Eos

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SCIENCE NEWS BY AGU

Monitoring an Eruption

Mapping the Asteroid Belt

Rivers That Shouldn't Exist

BOOTS ON THE GROUND

Our annual fieldwork issue follows geoscience from glaciers in Uganda all the way to databases in the cloud.

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ADVANCING EARTH AND SPACE SCIENCES

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"There's no roads, there's no helicopters, there's not even a donkey." It's just another day in the field.

The spartan accommodations available to scientists tracking glaciers in Uganda are not universal to geoscience fieldwork, but they indicate the lengths to which scientists will go to discover and document our planet's particularities. Read all about it on page 5.

Volcanologists on La Palma, the largest of the Canary Islands, faced a different challenge during their work in the field: an actively erupting volcano. Learn more on page 20.

Hazards like erupting volcanoes and melting glaciers may be no match for the "looming catastrophes of funding cuts, software obsolescence, and loss of community support," however. In this month's Opinion, on page 16, scientists share recommendations for supporting expert community-curated data resources.

Geoscience fieldwork is globe-spanning and mind-bending, and we hope you enjoy the ride.

On the Cover

Uganda Wildlife Authority guide Muhindo Rogers overlooks the landscape surrounding Mount Baker, which once hosted a glacier that has now melted.
Credit: Project Pressure

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Janice Lachance, Executive Director/CEO

First Global Comparison of Glacier Mass Change: They're All Melting, and Fast

Each year in early March, when summer turns to fall in the Southern Hemisphere, New Zealand glaciologists gather at an airfield in Queenstown to embark on a predawn flight above the spine of the Southern Alps.

For hours, they twist in the Cessna's narrow seats to train cameras on glaciers clinging to mountaintops. The images capture the glaciers' vanishing contours and the shifting snowline—the demarcation between the remains of the winter snowpack and exposed glacial ice.

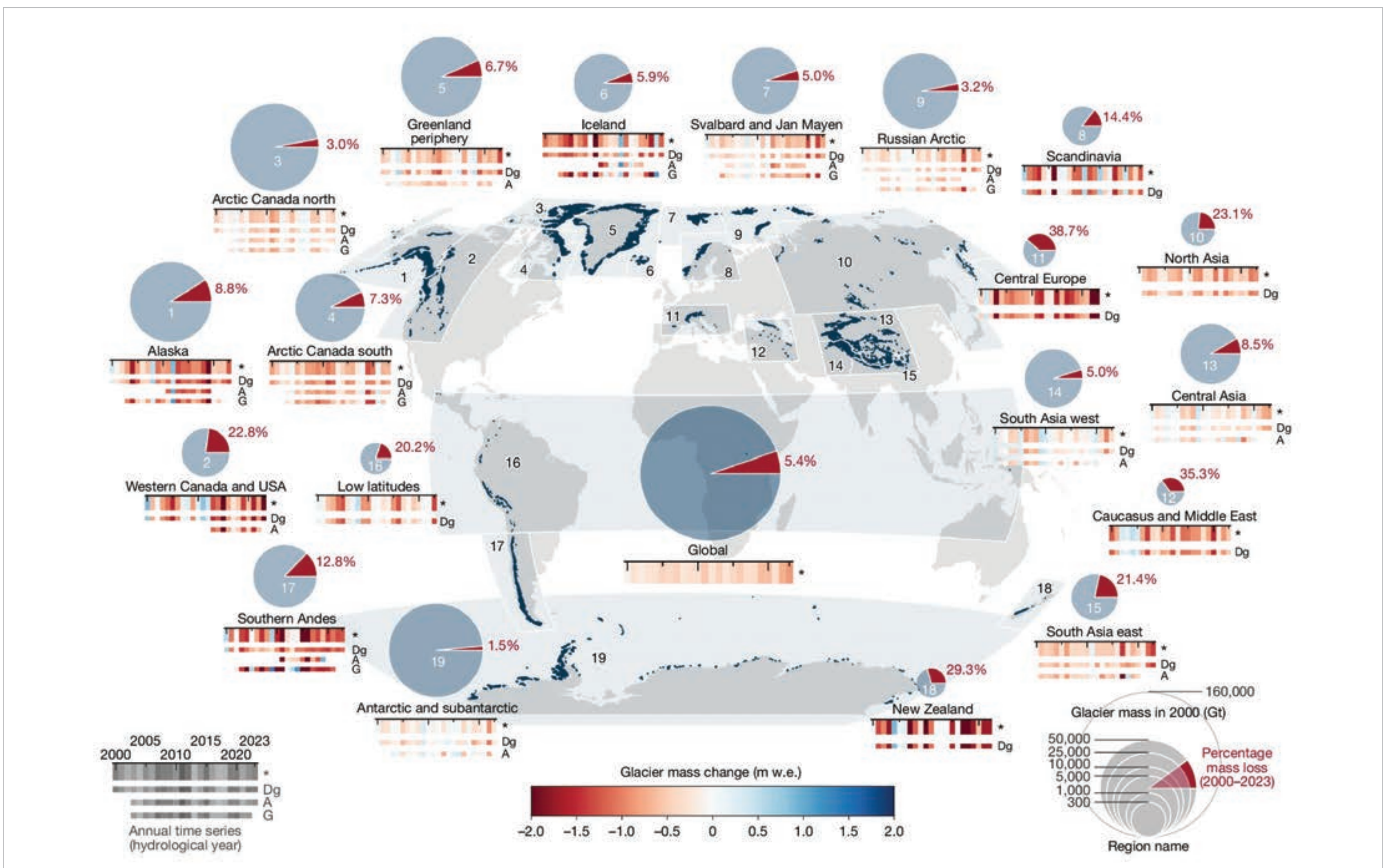
"It's like a bank account," said Andrew Lorrey, a climate scientist at the National Institute of Water and Atmospheric Research who has been coordinating the surveys for 16 years. "If we put in the same amount of snow in winter as we're taking out in summer, the glacier would be in balance, melting at its terminus but advancing downhill due to gravity and replenishing the ice that's lost."

But the surveys, which have been running since 1977, show that summer melt now far exceeds winter snowfall and "we're seeing the glaciers' terminus and sides, the whole body, diminishing."

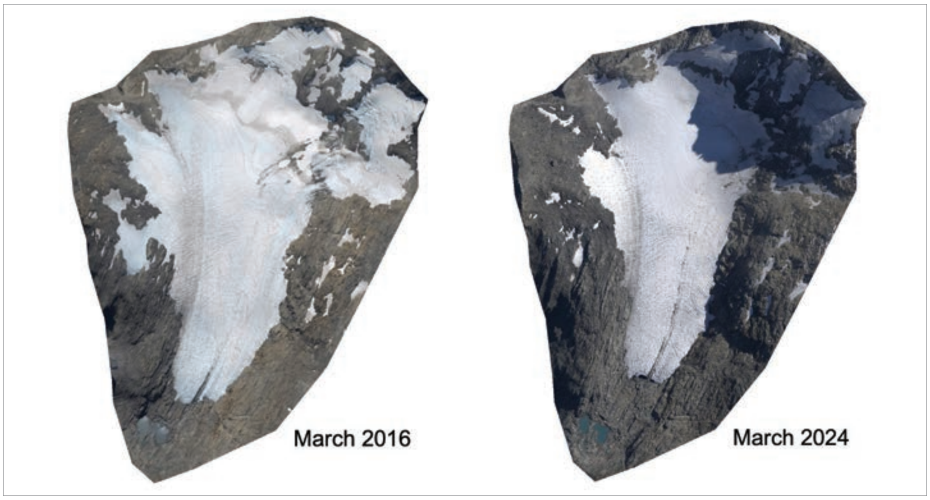
New Zealand has lost more than a third of its glacial ice, and the archipelago ranks third globally—after central Europe and the Caucasus—in the proportion of ice lost to rising temperatures, according to findings published in *Nature* by the first comprehensive global Glacier Mass Balance Intercomparison Exercise (GlaMBIE) (bit.ly/global-glacier-changes).

Global Assessment of Glacial Retreat

The project assessed observations from 35 international teams, with a goal of reconciling all methods used to track glacial mass changes. These methodologies range from in situ measurements (in which scientists stud individual glaciers with ablation stakes to



This map displays glacier mass changes from 2000 to 2023 as percentage loss (red slice in the pie chart) based on total glacier mass in 2000 (size of the pie chart). The colored stripes under each pie chart represent annual specific mass changes (in meter water equivalent) for a combined estimate (indicated with an asterisk) together with combined results from digital elevation model differencing and glaciological observations (Dg), altimetry (A), and gravimetry (G). Regional results are represented for hydrological years, that is, running from 1 October to 30 September in the Northern Hemisphere, from 1 April to 31 March in the Southern Hemisphere, and over the calendar year in the low latitudes. Global results are aggregated for calendar years. Credit: The GlaMBIE Team. Community estimate of global glacier mass changes from 2000 to 2023. Credit: The GlaMBIE Team, 2025, https://doi.org/10.1038/s41586-024-08545-z



New Zealand's Brewster Glacier shrank by 24% between 2016 and 2024. Credit: Lauren Vargo

record their shrinkage) to various satellite-borne sensors (which use optical, radar, laser, and gravimetry technologies to track changes in glacial surface elevation).

Bringing all these methodologies together, the GlaMBIE team produced a time series of global glacial mass change between 2000 and 2023, showing that collectively, the world's glaciers lost 5% of their total volume. "This may not seem much," said Michael Zemp, GlaMBIE project leader and director of the World Glacier Monitoring Service at the University of Zürich. But it means an annual global loss of 273 billion metric tons of ice.

