Eos

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SCIENCE NEWS BY AGU

The North Atlantic Is Getting Saltier

Democratizing Science in the Cloud

An Ancient Asteroid Ran Rings Around Earth

Now Ore Never

Geoscience is redefining its relationship with mining for a more sustainable future.

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From the Editor

A more sustainable future will rely, at least in part, on lithium-ion batteries. As we ring in 2025, they already power consumer electronics, vehicles, toys, and tools. Mining companies are aggressively analyzing deposits from Bolivia to the Basin and Range.

Despite increasing demand for lithium and other metals, mining is facing challenges recruiting workers. That's "A Major Miner Problem," as Emily Dieckman details in her feature story on page 16. The problem, haunted by mining's long association with environmental degradation and colonialist legacies, has no simple solutions.

Geoscience remains a crucial part of mining, of course. And this month, a trio of articles—"Here's Why Resolution Copper Wants to Mine Oak Flat" (p. 8), "Nevada Has Loads of Lithium. Here's Why." (p. 2), and "Iron Rich Volcanoes Hold Hidden Rare Earth Element Reserves" (p. 11)—puts headline news in its geologic context.

Finally, long after mining has ceased, the geosciences continue to inform research in affected communities, as demonstrated by this month's delightful Postcard from the Field (p. 32).

So brush up on yellow boy, consider how minerals made civilization, and do some hard thinking about soft metals.

16 Feature

A Major Miner Problem

By Emily Dieckman

Meeting mining's workforce needs has been a challenge for many reasons.

On the Cover

Emre Baykara/Pexels

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Nevada Has Loads of Lithium. Here's Why.

Lithium-rich brine evaporates at the Silver Peak Mine in Nevada's Clayton Valley. Lithium is leached from rhyolite source rocks and concentrated in basin reservoirs, where it has traditionally been pumped to the surface and allowed to evaporate in the desert sunshine. Credit: Scott Thibodeaux/Nevada Bureau of Mines and Geology/Jowitt et al., 2024

In Clayton Valley, a broad basin in western Nevada, aquamarine pools lie between brown-toned mountains under a clear blue sky. Similar basins and ranges naturally align like battalions from west to east across the state, though most are bone-dry. Clayton's still ponds are artificial—and rich in lithium.

Silver Peak, a tiny former silver mining town in this remote valley, became Nevada's first lithium production facility in 1966, decades before the metal became key to renewable energy technologies and national security. The facility, operated by the Albemarle Corporation, produces 5,512 tons (5,000 metric tons) of lithium carbonate annually.

Silver Peak is Nevada's only lithium-producing site, but that will soon change.

Historically, lithium had little economic significance, but surging demand for lithium-ion batteries has sharpened focus on these deposits. The U.S. Geological Survey reports that batteries, primarily for electric vehicles, comprise 87% of global lithium use. Analysts expect this share to rise to 95% by 2030. The United States produces a paltry 0.5% of global lithium, but new infrastructure in Nevada could revise that statistic.

"Nevada clearly has more lithium than any other state," said Christopher Henry, an emeritus geologist at the Nevada Bureau of Mines and Geology (NBMG).

"That's thanks to our tectonic setting," added James Faulds, a geologist also at NBMG.

The state's lithium deposits are a result of almost unimaginable geologic serendipity. Nearly everything relates to stretching crust: steep topography, abundant volcanic rocks, high heat flow, arid climate, and hydrologically closed basins, according to a new report from NBMG (bit.ly/NV-lithium).

From Water Comes Lithium

The tectonic history of North America's Basin and Range Province is complex. About 17 million years ago, crust previously thickened by ancient tectonic collisions began to stretch and thin, Henry explained.

Blocks of crust tilted like dominoes, forming basins where sediment and water pooled into shallow lakes and reservoirs. Magma rose through the thinning crust, spewing volcanic rocks to the surface, where they intermingled with cobbles, sand, and clay.

"Nevada clearly has more lithium than any other state."

Most of Nevada's basins are now dry, with only curled mud cracks and salts remaining as vestiges of yesteryear's lakes. Crustal extension continues today and is key to the state's vast lithium reserves.

"Nevada is the fastest growing state, tectonically speaking," Faulds said.

Lithium's story begins with igneous rocks, explained Simon Jowitt, an economic geologist at the University of Nevada, Reno. Most lithium mined worldwide is extracted directly from these hard rocks, including at the world's largest lithium mine, in Australia's Greenbushes pegmatite.

But Nevada's lithium source rocks (namely rhyolite, the erupted form of granite) contain only trace amounts of the metal—not enough to economically mine directly. Here geologists are instead interested in volcano sedimentary deposits, where the highly soluble metal is concentrated in nearby basins after being weathered out of its source rock.

> **"Nevada is the fastest growing state, tectonically speaking."**

Streams generally collect runoff and flow to the sea, but Nevada's arid climate and topography render most basins hydrologically closed. Streams instead bring water to internally drained basins, where it pools.

Runoff leaches lithium from rhyolites wherever they occur—from deep underground to the slopes of steep ranges. The lithium-enriched runoff accumulates in basins and slowly concentrates into brines.

"You've got something almost like a sponge," Jowitt said. "The water comes, but there's no escape."

In Clayton Valley, lithium-rich brine is either pumped to the surface to evaporate or processed through the still-emerging techniques of direct lithium extraction.

Lithium Clay Potential

Beyond brine, what excites geologists is the potential of Nevada's lithium clay.

The McDermitt Caldera, which straddles the Nevada-Oregon border, is an early manifestation of the Yellowstone hot spot, which ultimately formed a chain of volcanoes as the North American plate moved over a stationary heat source.

When McDermitt erupted 16.3 million years ago, a lake within the caldera filled with ash and smectite clay. As the lake evaporated, hydrothermal fluids transformed the lithium-rich smectite into even richer illite clay, especially at Thacker Pass at the southern end of the caldera. Today McDermitt is one of the world's largest known lithium deposits.

Uranium prospectors stumbled upon McDermitt in the 1970s. "The behemoth there is lithium," said Tom Benson, a volcanologist at Lithium Argentina Corp. With lithium neither economically attractive nor easily mined, however, production at the site never began.

Uplifted and tilted lithium-bearing sedimentary deposits extend through Rhyolite Ridge in Nevada. Sites like this hold significant potential for lithium resources. Credit: Michael H. Darin/Nevada Bureau of Mines and Geology/ Jowitt et al., 2024

Today the company's spin-off, Lithium Americas Corp, estimates that its Thacker Pass project may have access to 240 million tons (217.3 million metric tons) of the metal. It plans to start production around 2028.

Nevada's other calderas haven't yet yielded similar amounts of lithium, leaving geologists puzzled. "We're trying to figure out what happened at McDermitt," Faulds said.

Benson thinks the key is McDermitt's uniquely enriched rhyolites, formed when hot, dry magma melted lithium-rich continental rocks. In contrast, Nevada's older calderas formed in colder, subduction-like settings or melted crust with less lithium. "The tectonic setting and type of crust matter," Benson said.

Just 268 miles (431 kilometers) to the south, Rhyolite Ridge's tilted strata rise along the Silver Peak Range—Nevada's next lithium clay frontier. Once believed to sit atop a McDermitt-type buried caldera, Rhyolite Ridge is better understood as a faulted and drained Clayton Valley, Faulds explained.

Geologists think that lithium-rich rhyolitic tuff deposits initially accumulated in Rhyolite Ridge's tectonically active basin. As the basin developed, a lake formed, depositing clay-rich lake sediments over the volcanic rocks. Hydrothermal fluids seeped through faults and fissures, soaking the lake bed sediments with lithium from the rhyolites below. Later faulting uplifted and tilted these deposits, exposing the valuable clays.

To understand Rhyolite Ridge, "you take Clayton Valley, chop it up with faults, and uplift portions to expose enriched clays from lithium brines," Faulds said.

Ioneer USA Corporation is planning a lithium-boron mine and chemical processing plant at Rhyolite Ridge, with production expected to begin by 2028.

Meanwhile, in the hills outside Reno, the Tesla Gigafactory has produced enough lithium battery cells to power 500,000 electric vehicles every year since 2017. With McDermitt and Rhyolite Ridge production set to start amid ongoing Clayton Valley operations, Nevada's lithium production is expected to rise.

By **Evan Howell,** Science Writer

Hot Spot Lavas Around the World May Have Something in Common

When it comes to the lava they produce, no two volcanoes are the same. The composition of basaltic lava varies greatly from one part of Earth's surface to another.

For decades, geochemists have argued that this variation is because each volcano draws from a different rock reservoir in the mantle, the 2,900-kilometer-thick (1,800-mile-thick) portion of the planet that underlies the crust. A new study hints that the mantle may be more uniform than scientists thought.

Oceanic crust being subducted into the mantle at plate boundaries, the traditional argument goes, introduces new chemical elements to create these highly distinct reservoirs in the deep mantle. This idea, however, doesn't fit with geophysical understandings of Earth processes, which say that convection should mix all that mantle material into a uniform soup.

Volcanoes, according to that model of uniform mantle, should produce identical lava. So why don't they?


A homogenous mantle may be the source of hotspot lavas around the world, including Kīlauea, erupting here in 2018. Credit: Hawaiian Volcano Observatory/USGS

Tracing the Journey of Magma

In an attempt to answer this question, Matthijs Smit of the University of British Columbia and Ellen Kooijman of the Swedish Museum of Natural History collated data from more than 200,000 basalt samples collected from oceanic island volcanoes situated above mantle hot spots around the world. They determined the chemical composition of these lavas.

> **"The mantle that is down there makes a very specific, distinct, single kind of juice."**

Hot spot magmas start out deep in the mantle with lots of nickel in them. As they travel from their source, nickel crystallizes out of the melt, so magmas that make it to the surface and erupt as lava have a lower proportion of nickel than they did when they first formed.

Scientists can therefore use the amount of nickel in lava to gauge how far it has traveled. Pairing this with other chemical information, they can chart the evolution of a magma's chemistry, from melt to eruption.

"We actually found that they all follow a very distinct trend," Smit said.

That wouldn't be possible if they came from isolated, chemically distinct mantle reservoirs, Smit said. "If all the melts started out differently, we shouldn't see any clear trends," he explained.

The implication is that all hot spot basalts start from a single source magma derived from partial melting of a homogeneous deep mantle. "The mantle that is down there makes a very specific, distinct, single kind of juice," Smit said. "It comes out everywhere, and it just starts to live its own life from then on."

Old slabs of crust, he said, likely lie buried in the mantle, but only in the uppermost part.

As the magma travels up through the mantle and crust, it interacts with these crustal remains, leading to changes in its chemistry. "Depending on where the lava goes, depending on what kind of lithosphere it has to go through, what kind of crust it sees, it evolves in its own unique flavor," Smit explained.

These different "flavors," he said, account for the vast range of lavas found in hot spot volcanic regions around the globe. The research was published in *Nature Geoscience* (bit.ly/hot-spot-lavas).

A New Paradigm?

The study, Smit said, represents a completely new way of understanding Earth's mantle. It "basically turns everything upside down. The complexity's at the top, not at the bottom."

"It also makes the mantle more simple, which is probably more consistent with nature," Smit added.

Ananya Mallik, a researcher with the University of Arizona who was not involved in the study, said she found aspects of the research "compelling."

"It's an interesting idea that [the researchers] put forth," she said. "I think it may be a starting point for us to investigate this further."

She pointed out, however, that earlier research has found that to explain the high nickel content of ocean island basalts, oceanic crust must reach the deep mantle (bit.ly/olivine-free-mantle). “This study does not cite that paper,” she said. “I think that needs reconciliation.”

> **“To most mantle geochemists, these would have to be alarming conclusions, running contrary to a scientific consensus crafted over the past four decades.”**

The study was “too simplistic,” said Marco Brenna, a petrologist with the University of Otago in Aotearoa New Zealand who was not involved in the study. Its use of a global dataset, he said, “hides the local heterogeneities.”

“The problem is that there are more… unknown parameters than we can put our fingers on, and therefore every model, especially global ones that just blur the local particularities, will be misleading at best,” he wrote in an email.

Jon Woodhead, a geochemist at the University of Melbourne who was not involved in the study, wrote in an email that he initially also found the premise of the study “very hard to accept.”

“To most mantle geochemists, these would have to be alarming conclusions, running contrary to a scientific consensus crafted over the past four decades,” he wrote. However, he noted that he tested the idea using some geochemical data he had on hand. He wrote that “to my surprise,” he found “very convincing trends” that corroborated the study’s findings.

“It does seem clear that there is potentially a previously unrecognized issue at play here,” Woodhead wrote.

“Further research will likely be required before we can say whether any modification, or even upheaval, of the existing paradigm will result,” he wrote.

By **Bill Morris,** Science Writer

A Close Asteroid Encounter May Have Once Given Earth a Ring

Rings are a pretty common phenomenon in our solar system: All of the large planets have them, as do several dwarf planets. Now, a new look at old impact craters suggests that Earth may once have had a temporary ring created by the breakup of a passing asteroid that got too close.

“In the Ordovician, 466 million years ago, there’s a cluster of impact craters,” said lead researcher Andrew Tomkins, a planetary scientist and petrologist at Monash University in Melbourne, Vic., Australia. “It’s the only time in the Earth’s impact crater record when there was a distinct spike in the cratering rate.”

