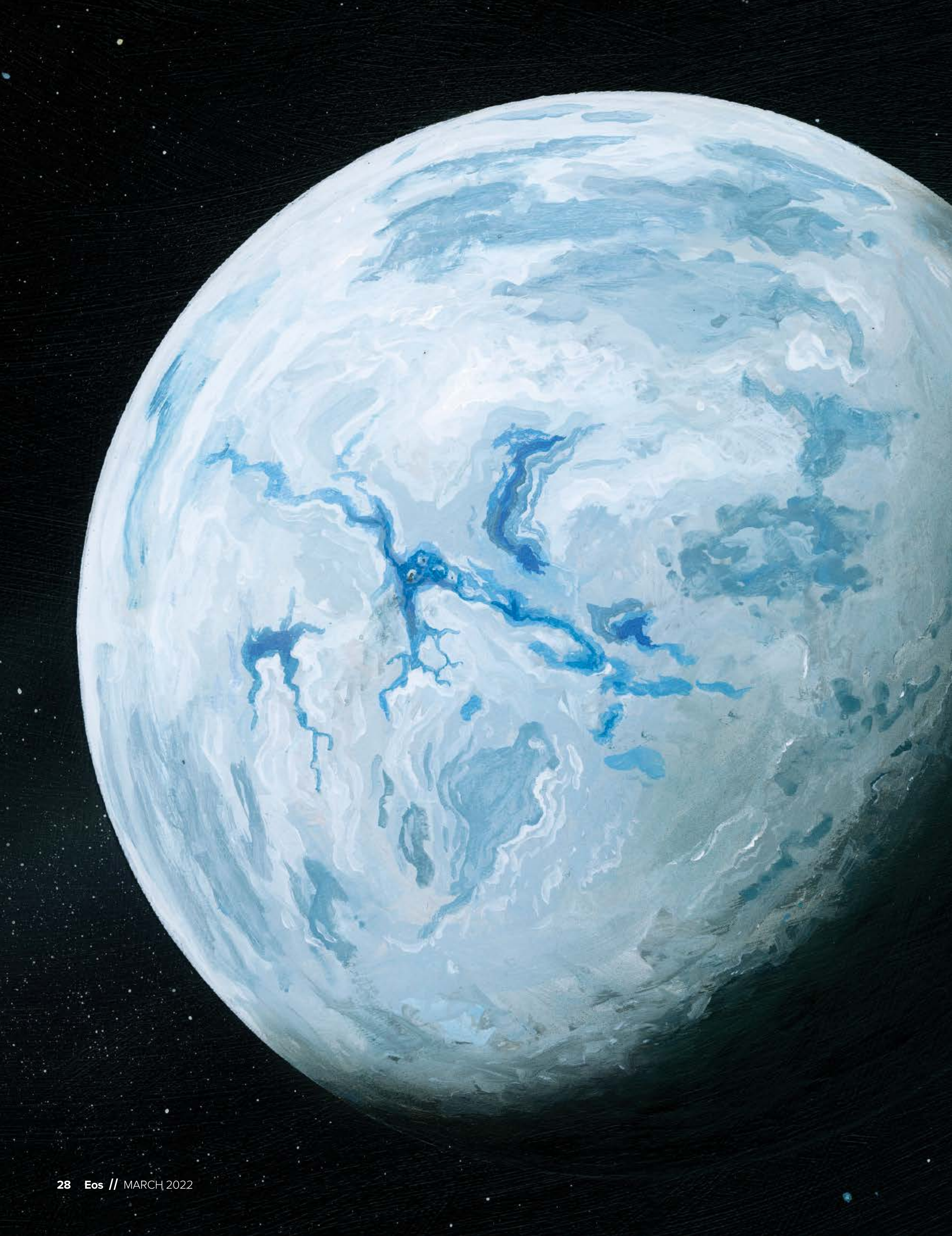
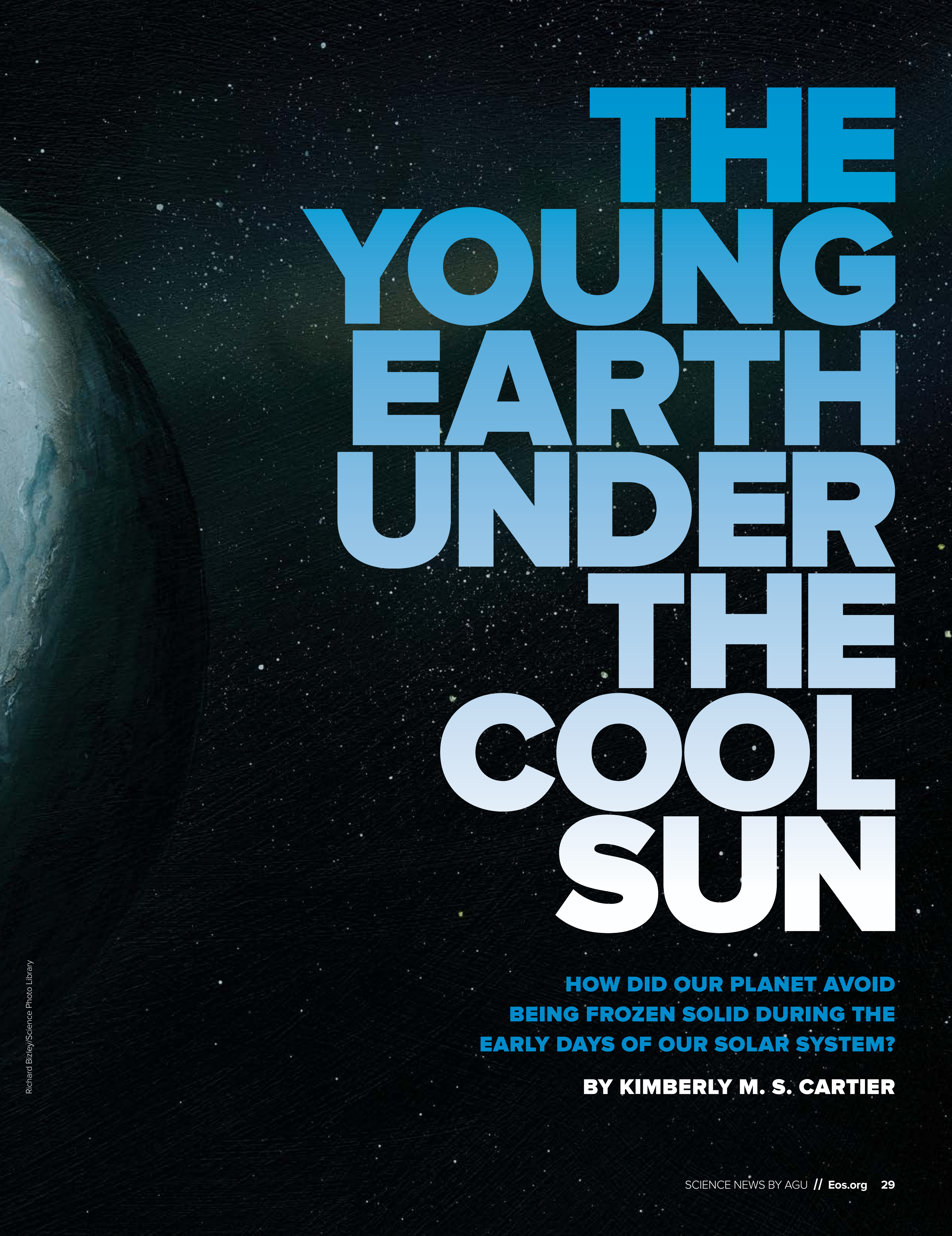




Richard Bizley/Science Photo Library

THE YOUNG EARTH UNDER THE COOL SUN

HOW DID OUR PLANET AVOID BEING FROZEN SOLID DURING THE EARLY DAYS OF OUR SOLAR SYSTEM?

BY KIMBERLY M. S. CARTIER

When Earth was still in its infancy more than 4 billion years ago, it was surrounded by chaos. The planet had nearly been shattered by a giant collision whose debris would go on to form the Moon. The detritus of planet formation was still regularly colliding with the newly reformed Earth. Elsewhere in the solar system, the gas giants were amassing their own satellites and clearing out chunks of rocks that refused to fall in line. And for those first few hundred million years, the Sun was still waking up, with fusion by-products slowly building and causing its core to contract and glow brighter. By the end of the Hadean, when Earth was a meager half a billion years old, the Sun shone at about 75% of its current brightness.

That poses a problem. Not much is known about what was happening on Earth at that time, but what little we do know suggests that there was some amount of liquid water present at or near the surface starting in the Hadean, and there is evidence that life itself began in the Archean (4.0–2.5 billion years ago). If modern Earth were suddenly to receive 25% less sunlight today, it would quickly freeze over, so how did early Earth manage to avoid it for 2 billion years?

For decades this question, dubbed the "faint young Sun paradox" by Carl Sagan and George Mullen in 1972, has been an intriguing research topic for geochronologists, deep-time paleoclimatologists, and astronomers, although the scientists currently working to answer the question prefer to call it not a paradox but just a "regular ol' problem."

"It isn't really a paradox in the way that we would normally understand it," said Colin Johnstone, an astrophysicist at the University of Vienna in Austria. A paradox describes a contradictory statement or phenomenon, and because it is somewhat naive to assume that early Earth was anything at all like modern Earth, he said, an explanation for the faint young Sun problem might not contradict settled science or the geological record at all. "It's more just something we don't quite understand," Johnstone explained, "and so the problem is, How is it that the Earth was not frozen given that the Sun was less bright in the past?"