"Every centimeter of sea level rise exposes another 2 million people to annual flooding somewhere on our planet."

"To put this in perspective," Zemp said, "the ice lost each year amounts to the water intake of the entire global population in 30 years, assuming 3 liters per person a day."

Andrew Shepherd, an Earth scientist at Northumbria University who has led a similar assessment of mass loss from polar ice sheets but was not involved in this project, welcomed the authoritative standardized framework provided by GlaMBIE.

Reconciling the different methodologies is important because "climate change isn't smooth," Shepherd said. Short-term in situ measurements can deliver contrasting results and each satellite technique has its strengths and weaknesses, but "bringing all methods together leads to a clearer picture of total ice loss," he noted.

Although all areas experienced ice loss, the GlaMBIE results showed significant differences between regions, ranging from 1.5% ice loss in the Antarctic to 39% in central Europe.

The largest overall contribution to ice loss (22%) came from Alaska, said Caitlyn Florentine, a research physical scientist with the U.S. Geological Survey in Bozeman, Mont., and a GlaMBIE member.

Alaska, like the Canadian Arctic and Greenland, has enormous volumes of ice. But the relatively low elevation and latitude of Alaskan glaciers meant that these ice fields "were the biggest contributor to sea level rise [from glaciers] in the first 2 decades of this century and are projected to continue [to be] until 2100," Florentine explained.

The GlaMBIE results revealed clear evidence of increasing melt rates, with a 36% jump during the second half of the study period, from 2012 to 2023. Mountain glaciers hold enough water to raise sea level by 32 centimeters if all were to melt. The ice that has already been lost from the world's mountains has contributed 18% more to sea level rise than the loss from the Greenland Ice Sheet and more than twice the loss from the Antarctic Ice Sheet.

"Even small amounts of sea level rise matter, because it leads to more frequent coastal flooding," Shepherd said. "Every centimeter of sea level rise exposes another 2 million people to annual flooding somewhere on our planet."

Zemp hopes to focus future work on assessing how glacier melt affects seasonal runoff, and that requires ongoing access to satellite data and higher-resolution remote sensing techniques. As some satellites and sensors approach the end of their missions, he's concerned about continuing the study. "If we are left without open access to high-resolution stereo imaging missions with a global coverage, we'd be blind to these changes," he said.

Gone This Century

In addition to the ice sheets in Antarctica and Greenland, there are more than 275,000 glaciers—or crystal cones, as Zemp calls them—in mountain ranges from the tropics to the polar regions. Only about 500 are monitored up close.

One is Brewster Glacier in New Zealand, which Te Herenga Waka–Victoria University of Wellington glaciologist Lauren Vargo visits regularly. She drills ablation stakes into the ice in spring and retrieves their exposed parts in fall.

She helped document that the glacier shrank by 24% and lost 17 meters in height between 2016 and 2024.

The retreat made Vargo's latest visit, in March, physically taxing, she said. "The more melt that happens, the more stakes you have to collect," she explained. "I don't think I could have carried any more stakes."

Many glaciers will not survive this century, Zemp said. Among these is one of his favorites, Oberaargletscher at Grimselpass in Switzerland, which Zemp has studied for almost a quarter of a century and, more recently, began visiting with his sons.

Oberaargletscher will be gone by 2050, regardless of any cuts to carbon emissions, Zemp said. Though the retreat is "interesting to witness as a scientist," he continued, "I am deeply sad that my sons and their generation will lose this fantastic glacier."

By **Veronika Meduna** (@veronikameduna.bsky.social), Science Writer

A 30,000-Year-Old Feather Is a First-of-Its-Kind Fossil

Valentina Rossi first saw the 30,000-year-old griffon vulture while a master's student in Rome in 2014. The fossil, which had been found by a local landowner near Rome in 1889, was remarkably well-preserved. She couldn't look away as her future collaborator, Dawid Iurino, presented about the fossilized imprint of the bird's head.

"I was mind-blown," Rossi said.

The presentation by Iurino, now an associate professor at Università degli Studi di Milano Statale, ended with a discussion of the bird's feathers. Rossi remembered him saying that determining exactly what the feather fossils were made of was a topic for future research, because analyzing such well-preserved structures was outside the expertise of the team of paleontologists at the time.

Now, a new study by Rossi, Iurino, and others, published in *Geology*, has finally revealed the answer: The feather fossils are made of zeolites—minerals made of aluminum and silicon compounds (bit.ly/fossil-feathers). This study is the first in which scientists have reported soft-tissue mineralization by zeolites.

"We finally did it," said Rossi, lead author of the paper and a paleontologist at University College Cork in Ireland.

It's extremely rare to find feathers preserved in three dimensions and even rarer to find mineralized feathers, Rossi said. The knowledge that the feathers were fossilized by zeolites, minerals that form naturally by reactions between volcanic rock and water, could guide paleontologists to target volcanic settings when searching for fossils.

"We finally did it."

"The more people look, the more people are going to find the preservation of materials that we previously thought was impossible," said Mary Schweitzer, a paleontologist and emeritus professor at North Carolina State University who was not involved in the new study.

Matching Minerals

Rossi and the team of scientists used a powerful electron microscope to study the shape and texture of the preserved structures, confirming that the tissue was mineralized. Then they analyzed the chemical structure of the fossil using multiple spectroscopy methods. "We recognized certain chemical bonds that are similar to those found in zeolites," Rossi said.

Certain soft tissues lend themselves to fossilization. Muscle tissues, for example, are commonly mineralized by the calcium phosphate mineral apatite. That's because muscle tissue already contains calcium and phosphorus, which jump-start the mineralization process.

Laboratory studies have shown that zeolites will form on biological materials in solutions of silicon and aluminum (bit.ly/zeolite-formation). But feathers do not contain these elements, making the zeolite fossil puzzling, Rossi said.

Schweitzer said that parts of certain molecules that make up decaying feather tissue may have an affinity for aluminum or silica but that more research would be needed to determine the exact chemistry behind the mineralization. Another explanation for the mineralization, Rossi suggested, may involve the pH of the soft tissue, especially as the tissue decays.

The findings "open up another window for fossilization."

A Vulture's Final Moments

The findings helped Rossi and her colleagues create a taphonomic model—a likely storyline of how the bird went from a living animal to a hunk of rock. Previous studies of the whole fossil had not indicated that the bird was injured; Rossi suspects toxic gases from a nearby volcanic eruption may have killed it.

Dead but intact, the bird lay in the path of a lava flow. Rossi thinks the vulture was prob-

Valentina Rossi and the research team used a variety of methods, including electron microscopy and multiple forms of spectroscopy, to determine that the feather fossils were made of zeolites. Credit: Dirleane Ottonelli

Unlike this 30,000-year-old griffon vulture feather, fossils are rarely found in three dimensions and are even more rarely found in mineralized form. Credit: Edoardo Terranova

ably quite far from the actual eruption and may have been covered by a cooler, slow-moving volcanic flow, as its tissues weren't destroyed by heat or turbulence.

The volcanic flow hardened and cooled with the griffon vulture beneath it. Eventually, rains soaked the rock, creating a fluid rich in minerals. The chemical composition of the bird's feathers spurred a reaction with the silicon- and aluminum-rich fluids, and zeolites formed, replacing the tissue. The feathers turned to stone faster than they decayed.

Something similar may have happened to many more specimens over Earth's history, which could mean that paleontologists are overlooking entire categories of rock in which highly preserved soft-tissue fossils may be found, the authors wrote. Volcanic settings are typically disregarded as likely spots to find fossils because volcanic flows are turbulent and hot and usually destroy soft biological material that might otherwise be fossilized. But the new paper's results mean there are likely some exceptions.

The findings "open up another window for fossilization," Schweitzer said.

By **Grace van Deelen** (@gvd.bsky.social), Staff Writer

A New 3D Map Shows Precipitous Decline of Ugandan Glaciers

Seen from above, the dozens of people trekking through the Rwenzori Mountains might have looked something like the inhabitants of an ant farm branching across the landscape, said Klaus Thymann. The expedition into the range on the border between Uganda and the Democratic Republic of the Congo included Thymann, an environmental scientist; Heïdi Sevestre, a glaciologist at the Arctic Monitoring and Assessment Programme; guides from the Uganda Wildlife Authority (UWA); and—predominantly—interested community members there to help with logistics.

The group was there in August 2024 to survey ice on the range's three tallest peaks and to create the first 3D model of the glaciers on Mount Stanley, whose apex, Margherita Peak, is the third highest in Africa at 5,109 meters.

"It's really a team work, and a very good one," said Thymann, founder and director of Project Pressure, a nonprofit organization focused on environmental issues.

Their newly analyzed data confirmed that Mount Speke, the second-highest peak in the range, no longer hosts a glacier (only static ice) and that Mount Baker, the third highest, is practically ice free. The researchers found that the surface area of the Stanley Plateau glacier fell by 29.5% between 2020 and 2024.

"Glaciers worldwide are shrinking or disappearing, so that's not a surprise," Thymann said. "I think what is surprising is how rapid it's going."

Jim Russell, a climate scientist and geochemist at Brown University who was not involved in the research, has been making expeditions to the Rwenzori Mountains since 2006. He called these glaciers a "canary in a coal mine."

"The recent retreat is really significant, and it's illustrating [that] substantial climate change is happening at high elevations," he said.

"There's no roads, there's no helicopters, there's not even a donkey."