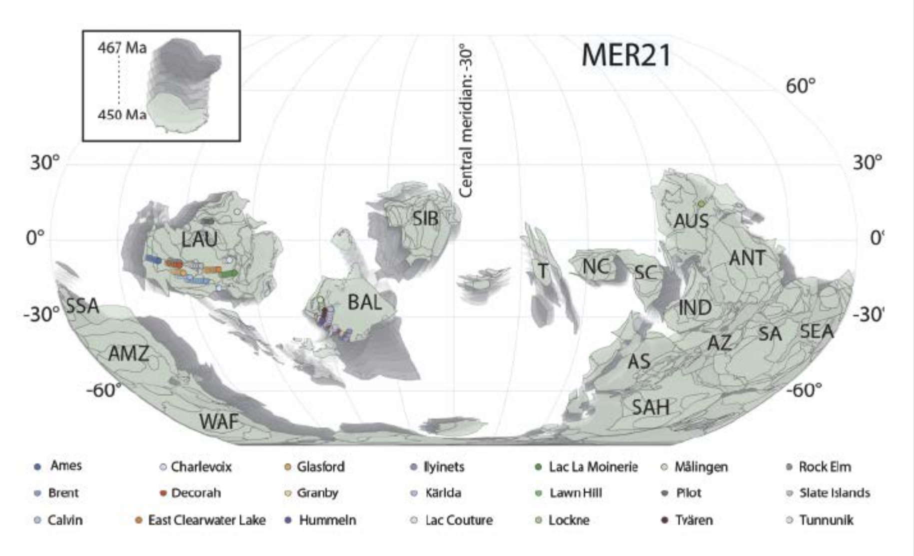
The flurry of impacts occurred between 485 million and 443 million years ago. Limestone around the world geochemically records the beginning of this spike with a heavy enrichment of L chondrite meteorite and micrometeorite debris. There are also 21 impact craters scattered across the continents that date back to this period.

How Did Those Craters Get There?

Tomkins and his colleagues wanted to investigate the origins of the impactors. Did a collision in the asteroid belt send L chondrite fragments hurtling randomly in all directions (including at Earth), or did the impactors’ journeys start closer by?

> **“The impact structures are really obvious, and we wouldn’t miss them if they were there.”**

The team used six plate tectonic reconstruction models to turn back the clock on Earth’s surface and trace the impact craters from their present-day locations back to their original locations. The models showed that 466 million years ago, all of the craters were concentrated within 30° of the equator. Plenty of crater-preserving crust was outside that narrow strip, so it’s not likely that nonequatorial Ordovician craters escaped notice.



Upon impact, the Ordovician craters (colored dots) were concentrated within 30° of the equator. MER21 refers to the plate tectonic model used to reconstruct the positions of the continents, and other labels are abbreviations of continent names: AMZ, Amazonia; ANT, Antarctica; AS, Arabian Shield; AUS, Australia; AZ, Azania; BAL, Baltica: IND, India; LAU, Laurentia; NC, North China; SA, Southern Africa; SAH, Saharah; SC, South China; SEA, Southeastern South America; SIB, Siberia; SSA, Southern South America; T, Tarim; WAF, West Africa. Credit: Tomkins et al., 2024, https://doi.org/10.1016/j.epsl.2024.118991, CC BY 4.0 (bit.ly/ccby4-0)

"The impact structures are really obvious," Tomkins said, "and we wouldn't miss them if they were there." The equatorial concentration is "quite unusual," he added.

If the impactors originated from a collision in the distant asteroid belt, the meteorites would have struck random locations on Earth, rather than falling along a narrow strip, Tomkins explained. What's more, there would also have been a flurry of impacts on the Moon and Mars at the same time, and there is no evidence of that.

Together these lines of evidence suggest that the Ordovician impacts are "all related to each other by a single L chondrite body that broke up around the Earth," Tomkins said.

For that to happen, an asteroid would have had to pass within Earth's Roche limit, a theoretical boundary within which Earth's gravity overcomes an object's internal strength and shreds it to pieces. (We saw this phenomenon happen to the comet Shoemaker-Levy 9 in 1992 when it got too close to Jupiter.)

Given enough time, debris within the Roche limit can concentrate into a ring. "That's what we're suggesting explains the distribution of impact craters," Tomkins said.

The hypothesized equatorial ring would have gradually dissipated over at least 40 million years, which is in line with theories that ring systems in the solar system are typically young and temporary features.

Using data collected from recent spacecraft missions to asteroids, the team calculated that the ring-generating asteroid was 10.5–12.5 kilometers (6.5–7.8 miles) across.

These results were published in *Earth and Planetary Science Letters* (bit.ly/Earth-ring).

Earth could have had rings at some point in its past. Credit: NASA; Kevin Gill, CC BY 2.0 (bit.ly/ccby2-0)

Must Be Rare, but Not Too Rare

Not everyone is convinced, however, that a ring is the best explanation for the Ordovician impact clustering. "The idea of a ring is supported by the volume of material and the size of craters linked to the event," said Elizabeth Catlos, a geoscientist at the University of Texas at Austin who was not involved with this research. "But," she added, "the data might be equally compatible with a single, large, fragmented asteroid with several pieces that happened to fall to Earth at different times over a segment of Ordovician time."

Catlos, who has studied Ordovician impacts, noted that it's notoriously hard to pin down exact ages for impact craters and that some of the minerals used to date them are susceptible to being reset by later heating, further confusing the geologic record. Some of the Ordovician craters might not be Ordovician at all. "The ring theory should be tested by pushing our analytical limits to get more precise dates from radiometric minerals reset during impacts," she said.

She added, "The ring idea is an exciting one to get other researchers, students, and the general public interested in the challenge of timing meteorite impacts."

"I would expect that the folks who do those sorts of studies are probably warming up their computers right now."

Andy Rivkin, a planetary astronomer at the Johns Hopkins University Applied Physics Laboratory in Laurel, Md., who was not involved with this research, said that the proposed close encounter "seems plausible."

"The meteorite compositions being considered are very common among near-Earth asteroids," which is a mark in favor of the ring theory, said Rivkin, who studies asteroids and their interactions with other objects.

Ten-kilometer-wide asteroids probably pass Earth every 70–80 million or so years, Rivkin estimated. He added that the alleged ring's lifetime of 40 million years is relatively short compared with Earth's lifetime but still long enough to account for the spread in crater ages. A ring-producing encounter is rare, which is why Earth doesn't have rings now, but probably not so rare that it's never happened at all.

Advanced simulations of Earth-asteroid encounters that more precisely calculate the likelihood of such an encounter, as well as account for the physical properties of L chondrite asteroids, would help convince Rivkin of the past existence of a ring.

"I would expect that the folks who do those sorts of studies are probably warming up their computers right now," he joked.

In fact, the researchers are currently working with astrophysics modelers to dial in on the likelihood that a ring formed and, if it did, exactly how big it would have been. Maybe down the line, Tomkins added, others might look into how opaque the ring was and whether its shade could have had an impact on global climate. If so, paleoclimate records might lend further credence to the idea of Earth's ephemeral ring.

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

The North Atlantic Is Getting Saltier

Seawater salinity is not the same everywhere, and ocean basins are becoming more disparate in their saltiness.

Data from ship- and satellite-based sensors show that the salinity contrast between the North Atlantic and North Pacific oceans has increased by about 6% over the past 50 years. Specifically, subtropical regions of the Pacific are becoming fresher, whereas the same regions in the Atlantic are becoming saltier. A new study in *Nature Climate Change* points out that this shift may have been driven by ocean warming and changes in wind circulation (bit.ly/salty-Atlantic).

"The finding is exciting," said study coauthor Yuanlong Li, an oceanographer at the Institute of Oceanology, Chinese Academy of Sciences, in Qingdao. Whereas most of the existing studies on ocean saltiness assume that freshwater fluxes alone control the salinity, "we show that ocean dynamics coming from surface wind and ocean warming also matter," he added.

Li and his colleagues set out to investigate how differences in salinity between the Pacific and Atlantic may be contributing to contrasting climate change effects such as sea level rise and oxygen loss.

They compared data on ocean salinity with climate simulations to look at how much the water column moved. This approach allowed the researchers to isolate how much of the salinity change was because of changes in ocean circulation due to sea surface winds or surface warming compared with changes in freshwater addition such as increased rainfall.

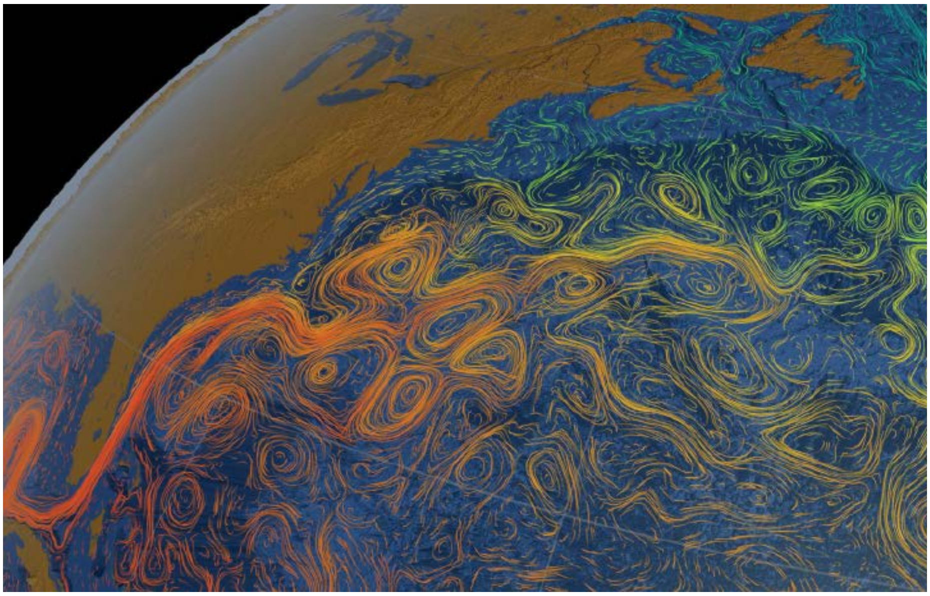
The datasets confirmed that in the top 800 meters of the tropical and subtropical regions of the oceans, the difference in salinity between the Atlantic and Pacific has increased by about 3.6%. Near the surface, the difference increased by 6%.

To look into the causes of salinity change at different depths, the researchers evaluated two main phenomena: heaving and spicing.

Winds and Warming

Heaving is the rising or falling of a column of water without its temperature structure being altered—like moving an entire layer cake up or down. In the ocean, heaving is caused by changes in ocean currents and temperatures and wind-driven upwelling and downwelling.

The researchers found that in the North Atlantic, the salinity increase in the upper 800 meters was mainly due to heaving driven by wind. Changes in surface winds pushed water together in the middle latitudes, causing saltier water to accumulate in these regions. Westerly winds in the North Atlantic have gotten stronger and are blocking salty water from moving north, leading to increased salinity at midlatitudes.



Ocean currents along the U.S. East Coast get colder as they travel north. Credit: NASA/Goddard Space Flight Center Scientific Visualization Studio

Spicing occurs when water masses mix or exchange heat and salt—like mixing the ingredients between each layer of a cake to change their flavors. The researchers found that the phenomenon was mainly driven by ocean warming, which led to changes in the density of the water. The boundary between warm surface water and deep colder water varies with latitude: It's shallower or at the surface closer to the poles, and deeper toward the equator. As the upper layer of the North Atlantic warms, the boundary migrates northward. Mixing occurs along that boundary.

The group's modeling work revealed that the North Pacific saw a slight freshening near the surface due to spicing. The top 400 meters of the North Atlantic saw a small additional increase in salinity due to spicing.

Overall, spicing and heaving lead to a noticeable increase in saltiness in the North Atlantic compared with the North Pacific.

A Fresh Look

"I think their analysis is new and looks at salinity changes in the Atlantic from a more ocean-centric perspective, rather than just focusing on the atmosphere," said Aixue Hu, a climate scientist at the National Center for Atmospheric Research in Boulder, Colo. Most previous research has centered on how atmospheric factors such as evaporation and precipitation affect salinity. This study, however, dives deeper into ocean circulation patterns and water properties to understand these changes better.

Though the study is a "great work of quantitative analysis," various other climate factors could also be playing a large role, said Arnold L. Gordon, a climate scientist and professor emeritus at Columbia University. Fluctuations between El Niño and La Niña, the North Atlantic Oscillation, and the Pacific Decadal Oscillation might be having a significant effect on wind-sea interactions, and they may also be driving the salinity changes, Gordon said.

In addition, a boundary current near the southern tip of Africa leaks salty and warm water from the Indian Ocean into the Atlantic Ocean. "This leakage has likely increased over recent decades and centuries," Gordon added. "Future research should expand looking into these relationships."

By **Saugat Bolakhe** (@saugat_optimist), Science Writer

Here's Why Resolution Copper Wants to Mine Oak Flat

In September, a group of advocates concluded a months-long "prayer journey" from the Lummi Nation north of Seattle to Washington, D.C., to deliver an appeal to the United States Supreme Court. The appeal asks the court to hear a case determining whether the government is violating the constitution by swapping government-owned land with Resolution Copper, a joint venture of two mining companies, Rio Tinto and BHP, for the development of a copper mine near Superior, Ariz.

The advocates, from the nonprofit Apache Stronghold, are the plaintiffs in the case. In *Apache Stronghold v. United States of America* (bit.ly/Apache-Stronghold-v-USA), they argue that the development of a copper mine would violate the First Amendment rights of Indigenous community members who consider Oak Flat, a 4,600-acre (19-square-kilometer) area above the copper deposit, an important religious site, said Naelyn Pike, a spokesperson for Apache Stronghold.

The area is one of many in southeastern Arizona that, by a twist of geologic fate, sit above significant copper deposits, making them magnets for mining operations.

The Copper Triangle Emerges

Arizona is home to some of the world's largest copper deposits, giving it the nickname "the Copper State."

Some of these deposits exist in the so-called Copper Triangle, southeast of Phoenix, which formed after magma intruded into the upper 5–6 miles (8–10 kilometers) of crust.

These intrusions may have been fed from a larger, deeper body of magma created when the Farallon plate was subducting beneath the North American plate during the Laramide orogeny, though their source is still debated by scientists.

The magma intrusions, like most ordinary igneous bodies of their size, carried dissolved metals, including copper. As the magma cooled in the shallow crust and minerals started to crystallize, highly pressurized, hot, metal-rich fluids were abruptly pushed into the surrounding rock along fractures. The fluid depressurized, cooled, and reacted with the rock around it to precipitate copper in the form of copper-iron sulfides such as chalcopyrite.