Finding a noncontradictory answer "gets more and more difficult with every million years you go back," said Georg Feulner, a deep-time paleoclimatologist at Potsdam Institute for Climate Impact Research in Germany. "The further back you go in time, all the uncertainties add up, and you just have to live with that. But still, I'm an optimist. By using an interdisciplinary approach, by understanding models better, by getting better isotope data, by understanding the space environment better, and by looking at the evolution of three of the four terrestrial planets in concert, I'm optimistic that we can narrow things down."

Solving this problem will help determine the conditions that led to life springing up on Earth and could help identify other planetary harbors of life.

"Early Earth basically was an exoplanet," said Claire Guimond, an exoplanet geoscientist at the University of Cambridge in the United Kingdom. "It could have been just as alien as a rocky exoplanet might be to Earth today—different atmospheric composition, different kinds of surface conditions, everything. A faint young star is always going to be something that a planet experiences. If you're interested in a planet being temperate enough to harbor conditions for the origin of life, then you're probably going to be interested in how likely it is that planets can overcome the lower luminosity."

"EARLY EARTH BASICALLY WAS AN EXOPLANET. IT COULD HAVE BEEN JUST AS ALIEN AS A ROCKY EXOPLANET MIGHT BE TO EARTH TODAY."

FIRE: THE YOUNG SUN

At more than 4.5 billion years old, the Sun is just bright enough to maintain (current) Earth's globally connected liquid ocean, and the Sun's X-ray and ultraviolet (XUV) radiation and flares are weak enough not to strip away Earth's protective atmosphere. But there is no way to look at the Sun today and know how bright it was or how intense its XUV radiation was during the Hadean or how it evolved to its present state. So where does that knowledge come from?

To understand the young Sun, astronomers look for clusters of stars in the galaxy whose members were all born at the same time, a circumstance that allows researchers to calculate the stars' age. If the cluster has stars that are of the same mass as the Sun, those stars can serve as snapshots of the Sun's history. From this approach we know that newborn Sun-like stars shine at about 70% of the Sun's current brightness and gradually get brighter throughout their lives. At 500 million years old (equivalent to the end of the Hadean), they reach roughly the 75% mark. With enough solar analogues of different ages to anchor solar evolution models, stellar astronomers have put together a fairly thorough timeline tracking the evolution of the Sun's brightness, size, and mass.

However, sometimes solar analogues behave differently from each other and offer a range of possibilities for our Sun's history. Our knowledge of the Sun's rotation speed, XUV radiation, activity level, and solar wind history remains incomplete. "When we look at a really young cluster where all the stars are just born, so about a million years of age, there's a big spread in the rotation rates for all the stars, and over time this spread goes away," Johnstone said. "By the age of the current Sun, all of these stars [rotate] the same, but they weren't the same for the first few million years. And this has a really big effect on how much [XUV] radiation the stars were emitting." Stars that rotate faster tend to emit more XUV radiation and also have a stronger stellar wind. "Since we only see the Sun now, when this spread in the rotation rates has already disappeared, we have no way to extrapolate backward," he said.

Heliophysical computer models, including some that Johnstone has worked on, estimate these properties under different solar evolution scenarios and evaluate their potential impact on early Earth's upper atmosphere. Geologic records rule out some possibilities, he said, like Earth having entirely lost its atmosphere at any point after the Moon-forming impact. "Any model that tells you that the atmosphere was rapidly lost in a million years, or something like that, can be discarded," he said. (That eliminates a higher fraction of solar evolution models than you'd think.)

Venus and Mars might yield further constraints on the young Sun's XUV radiation and solar wind. Just like Earth, both rocky planets have likely had atmospheres for their entire histories. However harsh the early Sun's radiation was, it spared those atmospheres, too. But because modern Venus and Mars lack plate tectonics, more

The rock in the center of this image, called Big Bertha, had two Hadean zircons buried within, scraped off Earth during the formation of the Moon. Apollo 14 astronauts carried the rock back to Earth. Credit: NASA

evidence from 4 billion years ago might survive on their surfaces.

WATER: HADEAN ZIRCONS

Astrophysicists reached a consensus on the probable evolution of the Sun's brightness in the 1950s and immediately started realizing the chilly implications for Hadean Earth. "The faint young Sun problem comes when astrophysicists and deep-time geologists collide," said Sanjoy Som, an astrobiologist at the Blue Marble Space Institute of Science in Seattle. But still very little is known about the processes that were occurring on Earth's surface during the first tenth of its life. "We want that story, but the further back you go in time, the rarer the rocks, and the more they have been modified by post-original processes. So we have to be careful. We don't want to be fooled by what later changes have done to them," Som said.

For a long time, explained Mark Harrison, geologists assumed that no Hadean rocks could possibly have survived the continuous churning of crust into mantle and back. Harrison is a geochemist at the University of California, Los Angeles. As its name suggests, Hadean Earth was initially assumed to be rather hellish, covered in a roiling magma ocean and subject to continuous impacts. During the past 2 decades, however, more evidence has cropped up suggesting that not only did Earth have a solid crust during that time but also liquid water was present.

OUR KNOWLEDGE OF THE SUN'S ROTATION SPEED, XUV RADIATION, ACTIVITY LEVEL, AND SOLAR WIND HISTORY REMAINS INCOMPLETE.

"The reason we don't have very many rocks from the Archean, and none from the Hadean, is because they just got subducted by plate tectonics," Guimond said. "There are a few places like in South Africa, Australia, and Canada where you do actually have these ancient continental cores made up of really old rocks, which just got preserved on the surface. The evidence for there being liquid water comes from zircons, which are very hard minerals that are difficult to erode."

Zircon grains are deep time's record keeper, and rare examples have been discovered that have survived since the Hadean. Nearly all of the Hadean zircons analyzed thus far have come from the Jack Hills region of Western Australia (as well as a few from western Greenland and northern Canada), although 14 other locations across the world contain Hadean zircons.

Lead isotope analyses show that the oldest Jack Hills zircons range between 4.1 billion and 4.4 billion years old, and inclusions

This piece of Archean quartz pebble metaconglomerate from the Jack Hills in Western Australia contains Hadean zircons that are 4.4 billion years old. Credit: James St. John, CC BY 2.0 (bit.ly/ccby2-0)

within the crystals provide unique insight into the geochemistry of Hadean Earth.

A few of these Hadean zircon grains can tell geologists that continent-like crust existed but not the extent of it and that liquid water was present but not how large the reservoir was. "Most everything else we see is consistent with the planet being basically frozen," Harrison said. "It's very likely that even in a snowball Earth scenario 4.2 billion years ago, there was still liquid water at the ice-rock interface. You don't need an ocean of liquid water.... The whole thing could be happening under 3 kilometers of ice."

Hadean zircons are very rare: About 2% of all Jack Hills zircons discovered so far date from the Hadean, and the percentage is 10 or 100 times lower in other locations. Terrestrial Hadean zircons can also be found on the Moon, however, whisked away to relative safety during the impacts that formed the Moon and spared the tectonic fate of their earthly counterparts, said Harrison. Two Hadean zircons have already been found there, hidden in a rock sample brought back by Apollo 14 astronauts.

"THE FAINT YOUNG SUN PROBLEM COMES WHEN ASTROPHYSICISTS AND DEEP-TIME GEOLOGISTS COLLIDE."

EARTH: CRUST AND MANTLE

Although some evidence exists that Hadean Earth had a crust and that some of it has survived to the present, how much of the surface it covered compared with the paleo-ocean is still unclear. "Continental coverage is important, because the ocean is much darker than land, by far," Som explained. "Land reflects light back into space more than ocean does—that's the albedo effect. If the planet Earth was much darker because it had much more extensive ocean coverage than today, that could also be a way for the planet to absorb more heat from sunlight" and remain unfrozen.

We also don't know how long it was before that crust was destroyed by plate tectonics. "In the Archean," said Guimond, "we really can't say for sure if we had plate tectonics happening." It's possible that for some time in the Hadean and the Archean, Earth had no plate tectonics at all and existed with a one-piece crust like that of present-day Mars or Venus. "When you do geodynamic modeling, the theory shows that stagnant lids might be a natural state for rocky planets," she said.

Whether early Earth had a stagnant-lid-type crust or today's churning plate tectonics is key to understanding whether greenhouse gases were released from the mantle into the atmosphere in sufficient quantities to keep the planet temperate. Hadean and Archean Earth likely had a much greater quantity of carbon dioxide (CO_2) in its atmosphere than modern Earth, and many deep-time paleoclimate models attempt to figure out how much CO_2 or another greenhouse gas would have been needed to sufficiently warm Earth.

All that greenhouse gas has to have come from somewhere. Although some small amount could have been deposited by the still-regular meteor strikes on early Earth, most of it would have come from magma outgassing. Scientists have extensively studied volcanic outgassing of CO_2 under today's tectonic paradigm, Guimond said, but there is no guarantee that early Earth operated under the same rules. Under a stagnant-lid regime, for example, "we found that CO_2 outgassing could be about an order of magnitude lower than we have today." That would put sharp limits on the amount of atmospheric CO_2 paleoclimate models can claim existed in the Hadean and Archean.