Sleeping Bags, Licorice, and Drones

Aside from essentials, such as sleeping bags and licorice ("It's all about the amount of flavor you can get with the least amount of volume," Thymann explained), the crew carried an array of equipment, including a generator,

Warming temperatures have led to massive glacier loss in the Rwenzori Mountains in Uganda. A recent expedition revealed a 29% reduction in the surface area of Mount Stanley's glacier, seen here, between 2020 and 2024. Credit: Project Pressure fuel and cables for the generator, three drones, and GPS hardware.

"There's no roads, there's no helicopters, there's not even a donkey," Thymann said. "Everything has to be carried in, so that makes science challenging because the logistics are difficult." With the weight of equipment and the need to acclimate to the elevation, it's a 5-day trek from the entrance of Rwenzori Mountains National Park up through tropical, bamboo, and alpine forests to the Stanley Plateau.

"We believe if we protect this mountain, if we fight hard to maintain the small ice, or the small glaciers that [remain], our gods will not be homeless."

Klaus Thymann (left) works with Kule Jocknus Bwabu Solomon and Muhindo Rogers of the Uganda Wildlife Authority to set up precision GPS points for photogrammetric survey. Glaciologist Heïdi Sevestre (right) joined the expedition to scan the ice with ground-penetrating radar. Credit: Project Pressure

Thymann led expeditions to the area in 2012, 2020, and 2022. In 2020, the team captured images of the plateau with consumer drones, then used photogrammetry to create a digital elevation model of the area.

When they returned in 2024, they went one step further. They used a surveying system to determine the precise GPS coordinates of eight points along the plateau, then set up a brightly colored target on each point. When they flew drones over the area to capture more than 850 photos, they could not only create a model but also anchor it to precise GPS coordinates. They also used the points to retroactively anchor the 2020 model. By comparing the two models, they determined the extent of ice loss on the plateau.

Sevestre, the glaciologist, also used ground-penetrating radar to determine the depth of the glaciers. "If you want to know volume, you have to know three dimensions. You have to know the *x*, the *y*, and then the *z*," Thymann said. "Nobody knew the *z*, so nobody knew the depth."

The researchers expect to publish more detailed findings, including glacier volume, later this year.

Russell said he was "amazed" the researchers were able to do this work in this remote area. Though there is no standard way of mapping glaciers, he added that the Rwenzori Mountains' glaciers have historically been mapped simply by tracing the movement of their edges. The Project Pressure team is "not just tracing the lowest elevation of the glacier," he said. "They're also able to kind of see the sides, see how that's shrinking, potentially see it thinning from the top."

Protecting the Home of Gods

The dwindling of Rwenzori's ice may be a bellwether of glaciers' futures worldwide, but closer to home its effects are already being felt.

The ice on the mountain range is the highest source of water for the Nile River and holds water that millions of Ugandans rely upon. Trekking tourism to Rwenzori Mountains National Park, a United Nations Educational, Scientific and Cultural Organization (UNESCO) World Heritage Site, also bolsters the local economy.

"This ice supports the people of the communities living around it, 100%," said Masereka Solomon, a tour guide in Uganda who began working with Thymann in 2012. Solomon has lived in the area for 34 years—his whole life—and has watched the ice retreat firsthand. For him and other Bakonzo people who live in the foothills of the Rwenzori Mountains, the glaciers also hold a deep religious and cultural significance, as they believe that their gods live in the ice atop the mountains.

"We believe if we protect this mountain, if we fight hard to maintain the small ice, or the small glaciers that [remain], our gods will not be homeless," Solomon said.

Thymann emphasized the role of the dozens of community members during the expeditions, from helping transport equipment up the mountain to spotting the drones and returning regularly to maintain time-lapse cameras. He and the other Project Pressure researchers analyze the data and share the results with UWA and locals.

He added that though the Bakonzo people understand that the retreating ice is caused by climate change, he hopes that this more detailed data will raise awareness of Uganda's shrinking glaciers.

By **Emily Dieckman** (@emfurd.bsky.social), Associate Editor

Large Outdoor Gatherings Expose Event-Goers to Severe Weather

In 2004, the Indianapolis 500 turned into the Indianapolis 450. Organizers shortened the famous automobile race by 20 laps (50 miles) after a tornado touched down near the Indianapolis Motor Speedway, where more than 200,000 spectators were in attendance.

Large outdoor gatherings such as this expose event-goers to the elements, and in some parts of the United States, severe weather can make that pairing deadly.

That's especially true of the New Orleans Jazz & Heritage Festival, which poses the highest lightning risk of more than 16,000 large outdoor gatherings analyzed by researchers in a recent study. Coors Field in Denver and an amusement park in Arlington, Texas, topped the study's lists for tornado exposure. The findings increase awareness of weather-related hazards among event attendees and venue managers alike, the researchers suggested.

Only a handful of studies have attempted to quantify weather-related risks at large outdoor gatherings, and even fewer have attempted to do so for a variety of events that occur across a large geographic area.

Stephen Strader, a hazards geographer and atmospheric scientist at Villanova University in Pennsylvania, and Jack Deppman, a doctoral student in geospatial analytics at North Carolina State University in Raleigh, recently did just that. Strader and Deppman focused on two forms of extreme weather—tornadoes and lightning—and determined risk indices for large outdoor gatherings across the United States.

The researchers started by mining tornado and lightning data. They analyzed a NOAA dataset of tornadoes that touched down between 1954 and 2020 and a dataset of cloud-to-ground lightning strokes pinpointed by the Earth Networks' Total Lightning Network from 2012 to 2020. For each type of hazard, the researchers calculated the average number of occurrences each month within grid cells measuring 80 × 80 kilometers.

Follow the Crowds

Strader and Deppman next assembled a list of large outdoor gathering spaces. The public venues tabulated in the Department of Homeland Security's Homeland Infrastructure Foundation-Level Data dataset served as a basis, and the researchers supplemented that listing with other locations such as football stadiums, concert venues, and horse racetracks.

For each location, Strader and Deppman determined the dates of events that occurred primarily outdoors and each event's maximum seating capacity. To do that, they mined sources ranging from reports to venue websites to news articles. Amassing all that information took about a year.

After limiting their final list of events to those that could accommodate at least 10,000 people, the researchers identified 16,232 unique events held at 477 venues. "It's a lot of data," said Deppman.

Next, the team determined risk indices for each event. Strader and Deppman's calculations took into account an event's maximum seating capacity, its frequency in terms of number of days per month, its seasonality, and the tornado and lightning climatology of its location. "We needed to capture all of those elements," Strader said.

Strader and Deppman calculated one lightning risk index and two tornado risk indices for each event. It was important to consider the risk of experiencing any tornado, independent of magnitude, and also the risk of experiencing a more damaging tornado, Strader said. That's because though more than four out of five tornadoes are classified as EF0 or EF1 on the Enhanced Fujita damage intensity scale, the vast majority of tornado-related fatalities occur during tornadoes rated EF2 or higher. "They're responsible for 99% of deaths," Strader said.

Music, Baseball, Roller Coasters, and More

When the researchers ranked the events, they found that the New Orleans Jazz & Heritage Festival topped the list for potential lightning exposure. "That stuck out like a sore thumb from the lightning standpoint," Strader said. This event, which draws roughly half a million attendees annually over a week and a half, occurs in April–May, which is when the risk of cloud-to-ground lightning peaks in southern Louisiana.

All of the other gatherings in the top 10 for lightning exposure were at amusement parks in Florida.

Coors Field in Denver in June topped the list for exposure to EF0–EF5 tornadoes. Other venues on the top 10 list included the New Orleans Jazz & Heritage Festival; several amusement parks in Texas, Florida, and Missouri; and the State Fair of Texas in Dallas.

When the team limited their analyses to more damaging tornadoes registering EF2–EF5, the Six Flags Over Texas amusement

The New Orleans Jazz & Heritage Festival draws roughly half a million people to the Crescent City every year. Credit: Richard Schneider/Flickr, CC BY-NC 2.0 (bit.ly/ccbync2-0) park in April was ranked first. Other amusement parks in Ohio, Florida, and Texas joined the top 10 list, as did Globe Life Field, a Major League Baseball stadium in Texas; the State Fair of Texas in Dallas; the Texas Grand Prix; and the Indianapolis Motor Speedway.

"Venues need to be, and generally are becoming, better prepared for these types of events."

"Amusement parks dominate the scores because they're open so many days per year," Strader said. The team's results were published in *Weather, Climate, and Society*, and the full ranking of events is available upon request from the authors (bit.ly/outdoor-event-exposure).

It's important for the operators of venues to look at these results, said John Jensenius, a meteorologist and lightning safety specialist and a member of the National Lightning Safety Council, who was not involved in the research. But event attendees also have responsibility for their own safety, he added. With weather apps widely available, people can make educated choices about whether to attend a particular event. "Avoidance is always the best answer if you think there's going to be lightning at an event," Jensenius said.

Some venue managers and event organizers are already taking weather-related risks seriously. Last year, a football game between Penn State and West Virginia universities was interrupted by lightning, and officials opted to evacuate Mountaineer Field at Milan Puskar Stadium, an outdoor space in Morgantown capable of holding roughly 60,000 fans.

"Venues need to be, and generally are becoming, better prepared for these types of events," said Roger Edwards, who retired last year as a meteorologist and lead forecaster at NOAA's Storm Prediction Center in Norman, Okla. Edwards was not involved in the research.

Strader is now thinking of ways to expand the team's database. There are plenty of other forms of extreme weather that could wreak havoc on a large outdoor gathering, he said. "What about wind, hail, flash flooding?"