Deposits such as these are known as porphyry deposits.

"You can think of it as a volcanic eruption in the subsurface," said Mark Barton, a geologist at the University of Arizona.

Analysis of sediment cores from the region indicates that three of these hydrothermal eruptions probably took place during the Late Cretaceous, about 65 million years ago.

The Copper Triangle "is really fertile for porphyry deposits," said Adam Simon, an economic geologist at the University of Michigan.

Arizona's "Copper Triangle" is home to one of the largest clusters of copper deposits in the world. Credit: Feoffer/Wikimedia Commons, CC BY-SA 4.0 (bit.ly/ccbysa4-0), and Hehnke et al., 2012, https://doi.org/10.5382/SP.16.07; modified by Grace van Deelen

Over time, extensional faulting caused by a stretching of the crust chopped up the porphyry deposits and caused blocks of rock to tilt like toppling dominoes, which moved the deposits closer to the surface. About 18 million years ago, an eruption from the nearby Superstition Caldera covered the area with volcanic tuff (ash), forming what is now Oak Flat.

The Resolution Copper project aims to mine high-grade copper ore from beneath Oak Flat, a site in Arizona with religious importance to some Indigenous groups. Credit: Russ McSpadden/Center for Biological Diversity

The top of the copper ore body is currently 1.5 kilometers (5,000 feet) below the surface at its shallowest.

Though ancient magmatism formed deposits throughout the West, southeastern Arizona is unusually convenient to mine, Barton explained. The underground copper has been lifted close enough to the surface to feasibly access, but is still buried deep enough to be preserved. That's thanks to the climate in southwestern North America, which has been relatively dry for much of the past 200 million years, preventing erosion from exposing the deposits.

High-Grade Potential

According to Resolution Copper, the deposit at Oak Flat is 1.5% copper. That's exceptional, said Barton and Simon, as most copper deposits in the southwestern United States are typically about 0.5% copper.

Because it costs the same amount of money to mine a high-grade deposit as a low-grade one, the Resolution site is particularly attractive for industrial activity, Barton said. "It's very large and it's exceptionally rich…certainly in the top 20 of these kinds of deposits around the world in terms of size and contained metal."

The high amount of copper at the site may also reduce the need to mine elsewhere, he said. Resolution Copper claims it will be able to produce as much as 18 billion kilograms (40 billion pounds) of copper over 40 years—enough for more than 200 million electric vehicle engines, according to the International Copper Association.

> **"It's very large and it's exceptionally rich… certainly in the top 20 of these kinds of deposits around the world in terms of size and contained metal."**

To access the ore, Resolution Copper proposed to use a method called panel caving or block caving, in which large sections of underground rock are cut and removed. The process eventually causes the surface to subside, permanently altering the land above.

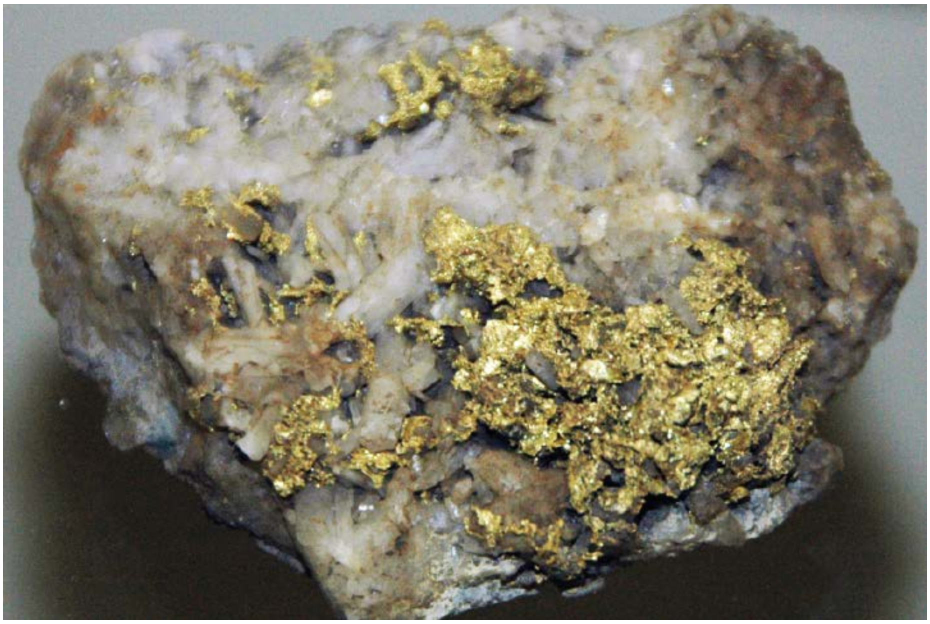
"There will be a large pit that is generated at the surface by the mining as a result of pulling this large volume of material out from underneath it," Barton said.

The current mining plan covers approximately 7,000 acres (28 square kilometers) of land, according to Tyson Nansel, the principal adviser for communications at Resolution Copper. The company has "committed to maintaining access to the Oak Flat campground as long as it is safe, meaning it will likely remain open for at least decades, or it may never be impacted," Nansel wrote in an email.

"Resolution Copper is committed to being a good steward of the land, air, and water throughout the entirety of this project," Nansel wrote. "Resolution Copper will be required to closely manage, monitor, and report subsidence impacts to the U.S. Forest Service before, during and after our mining operations to minimize the potential impact of our work and preserve natural features."

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

Earthquakes May Lace Quartz Veins with Gold



James St. John/Flickr, CC BY 2.0 (bit.ly/ccby2-0)

Most of the world's gold nuggets come from veins of quartz found in ancient mountain belts. Hot solutions of water and dissolved elements migrated deeply into these regions when they were active, depositing quartz along faults, fractures, and other rock boundaries. From those hydrothermal fluids, bits of gold also crystallized.

Until now, scientists have wondered how the gold could be concentrated enough to form such large (pebble- to fist-sized) nuggets. New research published in *Nature Geoscience* shows that ongoing earthquakes may have seeded and grown them (bit.ly/quake-nuggets).

Before this work, it was "almost impossible" to explain the concentration of gold located in some parts of quartz veins, said Damien Gaboury, a retired geologist from the Université du Québec à Chicoutimi in Canada who wasn't involved with the work.

"Because the solubility of gold is low in natural fluids, it would take a huge volume of fluid to make a gold nugget in a vein," said Chris Voisey, a geologist at Monash University in Melbourne, Vic., Australia, who led the new work. For example, if there's 1 part per million of gold in solution, it would take five Olympic swimming pools of that fluid to form a 10-kilogram (22-pound) chunk of gold.

That's where earthquakes come in. Earthquakes send seismic waves rippling through the earth, compressing and deforming rocks. Quartz, a mineral made of silica, has a property known as piezoelectricity. When quartz is squeezed, it produces electrons and generates voltage.

The voltage caused by tectonic stress such as that from earthquakes can play a role in some chemical reactions. Voisey and his colleagues wondered whether the reactions that form gold could also be affected, so they tested the idea.

Pounding Quartz

"What I wanted to do was basically make an earthquake in the lab," Voisey said.

Using a tool akin to an automated hammer, he pounded quartz crystals in a gold-bearing solution for an hour. When he looked at the crystals under a microscope, he saw tiny bits of metallic gold stuck to the quartz. "I went nuts," Voisey said. "I was, like, jumping around the lab, throwing chairs." A quartz piece that hadn't been hammered didn't show signs of gold metal.

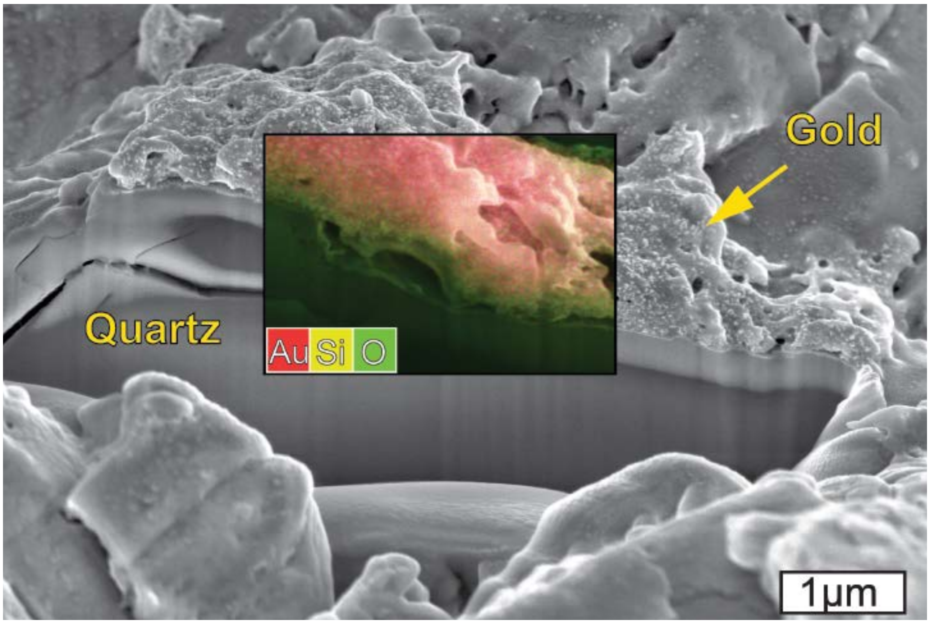
The researchers noticed that the gold had clustered on the mineral slabs rather than forming a uniform coating on the quartz. "It was basically trying to make nuggets," Voisey said.

When the group hammered quartz pieces that naturally had gold, they saw that gold from the solution deposited onto gold already in the vein. "That was the exciting bit," he said. "This was where we could start building large gold accumulations."

Because this deposition is an electrochemical process, the gold in solution prefers to glom on to metallic gold, an electrically conductive material, rather than on to quartz, which is an insulator and tends to trap charges rather than allowing a current to flow.

"This type of mechanism is exactly what you need to get that gold out of solution," said Iain Pitcairn, an ore geologist at Stockholm University in Sweden. "You need something that traps the gold that's in the fluid quickly and in one place, or else it just dissipates away and it never forms a gold deposit."

Although this experiment provides a first demonstration of how gold can form metallic chunks on environmental quartz electrochemically, the process is reminiscent of industrial processes for depositing gold, Gaboury noted.



This image, taken with a scanning electron microscope, shows where gold deposited on quartz after hammering that simulated the shocks of an earthquake. Credit: Chris Voisey

The places where orogenic gold deposits occurred would have experienced multiple low-magnitude earthquakes every day for between 10,000 and a million years, allowing gold to build up nearly continuously, he said.

Scientists have known that gold in natural fluids can form supersmall particles in some ores. And researchers have explored how quartz's piezoelectricity can kick off reactions to produce hydrogen. But how long, interconnected networks of gold formed in quartz was still unknown, said Pitcairn, who was not involved in the study. "It's the first time that somebody's really explained that kind of texture."

The new study puts together what scientists knew about quartz veins and the material properties of quartz. "It's probably one of the most important contributions since decades of research on gold deposits," Gaboury said.

There's far more to explore at the intersection of quartz piezoelectricity and geology, Voisey said. The team plans to continue investigating earthquake-enabled deposition and whether it can seed other minerals, such as those containing both gold and antimony.

The quest to understand orogenic gold deposits isn't over yet. Researchers still don't know what makes some veins stuffed full of gold and others not, Pitcairn said.

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

Iron-Rich Volcanoes Hold Hidden Rare Earth Element Reserves

The Kiruna Iron Mine in Sweden is the largest underground iron ore mine in the world. Credit: Andriy Baranskyy, CC BY-NC-ND 2.0 (bit.ly/ccbyncnd2-0)

Volcanoes that are rich in iron might be prime locations to find high concentrations of rare earth elements. Recent lab experiments have demonstrated that when iron-rich magmas experience volcanic pressures and temperatures, the resulting iron oxide-apatite (IOA) deposit separates into two unmixable melts, one of which is highly enriched in rare earth elements (REEs).

"The rare earth element contents can be close to 200 times higher than in the silicate-rich melts," said Shengchao Yan, a doctoral student at the Chinese Academy of Sciences' Institute of Geology and Geophysics and lead researcher on the new experiments.

The research, which was published in *Geochemical Perspectives Letters*, supports the idea that deposits of iron oxide and apatite, an iron-phosphate mineral mined globally for its iron, could be rich targets for REE exploration (bit.ly/REE-targets).

Not Rare, but Hard to Mine

Rare earth elements, the lanthanide series as well as yttrium and scandium, are key to a green energy transition because they are required for producing electric vehicle and wind turbine magnets, solar panels, and storage batteries. With the growing need to address the climate crisis, economies around the world face an increasing demand for REEs.

But supply is hard to come by. Despite the name, REEs are not rare. These metals exist around the world but are often found in small concentrations or are locked in other minerals. This makes REE extraction economically and environmentally unsustainable for most countries. Currently, 63% of the world's REE mining occurs in China.

However, rocks enriched in REEs have been found unexpectedly at iron mines in Kiruna, Sweden; El Laco, Chile; and elsewhere. The enrichment makes those REEs easier to extract.

These mines are sited on extinct iron-rich volcanoes that have large IOA deposits.