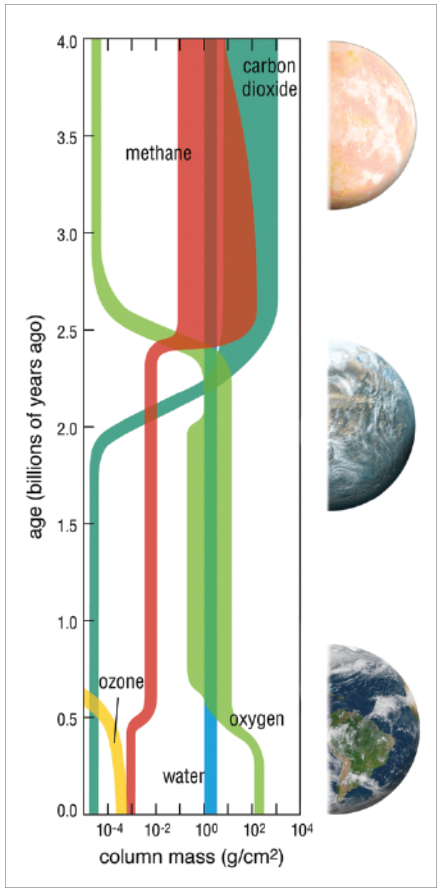
AIR: GREENHOUSE WARMING

However, the solution to the faint young Sun problem is not as simple as adding more greenhouse gases to your favorite paleoclimate model: There are an incalculable number of mixtures of greenhouse gases that might provide enough warming to Hadean Earth. Luckily, there are some constraints on what atmospheric mixtures are plausible. For one, rocks provide some limits on the temperature and pressure of the Archean atmosphere that can translate to a limit to how much greenhouse gas our atmosphere could have physically held, Som said, "but those measurements are spotty and are unknown for the Hadean." Earth's atmosphere in the Hadean could have been thicker than it is today.

Here, too, the unknown properties of the early Sun come into play. If the early Sun's XUV radiation and solar wind were near the upper limit of what has been measured for other Sun-like stars, much of Earth's early atmosphere would have been blasted away, necessitating an even higher output of greenhouse gases to compensate. Even in a lower-radiation scenario, such as one that Johnstone explored recently (bit.ly/low-radiation-co2), Earth's atmosphere would need to have been at least 40% CO_2 (compared with today's 0.04% and rising).

Moreover, there is the unknown factor of sea ice. After all, Feulner advised, the Hadean zircons can show only that liquid water was present, not whether it coexisted with ice. Surface ice, on sea or land, is a critical component of how much heat Earth absorbs or reflects: More ice reflects more sunlight away, which further cools the planet and freezes more ice. In some studies in which paleoclimatologists modeled periods of glaciation more recent than the Hadean, the inclusion of sea ice dynamics radically altered the quantity of CO_2 needed to thaw the planet (bit.ly/sea-ice-co2).

"When they switched off sea ice dynamics—just the fact that the sea ice gets pushed around by ocean currents and the wind—they could lower the CO_2 concentration by a factor of 100...before the planet fell into a snowball regime," Feulner said. If 3D paleoclimate models fail to include the movement of sea ice, he said, they could significantly underrepresent the amount of greenhouse gas needed to warm Hadean Earth.



Earth's atmospheric composition has changed dramatically over its history. During the Archean, a vertical column of air contained a high concentration (grams per square centimeter, g/cm^2) of carbon dioxide (dark green) and methane (red) and small amounts of oxygen (light green) and water vapor (blue). Only within the past billion years did the atmosphere gain ozone (yellow). Here a thicker line represents more uncertainty in the measured value. Credit: Roberge et al., 2019, https://doi.org/10.1117/12.2530475

FINDING THE MESSY SOLUTION

Are scientists close to answering why Earth was temperate under the faint young Sun? As more and more simulations are run—with different atmospheric greenhouse models, solar evolution scenarios, and mantle outgassing rates—many of them find at least one viable answer. So how will scientists narrow down the options?

Ultimately, Harrison said, we need more lithic evidence from the Hadean to put better geophysical constraints on the potential solutions. And that means more zircons, especially those that *don't* come from Jack Hills. "There is clear evidence that there was water at or near one location on the planet 4.3 billion years ago.... We have this one clear result from Jack Hills. There are 14 other locations that could allow us to address the question, How globally representative is Jack Hills?" he said. By analyzing Hadean zircons from across the globe in as much detail as those from Jack Hills, geochemists will start to pin down the extent of Earth's early oceans, which will further constrain the behavior of the crust, mantle, and atmosphere.

Beyond a boost in geophysical data, there is an almost unanimous call for better and faster 3D models of the interconnected Earth system: mantle and crust, sea ice and lower atmosphere, solar radiation and upper atmosphere. Each component of the system plays a key role in solving this early Earth puzzle. Arriving at a consensus solution will require a holistic and interdisciplinary approach that leverages the strengths of each field—paleoclimatology, geochronology, astronomy.

"Whenever there is a paradox or a problem of this type, people look for that one glorious solution which does it all," Feulner mused. "But there's probably no silver bullet. [The solution] is probably a mixture of many factors contributing to the warming... just a mix of more CO_2, less clouds, you name it. It's probably messier than many people think."

AUTHOR INFORMATION

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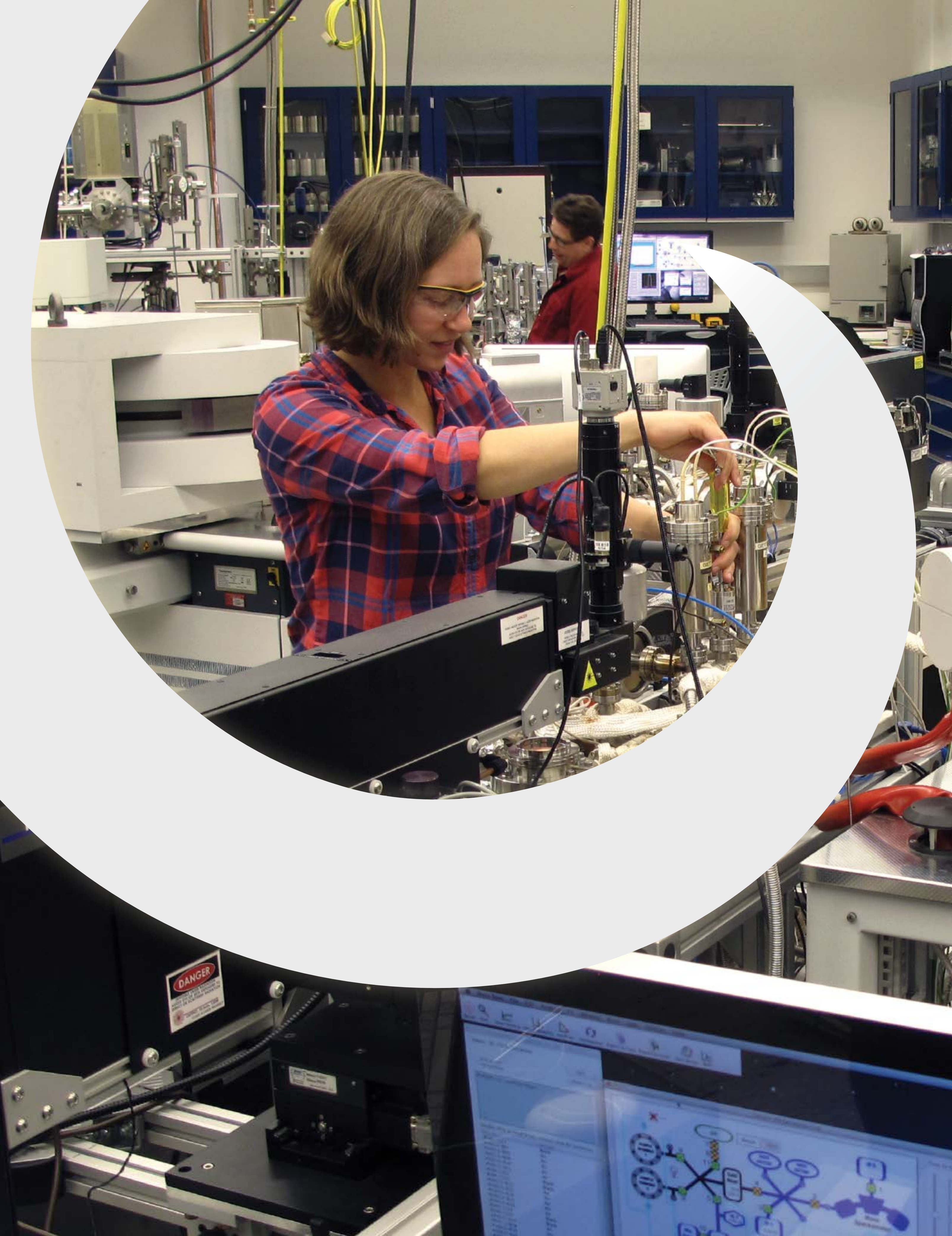
▶ Read the article at bit.ly/Eos-young-Sun


DANGER

LONG-TERM PLANNING FOR DEEP-TIME LABS

When directors depart argon labs, what happens to their expensive equipment, skilled staff, and institutional knowledge?

BY RICHARD SIMA

YOU REALLY CAN'T TAKE IT WITH YOU.

Kip Hodges spent much of his early scientific career at the Massachusetts Institute of Technology (MIT) establishing an argon dating lab with very specialized, very expensive mass spectrometers, high-powered lasers, and access to a nuclear reactor. When he left MIT after 23 years, he had to leave his instruments behind.

Because the instruments were funded by grants, they belonged to the university. Whether anyone was going to use the instruments after Hodges left was also up to the institution.

"Are they going to hire a new faculty member who would use that particular instrument because they've got this unbelievably valuable piece of research instrumentation at the facility?" Hodges asked. "Quite often, that's not what happens."

Research geologist Leah Morgan works in the U.S. Geological Survey Argon Geochronology Laboratory in Denver, Colo. Credit: Sam Johnstone

In a field dedicated to the investigation of deep time, the argon dating community faces challenges when planning for the long term.

MIT did not hire someone to replace Hodges, and though the laboratory was initially kept running by members of his research group, it eventually fell into disuse. A spokesperson for MIT confirmed in an email that "the argon dating lab no longer exists and there hasn't been one for about a decade."