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

A Geologic Map of the Asteroid Belt

Adobe Stock/roobcio

Where do meteorites come from? A new analysis of 75 fall events suggests that meteorites with different geologies travel from different places in the asteroid belt, which separates Mars and Jupiter (bit.ly/meteorite-origins). Researchers traced some types of meteorites to particular asteroid families, creating a geologic map of meteorite origins. Most meteorites in the analysis were generated by just a few recent collisions between asteroids.

"Understanding the asteroid belt is really looking into the past, into the formation of the solar system, and into all the dynamics that happened at that time," said Peter Jenniskens, coauthor on the new analysis and a meteorite astronomer at the SETI Institute in Mountain View, Calif. Those early interactions and collisions matter because much of the water on Earth and a lot of the organics likely came from primitive asteroids, he added.

Tracking Falls

Spacecraft have returned small volumes of material from the Moon, comets, and asteroids, but meteorites remain the primary way that scientists get their hands on space rocks.

"By reconstructing where specific meteorite types formed, we gain a clearer picture of the compositional and thermal gradients that existed when the solar system was young," said Michaël Marsset, an astronomer at the European Southern Observatory in Santiago, Chile. "This has major implications for understanding how habitable environments emerge, not just here but potentially in other planetary systems as well." Marsset studies small solar system objects and Earth impactors and was not involved in the new study.

But matching a meteorite to the asteroid it came from is a tall task.

"Asteroids in space look quite a bit different than the meteorites that we have in our laboratories," Jenniskens explained, "because the asteroids in space are covered by regolith and debris and they are exposed to solar radiation and solar wind." A meteorite might come from an asteroid's interior, which could look entirely different from its surface. That makes it challenging to use astronomical observations alone to match meteorites to their asteroid parents.

When someone witnesses a meteorite falling to Earth, scientists can try to backtrack its orbit to a point of origin. Combining this information with the meteorite's geochemistry, mineralogical structure, and age, they can then figure out which asteroid or asteroid family—a group of asteroids that originate from the same collision event—sent it hurtling toward Earth.

The trouble is that meteorites fall more or less at random, Jenniskens explained. It has taken a while to document enough of them to spot patterns, he said. Just 6 years ago, there were fewer than 40 meteorite falls with well-measured trajectories.

"The number of falls has doubled since that time," Jenniskens said.

Meteorite researchers have set up more than 2 dozen global camera networks that have detected many of these recent falls—roughly 14 falls per year. Also, the rising popularity of dash cameras and doorbell cameras has contributed to the surge of recent detections.

In the new analysis, about 36 of the 75 falls were recorded by residential security cameras, Jenniskens said. People report fireball sightings and submit videos for analysis. "We really depend on the citizen science."

Meteorite Ancestry

Jenniskens and his colleague Hadrien Devillepoix of Curtin University in Perth, Australia, reviewed the trajectories, geochemistry, mineralogy, and size of 75 meteorites. They also looked at the meteorites' ages, calculated on the basis of how long a rock's surface has been exposed to cosmic rays.

Though a few asteroids are suspected sources of certain meteorite types, a meteorite's age was often the key factor in figuring out which asteroid family produced the meteorite. The positions and movements of asteroids within a family evolve in a predictable way over time, and if this so-called dynamical age matched a meteorite's cosmic ray age, that family was more likely to be the meteorite's source.

Most of the meteorites originated from a handful of asteroid families, and different classes of meteorites could be traced to different parts of the asteroid belt.

Jenniskens and Devillepoix confirmed that very low iron LL-type meteorites, such as the Chelyabinsk meteorite, originated from the extensive Flora family in the inner asteroid belt. They tracked H-type chondrites to debris clusters in the Koronis, Massalia, and Nele families. They also traced low-iron L chondrites to the Hertha asteroid family, rather than to the previously determined Massalia family.

"It turns out that, yes, our HED meteorites seem to come from Vesta, not from its family."

"Hertha is covered by dark rocks that were shock blackened, indicative of an unusually violent collision," Jenniskens said. "The L chondrites experienced a very violent origin 468 million years ago when these meteorites showered Earth in such numbers that they can be found in the geologic record."

Marsset has also worked to trace meteorites to their asteroid origins, though his team used astronomical observations of asteroids and numerical modeling, rather than meteorite data.

"Even with these different approaches, we're mostly converging on similar conclusions," Marsset said. "Where we disagree, well, that's part of the fun! For example, I'd gladly bet a pint with Dr. Jenniskens and Dr. Devillepoix that L chondrites come from the Massalia family, not Hertha," he joked.

The team also looked at howardite, eucrite, and diogenite (HED) meteorites, achondrites that have long been tied to the Vesta asteroid family. According to the new analysis, the volume of HED material that made its way to Earth must have come from a collision so large that only something as large as Vesta would have survived. (Vesta is the second-largest object in the asteroid belt.) What's more, the cosmic ray exposure ages of HED meteorites closely match the ages of particular impact craters on Vesta's surface that were mapped by NASA's Dawn spacecraft.

"It turns out that, yes, our HED meteorites seem to come from Vesta, not from its family," Jenniskens said.

NASA's Dawn spacecraft orbited asteroid 4 Vesta and mapped its surface geology and chemistry. Debris from impacts that made some of these craters makes its way to Earth as howardite, eucrite, and diogenite (HED) meteorites. Credit: NASA/JPL-Caltech/UCAL/MPS/DLR/IDA, Public Domain

Decoding Solar System History

"What's remarkable about this work is the broader picture it starts to paint," Marsset said. "We are finally able to map specific classes of meteorites that fall on Earth to distinct regions in the asteroid belt and to specific asteroid families.... That's a major step toward understanding the compositional structure of the asteroid belt and, ultimately, how our solar system formed and evolved."

But it's just as important to understand where meteorites *aren't* coming from, he pointed out.

"While one might expect the meteorite flux to represent a broad sampling of material from across the entire asteroid belt, we now know that it is actually dominated by a few recent fragmentation events," Marsset said. "This insight helps us better understand the natural sampling bias in the meteorites we collect on Earth, and it also highlights which asteroid populations are underrepresented. That, in turn, can guide the targets of future space missions aimed at filling in those missing pieces."

By **Kimberly M. S. Cartier** (@astrokimcartier.bsky.social), Staff Writer

Departing Iceberg Reveals Thriving Antarctic Ecosystem

In mid-January, a team of scientists was sailing aboard a research vessel in frigid Antarctic waters. They planned to investigate an unexplored section of the Bellingshausen Sea and the creatures that live there, but were stymied by more sea ice than they expected.

"We found ourselves restricted to a smaller area," said Patricia Esquete, a marine biologist at the Universidade de Aveiro in Portugal and expedition co-chief scientist. "Instead of Bellingshausen Sea, we were restricted to the Ronne Entrance."

The team made the most of the situation, and they and their research vessel, Schmidt Ocean Institute's R/V *Falkor (too),* settled in to conduct science operations in front of the ice shelf.

While checking satellite images of sea ice extent, they noticed that a crack had formed along the edge of the George VI ice shelf about 30 kilometers from their location. They jotted it down but didn't worry about any dangers it posed. Such cracks can take weeks or months to fully force a break from the shelf and form an iceberg, Esquete explained.

But when the next batch of satellite images came through a few days later, the team was surprised to see that a 510-square-kilometer iceberg had broken off and was drifting along (and occasionally bumping against) the coast of the Antarctic Peninsula. The departure of the Chicago-sized iceberg, A-84, revealed a patch of polar seafloor that had been covered by ice for years, and possibly centuries.

"As soon as we realized that the iceberg had moved on and left that space for us to sample, we immediately decided to go there and see [what] the seafloor looks like under the ice," Esquete said. When they arrived, they found a thriving ecosystem rivaling those in nutrient-rich open waters.

"We immediately decided to go there and see [what] the seafloor looks like under the ice."

Luck and Daring

Before A-84 calved, the team was poised to document the biodiversity of a nearby deep-sea ecosystem, collect sediment samples, study underwater ocean dynamics, and create seafloor maps.

"A holy grail for oceanography is not only mapping the entirety of the deep seabed in high resolution in terms of its shape and structure, but also in terms of specifically what lives there and how," said Dawn Wright, an oceanographer and chief scientist at Environmental Systems Research Institute (Esri) in Redlands, Calif., who was not involved with this expedition.

Sea ice impedes that goal: Research vessels can't get too close to the ice shelf, and remotely operated vehicles (ROVs) and autonomous underwater vehicles can travel only so far from the ship to explore under the ice.

The procedures involved in securing funding and scheduling a ship can make seagoing research in the Antarctic a slow process, explained Joan Bernhard, a biological oceanographer at Woods Hole Oceanographic Institution in Massachusetts. Planning an expedition like the one in January can take years or even decades, with few exceptions.

Some expeditions have been able to mobilize when seafloor is newly exposed. After Larsen C calved in 2017, for example, research vessels arrived in the area about a year later—much faster than average. Changes at the surface take time to affect the seafloor, but even with such a quick response time, researchers still missed the opportunity to establish a pre-calving baseline.