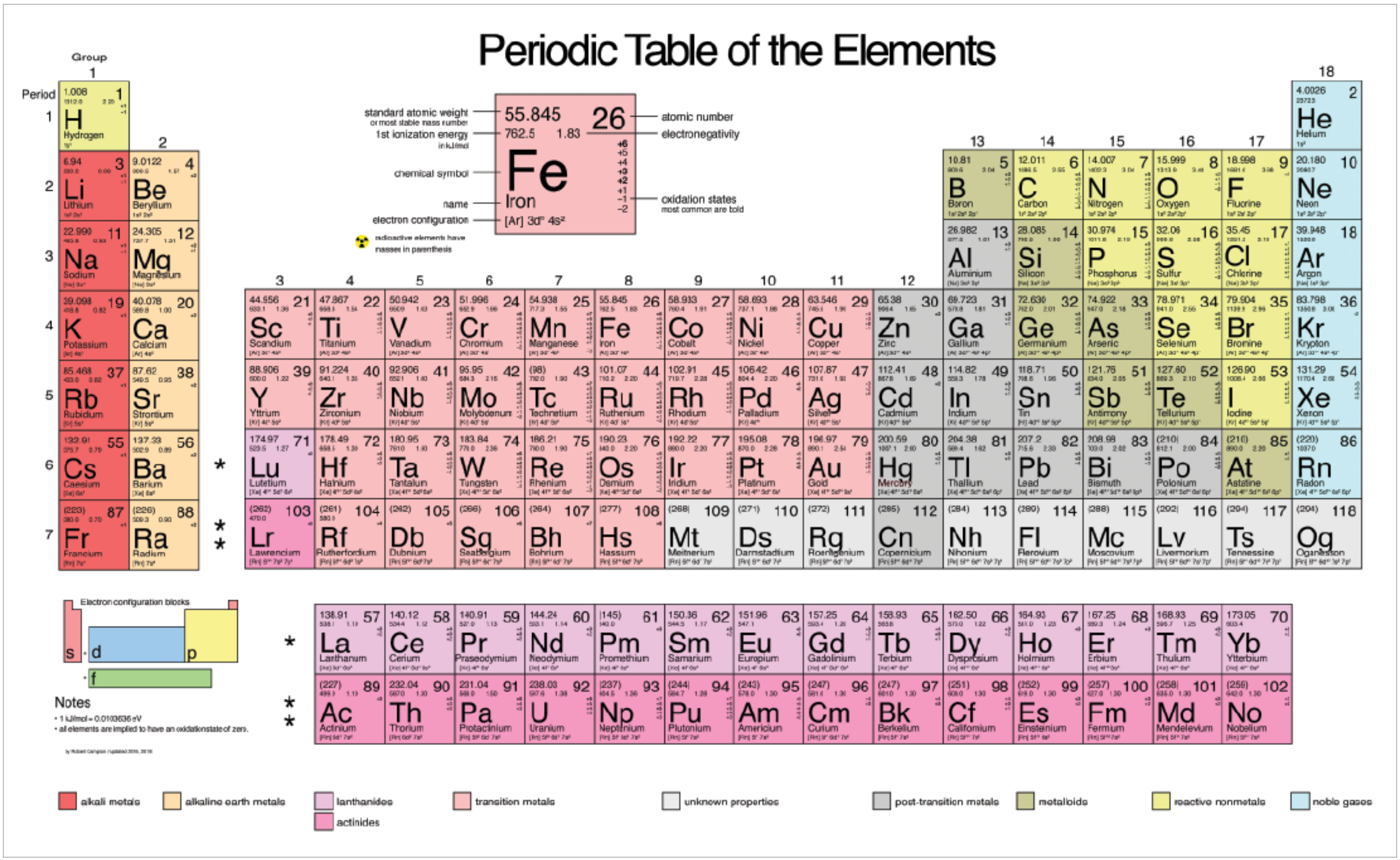
"In many cases when we find rare earth elements or metals in general, we find them by accident," explained Michael Anenburg, an experimental petrologist at Australian National University in Canberra and a coauthor of the new research. "Those mines are mining iron oxide. They're mining magnetite. They never looked [to see] if they even have any rare earth elements."

The discovery of concentrated REEs inside IOA deposits has prompted mining experts and geologists to ask, "Is that just by accident, or is there something about those magmas that makes them like that?" Anenburg said.

To explore the possible conditions under which the REEs became separated out and concentrated in the IOA deposits, the researchers subjected magmatic mixtures to volcanic pressures and temperatures in the laboratory. They observed that under those conditions, the magmas separated into two unmixable, or immiscible, components: an iron phosphate (FeP) melt and a silicate melt.

The REEs concentrated more strongly in the iron phosphate melt than in the silicate-

El Laco in Chile is an iron-rich volcano complex and also a source of rare earth elements. Credit: Daniel P. Gauer/ Wikimedia Commons, CC BY 2.0 (bit.ly/ccby2-0)



Rare earth elements, marked here with asterisks, are key to developing clean energy at scale. Credit: 2012rc/Wikimedia Commons, CC BY 3.0 (bit.ly/ccby3-0)

rich melt, Yan said, and lighter REEs concentrated more strongly than the heavier ones. The FeP melt was enriched in lanthanum, the lightest of the lanthanide series, about 200 times more than the silicate was, and lutetium, the heaviest lanthanide, was enriched about 100 times more. (Yttrium and scandium, the lightest nonlanthanide REEs, inexplicably did not follow this trend.)

Untapped Potential

Although these experiments are not the first to show that IOAs are rich in rare earth elements, they can help geologists understand one mechanism by which these melts become enriched.

“Overall, I think it’s a fantastically useful contribution and sheds important light on the debated process of IOA genesis and in particular the process and extent of REE enrichment in this enigmatic class of deposits,” Tobias Keller, a computational geochemist at the University of Glasgow in Scotland who was not involved with the research, wrote in an email.

“We can try to find the optimal formation conditions of the deposits, so people can reduce or narrow down the exploration location of these deposits.”

These experiments add weight to the hypothesis of a volcanic origin for IOA deposits, Keller explained, and provide “important confirmation that REE partitioning between such immiscible liquid pairs strongly favors the FeP-rich melt.” This research helps explain the occurrence of REE-enriched apatite in Kiruna, Sweden, Keller added. But just how these distinct melts form separate bodies of iron-rich magnetite and REE-rich apatite is still a mystery, he wrote.

The iron-rich volcanoes upon which IOA deposits are found are now extinct, Yan noted. By modeling iron-rich volcanoes throughout their evolution, he said he hopes to explore how REE enrichment may have changed over Earth’s history.

“We can try to find the optimal formation conditions of the deposits, so people can reduce or narrow down the exploration location of these deposits,” Yan said.

“Rare earth elements are critical metals,” Anenburg said. A country might not need a large supply now, but global demand will only continue to grow. Knowing whether an active iron mine might also be an untapped source of REEs could pay dividends in the future.

“It’s a win-win,” he said, “because the company gets more value out of the stuff they’re mining anyway. And then the environment wins, because we don’t need to put a new hole in the ground.”

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

Democratizing Science in the Cloud

The geoscience community is undergoing a pivotal transformation from unevenly distributed local computing resources to an on-demand and cloud-based computing infrastructure. This transition is necessary to meet the growing computational needs of scientific research, educate the next generation of geoscientists, and tackle critical environmental challenges.

Cloud computing refers to the delivery and use of computing resources, such as processing power, data storage, and software, via an Internet connection as needed, allowing users to access these resources without the need for local infrastructure. Cloud computing is quickly becoming an essential tool for Earth and space scientists because of the increasing complexity and volume of scientific data and larger computing power needs. At the same time, "the cloud" is streamlining scientific workflows and enabling new kinds of analyses and collaborations across scientific disciplines.

Although the scientific benefits are clear, a number of challenges continue to slow adoption of cloud computing: training in new technologies, concerns about vendor lock-in, and the ongoing need to manage costs in a stable computing environment.

A NASA-funded, cloud-based computational research environment established in 2022 called CryoCloud addresses these challenges using a transferable community framework to deliver greater scientific inclusivity, reproducibility, and collaboration.

CryoCloud's Community Framework Catches On

The CryoCloud team partners with cloud engineers at the International Interactive Computing Collaboration (2i2c), a nonprofit, open-source cloud platform service provider for research and education. Together they curate CryoCloud with tools and workflows designed for cryospheric researchers.

The CryoCloud community framework has established a stable, cost-effective, and long-lasting platform that promotes innovation, flexibility, and community empowerment. CryoCloud's streamlined technology, training workshops, and ease of use increase access for a wide range of researchers, allowing them to reap the benefits of cloud computing and develop effective computational research practices while minimizing challenges (Figure 1).

CryoCloud's community focal point is JupyterHub, a cloud-based interactive computing environment. JupyterHub offers a flexible and powerful user interface that integrates various tools and workflows, allowing users to write and execute code, visualize data, manage files, and collaborate in a single, unified workspace. CryoCloud minimizes technical barriers, including for new users, that can prevent researchers from transitioning to cloud computing by eliminating the need for cloud engineering expertise. This allows users to focus on what they do best: science.

CryoCloud's front end uses familiar computing interfaces, making it look and feel like a local computing setup as it works with popular interactive development environments such as JupyterLab, Visual Studio (VS) Code, and RStudio for coding in common coding languages.

Starting with a pilot involving NASA's Ice, Cloud, and Land Elevation Satellite-2 (ICESat-2) science team in October 2022, the CryoCloud team has onboarded more than

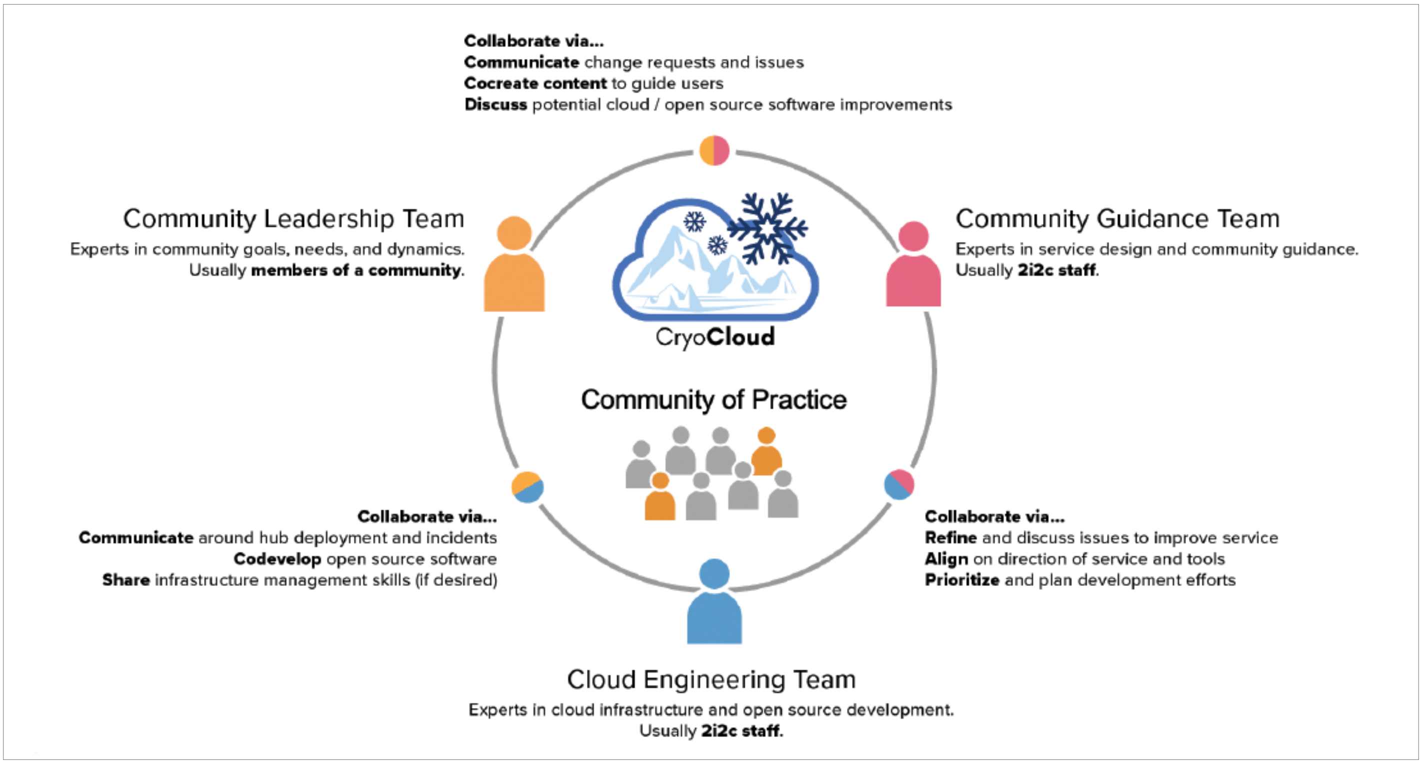


Fig. 1. CryoCloud has a community framework model. Credit: CryoCloud; adapted from 2i2c.org

CryoCloud, an interactive cloud-computing platform designed for the NASA cryosphere community, is accessible from any Internet-connected device—including this one used by coauthor Matthew Siegfried in Antarctica. Credit: Philipp Arndt

500 scientists through a variety of outreach methods.

CryoCloud has supported small hybrid community workshops such as the Future of Greenland ice Sheet Science (FOGSS) workshop, as well as conferences at larger scientific gatherings like AGU's annual meeting. The CryoCloud JupyterHub has served as the computing infrastructure for 12 hackathon-style educational and collaborative research workshops centered on NASA ICESat-2 altimetry data, QGreenland (a free mapping tool for interdisciplinary Greenland-focused research, teaching, decisionmaking, and collaboration), other satellite and airborne science missions, transdisciplinary science initiatives, and community software tools and skills. These educational hackathons teach participants data analysis, collaboration, and open science skills while offering unstructured time for coding, data exploration, and collaborative research ideation.

CryoCloud simplifies the use and adoption of advanced computing resources for students and scientists by providing a centralized JupyterHub environment, eliminating the need for participants to manage diverse local software installations and configurations. This allows event organizers and instructors to focus on hackathon content and learning objectives rather than on technical setup. In addition, instructors often contribute to CryoCloud's growing knowledge base by documenting effective workflows that emerge during events [*Fisher*, 2023; *Wong*, 2024], which helps create more tools and templates for future educational events and user teams.

Learning resources from these events are maintained and accessible through CryoCloud's Jupyter Book website.