"It was sad for me to see that instrument sort of go fallow after a few years, but at the same time I understand it," said Hodges, a geoscientist who now directs the Noble Gas Geochronology and Geochemistry Laboratories at Arizona State University.

Argon labs can date rocks as old as the solar system and have been instrumental in clarifying the geochronology of occurrences ranging from the Chicxulub impact event to the volcanic eruption that famously buried Pompeii. They are expensive to maintain and require expertise to manage. When supervisors retire or leave, their argon labs often simply disappear, leaving equipment, as well as support staff and other scientists who relied on them, in the lurch. Some argon dating labs also run samples for external and industry clients, meaning that a shutdown disrupts research far beyond what was pursued in the lab.

"Sadly, what often happens is they get mothballed," said Paul Renne, a geologist at the University of California (UC), Berkeley and director of the independent nonprofit Berkeley Geochronology Center, the longest-running argon lab in the United States. "And very often you'll hear by various listservs or word of mouth that so-and-so is retiring, and there's nobody in the queue to take over the lab, and so there's a mass spectrometer for sale. This is not uncommon."

Even the renowned Australian National University argon laboratory run by Ian McDougall, the grandfather of the technique, could not escape this fate.

"His lab is basically abolished—it's gone," said Anthony Koppers, a marine geologist, associate dean of research at Oregon State University, and director of the school's Argon Geochronology Lab. "It would have been such a cool lab to maintain because of simply the name recognition and the importance to the entire field."

Therein lies the irony: In a field dedicated to the investigation of deep time, the argon dating community faces challenges when planning for the long term. These challenges also confront laboratories housing expensive and highly specialized equipment in other scientific fields when a lack of coordination or a plan for continuation after a lab director leaves leads to a cascading disruption for everything and everyone connected to the lab.

In the case of argon dating, the lack of coordination and planning is not for a lack of importance. Recently, a decadal report by the National Academies of Sciences, Engineering, and Medicine (NASEM) highlighted how essential geochronology is for the Earth sciences and recommended further funding for it (bit.ly/geochronology-funding).

"We're not thinking about things on very long timescales," Hodges said of the argon dating community. "We're thinking about things over the next few months.... We don't want to say, 'Where is this mass spectrometer going to be in 15 years?'"

"NO BLUEPRINT" FOR REPLACING ARGON LAB HEADS

There are about 20 argon dating labs in the United States—and about twice that number outside it—most of which are run by senior supervisors who are nearing retirement age.

"There aren't a lot of young argon geochronologists," said Courtney Sprain, a geoscientist at the University of Florida. "We're very top heavy."

The argon dating method, which was developed in 1966, "is just getting mature enough that you're starting to get to where there is succession needed," said Leah Morgan, a research geologist with the U.S. Geological Survey's Geology, Geophysics, and Geochemistry Science Center in Denver.

And even when a scientist has their name on the lab, their control over its direction usually lasts only as long as their paychecks. "It's sort of surprising to many that when faculty retire, they really don't have any real influence over what happens to their labs," Renne said.

Instead of looking for a candidate to take over this established resource that the university has invested in for decades, faculty search committees often look for the best candidate in a broader field. It can be difficult to balance the large monetary investments already made in buying equipment for the argon lab and hiring top-notch researchers who could augment the institution in other ways.

"I think that might be an issue in most high-level research departments you talk to," said Brad Singer, professor and chair of the Department of Geoscience at the University of Wisconsin–Madison and director of the WiscAr Geochronology Lab. Singer himself chaired one such search committee to hire new isotope geochemists. "There's no blueprint for this."

IN GEOLOGY, TIMING IS KEY

The status of argon labs is important for the field of geochronology, the science of dating Earth materials and geological events. Geochronology, in turn, touches all aspects of our understanding of Earth in its vast spatial dimensions by adding knowledge about that vast fourth dimension: time.

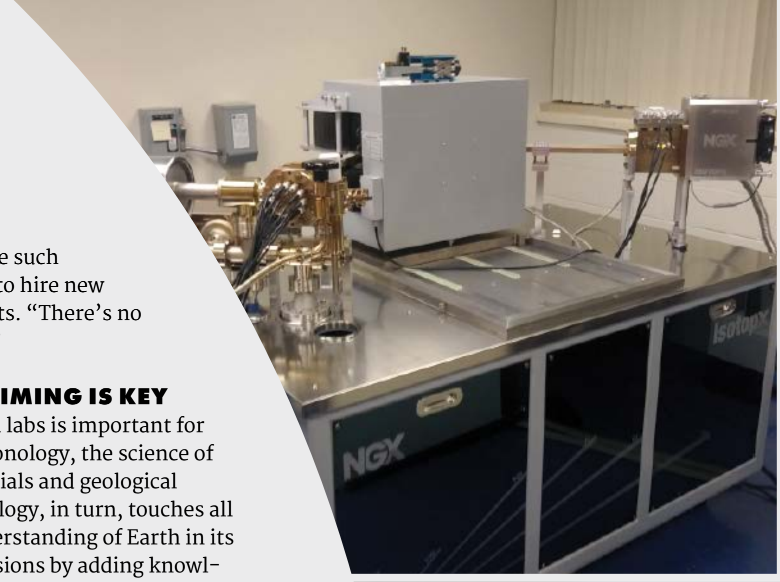
Argon dating, also known as argon-argon dating because it relies on measuring two isotopes of the element (argon-40 and argon-39) in samples, is a versatile technique that can date materials across a massive time span with a high degree of precision. "The argon-argon method can date materials as old as the solar system—theoretically older, but we don't have any such things to play with," Renne said. "So [we have material] 4.6 billion years old to really just a few thousand years old."

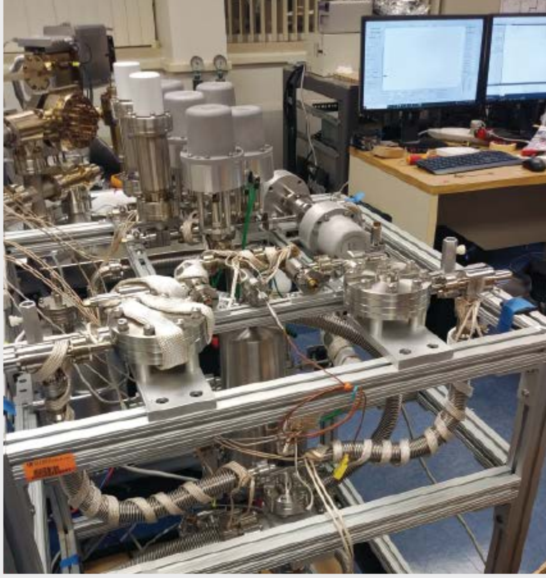
"It's great for a ton of geologic processes; we just can't fundamentally understand them until we know rates and dates," said Sprain. "We need to know how fast processes are occurring. And we need to know when they're occurring."

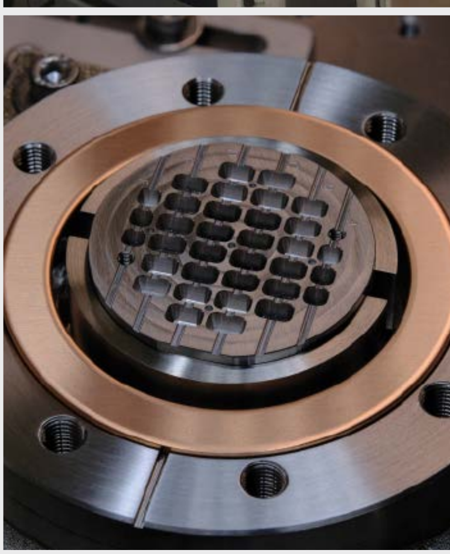
The technique can be applied to any rock or mineral containing the common element potassium (which decays to argon). It has been critical in dating events as wide-ranging as the most famous eruption of Vesuvius, meteorite formation, and milestones in evolutionary biology and history. Almost everything we know about the 66-million-year age of the mass extinction event associated with the Chicxulub crater, for instance, comes from argon dating, Hodges said.

But all the precision and versatility that the technique affords require costly equipment to be purchased, maintained, and staffed.

Samples first need to be irradiated with neutrons, so access to a







Clockwise from top left: The new IsotopX NGX multi-collector noble gas mass spectrometer recently installed at the University of Florida (UF) (Courtney Sprain/UF); This fully automated extraction line at UF was custom-built and designed by Tim Becker. The extraction line includes a cryogenic trap and two getters for gas purification, in addition to an air pipette system. Samples will be heated and introduced into the system using a CO_2 laser system (not shown) (Courtney Sprain); Courtney Sprain in front of the new IsotopX NGX multi-collector NGX noble has mass spectrometer and extraction line at UF (Courtney Sprain); Loading of a stainless steel sample tray holding 34 geological samples for $^{40}Ar/^{39}Ar$ dating into an ultra-high vacuum chamber. The lid of the sample chamber has been taken off to allow loading. Typical samples in this tray are 1–4 milligrams (Daniel E. Heaton/Oregon State University); Close-up of source on IsotopX NGX mass spectrometer at UF. The source ionizes the incoming gas that allows it to be sent down to the detectors (Courtney Sprain).

“A good mass spectrometer will, if it’s taken care of through the years, last a whole lot longer than most faculty careers.”

nuclear reactor is required. A high-powered laser is needed to successively heat up the samples to release the inert argon atoms so they can be measured by a mass spectrometer. And because the air we breathe is roughly 1% argon, that air must be pumped out of the machine to prevent it from contaminating readings from the sample.

“You have to do everything under ultrahigh vacuum,” said Koppers. “The vacuums that we have in the mass spectrometers in our systems are better than space.”

The mass spectrometers at the heart of argon labs can cost upward of half a million dollars each, not including mineral extraction equipment and other necessary tools. When the building in which Koppers’s lab was located caught fire several years ago, he had to replace everything in the lab—at an expense of close to $2 million that, thankfully, insurance reimbursed.