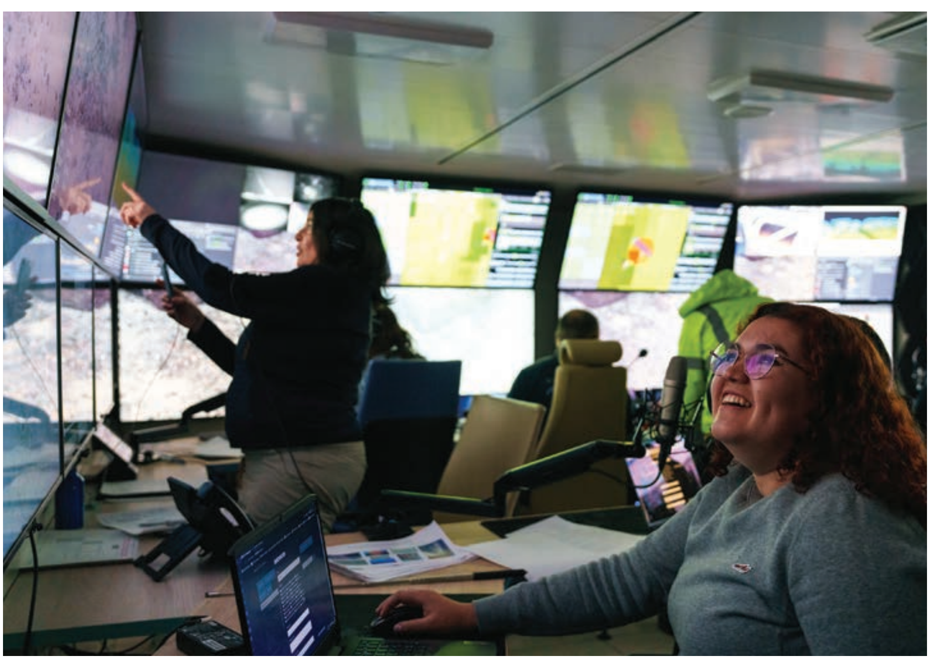
After most calvings, "any newly exposed seafloor will have been subject to open-water conditions for years; currents could import alien species potentially impactful to indigenous taxa," said Bernhard, who was not involved with the *Falkor (too)* expedition.

Iceberg A-84 calved on 13 January. *Falkor (too)* reached the newly exposed seafloor just 12 days later.

After relocating, the researchers conducted the same suite of science observations they had originally planned, just in the newly exposed location. Thanks to the quick pivot, the team was able to observe the area as if it were still covered by the ice—an "incredibly rare" opportunity, Bernhard said.

"In my view, nowhere has serendipity in ocean science proved more critical," Wright said of the expedition. Operating in those conditions is hard enough, and it's even tougher to be in the right place at the right time, she added.

Esquete acknowledged the expedition's fortune. "Good luck played a huge role. We



As creatures of interest are spotted on video screens, Maritza Castro of Chile's Universidad Católica del Norte and other researchers react with excitement in the remotely operated vehicle mission control room on board R/V Falkor (too). *Credit: Alex Ingle/Schmidt Ocean Institute, CC BY-NC-SA 4.0 (bit.ly/ccbyncsa4-0)*

R/V Falkor (too) *maneuvers around icebergs while conducting research in the Bellingshausen Sea off Antarctica, before shifting course to explore newly revealed seafloor. Credit: Alex Ingle/Schmidt Ocean Institute, CC BY-NC-SA 4.0 (bit.ly/ccbyncsa4-0)*

cannot deny that," she said. "But there's also value in daring to explore the unexplored." The team would have missed the opportunity had they not already been exploring one of the most remote parts of the world.

"Good luck played a huge role. We cannot deny that. But there's also value in daring to explore the unexplored."

Thriving Beneath the Ice

The researchers collected sediment samples, used lidar to create bathymetric maps, and studied the water column and ocean currents. They are still analyzing those data. They also deployed the ROV *SuBastian* to document the biodiversity of the deep sea and found a thriving ecosystem spanning the trophic web: corals, sponges, invertebrates, cephalopods, king crabs, and krill, as well as a few unknown species.

"I was excited to see what appeared to be meter-tall sponges, 'giant' pycnogonids (sea spiders), and large ophiuroids (brittle stars), all similar to those known from the McMurdo Sound region," Bernhard said.

"What surprised me was the sheer variety of organisms that were found, as well as the huge sizes of some of the deep-sea sponges that had apparently been growing for hundreds of years under such harsh Antarctic conditions," Wright said.

What's more, the team found several species that filled discrete ecological niches, which suggested that the ice-covered ecosystem received a steady, high-level influx of nutrients and may have been there for a while, Esquete said.

"Basically, we found the same type of ecosystems that you can expect in that area of the Bellingshausen Sea," Esquete said. But unlike the other areas the team studied, this ecosystem thrived "in an area that's been permanently covered by ice for probably centuries."

That in itself was surprising, she said. Most deep-sea ecosystems that aren't covered by thick ice receive nutrients that trickle down from photosynthetic organisms near the surface. Scientists think that nutrients carried on deep-sea currents supply nutrients to benthic ecosystems where ice prevents top-down nutrient delivery.

"I was mildly surprised by the plethora of sea anemones on a boulder adjacent to a barrel sponge because all are filter feeders," Bernhard said. "Such abundance implies currents are strong enough to transport sufficient organic matter to this area."

A Future Without Ice

The *Falkor (too)* researchers returned to the mainland after weeks studying the newly discovered Bellingshausen habitat. They hope for a return trip to investigate how that patch of seafloor changes now that its icy cover has drifted off. Nutrients trickling down from photosynthetic algae might now be available, but the ecosystem has already adapted to and thrived on a lower nutrient supply.

"Open-water conditions may imperil these ecosystems," Bernhard said. "More settlement of organics to the seafloor…could cause an ecological imbalance."

This ecosystem could be a bellwether for changes across polar ecosystems as climate change melts Antarctic ice.

"The accelerating loss of polar ice that protects these ecosystems, including channeling of nutrient-rich currents to them, does not bode well for their vitality," Wright said. "But there is so much that we just don't know. The oceanographic community will be watching the results of this expedition as they become available with intense interest. It has direct bearing on the overall health of the planet."

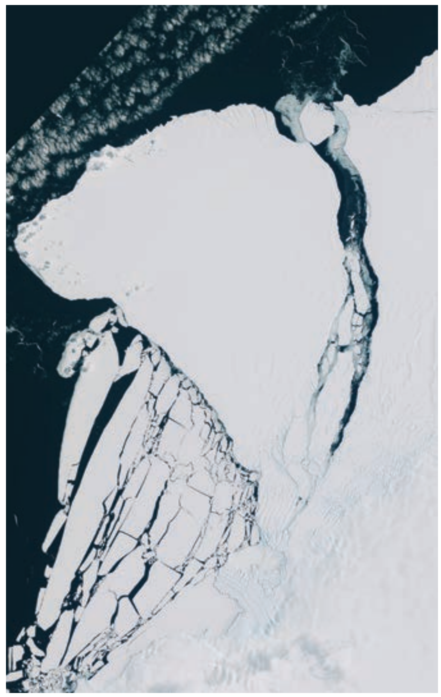
By **Kimberly M. S. Cartier** (@astrokimcartier.bsky.social), Staff Writer

"Transformational" Satellite Will Monitor Earth's Surface Changes

In June, scientists were planning to launch a satellite to provide unprecedented, high-resolution coverage of some of the most remote and rapidly changing parts of the world. The NASA-ISRO Synthetic Aperture Radar (NISAR) satellite, a joint mission between NASA and the Indian Space Research Organisation (ISRO), will scan nearly the entire globe twice every 12 days to measure changes in Earth's ecosystems, cryosphere, and land surface.

"In my eyes, it's orbiting magic," said Alex Gardner, a glaciologist at the Jet Propulsion Laboratory (JPL) in Pasadena, Calif., and a member of NISAR's cryosphere science team. NISAR will provide high-resolution radar imagery that will enable scientists to track glaciers and ice, biodiversity, soil moisture and water placement, and land displacements from events like earthquakes and landslides.

"When there's an earthquake and you can see displacements from 500 kilometers up that you wouldn't even be able to notice if you were standing on the ground…that's orbiting magic," Gardner said.



On 23 January 2023, a large iceberg broke away from Antarctica's Brunt Ice Shelf. NISAR's orbit will help glaciologists monitor incidents like this in Earth's rapidly changing cryosphere. Credit: Contains modified Copernicus Sentinel data (2023), processed by ESA, CC BY-SA 3.0 IGO (bit.ly/ccbysa3-0igo)

Double Radar

As this issue went to press, NISAR was scheduled to launch in June from the Satish Dhawan Space Centre in India. It is the largest, though not the first, satellite collaboration between NASA and ISRO, explained Paul Rosen, NISAR project scientist at JPL. "We had some other collaborations in both planetary and Earth science, but not at this level of magnitude," he said.

The satellite plays host to two synthetic aperture radar (SAR) systems that operate at different microwave wavelengths, one longer (L band, at a wavelength of 24 centimeters) and one shorter (S band, at a wavelength of 10 centimeters). SAR is a technique used to create high-resolution images from lower-resolution instruments. The instruments emit continuous pulses of microwave radiation and use the light that bounces back, as well as the time delay, to create backscatter images.

"We made sure that the two radars could work together," Rosen said. "They're highly in sync, and we can turn them on together or operate them separately."

Unlike visible-light imaging, SAR is not limited by the time of day or the weather, explained Deepak Putrevu, an engineer and colead of NISAR's ISRO science team at the Space Applications Centre in Ahmedabad, India. "It uses microwaves for imaging, so that makes it able to penetrate the clouds and to image even during the nighttime….The SAR technology enables us to have day and night coverage and all-weather imaging capability."