Accessible, Flexible, Scalable, and Cost-Effective

CryoCloud simplifies access to cloud-based datasets, which are integral to NASA's Open-Source Science Initiative. Storing data in cloud-optimized formats speeds up data read-ins by a factor of 10–100 and allows users to read in data subsets, which maximizes efficiencies in computer memory usage and reduces analysis times. With CryoCloud, researchers can rapidly search and stream these large datasets to better manage the increasing volume, velocity, and variety of big data that are now commonplace in geosciences research.

In addition to accelerating scientific workflows for cloud-native data processing, CryoCloud has developed and documented in its Jupyter Book reproducible workflows for accessing non-cloud-hosted and legacy data formats. These workflows simplify the time series and data fusion investigations required for quantifying the complex processes that are changing our planet [*National Academies of Sciences, Engineering, and Medicine*, 2018].

Many NASA datasets have not yet been transitioned to be cloud hosted or stored in cloud-optimized formats, so the CryoCloud community partners with data providers to improve existing and future datasets. CryoCloud advocates for the full adoption of findable, accessible, interoperable, and reusable (FAIR) data standards and serving data products in cloud-optimized formats. Meeting these standards maximizes user benefits, expedites cloud adoption, and makes geoscientific computing state of the art.

CryoCloud is user ready with built-in and stable programming environments for Python, R, MATLAB, and desktop applications like QGIS. These environments eliminate the overhead associated with building one's own software environment.

For users with unique needs, the system provides flexibility, with the option to bring one's own environment, making it possible for different kinds of researchers to use CryoCloud's community framework.

> **With CryoCloud, researchers can rapidly search and stream large, cloud-optimized datasets to better manage the increasing volume, velocity, and variety of big data that are now commonplace in geosciences research.**

Cloud-computing resources are typically available on a pay-as-you-go basis, allowing a Jupyter Hub like CryoCloud to scale its usage on the basis of current needs. This approach avoids the cost of unused hardware and enables the scaling of servers from the typical background usage of individual and teams of researchers to hosting more than 100 workshop participants seamlessly for about $1 per person per day [*Fisher*, 2023].

Flexibility in the CryoCloud infrastructure also allows individual researchers and research teams with large and diverse computing needs (leveraging artificial intelligence and machine learning methods, for instance) to bring cloud-computing credits into CryoCloud to access more powerful systems, including GPUs (graphics processing units), which are specialized processors designed to perform complex computations.

Accelerating Scientific Discovery with Analysis Tools and Pipelines

CryoCloud has helped scientific teams debug and innovate tools, making them more useful to a wider swath of cryospheric researchers. It has supported a team from the University of Washington, for example, in building SlideRule Earth, a Python tool for on-demand data processing of various remote sensing data products [*Shean et al.*, 2023]. National Snow and Ice Data Center and ICESat-2 software developers work hand in hand with the CryoCloud team and users to create new cloud data access workflows and identify ongoing user needs (such as earthaccess and icepyx libraries). Geographic information system (GIS) tool developers have adapted CryoCloud to make desktop-only tools accessible through a cloud-based "virtual desktop," expanding their usability and availability [*Fisher*, 2023].

The toolchain available in CryoCloud allows for the streamlining of analysis workflows such as a polar Landsat sea surface temperature processing algorithm [*Snow*, 2023]. This cloud workflow eliminates onerous searching, downloading, unzipping, and stacking bands of Landsat scenes, a process that now requires only a few lines of code.

With fast data streaming and full automation using open-source Python packages in active development by other CryoCloud users, the algorithm reduces researcher time investments by weeks. It also eliminates the need for saving many data processing outputs, reducing data storage needs by 2 orders of magnitude. Making data processing pipelines reproducible and open allows future researchers to innovate more rapidly, accelerating scientific discovery.

An Open Science Blueprint for Democratizing Science

By facilitating sharing of data, code, tools, and scientific workflows across multi-institutional teams, CryoCloud is more than a computational tool; it is a nexus for scientific innovation, collaboration, and community building. By fostering this open science environment, CryoCloud is laying the groundwork for a more collaborative and transparent approach to scientific research, and it is helping to unify previously siloed groups into an integrated community focused on understanding Earth's cold regions. CryoCloud's cofounder and lead, Tasha Snow, was recognized with an AGU 2023 Open Science Recognition Prize [*Mines Staff*, 2023] for building CryoCloud upon these open science principles.

The collaboration between CryoCloud and 2i2c has resulted in a versatile platform that transcends cryospheric research. Its adaptable architecture allows for standardized and reproducible research environments that other scientific fields can use as a blueprint for their transition to cloud-based research [*Snow et al.*, 2023]. This adaptability is crucial in an era in which interdisciplinary research is becoming increasingly important for tackling complex scientific challenges. The CryoCloud community framework is durable, flexible, and cost-effective.

Making data processing pipelines reproducible and open allows future researchers to innovate more rapidly, accelerating scientific discovery.

Cloud-based interactive computing platforms like CryoCloud provide scientists with access to computational resources scaled to their needs without requiring expensive local infrastructure that is unequally distributed. This design democratizes access to cost-efficient computational resources across a diverse swath of researchers, including early-career scientists, marginalized groups, and researchers at smaller institutions and in developing countries.

After being established with funding from NASA's ICESat-2 mission for its science team, CryoCloud has been freely accessible to the NASA cryospheric research community, thanks to funding from NASA and its Transform to Open Science program. This democratization of science is a crucial step toward a more inclusive and equitable scientific enterprise.

A Changing Research Ecosystem

CryoCloud represents a shift in how scientists conduct research and education. Researchers are learning and developing the tools necessary to fully harness the big data revolution.

Small, siloed research groups are transforming into transdisciplinary research networks. CryoCloud makes these shifts possible through a community-empowered, self-sustaining ecosystem.

In this ecosystem, users and developers coproduce to enhance existing resources and tools and are committed to maximizing every investment dollar by developing innovative approaches to research and education.

The CryoCloud community framework reimagines research to make collaboration and accessibility keystones of scientific discovery and provides a blueprint for any scientific community to transition to cloud-based computing.

Acknowledgments

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A MAJOR MINER *PROBLEM*

by Emily Dieckman

Alia Rahma/Pexels

Economic geology, mining, and mineral resources programs are working to meet the needs of an industry that's struggling to find employees—at a time when some say they're needed more than ever.

Before she was a mining engineering professor, Priscilla Nelson was a "hippie chick," seen here volunteering for the Peace Corps in Ecuador in the 1970s. Credit: Priscilla Nelson

The summer of 1969 was approaching, and Priscilla Nelson, a self-proclaimed "hippie chick," had a muddy decision to make: attend Woodstock or go to geology field camp.

In the end, she chose rocks over rock 'n' roll. It was an exciting era for geology, with the theory of plate tectonics only starting to gain wide acceptance. The upcoming Apollo 11 mission promised to give the world a new perspective on the rock we call home, and Nelson loved being let loose on a plot of land to map geologic features—just her and the rocks.

Nelson went on to a career spanning engineering, academia, and government and is currently a professor of mining engineering at the Colorado School of Mines.

As her career rose, the reputation of the mining industry—particularly in the United States and Canada—sank. Nelson, who also was a Peace Corps volunteer in the 1970s, suggested that this souring public attitude may have been related to a rise in concerns about the environment. The 1970s brought the National Environmental Policy Act, which required U.S. federal agencies to assess proposals' environmental impacts, and the Clean Water Act, which regulated water quality and the release of pollutants.

"The '70s were [when] we saw the blue marble of the Earth in the sky and realized the finiteness of everything," Nelson said.

Mining, to many, seemed contrary to this spirit of treating Earth's resources as precious. Declining public sentiment, stricter regulations, and reduced ore grades in the United States led mining companies to take much of their operations outside the country—especially to poorer nations where they could pay lower wages and face fewer environmental and health regulations, such as the Democratic Republic of the Congo—and the United States to simply import minerals from countries such as China and Mexico.

Though the domestic mining industry says it has made strides to treat the environment with more care, it's facing an increasingly urgent recruitment problem.

The number of mining engineering programs at U.S. colleges and universities has fallen from 25 in 1982 to 14 today. Mining graduations in the United States dropped by 39% between 2006 and 2023. In 2022, 71% of mining leaders reported in a McKinsey & Company survey that the shortage of workers was preventing them from meeting production targets and strategic objectives.

At a workshop hosted by the National Academies of Sciences, Engineering, and Medicine and supported by the U.S. Geological Survey (USGS) in 2024, Vlad Kecojevic, secretary general of the Society of Mining Professors, noted that only 162 students earned mining engineering degrees in the United States in 2023. That's not enough to keep pace with an estimated employment demand of 400–600 graduates per year. A 2023 report by Deloitte found that nearly 50% of skilled engineers in the mining sector will reach retirement within a decade.

> **"One day we woke up and looked around and went, 'We're all old. Where's the new generation?'"**

"For many years that went by, we kind of, as an industry, recycled all our old miners," said Bill Bieber, executive director of the Mining and Petroleum Training Service at the University of Alaska Fairbanks. "And one day we woke up and looked around and went, 'We're all old. Where's the new generation?'"

Why Mine?

"You can't have a modern standard of living without mining, and we mine more now than at any other point in human history," said Simon Jowitt, an economic geologist at the University of Nevada, Reno.

Mined minerals are in our buildings, roads, vehicles, pipes, electronics, cosmetics, furniture, appliances, and more. Cell phones contain at least a dozen minerals.

It's not only current technologies that need mineral resources, mining experts argue, but also those of the future: Renewable energy technology, including solar panels, wind turbines, and electric vehicles, needs elements such as silicon, cobalt, lithium, manganese, copper, and rare earth elements such as neodymium and praseodymium.

A 2022 White House briefing noted that global demand for critical minerals is expected to rise 400%–600% over the next several decades. The United Nations Trade and Development Board projected in a 2024 report that to achieve net zero emissions by 2030, the world will need approximately 80 new copper mines, 70 new lithium and nickel mines each, and 30 new cobalt mines.

When experts—such as the nearly 150 who gathered at the 2024 National Academies workshop—discuss the workforce problem, they often mention ideas for how the federal government could support the mining industry, both financially and organizationally. But the effort isn't limited to the government.

Across the country, U.S. educational institutions are working to remedy the mining workforce problem by addressing several barriers: a lack of awareness about the role of mining in modern life, perceived demands and inconveniences of a mining career, and negative public opinion of the industry.

Knowing Squat

Many people who work in or study mining or geology are emphatically aware of the role minerals play in everyday life. Sterling Ferguson, an economic geology undergraduate at the University of Nevada, Reno, grew up in an area of northeastern Nevada where mining is prevalent.

"I've been surrounded by mining my entire life," he said. "I grew up, like, 'Everybody works in a mine. The world needs mining.'"

Kwame Awuah-Offei, a professor of mining engineering at Missouri University of Science and Technology (Missouri S&T), said that when he was growing up in Ghana, people there were more aware of mining. As a major part of the country's economy, mining is often in the news, he said.

But not everyone has the same awareness. In most of the United States, industries larger than mining, such as Google or Apple, tend to dominate headlines.

"Unless something bad happens," Awuah-Offei said. "Then mining is in the news."

> **"When students know about mining, they start to think it's cool. The problem is they usually know squat about it."**

In a survey of 344 random students at the University of Arizona, 67% said they had "little to no knowledge of mining at all." The state was the top producer of nonfuel minerals in the United States in 2023, according to a USGS report.

"It's just something that a lot of people just have no idea is out there," said Lynnette Hutson, a Ph.D. student in mining and geological engineering at the University of Arizona who worked in the mining industry for a decade prior to starting her degree.

"When students know about mining, they start to think it's cool," said Isabel Barton, a mining and geological engineer and associate professor at the University of Arizona. "The problem is, they usually know squat about it."

Mining's proponents believe that raising public awareness about the industry's role in modern life is key to fostering interest in related careers. Many say this effort needs to start earlier.

Nelson, the Colorado School of Mines professor, lamented that elementary and middle school curricula rarely include information about Earth resources.

High school isn't much different, and Nelson acknowledged that changing graduation requirements is no simple task. For now, she suggested high schools could offer an Advanced Placement course that students could take remotely to earn certificates in Earth resources management and potentially high school or even college credit.

At the college level, some universities and individual faculty are working to educate students about the importance of mining.

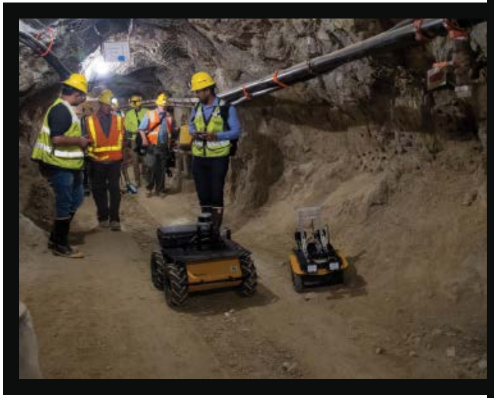
Barton created a YouTube series called *How Minerals Made Civilization*, which examines the role mineral resources have played in defining the course of history. She teaches a course listed in both the mining and geological engineering and anthropology departments on the same topic.

The University of Arizona's School of Mining and Mineral Resources offers classes, K–12 outreach, and research funding to prepare people in a range of disciplines—including environmental engineering, law, and hydrology—for the mineral resources workforce.

The Society for Mining, Metallurgy and Exploration Foundation's Minerals Education Coalition exists to educate the broader community and K–12 students about the role of mined materials in everyday life. For example, it created an infographic highlighting the estimated amount of minerals, metals, and fuels an American born in 2024 will use in their lifetime: 3.06 million pounds (1.4 million kilograms).

Visions of Shovels and Pickaxes

Even when people are aware of the role of mining in their everyday lives, they don't always want to join the profession.



Students test underground robotics in the Colorado School of Mines' Edgar Experimental Mine. Credit: Colorado School of Mines

Graduation attendees tour the Mining and Petroleum Training Service's Underground Mine Training Center facility off the Alaska Highway outside Delta Junction in 2022. Credit: UAF photo by Eric Engman

Working as a mining engineer often means working at a rural mine. Some engineers choose to live in the relatively small communities near mine sites, whereas other spend hours a day commuting from larger cities. A travel-heavy work schedule can make it difficult to start a family. Living in a rural community can compound issues employees of any sector might face, such as difficulty finding childcare, Hutson said. Limited employment opportunities for spouses can be another problem.