“So [it’s] a really interesting and important problem: What happens to these older instruments?” Hodges said.

MASS SPECS FOR SALE

The original mass spectrometer widely used in argon and other forms of noble gas dating, a mass analyzer product (MAP), is a reliable workhorse that decades after its invention can still be used, because there has been no change in the underlying technology, “the real guts of the mass spectrometer infrastructure,” Singer said.

“The electronics you have to replace and the magnet controller you have to replace and vacuum systems you have to update and all this sort of stuff, but they have a very long life,” Hodges said. “The point is that a good mass spectrometer will, if it’s taken care of through the years, last a whole lot longer than most faculty careers.”

However, the company that manufactured the original MAP instruments has gone out of business. As a result, the main way to acquire spare parts is to purchase them from other laboratories that no longer need them. When argon labs are mothballed, their machines are often put up on the noble gas network listserv to be sold to other labs for parts.

“People have literally driven across the country to go and pick up old mass spec parts,” Sprain said. “Usually, when a lab’s decommissioned, if the system is old, the university isn’t going to get a lot of money if they try to sell it.”

Newer mass spectrometers are available, however, and geochronologists starting their own labs typically invest in these instruments because of their higher sensitivity and throughput. Such an investment usually requires overcoming the substantial barriers of writing a successful grant application and negotiating a generous start-up package from a research institution.

When Kevin Konrad arrived at the University of Nevada, Las Vegas (UNLV) to start his new argon lab, there was still an old mass spectrometer there, but he opted to purchase a new machine in the summer of 2021. “The MAP was something of a time bomb, so if something broke on it, I would be a fish out of the water,” he said.

Konrad said he is hoping to sell the old machine, but the buyer would need to pick up and transport the instrument: It is difficult to ship anything that has encountered radioactive materials, as the MAP has, and the magnet inside weighs about 700 pounds (318 kilograms).

“If I can’t sell the whole mass spec, then I might actually put it as a museum piece in the lobby—put a little cage around it and basically say this is what a mass spectrometer looks like,” Konrad said.

Yet the older machines have more than just historical value.

Singer said his lab is converting an old mass spectrometer used for argon dating to make measurements of helium-3, which would allow the lab to start doing surface exposure dating, adding new research capacity.

Old mass spectrometers can also still generate reliable argon dating data. When Sprain started her laboratory at the University of Florida, she opted to purchase a new instrument because the university’s mass spectrometer had been broken for about 10 years following a lightning strike that rendered its magnet nonfunctional. Sprain said she hopes to obtain a replacement part for the magnet to get it running again.

“It’d be really nice to have just a good standard workhorse instrument on top of the new one,” Sprain said. With argon, she explained, whatever the sample may be (a single grain of a potassium-rich mineral, lots of crystals of one mineral, or a whole rock aliquot), it may be full of material that can “dirty up” the insides of the instrument. “So we could then even potentially run really dirty samples on the old system.”

STAFF LEFT IN THE LURCH

The dissolution of argon labs affects not only the equipment but also the people who make them run. Replacing a lab supervisor is not easy, said Konrad. “Argon geochronology does one thing only, which is date rocks. And so if [an institution doesn't] want someone who can date rocks, the whole lab has to basically go. You can't just take someone who roughly knows about the field…and expect them to run [an argon lab], because it's a very involved process."

When Kathleen Zanetti arrived at UNLV in 1998, she and her supervisor, Terry Spell, built an argon lab and its then state-of-the-art mass spectrometer and mineral extraction line. As the lab manager, Zanetti was responsible for all daily operations, including maintaining and repairing the equipment and running and analyzing samples.

But when Spell retired in 2018, Zanetti was essentially left to run the lab alone, meeting with and running samples for external clients. However, "because [university officials] consider it a dead lab without having a supervisor, they were going to shut the lab down," Zanetti said.

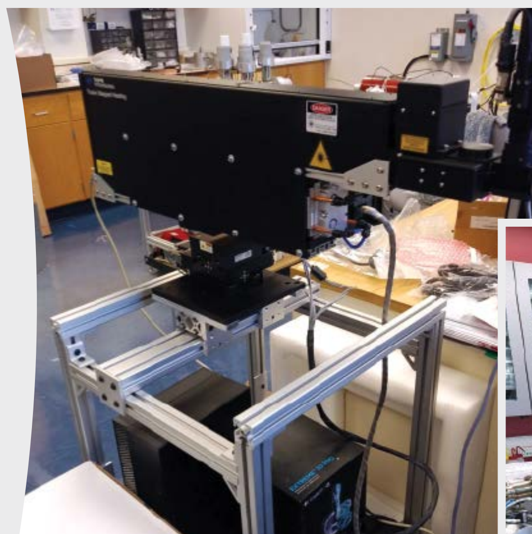
"So it was a little concerning. I started to look for new jobs," Zanetti said. "But it was hard because I pretty much pigeonholed my career by doing argon dating for 23 years. There's not much call for that, and a lot of other labs, you know, keep their technicians and managers for life."

Zanetti estimated that it would take several years to train someone new to manage an argon lab, but it can be difficult for staff to transition to another argon lab that could use their expertise.

"They try, but they're not always successful," Renne said. "I think a lot of the people that are sort of orphaned when somebody retires, they go on to different positions, different lines of work."

Hodges agreed. "The technical support problem is a big, big issue" when labs transition, he said. "And it's something that as a geoscience community, we need to figure out."

Zanetti, to her relief, was able to keep her job when Konrad was hired to take over the lab in 2020.



Clockwise from top left: A sanidine crystal glows yellow-white hot as it releases its gas for dating at Oregon State University's (OSU) Argon Geochronology Laboratory (Anthony A. P. Koppers/OSU); This double set of ThermoScientific ARGUS-VITM multi-collector mass spectrometers at OSU's Argon Geochronology Laboratory provides increased capacity to carry out up to 80,000 analyses per year (Daniel E. Heaton); Automated valves in a custom-built extraction line designed by Tim Becker control the flow of gas into a mass spectrometer at UF (Courtney Sprain); Dan Miggins (right) and Daniel Heaton replace a gold vacuum seal on the ARGUS-VITM multi-collector mass spectrometer at the OSU Argon Geochronology Laboratory (Anthony A. P. Koppers); The Group 18 Laboratories at Arizona State University house geochronology analytical facilities (Kip Hodges/Arizona State University); This Teledyne-Cetac Fusions CO_2 laser will be used to heat samples and release gas into the mass spectrometer at UF (Courtney Sprain).

> “How do we make sure that these instruments have a life of their own that doesn’t depend on the whims of somebody who decides they want to change university or somebody who decides they want to retire?”

LOSS OF INSTITUTIONAL KNOWLEDGE

In addition to impacts on individuals and institutions, the closing of argon labs has a wider impact on the field at large. Institutional knowledge and technical know-how can be lost.

“The issue is a lot of the things in the actual lab—chasing leaks, trying to figure out what the best kind of settings are for certain measurements and everything—none of that will ever be published or made publicly available. It’s just lab knowledge,” said Konrad, who still occasionally emails Koppers, his graduate mentor, for advice.

“Someone’s had a lab for decades, and then they retire, and no one’s taking it over. Their legacy and everything they’ve built, and all of that knowledge that used to be housed at that institution, is gone,” Sprain said.

Though many institutions do not hire replacements for retired argon lab directors, a few argon labs have maintained a line of succession, passing the lab from generation to generation.

Koppers is the fourth director of his lab, now in its 52nd year of operation at Oregon State University. When Koppers arrived in 2007, he overlapped with his predecessor, Robert Duncan, and the pair wrote a grant proposal for a new mass spectrometer together.

“I think we got funded because of this concept of making a transitional period where there was overlap with two professors running the same facility,” Koppers said, noting that this allowed him to learn the ropes from Duncan and signaled to the community that a successor was already in place and that the lab could run for decades to come.

Similarly, there’s a long history of argon labs based at the U.S. Geological Survey, with the earliest started in Menlo Park, Calif., in the 1970s. And unlike at many academic institutions, “there is a vested interest in keeping an argon lab,” said Morgan. She coleads the Denver argon lab with the previous director, Michael Cosca, who joined the lab in 2008, allowing for an overlap in leadership.

The lack of a succession plan is the reason the Berkeley Geochronology Center exists now as an independent research institution, Renne said. His argon dating lab was created in the late 1950s on the UC Berkeley campus, but when cofounder Garniss Curtis retired, the department had no plans to replace him; fortunately, a new private institution, the Institute of Human Origins, was being formed nearby, and the lab was able to find a home there before ultimately branching off on its own.

But now lab leadership at the Berkeley Geochronology Center has learned its lesson and has a clear succession plan in place, Renne said. “We’re all still very much interested in what we do.… We obviously will have to have a next generation coming in within the next, let’s say, 5 years.”

THE FUTURE OF ARGON LABS

“How do we make sure that these instruments have a life of their own that doesn’t depend on the whims of somebody who decides they want to change university or somebody who decides they want to retire?” Hodges said.

More organization within the field could help address this question.

In 2020, the NASEM decadal report on the Earth sciences recommended funding a National Consortium for Geochronology. Sprain and Morgan, with other researchers, have since applied to acquire funding to start building such a consortium to support workshops, increase community building, and bolster organization among argon geochronologists.

Another positive step could be establishing pipelines or networks of technical expertise to keep these valuable instruments running. For example, a national consortium or network of individual labs developing training programs for technical staff and lab managers could make these career paths in argon labs more viable for students, Morgan said.

“I think we need to be thoughtful; we need to be strategic as opposed to tactical,” Hodges said. “Right now, we’re all being tactical about this.”