NISAR's orbit will cause it to pass over the same locations every 12 days. Because SAR can map an area as it both approaches (ascending orbit) and departs (descending orbit), NISAR will be able to scan each area twice every 12 days. Each space agency provided one of the radar systems, as well as other components of the satellite, the launch system, and the data management infrastructure.

"We jointly operate the mission and jointly do the science," Rosen added.

"It's got a lot to deliver on, but I don't feel that nervous about it," Gardner said. "Aspects of these technologies have flown before," he added. For example, the European Space Agency's Sentinel satellites carry SAR instruments that have helped scientists understand the cryosphere, Earth surface processes, and ecosystems. But NISAR's dual radar frequency bands are a first for Earth-observing satellites. The systems will be able to detect changes at different physical scales—L band for large structures and S band for smaller ones—as well as provide higher-resolution images together than can be achieved individually.

Global Surface Changes

One of NISAR's primary science objectives is to observe changes to the cryosphere and glaciers around the world. That's Gardner's wheelhouse.

"Glaciers are just these really fantastic living creatures," he said. NISAR will monitor seasonal growth and retreat patterns of glaciers around the world, with a special focus on those of the West Antarctic Ice Sheet like Pine Island and Thwaites.

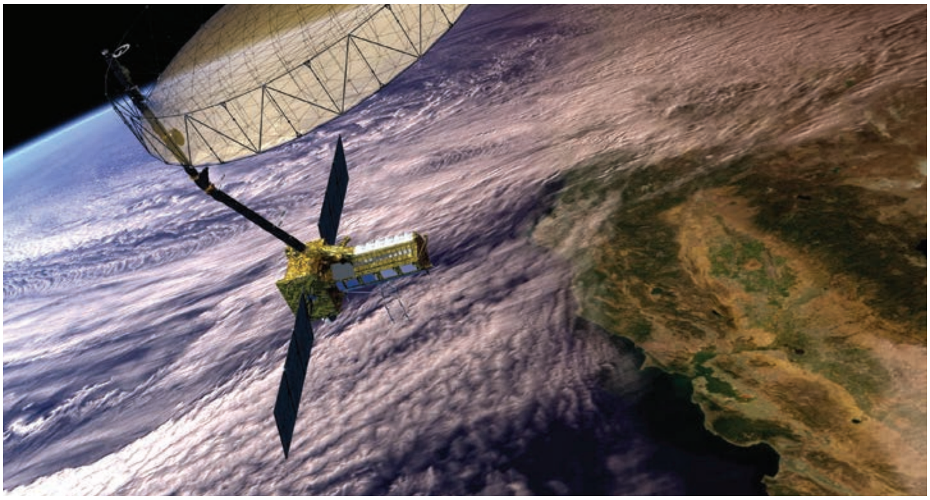
"They just have such large societal consequence that there'll be a lot of attention there," Gardner explained. More broadly, he said, those seasonal patterns can be a good predictor of long-term changes in the cryosphere.

NISAR will also be able to observe the vertical displacements of ice sheets, which Gardner said will allow cryosphere scientists to map where floating ice sheets meet grounded ice, a boundary called the grounding line.

"It's really hard to measure, and it's been done locally but not really at large scale," he said. "We can watch [the] position of that grounding line change with time, which is an indicator of vulnerability" to warming temperatures.

NISAR will measure global biodiversity and soil moisture. The two radar frequency bands will be especially helpful with this, Putrevu explained. "With forest biomass, the L-band system will be able to see the dense forest with more sensitivity. But when we use the S-band system, you can use it for sparse vegetation, as well."

The SAR systems will be able to see through crop cover and measure soil moisture, Putrevu added, which will provide key information for farmers and agribusiness. He also highlighted the importance of closely monitoring changes in land deformation, which



NISAR, illustrated above, will measure biomass, natural hazards, sea level rise, and groundwater. Credit: NASA/JPL-Caltech, Public Domain

might suggest imminent earthquakes or landslides.

"All the applications have a societal benefit attached," Putrevu said. "It gives a great deal of satisfaction that this will actually be useful for society."

A Data Deluge

The satellite will spend its firsts 90 days conducting its commissioning tests and reaching its science orbit. "But as we progress, we're going to get little peeks behind the curtains that we are going to be so enthusiastic about as we see the imagery start to really mature, and the data processing mature, the data acquisition mature," Gardner explained. "There'll be a progression from a first-light image to science-ready data."

Every pass of the satellite will provide an order of magnitude more data than past satellites have delivered. Much of the final preparation before launch involved developing the infrastructure needed to efficiently receive, process, and make available such large quantities of data.

"Once NISAR comes online, the sheer volume of new data that we're going to be dealing with requires the development of novel tools," Gardner said. "NISAR is really leaning into cloud architecture" for data storage, availability, and computing, so that users don't have to download massive quantities of data to individual servers. "Moving data around is one of the largest bottlenecks with missions like this."

"We have been preparing for the last couple years to get all of our algorithms working really efficiently in the cloud," Gardner said, "so that when the fire hose of data comes online, we can get in there, plug into that data stream, and benefit from it really early on."

Putrevu said that scientists and students across India have been participating in workshops since 2014 to learn how to access, process, and produce science from NISAR's data. "That shows how the community is getting geared up to use the data," he said in April. "Everyone is eagerly looking forward to [launch] day."

Gardner cautioned that it might be a year or two before NISAR data yield new scientific outcomes because the volume of information requires such novel processing tools. The mission's nominal lifetime is 3 years, and once the analysis gets up to speed, discoveries derived from those data will likely continue for decades.

"Without a doubt, it will be a legacy dataset," Gardner said. "It's going to be transformational."

By **Kimberly M. S. Cartier** (@astrokimcartier.bsky.social), Staff Writer

The Valuable, Vulnerable, Long Tail of Earth Science Databases

Imagine a database containing all of the world's Earth science data, from those characterizing hazards like earthquakes and volcanoes to those recording changes in the atmosphere and the ocean. This hypothetical resource had been built up, little by little, through untold piecemeal contributions from individuals and small teams of researchers, many of the observations gathered from sites now inaccessible or destroyed. Then, after decades (centuries, even) of collection, a catastrophic flood took the server offline and wiped out the data.

How long would it take to replace these data? How much would it cost to do so? And how much cheaper would it have been instead to invest in better safeguarding this critical scientific infrastructure?

Versions of this hypothetical database containing not all but, nevertheless, substantial collections of the world's Earth science data are real. In fact, there are dozens of them, and the threat of their demise is real as well.

The looming catastrophes facing them—funding cuts, software obsolescence, and loss of community support—may sound more mundane than massive flooding but may pose a greater risk and be no less damaging.

These sorts of database disasters can be subtle and are challenging to prevent because maintaining research databases is a complex, interdisciplinary practice requiring technical expertise in cyberinfrastructure development, deep engagement with disciplinary experts, and sustained political and financial support. Prevention of database loss is also challenging because problems like software obsolescence are both slow moving and omnipresent. The destruction they cause may go unnoticed until it's too late.

Databases in the Earth and environmental sciences (EES) are particularly valuable—and particularly vulnerable. Whereas in fields like astronomy and high-energy physics, many researchers may primarily use data collected by a single high-powered tool (e.g., the Hubble Space Telescope or the Large Hadron Collider), EES researchers often must go through a laborious process of integrating data from various sources to enable large-scale studies.

Indeed, much EES research depends on the reuse and integration of heterogeneous, "long-tail" datasets—those collected over years to decades by small, distributed teams with relatively small amounts of funding (Figure 1, top) [*Heidorn*, 2008].

Such data are typically accessible only through community-curated data resources (CCDRs) [*Williams et al.*, 2018a], which are researcher-led data infrastructures to which scientists contribute, curate, and integrate data with the goal of studying phenomena such as the global carbon cycle and biodiversity dynamics. Expert data curation and stewardship of these long-tail data are critical to advancing understanding of Earth system dynamics across scales. However, demonstrating these resources' value to science and society can be difficult because they are built over long periods of time and by