However, such perks as a 4-day workweek, which Hutson had at most of her industry jobs, help to offset inconveniences and make personal travel easier.

Though it's not for everyone, she said she finds mining to be an interesting field with good pay. (As of May 2023, the median annual wage was $100,640 for mining and geological engineers according to the U.S. Bureau of Labor Statistics.)

"If you're kind of technically minded, there's a lot of interesting, challenging roles that can be pretty rewarding," Hutson said.

Jowitt, the economic geologist, suggested building on these perks by borrowing tactics from other industries. As a traveling nurse practitioner, Jowitt's wife is often away from home, but she ultimately works fewer days than Jowitt does and makes about the same salary he does as a tenured professor. Benefits such as airline miles don't hurt either.

"If the industry wants to attract and keep talented and skilled people, then I think we need to think about how best to help those people have a good work-life balance," he said.

When it comes to attracting skilled workers, some programs are focused on making training more accessible.

"You're operating a million-dollar haul truck with pressurized cab and air-conditioning and backup cameras. It's a very different mining world than it used to be."

The Mining and Petroleum Training Service teaches students hands-on skills at remote mining camps. The surface mine course is 2 weeks long, and the underground mine course lasts 6 weeks: 2 weeks in an underground classroom, 2 weeks off, and 2 weeks of hands-on experience in a mine. No prior experience is required, and state funding is available to Alaska residents.

Most of the students attending aren't considering traditional secondary education, said Bieber, the program's director. Many are underemployed and have families, and the short length of the program makes it possible for them to attend. Mining companies even pay a stipend to help some students cover bills while they're in class.

In the underground mining program, students learn skills that range from operating jackleg drills and underground muckers to soft skills such as teamwork and cross-cultural communication.

"We drill and blast and muck, all of the things that these students are going to be doing on the job," Bieber said. They're grabbed up at graduation by employers, if not before.

He added that the program allows students to update their perception of mining, which, before the training camps, might include visions of sledgehammers, shovels, and pickaxes.

"You're operating a million-dollar haul truck with a pressurized cab and air-conditioning and backup cameras," he said. "It's a very different mining world than it used to be."

So far, the mining camps have trained more than 560 people, 40% of whom are Alaska Natives or members of other minoritized groups. Bieber estimated that about half are women. Two years after being hired, about 87% of people who completed the program are still with the company that hired them.

A Legacy of Harm

Perhaps the biggest factor affecting the mining workforce pipeline is the industry's reputation. Many view it primarily as an entity that causes pollution, puts profit over people, and takes advantage of communities.

Such criticisms aren't unfounded.

> "I have never considered a career in mining because I am driven to restore degraded land, not play an active role in degrading it."

A 2011 report from the Government Accountability Office determined that of at least 161,000 abandoned hard rock mines in the 12 Western states and Alaska alone, at least 33,000 had degraded the environment. In 2019, the Associated Press analyzed records from 43 contaminated federal mining sites and reported that on average, more than 50 million gallons (189 million liters) of toxic wastewater flows into ponds and streams each day. Roughly 20 million gallons (76 million liters) of it is left untreated.

Lithium mining, which often occurs in the drought-stricken Southwest, requires billions of gallons of water. And catastrophic incidents such as tailings dam failures can not only wreak havoc on the environment but also cause deaths.

Mark Samolej, an undergraduate studying restoration ecology at Colorado State University (CSU), wrote in an email to *Eos* that he sees mining at the scale it is done currently as a "bane to the things I care most about." Samolej is the vice president of the CSU chapter of the student-run Society for Ecological Restoration.

"My perception of careers in mining specifically are that they are historically high risk, physically demanding, and ecologically destructive," he wrote. "I have never considered a career in mining because I am driven to restore degraded land, not play an active role in degrading it."

Moreover, U.S. mining companies have historically developed sites on Indigenous lands or in poorer nations, often without the consent or input of communities. Many Indigenous groups and environmental advocates have resisted this development and pushed companies to adjust their practices. Some have even taken the federal government to court.

Today multiple groups are fighting construction of new operations such as the Resolution Copper Mine in central Arizona, which members of the San Carlos Apache Tribe say threatens to destroy sacred land.

Others argue that the industry has worked to improve its practices. Resolution Copper's website claims that after hundreds of consultations with Native American tribes, the company changed the project scope to avoid areas with the greatest cultural significance.

Major companies such as Freeport-McMoRan and the Newmont Corporation release annual sustainability reports, highlighting efforts to financially support communities affected by mining operations, improve safety and efficiency, reduce carbon emissions, and recycle water.

Many academic institutions are conducting research into and offering education on the same areas. Examples include the University of Arizona's Center for Environmentally Sustainable Mining, Montana Technological University's Center for Environmental Remediation and Assessment, Missouri S&T's graduate certificate in sustainability in mining, and the University of Alaska Fairbanks's natural resources and sustainability Ph.D. program.

The Colorado School of Mines Payne Institute's Native American Mining and Energy Sovereignty Initiative (NAMES) works to help Indigenous communities find financial success, energy security, and sovereignty in the energy transition. The initiative's projects include creating a scholarship for Native American students studying at the school and developing a fund to support research into energy and minerals development as they relate to tribes, in collaboration with tribes and Tribal Colleges and Universities.

Rick Tallman, who is managing the undertaking, described NAMES as "not a pro-mining initiative, [but] a pro-knowledge initiative." Understanding mining, he suggested, is key for tribal communities to make decisions about the practice on their lands—whether that means fighting mining efforts or exploring and taking ownership of mineral development opportunities. According to MSCI data, 68% of cobalt, 89% of copper, 79% of lithium, and 97% of nickel reserves are located within

Alyssa Lindsey, a graduate student in economic geology, toured the Paracatu Mine in Brazil during a Society of Economic Geologists field trip in summer 2024. Credit: Alyssa Lindsey

The Resolution Copper Mine is next to the town of Superior, Ariz. Credit: zeesstof/Flickr, CC BY-SA 2.0 (bit.ly/ccbysa2-0)

35 miles (56 kilometers) of Native American reservations.

Daniel Cardenas, a Pit River Tribe member and the CEO, president, and chairman of the board of the American Indian Infrastructure Association and the National Tribal Energy Association, is a cofounder of the NAMES initiative.

Tribal sovereignty, he said, means that all tribes are free to make their own informed decisions, including those related to mining. "I'm a strong believer in not just jobs, but also wealth creation, where [tribal] communities should have the opportunity to create wealth like everybody else in America," he said. "A lot of times, as we move forward, the way for them to do it is through critical minerals. It's a fresh opportunity for tribes, for tribal communities, to sort of make their own way and have the money and the resources to actually benefit from resource extraction."

"It seems very likely that Indigenous people all over the world will be the most impacted by extracting all the minerals we need for the energy transition," Tallman said. "But the challenge is that if we don't extract those minerals, and we're not successful in the energy transition, those same people will be the [most greatly] impacted by climate change if we fail. And so it's not an option to just not mine the minerals we need."

George Luxbacher, a deputy associate director for mining at the National Institute for Occupational Safety and Health and a former president of the American Institute of Mining, Metallurgical, and Petroleum Engineers, said he's seen the mining industry make enormous strides in environmental stewardship and technological efficiency over the course of his career. "Everyone's committed to a different path today, yet the perception of the public is still, we do things the way we used to," he said.

Mining for a Renewable Future?

Many agree that one of the greatest hopes for the mining and minerals industry is for it to show itself to be—and continue making itself—part of the solution to the climate crisis, rather than part of the problem. By studying, researching, or working in mineral resources, students who care about the environment could help improve the industry's environmental and social stewardship from within, Jowitt suggested.

Alyssa Lindsey, a master's student in economic geology at the University of Nevada, Reno who worked as a geologist for mining companies for several years, may be one such example. She "didn't know anything about mining, especially mining in the U.S." until she went to Nevada as an undergrad for summer field camp.

"Since I started working, I have seen the progress that has been made and how environmental protection is truly at the forefront," she wrote in an email. "I learned that we will either be mining metals here or buying them from elsewhere around the world. To me, it seems like the better option is to be involved in the mining process here, where it is strictly regulated."

Some are critical of this idea. Roger Featherstone, director of the Arizona Mining Reform Coalition, said he believes the idea that we can "mine our way out of the climate crisis" is flawed logic, noting that many studies showing the world needs more mining than ever are funded by mining companies.

Tallman emphasized that to attract talent, the mining industry needs to act in a way that makes young people want to get involved—"not just a spin or an angle, but it needs to be a genuine effort" to treat people and the planet responsibly.

Mining proponents say the industry's role in the green energy transition goes beyond mining materials for renewable energy technologies. Repurposing mine waste, for instance, could turn something toxic into clean energy for generations to come. There's also research on how accelerating the weathering of mine tailings could be a way to sequester carbon.

> **"It's a fresh opportunity for tribes, for tribal communities, to sort of make their own way and have the money and the resources to actually benefit from resource extraction."**

"If we could figure out how to do this," Nelson said, "we would have mining and tailings become the savior of the atmosphere."

Being a part of an industry that could help power the energy transition, to her, "is like reengaging something that was very fundamentally part of my values back in the late '60s and early '70s," she said. "I'm right smack back into it. So, now, I'm an old hippie chick."

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California Wildfires and Weather Are Changing Erosion Patterns

Like many states, California is facing a growing number of climate-related extremes: The annual acreage scorched by wildfires in the state increased fivefold between 1972 and 2018, and burns are also growing more intense. In addition, excessive rain is increasing flooding, landslides, and erosion, which can devastate terrain already reeling from fire damage. Large amounts of soil are prone to eroding after a wildfire, especially if heavy rainfall occurs within a year of the burn.

Dow et al. studied 196 fires that occurred between 1984 and 2021 and found that postfire sediment erosion increased statewide during this period. They used a combination of postfire hillslope erosion modeling and measurements of debris flow volume from both real and modeled events.

Both Northern and Southern California have been affected by large fires, but the two regions experience differences in climate and resulting fire patterns and postfire erosion patterns.

In Northern California, postfire damage most often occurs as typical hillslope erosion, or the wearing away of the top layer of soil. There, the researchers found that the mean amount of erosion occurring in the year following a fire increased tenfold from 1984–1990 to 2011–2021. The highest sediment load (about 7 metric megatons, or 7.7 megatons) occurred in 2018, when the destructive Carr and Camp fires burned and a particularly rainy year followed.

In Southern California, postfire erosion more frequently occurs as debris flows, or fast-moving, liquefied blends of mud, rock, and soil. The years 2003, 2007, and 2017, during which major fires occurred, were the largest sediment-producing years (at 6.9, 3.9, and 2.7 metric megatons (7.6, 4.3, and 3.0 megatons) of sediment load, respectively). All were followed by low water periods. The researchers didn't find an obvious pattern in how erosion magnitudes changed over time in Southern California, though they say that may be because of the episodic nature of major postfire debris flow events. The frequency of these events is forecast to increase with climate change.

This burned watershed warning sign was damaged in the Rim Fire in 2013. Credit: U.S. Department of Agriculture, CC BY 2.0 (bit.ly/ccby2-0)

Statewide, 57% of erosion occurring in the year after a fire occurred upstream from reservoirs, meaning the resulting sediment also poses a threat to water supply in a state already contending with water concerns. The database provided by this study could help water resources managers plan to mitigate these effects.

As the likelihood of large fires and historically damaging rains in California increases with climate change, postfire erosion will present a growing risk to waterways and surrounding communities, the researchers say. (*Journal of Geophysical Research: Earth Surface*, https://doi.org/10.1029/2024JF007725, 2024) **—Rebecca Owen,** *Science Writer*

The Moon's Tides Hint at a Melty Lunar Layer

We know that beneath its crater-pocked silicate crust, the Moon has an olivine mantle and a metallic core. Some research also has suggested that a partially molten layer may lie at the base of the otherwise solid mantle, sandwiched between it and the solid core. But other evidence disagrees.

Now, *Goossens et al.* present new measurements that support the existence of this somewhat melty transitional zone, which could have implications for our understanding of the Moon's structure, origin, and evolution.

The new evidence arose from an analysis of tides on the Moon. Just as the gravitational pull of the Moon and the Sun periodically distorts Earth's shape and gravitational field—causing the oceans to rise and fall—the Earth and the Sun both tug on the Moon, causing tidal effects that warp the Moon's shape and gravity.

The Moon's response to tidal forces depends, in part, on its deep interior structure, so researchers can study this response for clues about the lunar subsurface.