In other words, to continue studying Earth’s deep past, the field must also look—and plan—farther into the future.

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▶ Read the article at bit.ly/Eos-argon-labs

The Perspective from Space Unlocks the Amazon Water Cycle

The Amazon River and its tributaries, as seen from the International Space Station, have intricate and complex hydrology. Credit: Alexander Gerst, CC-BY-SA 2. (bit.ly/ccbysa2-0)

The Amazon basin is the world's largest river basin, with intricate and complex hydrology. It stretches across seven nations and feeds four of the 10 largest rivers in the world. The basin encompasses dense tropical forests, extensive floodplains, and interconnected wetlands. The region also receives a lot of rain—approximately 2,200 millimeters (86 inches) per year. Gaining a better understanding of Amazon hydrology is essential, especially in light of the ongoing environmental changes across the basin, from increasing floods, droughts, dam building, and deforestation.

Given the size and complexity of the ecosystem, scientists have used satellite technology to turn the Amazon into the world's premier remote sensing laboratory for hydrological and water cycle science. And more exciting science is on the horizon—NASA soon plans to launch two dedicated hydrology satellites: the Surface Water and Ocean Topography (SWOT) mission and the NASA-ISRO SAR (NISAR) mission.

In advance of the upcoming remote sensing missions, *Fassoni-Andrade et al.* recently published a comprehensive review of the basin's hydrology. An international team of more than 20 scientists compiled the study, which looks at 3 decades of work. The assessment evaluates precipitation, evapotranspiration, surface water, aquatic ecosystems, environmental changes, and more through the lens of remote sensing. The review provides a holistic view of the Amazon's water cycle while laying out challenges and knowledge gaps for future research in the region.

The authors treat each topic as a subreview—for example, looking at precipitation, they discuss how infrared and microwave sensors monitor rainfall and describe the algorithms that process the data. They then report on successful remote sensing applications, such as how one project used satellite data to delineate the beginning and the end of the Amazonian wet season. Last, the authors outline some challenges of measuring precipitation through remote sensing, including those related to the asymmetry of satellite readings and weather processes on the ground. They apply a similar structure to the other themes evaluated in the review.

According to the authors, their study serves as a model for synthesizing large-scale hydrological information about other river basins. While the knowledge reviewed in the paper needs to be translated to water management and environmental governance, the authors hope the study will lead to an integrated monitoring and research agenda across the basin. (*Reviews of Geophysics*, https://doi.org/10.1029/2020RG000728, 2021) **—Aaron Sidder,** *Science Writer*

Stratospheric Balloons Listen In on Ground Activity

Earthquakes, volcanic eruptions, and even severe weather events produce a medley of low-frequency infrasound waves below the range of human hearing. Researchers can investigate these sounds to gain a deeper understanding of our planet. In addition to natural events, infrasound sensors can pick up events caused by human activity, from city noise to nuclear explosions.

As part of a larger research team, *Bowman and Krishnamoorthy* detonated a canister located about 50 meters below the ground that was filled with an explosive equivalent to 10 tons of 2,4,6-trinitrotoluene (TNT). A network of instruments on the ground—including accelerometers, seismometers, and microbarometers—recorded ground shaking and pressure waves from the explosion. Ground sensors picked up the pressure waves 12 kilometers from the blast, but another array about 46 kilometers away heard nothing.

By contrast, the researchers report, microbarometers carried by solar-powered hot-air balloons in the lower stratosphere, more than 20 kilometers above Earth's surface, detected infrasound signals from the buried chemical explosion. The researchers propose that the balloon-borne microbarometers detected a strong signal because the troposphere directs sound upward. In addition, the sensors would not have been affected by background noise and sound-scattering features on the ground.

The new study supports further use of balloon-borne microbarometers for investigating geophysical activity and monitoring explosions on Earth. The results also support mission concepts proposing to use balloons to explore Venus and investigate volcanic activity and venusquakes via infrasound. (*Geophysical Research Letters*, https://doi.org/10.1029/2021GL094861, 2021) **—Jack Lee,** *Science Writer*

Cosmic Dust May Be a Key Source of Phosphorus for Life on Earth

When Earth formed 4.5 billion years ago, any phosphorus that was present likely sank into the molten core because of the element's distinct chemical properties. However, phosphorus is essential for life; it is found in DNA, RNA, and other important biological molecules. So it is probable that the phosphorus that made life possible was delivered to Earth's surface from extraterrestrial origins, and previous studies have suggested meteorites as potential sources.

Now *Plane et al.* present a new analysis suggesting that much smaller extraterrestrial particles known as cosmic dust may deliver phosphorus to Earth's atmosphere, where a series of chemical reactions repackage the element into biologically useful forms—namely, metal phosphites and phosphates—that eventually settle onto Earth's surface.

When cosmic dust enters the atmosphere, air friction causes it to undergo a process of vaporization and melting known as ablation. The new research builds on earlier work in which cosmic dust–sized meteoric fragments were flash heated to simulate ablation and the release of phosphorus-containing molecules was detected. Computational modeling of this process provided further support for cosmic dust as a significant source of phosphorus on Earth's surface.

The researchers constructed a network of chemical reactions that outline the specific process by which cosmic dust ablation could produce biologically useful phosphorus molecules. To do so, they combined real-world results from laboratory studies of chemical reactions with theoretical predictions for reactions that have not yet been studied in the lab. Then the researchers incorporated the reaction network into a global climate model.

The reaction network and the model simulations provide new support for the ablation of cosmic dust and subsequent chemical reactions as a source of biologically useful forms of phosphorus. These molecules are incorporated into tiny "meteoric smoke" particles that settle onto Earth's surface. The authors suggest that the particles could be a significant and continuous supply of phosphorus for life on Earth.

In addition, the researchers predict which regions, per year, might receive the greatest amount of phosphorus delivered by cosmic dust, in particular, the northern Rockies, the Himalayas, and the southern Andes. They also predict that a narrow atmospheric layer of OPO—a phosphorus-containing molecule—might encircle Earth 90 kilometers above its surface.

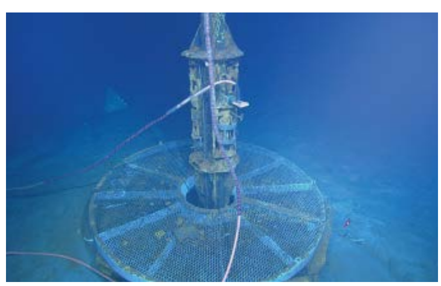
Future research could confirm the existence of the predicted layer. Researchers could also explore the possible role of cosmic dust–delivered phosphorus during the rise of life on Earth, when limited amounts of phosphorus could have constrained biological activity. (*Journal of Geophysical Research: Space Physics*, https://doi.org/10.1029/2021JA029881, 2021) **—Sarah Stanley,** *Science Writer*

Faults in Oceanic Crust Contribute to Slow Seismic Waves

The natural structure of the rigid oceanic crust that forms a shell around much of Earth contains cracks and faults. These fissures act as pathways for heat, water, and chemical solutions to move between the ocean and the lithosphere.

Scientists traditionally use seismic waves to uncover the nature of oceanic crust, including lithology and structure. When seismic compressional waves, or *P* waves, travel along fault trends, the wave speed remains largely unaffected. In comparison, previous research has discovered that seismic velocities can be up to 20% slower when waves pass across local faults and fractures compared with when they cross less fractured crust. In addition, prior work has used remote seismic detection to map out the large-scale seismic speeds of oceanic crust.

In a new study, *Sun et al.* characterized formation-scale mechanical properties using direct, in situ measurements of fluid pressure and colocated seismic records. They used an array of boreholes and seafloor instruments connected to Ocean Networks Canada's cabled NEPTUNE observatory, which spreads across the Juan de Fuca and North American plates. To understand how compressible the crust is, the team compared seismic surface wave strain with formation fluid pressure variations caused by distant large earthquakes. Although the use of formation fluid pressure as a proxy for strain has been applied to other settings, this study is the first to use the approach at seismic frequencies in an offshore setting.



The CORK (Circulation Obviation Retrofit Kit) borehole monitoring observatory, pictured here, is connected to Ocean Networks Canada's NEPTUNE cable system. It can monitor fluid pressure within the oceanic crust, which contains faults and fractures that act as pathways for water, heat, and chemical exchange between rock and ocean. Credit: Ocean Networks Canada

The researchers' compressibility determinations indicated that in the faulted oceanic crust, seismic waves traveling in the cross-fabric direction would be slowed by more than 50%. This slowing is much more dramatic than all previous standard seismic measurements have shown and suggests that there may be ubiquitous—and previously unrecognized—fracturing in the upper hundreds of meters of oceanic crust.

Their results indicate that the degree of fracturing of shallow oceanic crust is substantial and has direct influence on hydrothermal circulation and slab hydration. The crust where this study was carried out is 3.6 million years old, and the authors hope new offshore borehole monitoring in other locations will better define the nature of faulting and the crust's hydrologic properties. (*Geophysical Research Letters*, https://doi.org/10.1029/2021GL095347, 2021) **—Sarah Derouin,** *Science Writer*

New Theory Connects Tree Uprooting and Sediment Movement

The critical zone is Earth's outer skin, the space between treetops and bedrock, which comprises rock, water, soil, air, and the flora and fauna that live near the surface. As floods, landslides, and other geologic hazards shape landscapes, they transform the critical zone and the life-giving processes that support ecosystems.

One often overlooked but consequential process that shapes the critical zone is tree throw, also known as windthrow, which typically occurs during intense wind or ice storms. When a tree falls on a hillside, it carries with it the soil attached to its roots. The dislodged substrate eventually migrates downhill, contributes to erosion, and leaves behind pits and mounds on the surface.