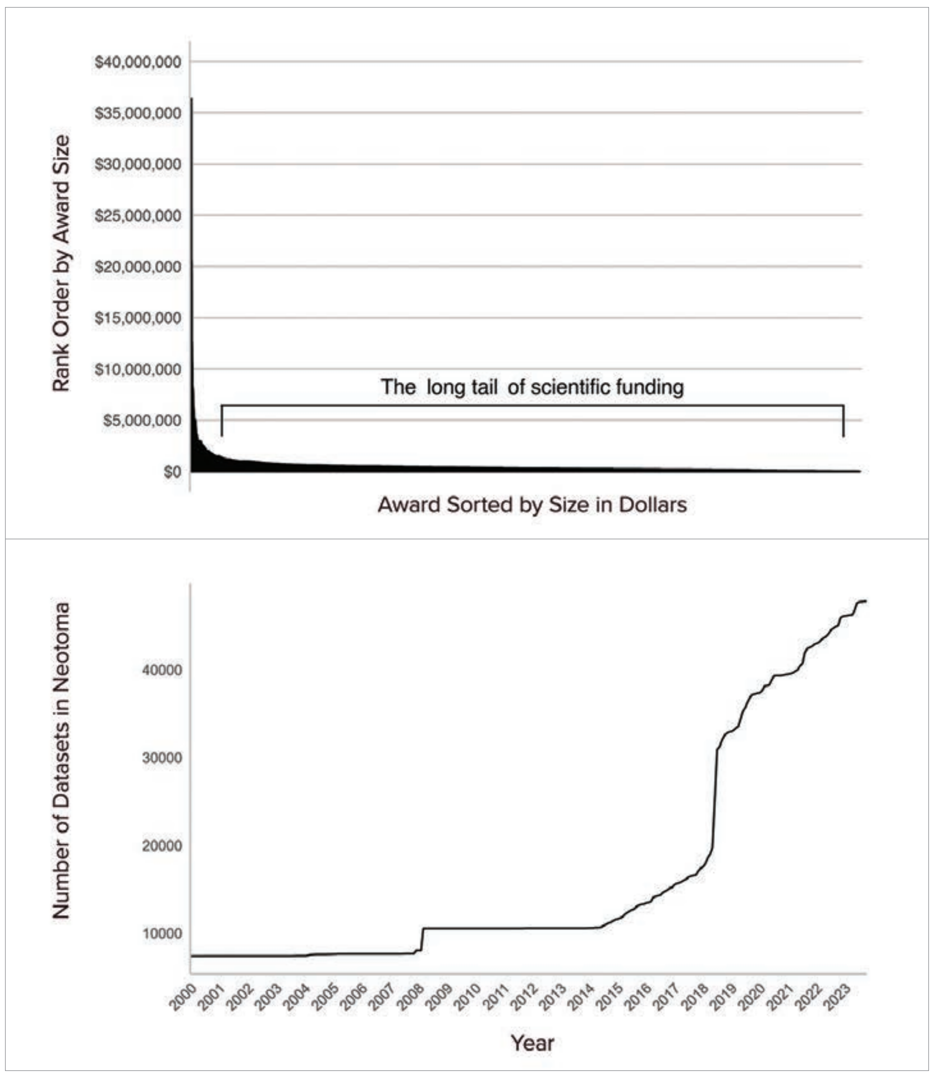


Fig. 1. The data produced by the long tail of scientific funding (top)—the roughly 80% of awards that account for only about 44% of all National Science Foundation (NSF) grant funding—are wildly diverse and collectively represent the critical foundations of most scientific disciplines. In the long tail, curation by communities of experts can build big, high-quality datasets as many heterogeneous small datasets are collected. Such growth is demonstrated by the increasing data volume, expressed as the number of datasets, in the Neotoma Paleoecology Database (bottom). Credit: Nora Schlenker (The top plot is updated from Heidorn *[2008] using 2022 data from NSF by the Numbers)*

many people via curatorial labor that is often invisible to standard academic metrics of productivity.

Small Teams Build a Billion-Dollar Asset

As a case study to illustrate the hidden value of expert-curated datasets in EES, we calculated the simplest metric of value, replacement cost, for the Neotoma Paleoecology Database [*Williams et al.*, 2018b]. Neotoma is a CCDR that gathers and shares datasets of species abundances, as recovered from the sedimentary record, that document past ecological dynamics spanning centuries to millions of years.

Expert data curation and stewardship of long-tail data are critical to advancing understanding of Earth system dynamics across scales.

More than 1,600 papers citing Neotoma data have themselves been cited nearly 50,000 times. In addition to many other timely research applications, the database is widely used to study the effects of human activity and changing climates on species and ecosystems, which can improve forecasts of ecological responses to current climate trends. Neotoma data have shown, for example, that current rates of ecological change are as fast as or faster than those that accompanied widespread ecological transformations at the end of the last ice age, roughly 11,700 years ago [*Mottl et al.*, 2021].

Each dataset in Neotoma was collected and submitted by a small team of scientists, with usual times to publication of 2 years or longer after samples were collected. The database is continually growing and at the time of writing included 34,100 datasets (Figure 1, bottom) comprising analyses of 450,000 individual samples from 155 countries and 20,800 field sites. Neotoma also stores more than 44,000 radiometric sample ages, which provide temporal context for sedimentary archives.

The total data volume of Neotoma is small (about 6 gigabytes), but its replacement cost is quite high: at least $1.5 billion (Figure 2).

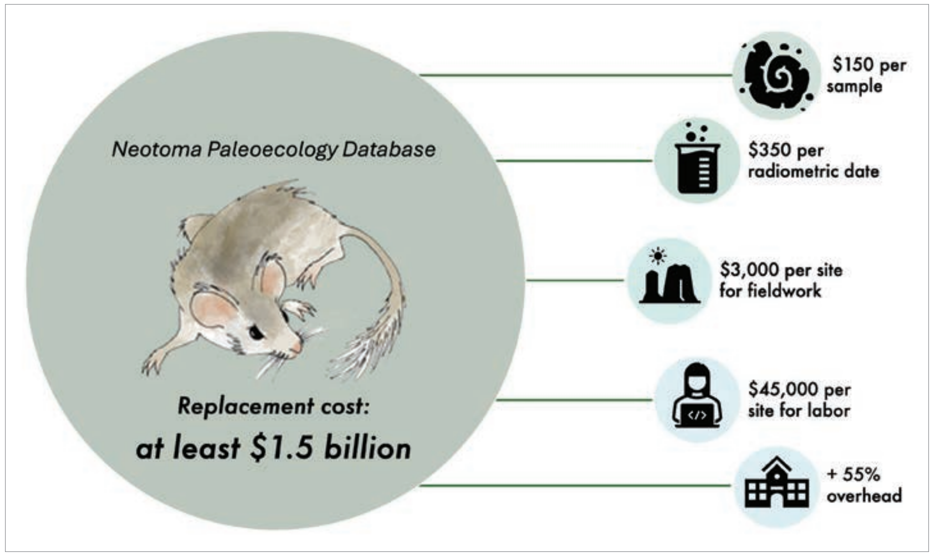


Fig. 2. The replacement cost of the Neotoma Paleoecology Database—named for Neotoma, *the pack rat genus—can be conservatively estimated at $1.5 billion by factoring in costs for sample preparation and analysis, fieldwork, labor, and overhead. However, that figure does not include the costs of the many hours of additional labor put into rigorous curation of the database. Credit: Andrea Thomer*

We calculated this overall amount using estimates informed by decades of experience building and reviewing grant budgets for fieldwork, sample preparation and analysis, labor, and overhead. These estimates include $3,000 per site for fieldwork, $150 per sample to cover expert time and analytical costs, $350 per radiometric date, and $45,000 per site for labor (i.e., 1 year of a graduate student's time to analyze and publish data), all increased by 55% to account for institutional overhead costs.

The fiscal year 2022 budget of the U.S. National Science Foundation's (NSF) Sedimentary Geology and Paleobiology (SGP) program, the major U.S. funder of this research, was $10.4 million.

Of course, exact costs can vary; overall, though, these estimates are conservative because, for example, graduate students often need more than 1 year per site, principal investigator salaries are not included in the estimates, and infrastructure-dependent research such as ice core or oceanographic drilling has higher costs.

It would take SGP roughly 145 years to rebuild Neotoma's archives—assuming all program resources were devoted to this activity. In fact, many records would be impossible to re-collect because some sites have been destroyed or become inaccessible. This example underscores a central characteristic of long-tail scientific data: At best, they are extraordinarily expensive to replace, and at worst, they are irreplaceable.

A central characteristic of long-tail scientific data is that, at best, they are extraordinarily expensive to replace and, at worst, they are irreplaceable.

The Pricelessness of Community Curation

Our direct replacement estimate for Neotoma is also conservative compared to the resource's true worth because it fails to capture the value that community curation adds. For instance, the use of community-developed standards and common vocabularies in Neotoma (and other CCDRs) helps tame the inherent heterogeneity of long-tail data and makes Neotoma's data fundamentally more reusable than data deposited in generalist repositories.

Whereas generalist repositories, which accept any kind of data, typically lack strict curatorial standards, domain-specific CCDRs

like Neotoma often reformat data into a common structure. They also describe data using standardized or controlled vocabularies for species names, measurement units, and other variable names. Controlled vocabularies are essential for large data syntheses using geoscientific data from many sites. For example, if two scientists use different versions of a species name for the same fossil specimen, then estimates of past biodiversity will be artificially increased.

Curation by community experts also builds trust with researchers, who will not reuse data they don't trust [*Yoon*, 2017]. So Neotoma's reputation as a well-curated resource is as valuable as the technical work of data curation. The replacement cost estimate further omits the value of time and resources saved by researchers and others as its data are repeatedly reused: Each time a study reuses Neotoma data, this value increases, reflecting the mounting savings for teams not needing to collect, aggregate, and harmonize the data themselves. Clearly, these intangibles, though harder to quantify than field, labor, and analytical costs, carry great benefit.

Better Support for the Long Tail

Neotoma is one of many vital CCDRs in the Earth and environmental sciences. Other examples include AmeriFlux and FLUXNET; the Botanical Information and Ecology Network (BIEN); the Global Biodiversity Information Facility; and Interdisciplinary Earth Data Alliance databases like SESAR, the Paleobiology Database, the Nutrient Network (NutNet), Water Isotopes, and VertNet. Each of these has its own potential replacement costs, some less than Neotoma's and some more. Each also offers its own case study in resilience and precarity.

Although CCDRs have, in some cases, persisted across multiple generations of scientists—indeed, they are where many EES researchers get essential data science training—their financial and technical sustainability is an ever-present concern. Many continue to be or were at least initially funded with federal grants, but their persistence and growth also depend—sometimes to a large extent—on grassroots, volunteer labor by experts with highly specialized and in-demand skill sets. This reliance on specialized, uncompensated labor introduces precarity because traditional metrics of productivity and impact in academic careers continue to undervalue, and thus disincentivize, the essential work of data science and stewardship [*Merow et al.*, 2023; *Goring et al.*, 2014; *Williams et al.*, 2018a].