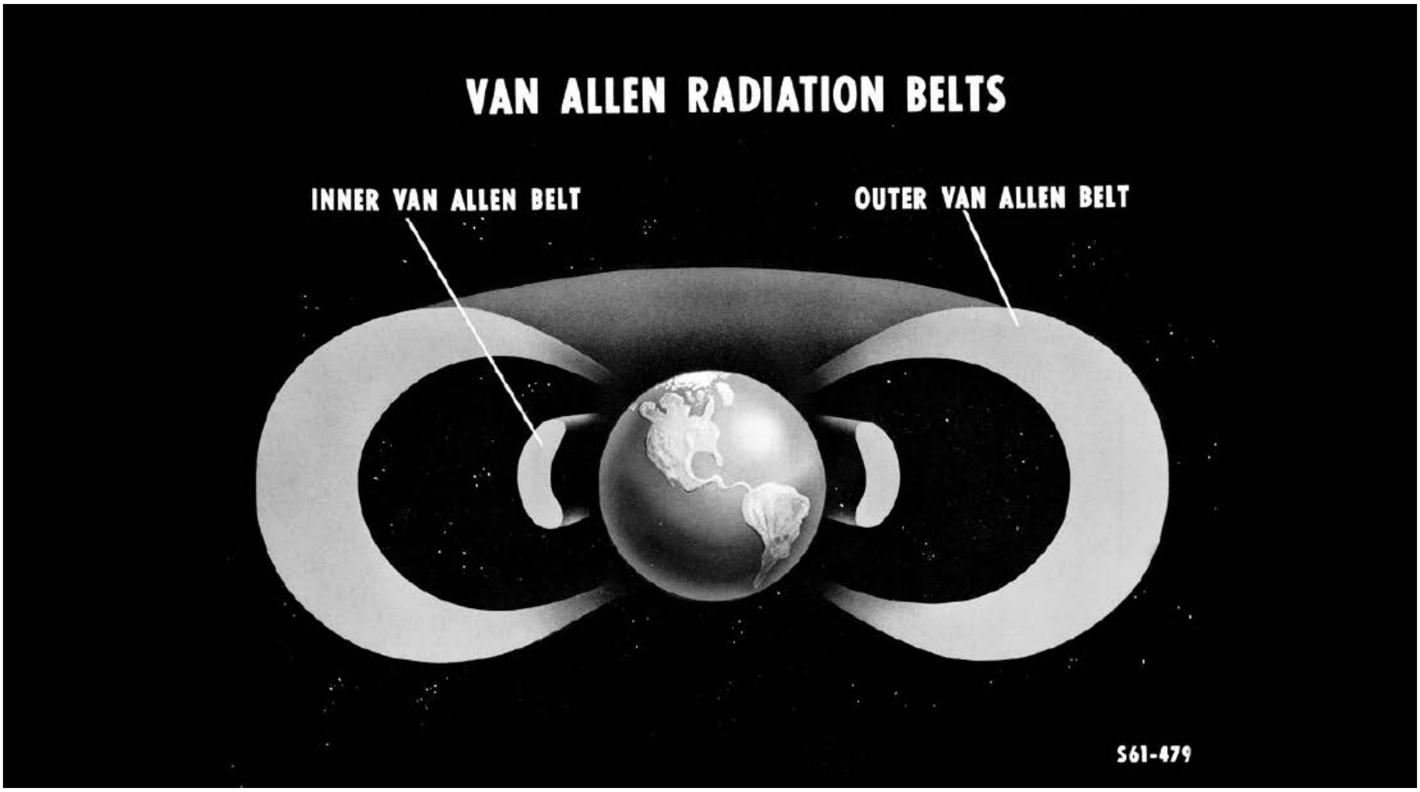
Earlier research had already explored the Moon's gravity changes in response to tides over the course of a month. In the new work, researchers captured yearly changes for the first time by analyzing data from NASA's satellite-based Gravity Recovery and Interior Laboratory (GRAIL) mission and the Lunar Reconnaissance Orbiter.

Next, they incorporated both the monthly and yearly lunar gravity changes, along with other information such as the average density of the Moon, into a model simulating the structure of the Moon's interior. They found that without including a softer layer at the base of the mantle, it was impossible for the model to reproduce the observed gravity measurements. In other words, a partly gooey deep mantle layer is highly likely to exist, this research suggests.

The researchers speculate that if it does exist, the partially molten layer may consist of a titanium-rich material called ilmenite.

However, more research is needed to better understand this layer and determine the heat source that maintains the melts over presumably billions of years. (*AGU Advances*, https://doi.org/10.1029/2024AV001285, 2024)
—Sarah Stanley, *Science Writer*

Audible Storm Waves Could Turbocharge Earth's Radiation Belts



New research suggests that electromagnetic chorus waves could raise radiation levels in Earth's Van Allen belts more dramatically than previously expected. Credit: NASA's Goddard Space Flight Center/Historic image of Van Allen belts courtesy of NASA's Langley Research Center

Encircling Earth are the Van Allen radiation belts—vast, doughnut-shaped rings of highly energetic charged particles, mostly originating from the Sun, that are trapped by our planet's magnetic field, or magnetosphere. The belts prevent dangerous radiation from reaching Earth's atmosphere, but can also pose hazards to nearby spacecraft.

When the Sun unleashes a burst of solar wind toward Earth, it can cause particles in the Van Allen belts to accelerate, increasing radiation to even more dangerous levels.

Now, research by *Santolík et al.* suggests that an especially intense superstorm, such as the Carrington event of 1859, could boost Van Allen belt radiation to more extreme levels than previously expected.

This is thanks to a specific type of electromagnetic wave known as a chorus wave. Chorus waves are a kind of whistler wave, named for the sound emitted by a radio receiver when they are detected.

These naturally occurring waves ripple through the "ocean" of charged particles, or plasma, that surrounds Earth, including the Van Allen belts.

During geomagnetic storms, chorus waves occurring close to Earth's geomagnetic equator typically accelerate the particles trapped in the Van Allen belts, boosting radiation levels. But when these waves propagate to higher latitudes, they more often may knock trapped particles free, scattering them into the atmosphere and reducing radiation.

Until now, few studies have addressed the net effects of these processes during particularly intense space storms. To get a clearer picture, the researchers compiled wave data from NASA's Van Allen Probes around the equator and the European Space Agency's Cluster spacecraft at high latitudes. They used the data to run 2D simulations of Van Allen belt particles buffeted by chorus waves during extreme storms.

The simulations suggest that an extreme storm would intensify low-latitude chorus waves, dramatically accelerating Van Allen particles and boosting radiation levels. However, contrary to expectations, high-latitude chorus waves would not similarly intensify, so any particle scattering would not be nearly enough to make up for the boost in particle acceleration.

Overall, chorus waves would increase radiation to levels far beyond any previously measured during the space age, creating an especially harsh environment for infrastructure.

The authors write that these findings could aid preparation for future extreme events. They also could deepen understanding of Jupiter's and Saturn's radiation belts, which experience electromagnetic waves similar to chorus waves near Earth. (*AGU Advances*, https://doi.org/10.1029/2024AV001234, 2024)

—Sarah Stanley, *Science Writer*

How an Ocean-Sized Lake May Have Formed on Ancient Mars

Geological evidence on Mars indicates that 3.6 billion years ago, an intense pulse of water carved rivers and lakes across the planet, an abrupt shift from the preceding 500-million-year era of much gentler fluvial activity. Researchers have long puzzled over the cause. A new study by *Buhler* shows, paradoxically, that the collapse of the Martian atmosphere and entry into a colder climate may have melted the polar ice cap and triggered global-scale flooding.

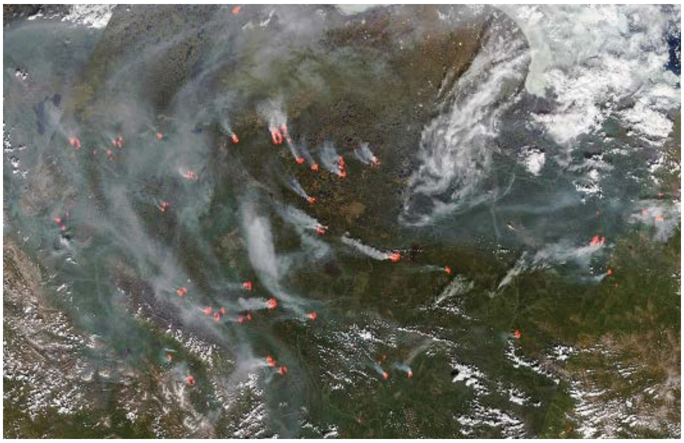
Mars's atmosphere is primarily made of carbon dioxide gas. It began thinning billions of years ago until about 3.6 billion years ago, when the atmosphere became so thin that it froze, collapsing to the ground in its solid form, dry ice.

At this time, Mars had a huge water ice sheet over its south pole. Buhler modeled the effect of the atmosphere freezing on top of this water ice. In the model, the dry ice layer acted as a thermal blanket, holding in heat produced by the Martian interior and causing some of the underlying water ice to melt. In total, about 4% to 40% of the water ice could have melted, an amount of water equivalent to between 20% and 200% of the water currently found near the surface on Mars.

The model showed that the meltwater could feed a system of rivers and fill a huge crater called Argyre Basin past its brim, creating a lake the size of the Mediterranean Sea. The modeled river and lake system would have existed beyond the edge of the south polar ice sheet, where globally cold climate conditions would have caused their surfaces to freeze. Rivers could have carried water almost 10,000 kilometers from the south pole to the northern plains. Buhler writes that this is the only plausible mechanism yet identified that could produce enough water to fill Argyre Basin past its brim.

Formation of the Argyre paleolake could have sparked a hydrologic cycle that lasted for around 100 million years, until the continuous slow loss of carbon dioxide to space depleted the effectiveness of the dry ice thermal blanket. Water from the lake may have evaporated, recondensed at the poles, and then traveled once again to the lake. (*Journal of Geophysical Research: Planets*, https://doi.org/10.1029/2024JE008608, 2024) **—Saima May Sidik,** *Science Writer*

Arctic Warming Is Driving Siberian Wildfires



Wildfires dot Russia's Siberian Arctic, imaged by the Terra satellite in June 2020. Such fires are becoming significantly more common in the region. Credit: Pierre Markuse/Flickr, CC BY 2.0 (bit.ly/ccby2-0)

Wildfire activity in central Siberia, Russia, has doubled in the past 2 decades, scorching vast areas of forest and releasing carbon stored in the rich soils and permafrost underneath. The Arctic is warming faster than the rest of the world, and scientists already know that the effects of climate change can exacerbate wildfires. But the specific factors driving enhanced Siberian wildfire activity aren't fully understood, making it difficult to predict future burning accurately.

In new research, *Huang et al.* demonstrate that the rise in Siberian wildfires is related to drought, drying soils, and decreased rainfall caused by Arctic warming. In addition, they identify a potential feedback in which wildfires suppress precipitation in the region, further drying soils and making fires even more likely. Water vapor in the atmosphere typically condenses around aerosol particles to form droplets, which come together as clouds and can fall as rain. But droplets formed around aerosols in wildfire smoke are smaller—often too small to form raindrops.

The authors used data from the Moderate Resolution Imaging Spectroradiometer (MODIS) instruments on the Terra and Aqua satellites to track wildfire activity between 2002 and 2022 and paired them with data on wildfire smoke, regional climate, and permafrost extent. Then they used Community Atmosphere Model version 6 of the Community Earth System Model to simulate aerosol-climate interaction over Siberia.

The authors calculated the Fire Weather Index, a measure of how likely a fire is to both start and spread, for two different simulations: one that incorporated historical data about wildfire emissions and one that removed fire activity. They found that the Fire Weather Index was 10% higher in the former simulation because wildfire aerosols suppressed precipitation. In fire-intensive areas, the index was up to 40% higher.

Simulations of future conditions following low- and medium-emissions pathways suggest that reduced precipitation could cause soil moisture in the region to decrease by 28% and 39%, respectively, by 2100. This drying, the researchers report, could lead to an increase in fire severity of 200% or more by the end of the century. (*AGU Advances*, https://doi.org/10.1029/2023AV001151, 2024) **—Nathaniel Scharping,** *Science Writer*

New Details About a Very Old Eruption and Flood

In the year 946 CE, the Changbaishan-Tianchi volcano, on the border between China and North Korea, erupted ferociously. The eruption released dozens of cubic kilometers of magma and triggered a massive flood from the lake atop the volcano's summit, known today as Heaven Lake. Evidence of the flood can still be seen in the form of boulders and smaller rocks that washed down from the upper reaches of the volcano.

Changbaishan-Tianchi, known as Baekdu in Korean, could erupt again, so volcanologists want to understand the risks it poses. To investigate the catastrophic flood that followed the 946 eruption, *Qin et al.* dug into the layered deposits from the volcano. Their work suggests that at least 1 cubic kilometer (0.24 cubic mile) of water spilled from the volcano's caldera, causing sediment to erode at rates as high as 34 meters (112 feet) per hour over about 3 hours.

The researchers also concluded that the eruption consisted of two phases, with the flood occurring between the two. Other scientists have hypothesized that the flood gushed out in one outburst after the eruption cracked the volcano's rim, but this study's authors found that scenario unrealistic because the sediment is not as widely spread as would be expected from one sudden gush of water.

More than a thousand years ago, Heaven Lake flooded the surrounding area when the Changbaishan-Tianchi Volcano, on the border between China and North Korea, erupted. Credit: Charlie fong/Wikimedia Commons, Public Domain

The researchers suggest three alternative scenarios. In the first, the water simply overflowed the edge of the caldera in response to magma rising from below. In the second, the volcano triggered an earthquake that collapsed the inner wall of the caldera into the lake, causing it to overflow. And in the third, precipitation prior to the event filled the caldera to capacity and weakened the crater rim, allowing the water to flow out.

Understanding ancient floods like the 946 event may help vulnerable populations prepare for future natural disasters, not just at Changbaishan-Tianchi but also at volcanoes around the world, the researchers write. (*Water Resources Research*, https://doi.org/10.1029/2024WR037085, 2024) —**Saima May Sidik**, *Science Writer*

Exploring an Underwater Volcano from 16,000 Kilometers Away

A remotely controlled research vessel has gathered some of the first comprehensive measurements from within the massive crater left by the Hunga volcano (formerly known as Hunga Tonga-Hunga Ha'apai) after it erupted 2 years ago.

The underwater eruption of the Tongan volcano in January 2022 sent a plume of ash and gas 20 kilometers (12 miles) into the atmosphere and excavated a crater 850 meters (half a mile) deep on the ocean floor. The eruption's effects above the ocean have been well studied, thanks to comprehensive networks of global monitoring systems.

But logistical difficulties and ongoing danger made it harder to investigate underwater conditions following the eruption.

Walker and de Ronde present one solution: an uncrewed vessel piloted by remote operators 16,000 kilometers (10,000 miles) away.

In new research, they share results from three missions over the crater undertaken in summer 2022. The research vessel, operated by technicians in the United Kingdom, was equipped with multibeam sonar for mapping the crater and instruments to measure characteristics including temperature, turbidity (cloudiness), and the chemistry of the water within.