Researchers have typically relied on field measurements that quantify the amount of soil on the roots to measure sediment displacement from tree throw. Using that knowledge, they can then extrapolate across a landscape using the volume of measured soil combined with known storms. However, because extreme weather events are relatively rare, it is difficult to capture the full extent of the impact that sediment displacement from tree throw can have without a long historical record or an expansive study area.

In a new paper, *Doane et al.* develop a theory that connects tree uprooting, hillslope sediment transport, and topographic roughness. It is the first theory to address surface roughness from tree throw. The authors believe it can serve as a foundation for quantifying the impacts of tree throw across a landscape.

The authors demonstrated their concept using Brown County in southern Indiana as a case study. In the study area, tree throw accounts for 11%–18% of hillslope sediment change. In addition, the research revealed that east facing hills have more frequent tree throw events, aligning with dominant wind patterns.

The findings of this study suggest how extreme wind events can shape terrain by uprooting trees. By using high-resolution topographic data, the approach can help constrain sediment production from tree throw across large landscapes. Furthermore, the theory can help clarify critical zone processes across extensive areas, the authors note. (*Geophysical Research Letters*, https://doi.org/10.1029/2021GL094987, 2021) **—Aaron Sidder,** *Science Writer*

Trees falling on hillsides—called tree throw or windthrow—leads to erosion and other surface disturbance that shape's Earth's critical zone. Credit: Brian Yanites

Researchers Zero In on Methane Released from Reservoirs

Methane is a potent greenhouse gas that accounts for about a fifth of today's global warming. In addition to methane emitted from livestock and agricultural practices, the gas is also spewed from the production, transport, and burning of fossil fuels and the breakdown of organic material. Methane is released into the atmosphere continually. Scientists track these emissions to use in climate modeling and greenhouse gas budgeting studies, so accurate measurements and emissions modeling systems are crucial.

Wetlands and inland water bodies like reservoirs contribute a substantial amount of methane to the atmosphere, but prior estimates are limited and highly variable. Prior global reservoir emissions estimates ranged anywhere from 18 to 70 teragrams of methane per year.

Now a new study by *Johnson et al.* uses a grid approach to estimate daily methane emissions from reservoirs. Their approach gives detailed estimates of methane flux, both geographically and by time.

The authors note that the amount of methane released from reservoirs can vary depending on the area of the reservoir, local climate, time of day or year when flux measurements are taken, and freeze-thaw cycles. To better capture these fluctuations, the researchers set up a 0.25° × 0.25° (latitude-longitude) grid pattern over reservoirs around the world. They used available methane measurements reported for reservoirs, correcting for differences created by taking measurements at a certain time of day or season. They used satellite observations to define ice-free emissions periods to model total global emissions.

Using the average methane flux estimates for each grid and the duration of emissions periods, the researchers calculated global daily emissions over a full yearly cycle. They found that the global surface area of reservoirs is nearly 300,000 square kilometers and that reservoirs are concentrated in temperate and tropical regions. Reservoirs in temperate and tropical regions had higher methane emissions (121.4–140.9 milligrams per square meter per day) compared with boreal reservoirs (3 milligrams per square meter per day), and warmer months produced higher emissions.

Globally, the researchers estimated that 10.1 teragrams of methane are emitted from reservoirs per year—lower than previous estimates. The authors note differences in surface areas, treatment of seasonal/daily emissions measurements, and shorter emissions periods to account for the reduced estimates. They say that their new methods help reduce the uncertainties in global methane budgets and that their estimates will be useful for bottom-up biogeochemical and top-down atmospheric methane emissions estimates. (*Journal of Geophysical Research: Biogeosciences*, https://doi.org/10.1029/2021JG006305, 2021) **—Sarah Derouin,** *Science Writer*

Air Pollution Poses Inequitable Health Risks in Washington, D.C.

Levels of air pollution are increasing throughout many cities around the world. Previous studies have shown a strong association between the presence of fine particulate matter with a diameter of less than 2.5 micrometers ($PM_{2.5}$) and health risks, including cardiovascular and respiratory diseases, lung cancer, and asthma. Although the Clean Air Act has improved air quality in the United States since its inception in 1970, its improvements have not been equitable—marginalized people are consistently exposed to higher air pollution levels and, by extension, greater health risks. To address these inequities, information about exposure levels and disease rates at the neighborhood scale are necessary.

In a new study, *Castillo et al.* home in on Washington, D.C., to determine the extent of the disparity in $PM_{2.5}$-related cases of mortality and disease. The authors analyzed $PM_{2.5}$ concentration data gathered from satellites as well as two data sets on disease rates—a small-scale estimation data set from the Centers for Disease Control and Prevention's 500 Cities Project and another local administrative data set from the D.C. Department of Health. They used five neighborhood-level factors—education, unemployment, income, race and ethnicity, and life expectancy at birth—to analyze the differences in estimated $PM_{2.5}$-related mortality and disease outcomes between D.C. subgroups.

An aerial view of Washington, D.C., where health risks from air pollution are uneven and inequitable, a new study reports. Credit: U.S. Air Force Tech. Sgt. Andy Dunaway

Researchers found that although $PM_{2.5}$-related health problems have decreased in Washington, D.C., over the past 20 years, these problems are uneven and inequitable across neighborhoods and subgroups. Of the 51 neighborhoods studied, the 10 with the highest $PM_{2.5}$-related health risks had 10% lower education and employment rates, 10% more people living in poverty, and $61,000 lower median household income compared with their less at-risk counterparts. The 10 neighborhoods with the highest $PM_{2.5}$-attributed mortality had 54% more Black residents. Generally, neighborhoods in D.C.'s Southeast quadrant were more at risk than those in the Northwest. Risk of chronic obstructive pulmonary disease, lung cancer, and stroke mortality was 5 times higher in Southeast wards, and risk of asthma-related emergency department visits was 30 times higher than in Northwest wards.

Castillo and colleagues say their study can provide important insight for mitigation strategies in Washington, D.C., and beyond. Fine-scale disease data, they say, should be taken into account during policymaking to lessen health inequities in cities. (*GeoHealth*, https://doi.org/10.1029/2021GH000431, 2021) **—Alexandra K. Scammell,** *Associate Editor*

Rock Structure Explains Slow Seismic Waves

Subduction zones produce some of Earth's largest and most damaging earthquakes, including the 1964 Great Alaska earthquake and the 2011 Tōhoku-oki earthquake. The magnitude 9.2 Great Alaska earthquake produced tsunamis that caused deaths and damage as far away as California. The magnitude 9–9.1 Tōhoku-oki earthquake rocked the seafloor off the coast of Japan, producing a devastating tsunami that caused more than 18,000 deaths. Understanding how physical properties of fault rock affect slip behaviors at subduction plate boundaries will help scientists better assess where similar megathrust earthquakes might occur.

On the basis of measurements of slow seismic wave speeds, scientists previously hypothesized that rock along a subduction plate interface has a high pore pressure due to anomalously high fluid content. *Miller et al.* now provide an alternative explanation based on analyses of exhumed metamorphosed sediments from Kodiak Island, located off the southern coast of Alaska. These samples resemble rocks found at the plate interface of the Alaska-Aleutian subduction zone.

These metamorphic rocks are foliated and have repetitive sheetlike structures. The researchers made acoustic velocity measurements of these samples in the laboratory and found that measurements made perpendicular to the layers reproduced slow seismic wave speeds previously measured along the eastern Aleutian margin. Physics-based models confirmed that the mineral composition of the samples and cracks aligned with foliation and could explain the measured velocities.

The researchers propose that elevated pore pressure isn't required for the slow seismic wave speeds that have been observed along megathrusts. Instead, they suggest that the velocities could be due simply to the presence of foliated metasediments. The new data underscore the importance of accounting for rock properties in studies of subduction zones. (*Geophysical Research Letters*, https://doi.org/10.1029/2021GL094511, 2021) **—Jack Lee,** *Science Writer*

Capturing How Fast the Arctic Ocean Is Gaining Fresh Water

The surface of the Arctic Ocean is getting fresher. As climate change progresses, shifts in processes such as precipitation and ice melt are reducing the salinity of Arctic surface waters, which could disrupt marine ecosystems and carbon storage. However, computer models designed to help predict the effects of climate change do not accurately reflect real-world observations of Arctic surface salinity—and it's unclear why.

Now, research by *Rosenblum et al.* suggests that two generations of one of the most widely used state-of-the-art climate models misrepresent the mixing of fresh Arctic surface waters with deeper waters. This error, the authors say, contributes to the underestimation of declining surface salinity in the region.

These new insights arose from an analysis of two sophisticated Earth system models—Community Earth System Model (CESM) versions 1.1 and 2—that are used to help scientists better predict Earth's future. The researchers used the models to estimate the salinity of the Arctic Ocean's Canada Basin in 1975 and from 2006 to 2012 and compared those estimates with real-world measurements of salinity for the same region and time periods.

Unlike previous studies that have explored underestimation of Arctic salinity, the researchers considered season-by-season changes in salinity, not just annual data. They used yearlong below-ice observations that were collected by scientists in 1975 during the Arctic Ice Dynamics Joint Experiment and by automated instruments attached to sea ice from 2006 to 2012.

The analysis showed that both models' estimates did not match the observations. Although the estimates are accurate for 1975, they overestimate salinity from 2006 to 2012. To figure out why the model estimates did not match the observations, the authors first analyzed whether the models accurately capture seasonal sea ice volume and processes that add fresh water to the ocean at its surface, including melting ice, river runoff, and precipitation. They found these estimates to be accurate, suggesting that these aspects of the models are not to blame.

However, the researchers showed, the models deviate significantly from observations in capturing how fresh surface waters mix with deeper ocean waters. Specifically, the models overestimate the depth of mixing, and this unrealistically deep mixing range ultimately contributes to the models' underestimations of surface salinity.

According to the authors, the findings of this study can inform refinements of the two analyzed models, as well as of other climate models, so they can more accurately predict future declines in Arctic surface salinity and the resulting effects on sea ice, ecosystems, and the planet. (*Geophysical Research Letters*, https://doi.org/10.1029/2021GL094739, 2021) **—Sarah Stanley,** *Science Writer*

How Fault Surface Features Can Tell Us About Future Earthquakes

Earthquakes cannot be forecast like weather, but fault line characteristics, such as structural maturity, can give hints about how a future earthquake may act. Structural maturity is related to the age of a fault, but especially important is its "experience," how much a fault has developed and changed over time and with activity.

Mature and immature faults generate very different earthquakes. Mature faults release less stress, but their rupture propagates quickly down their length, whereas immature faults create high-energy, slower quakes. A quick assessment of a fault's maturity will help scientists better understand the risks they pose to nearby communities.

A new study seeks to quantify faults' maturity into a useful metric to help assess earthquake risks. *Manighetti et al.* measured surface features of fault lines that previous studies had evaluated at several maturity levels. They then analyzed their measurements to see how they related to the maturity judgment.

The researchers found that corrugation (i.e., undulation) and step-overs were good maturity indicators. Immature faults were reliably shorter, with high corrugation and high step-over density. As faults matured, they lengthened and smoothed out, reducing undulations and step-over density.

These traits are reliable across faults, and they are also detectable at low resolutions. Scientists can map as little as a third of a fault's length at relatively low resolution and still generate an accurate assessment of the fault's maturity. This means that these metrics are practical for models and hazard assessments. Applying neural networks to the mapping process would make this method even easier, according to the authors. (*Geophysical Research Letters*, https://doi.org/10.1029/2021GL095372, 2021) **—Elizabeth Thompson,** *Science Writer*

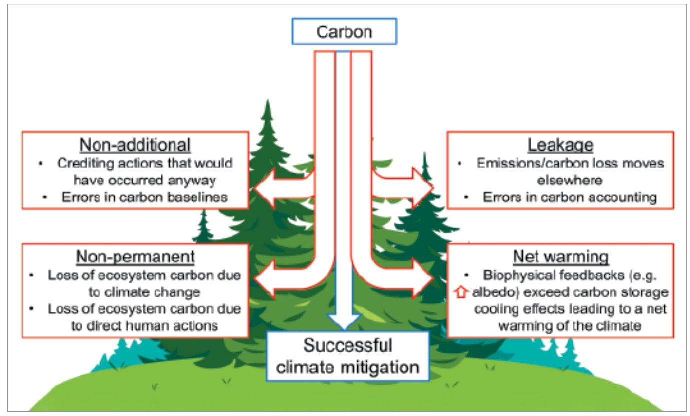
The San Andreas, a mature strike-slip fault, is well studied because it lies near major population centers. Understanding fault maturity here and at other locations can help scientists model earthquakes and assess risks to nearby communities. Credit: Doc Searls, CC BY-SA 2.0 (bit.ly/ccbysa2-0)

Permanence of Nature-Based Climate Solutions at Risk

Mitigating climate change will require both reducing emissions and increasing carbon sinks. Nature-based climate solutions (NCSs) involve efforts to conserve ecosystems that could serve as effective carbon sinks to help mitigate climate change. But what if climate change renders these same ecosystems vulnerable to loss of carbon storage rather than gain?

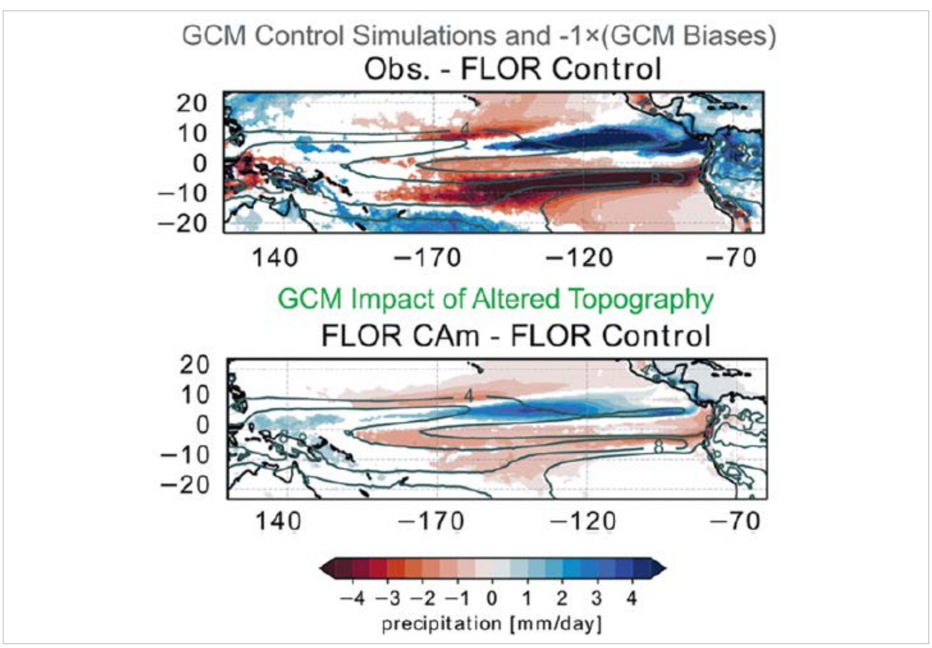
Coffield et al. use several complementary statistical approaches to evaluate the potential permanence of carbon storage in forests and other wildlands of California. They project that, because of climate change, several proposed areas for ambitious expansion of NCSs may not be able to support carbon-rich forests by the end of this century.

In a companion Viewpoint, *Anderegg* explains the need to understand such risks when promoting NCSs. He argues that NCSs still show good potential, but they must be paired with significant emissions reductions to viably contribute to overall climate mitigation. (https://doi.org/10.1029/2021AV000384 and https://doi.org/10.1029/2021AV000490, 2021) **—Eric Davidson**



Key requirements for making forest-based natural climate solutions successful for climate mitigation are shown here. Examples of major potential pitfalls are listed under each requirement. Credit: Anderegg

Raising Central American Orography Improves Climate Simulation



The differences in March-April-May (MAM) mean precipitation over the tropical Pacific between observations (Obs.) and a control model (FLOR, Forecast-Oriented Low Ocean Resolution) shown in the upper panel indicate that the model underestimates precipitation in the northeastern tropical Pacific (dark blue) and overestimates precipitation in the southeastern tropical Pacific (dark red). The lower panel shows the difference in MAM mean precipitation between a model with elevated Central American orography (FLOR Central America (CAm)) and the control model, indicating that elevating the orography results in more modeled precipitation in the northeastern tropical Pacific and less in the southeastern tropical Pacific, in better agreement with observations. Credit: Baldwin et al.

Global climate models (GCMs) suffer from biases in their representation of mean state tropical rainfall, especially in relation to the Intertropical Convergence Zone (ITCZ), where much of Earth's rain falls. The models often show peaks in precipitation on both sides of the equator, rather than just to the north of the equator as is observed. This "double ITCZ bias" limits the fidelity of GCMs in projecting future climate. Much effort has gone into mitigating this bias since the early days of GCM development, but it has not been alleviated.

Baldwin et al. suggest that a significant portion of the double ITCZ bias originates because of how Central American orography, which in reality influences tropical wind patterns and rainfall, is treated in models. Mountain peaks are often smoothed out in models that average observed orography onto model grids.The researchers demonstrate that raising the elevation of Central American orography in models reduces the double ITCZ bias, because the northeastern tropical Pacific becomes warmer owing to blocked easterlies. The study offers a simple, computationally inexpensive, and physically based method for reducing the pervasive double ITCZ bias. (https://doi.org/10.1029/2020AV000343, 2021) **—Sarah Kang**

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Greetings from Sri Lanka!

The emission of greenhouse gases (GHG) from aquatic and terrestrial ecosystems has a major impact on global climate. Leading efforts in monitoring and quantifying GHG fluxes are based on measurements with eddy covariance and closed-chamber techniques. The measured data are then used to calibrate the models that estimate global GHG budgets.

However, measurements of GHG emissions are largely concentrated in North America and Europe, whereas the low- and middle-income countries in the Global South, including those in Southeast Asia, remain largely underrepresented. Unfortunately, these countries have emerging environmental problems due to increasing population and rapid changes in land use patterns. Lack of funding and political uncertainties are among the major factors leading to very limited measurements in these underrepresented countries. Consequently, the specific role of GHG emissions from these regions has been considerably downplayed in the global GHG budget.

A study funded by the Asia-Pacific Network for Global Change Research takes a regional approach to measuring GHG emissions from rice paddy ecosystems, which constitute a major source of the highly potent greenhouse gas methane, in southern Asian agroecosystems. Measurement campaigns have been undertaken in selected paddy sites in Sri Lanka, India, and Japan to estimate methane emissions in two paddy cycles throughout the year.

The photo shows an experimental paddy site belonging to the Rice Research and Development Institute in Batalagoda, Sri Lanka. Tharindi Lakshani, a postgraduate student in the Department of Civil Engineering at the University of Peradeniya in Sri Lanka, is sampling gases from the paddy site for measurement of methane concentrations.

The study envisages contributing to the local and regional database on paddy emissions, thereby helping to close critical gaps made by the lack of dependable data from underrepresented regions.

—**Dr. Chamindu D.T.K.K.,** Department of Civil Engineering, Faculty of Engineering, University of Peradeniya

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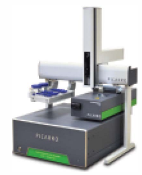

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