The authors found evidence of ash plumes and ongoing venting within the crater 7 months after the eruption, as well as separate areas of carbon dioxide degassing, indicating the site remained active. The high crater rim was trapping much of the plume within the crater, with small amounts escaping through two breaches, which could affect ecological recovery in the area, they report. It's not yet clear whether the plume was due to volcanic or hydrothermal activity or some combination of the two.

The mission's success in using a remotely controlled vehicle to conduct comprehensive sampling of an active submarine volcanic crater highlights the value of uncrewed missions for gathering data in these potentially dangerous environments. In addition, finding persistent evidence of venting and degassing at the volcano, despite little evidence of activity on the surface, underlines the importance of underwater missions such as these for monitoring active volcanoes in the oceans, and such missions should be applied elsewhere, they argue. (*Geochemistry, Geophysics, Geosystems*, https://doi.org/10.1029/2024GC011685, 2024) —**Nathaniel Scharping**, *Science Writer*

Storms Are Knocking Down More and More Trees in the Amazon

The Nauta windthrow event occurred in 2009 south of Iquitos, Peru, in the western Amazon. Credit: Daniel Magnabosco Marra, David Urquiza-Munoz

During some convective storms, downdrafts can have enough force to snap or completely uproot trees in a phenomenon known as windthrow. Windthrow events, which can range from just a few trees to many hectares in size, can affect the structure and composition of forests. Climate change has caused powerful storms to grow in number and intensity, and windthrows are one way to track this growth in the Amazon.

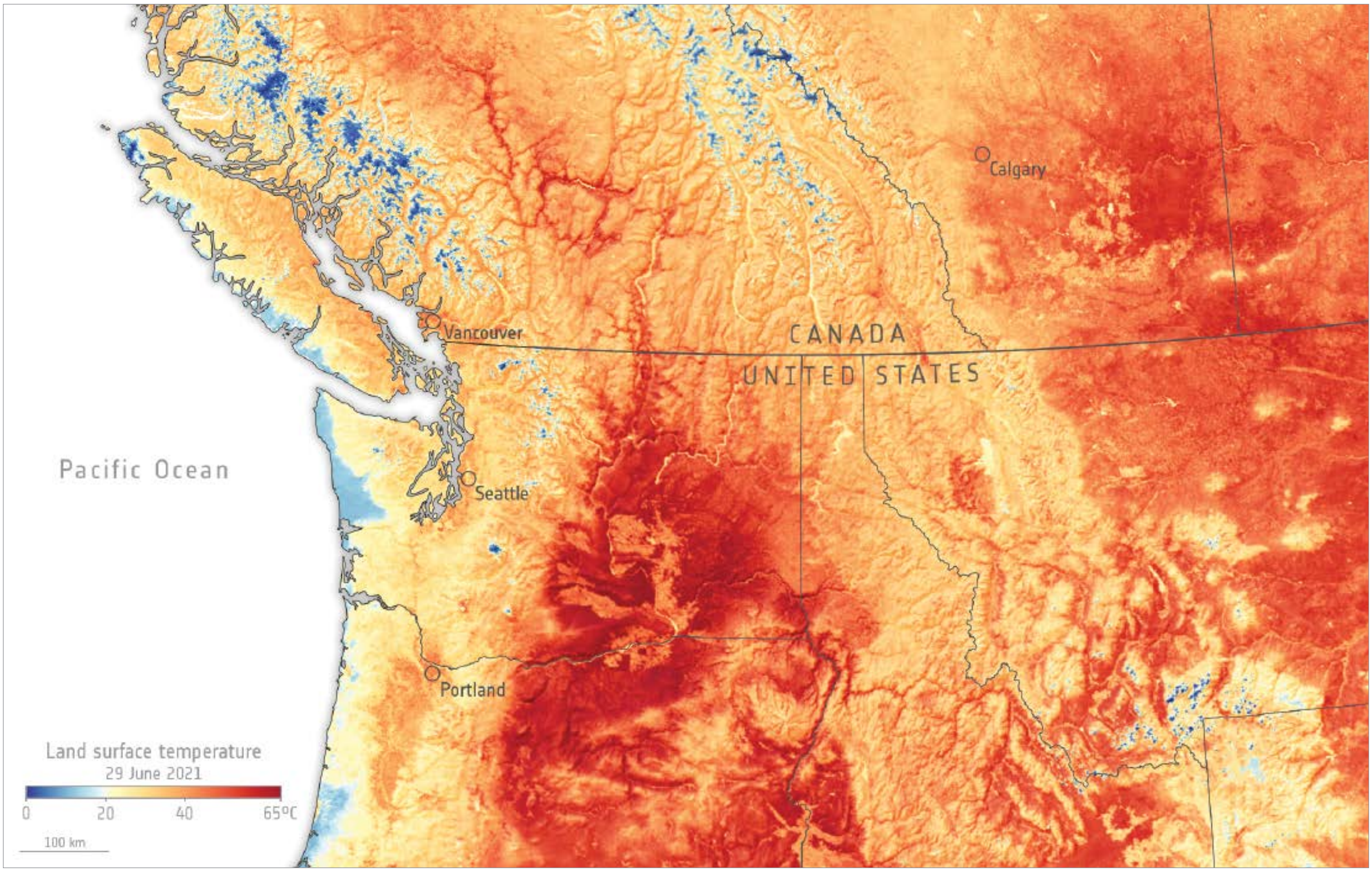
Urquiza-Muñoz et al. used data from Landsat satellites to compile an annual database of large windthrows (which they classified as affecting more than 30 hectares, or 74 acres) in the Amazon between 1985 and 2020. They found that the number of windthrows and the area affected by them have increased nearly fourfold over that time, from 78 windthrows affecting 6,900 hectares (17,050 acres) in 1985 to 264 windthrows affecting 32,170 hectares (79,494 acres) in 2020. Most events occurred in the central and western Amazon.

The authors created mosaics of images from the Landsat data for each year, excluding tiles with heavy cloud cover. Then they compared each tile in the mosaic to the corresponding tile from the previous year, looking for spectral signatures that indicated downed and uprooted trees. In all, they found 3,179 large windthrows over the study period. The largest windthrow felled trees over an area of more than 2,543 hectares (6,284 acres).

The authors found that some areas have much higher windthrow activity than others: Areas with more than two windthrows over the period analyzed accounted for just 3% of the study area but 35% of the windthrows. Though these events are becoming more common in general, the researchers did not find a trend of increasing or decreasing individual windthrow size over time.

The authors' data support observations that intense storms are becoming more common in the Amazon, though they were unable to explain why there was a large variation in windthrow events between different years. Their dataset will be a useful benchmark for future studies assessing the dynamics of windthrows and could further illuminate how windthrows affect forest processes, the authors say. They suggest that improved satellite imagery resolution could allow researchers to find and study smaller windthrows in the future, and lidar technology could improve understanding of windthrow effects outside of core damage areas. (*AGU Advances*, https://doi.org/10.1029/2023AV001030, 2024) **—Nathaniel Scharping,** *Science Writer*

Machine Learning Could Improve Extreme Weather Warnings



In June 2021, the U.S. Pacific Northwest and southwestern Canada experienced a significant heat wave, with temperatures hitting 43°C (109°F) in Portland, Ore., for example. Credit: Contains modified Copernicus Sentinel data (2021), processed by the European Space Agency, CC BY-SA 3.0 IGO (bit.ly/ccbysa3-0igo)

Because small changes in atmospheric and surface conditions can have large, difficult-to-predict effects on future weather, traditional weather forecasts are released only about 10 days in advance. A longer lead time could help communities better prepare for what's to come, especially extreme events such as the record-breaking June 2021 U.S. Pacific Northwest heat wave, which melted train power lines, destroyed crops, and caused hundreds of deaths.

Meteorologists commonly use adjoint models to determine how sensitive a forecast is to inaccuracies in initial conditions. These models help determine how small changes in temperature or atmospheric water vapor, for example, can affect the accuracy of conditions forecast for a few days later. Understanding the relationship between the initial conditions and the amount of error in the forecast allows scientists to make changes until they find the set of initial conditions that produces the most accurate forecast.

However, significant financial and computing resources are required to run adjoint models, and the models can measure these sensitivities up to only 5 days in advance.

Vonich and Hakim tested whether a deep learning approach could provide an easier and more accurate way to determine the optimal set of initial conditions for a 10-day forecast.

To test their approach, they created forecasts of the June 2021 Pacific Northwest heat wave using two different models: the GraphCast model, developed by Google DeepMind, and the Pangu-Weather model, developed by Huawei Cloud. They compared the results to see whether the models behaved similarly, then compared the forecasts to what actually happened during the heat wave. (To avoid influencing the results, data from the heat wave were not included in the dataset used to train the forecasting models.)

The team found that using the deep learning method to identify optimal initial conditions led to a roughly 94% reduction in 10-day forecast errors in the GraphCast model. The approach resulted in a similar reduction in errors when used with the Pangu-Weather model. The team noted that the new approach improved forecasting as far as 23 days in advance. (*Geophysical Research Letters*, https://doi.org/10.1029/2024GL110651, 2024) **—Sarah Derouin**, *Science Writer*

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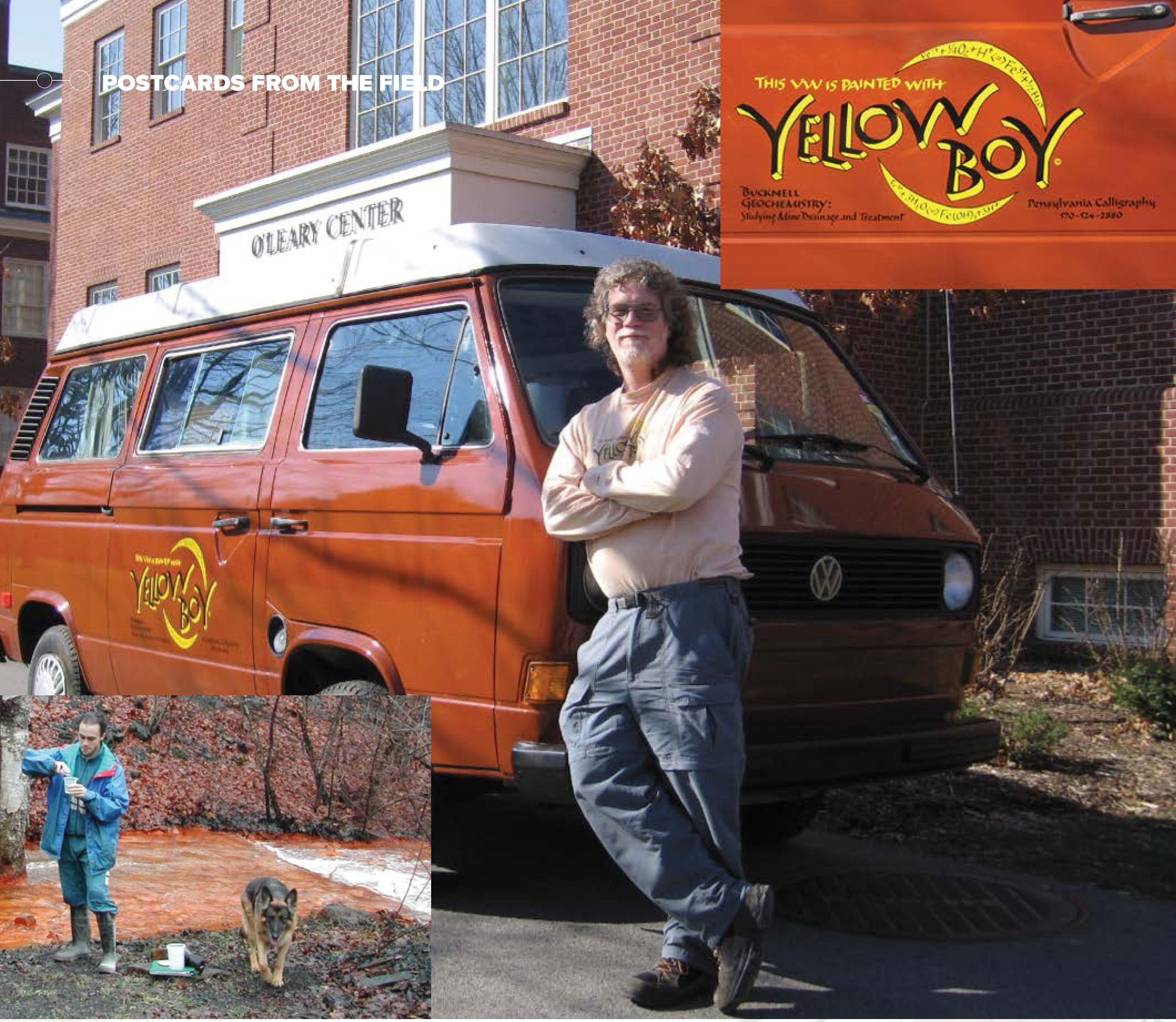

Hello from Bucknell University and the nearby anthracite coal mining region of central Pennsylvania!

I studied mine drainage and treatment for most of my career. Mine drainage (often but not always acidic) begins with the oxidation of pyrite found with coal deposits, resulting in damage to ecosystems. Stream bottoms get coated with "yellow boy," an informal mining term for the bright orange iron hydroxide solids that precipitate.

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Many years ago I wondered whether these iron hydroxides could be collected from treatment systems and used as a resource. The main picture, taken in 2000, shows my 1982 VW Vanagon painted with a painstakingly mixed combination of yellow boy and clear coat. The resulting gorgeous finish varied in hue with the ambient light. The top inset photo shows the yellow boy decal from the side of the van depicting two of the reactions responsible for mine drainage.

The bottom inset picture shows Bernardo Castro-Tejada, a Bucknell exchange student from Spain, and "Harriet the Geochemistry Field Dog" (RIP) walking away from the actual discharge that was the source of the pigment for the van.

—**Carl Kirby,** Geology and Environmental Sciences, Emeritus, Bucknell University, Lewisburg, Pa.

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