How might society better support these crucial, multigenerational data resources and the people who maintain them?

Diversifying funding streams for CCDRs could further enhance their sustainability.

CCDRs must be recognized as one of the most effective ways to compound the value of long-tail scientific research—the more they're used, the more valuable they become, and the more they reduce additional costs for scientists and funders. The scientific community also needs to acknowledge that both the human and technical components of CCDRs are critical to these resources' long-term functionality and need sustained support. The roles of data stewards and curators must be formally recognized as important professional work.

Most important, CCDRs should be funded as sustained infrastructure. The biggest challenge to maintaining these resources is the current system by which they're supported on a short-term, grant-by-grant basis on 3- to 4-year cycles. Ideally, federal grant models for CCDRs should both lengthen the time horizon of funding cycles to 5–10 years and increase funding levels to better support infrastructure and personnel for core functionality.

NSF programs such as Geoinformatics and Infrastructure Capacity for Biological Research (Capacity) have moved in this direction by enabling longer support horizons for data resources. Still, sustainability and tight budgets for CCDRs remain significant issues. More robust support for infrastructure and personnel can be complemented by science-driven campaigns on typical 3-year grant cycles that both add data to these resources and use them for research at spatiotemporal scales not achievable by individual site-level studies.

Diversifying funding streams for CCDRs could further enhance their sustainability [*Virapongse et al.*, 2024]. One possibility is to implement pay-to-submit models, in which researchers pay a fee to archive their data. These models increasingly sustain generalist repositories (though, often, the fees are hidden from researchers) but unfortunately tend

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to work less well for CCDRs. Although CCDRs' data curation requirements add value, they rely both on work by paid skilled experts and on donated time, goodwill, and expertise by scientists. These elements may necessitate data submission fees that are cost prohibitive for researchers and make it harder to achieve the economies of scale that work for generalist repositories.

Reducing the curatorial effort in CCDRs by building data pipelines from the point of collection to their availability as a community data resource is one way to reduce costs. Still, work is needed to explore reasonable fee-for-service models that account for the value of time donated to CCDRs while offering generous waiver policies for individuals and institutions that simply don't have the capacity to contribute either time or money.

Private foundations can also engage more in supporting community-led scientific data resources as loci of transformative scientific discovery, artificial intelligence development, and next-generation scientific training. And apart from funding bodies like NSF, other federal agencies that increasingly rely on (and sometimes mandate the use of) CCDRs for data archiving and sharing should also develop sustained service agreements and funding support models for these resources.

CCDRs in the Earth and environmental sciences build, support the accessibility of, and compound the value of long-tail data, thereby powering critical scientific research into how our planet is changing and the societal and ecosystem effects of this change. By inadequately supporting these resources, we risk losing and potentially needing to replace them, an extremely costly, yet preventable, outcome.

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Authors' Note: This article was written in 2024, before dramatic cuts to multiple science agencies were enacted by the U.S. federal government. Although we have not updated it to reflect on these changes, we believe our core argument is all the more timely: Scientific collections and data repositories are among the most vital, valuable, and cost-effective ways of supporting science, and they need continued funding and support.

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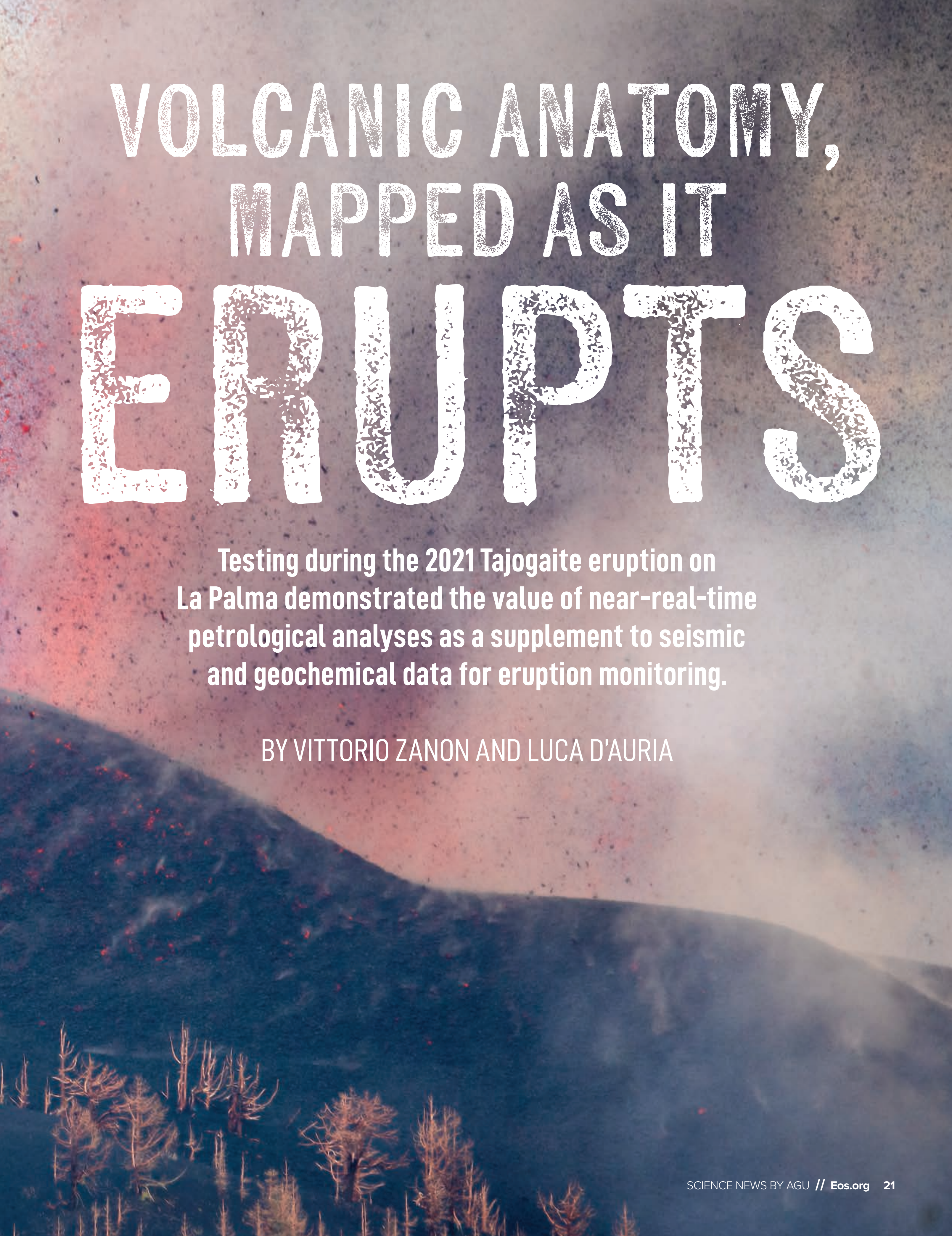
Opposite: iStock.com/Muhamad Chabib alwi

Lava and gases erupt from part of the Cumbre Vieja volcanic ridge on La Palma in the Canary Islands on 20 September 2021. Credit: Eduardo Robaina/Wikimedia Commons, CC BY-SA 3.0



VOLCANIC ANATOMY, MAPPED AS IT ERUPTS

Testing during the 2021 Tajogaite eruption on La Palma demonstrated the value of near-real-time petrological analyses as a supplement to seismic and geochemical data for eruption monitoring.

BY VITTORIO ZANON AND LUCA D'AURIA

On 19 September 2021, the island of La Palma, one of the Canary Islands off the northwestern coast of Africa, experienced its first volcanic activity after more than 50 years of dormancy.

In 2021, the Tajogaite volcanic cone formed on La Palma in Spain's Canary Islands as a result of about 3 months of continuous eruptions of tephra and lava. It was the first volcanic activity on La Palma since the Teneguía eruption in 1971. Credit: Instituto Volcanológico de Canarias

The eruption lasted about 3 months and created a new volcanic cone, named Tajogaite, along the island's Cumbre Vieja volcanic ridge. It released large plumes of ash and gas, as well as roughly 200 million cubic meters of lava that spread over 12 square kilometers of the island, burying or severely damaging urban settlements and roads. The event forced the evacuation of about 7,000 people and caused more than 842 million euros in damages.

Data reported by gas geochemists and geophysicists had foretold a possible eruption since 2017 (although its likely timing was uncertain). Research identified an anomalous gas composition in a spring used as a monitoring site, as well as dispersed seismic activity caused by the magmatic reactivation of the volcano (Figure 1). However, actual volcanic precursors, such as well-localized ground deformation, seismicity, and gas emissions, were detected only 8 days before the eruption [*D'Auria et al.*, 2022].

Real-time seismic readings, satellite-based analyses, and other data collected on-site during the Tajogaite eruption provided vital information not only for keeping surrounding communities safe but also for guiding and managing associated scientific efforts. By comparison, the first published petrographic and geochemical analyses of Tajogaite lavas, done using rocks collected only in the first week of the eruption, weren't released until early 2022 for the purpose of describing the erupted material. Months later, other petrological and geochemical studies were published, describing the conditions and origin of the magmas, their rheological properties, and their dynamics during the eruption.

Petrologists' work with respect to volcanoes can be likened to conducting autopsies, providing insights into the causes and behavior of eruptions after the fact. This information is highly valuable, but the typically lengthy time lags before it is available reduce the usefulness of petrological monitoring as an effective scientific tool during volcanic eruptions.

In recent years, however, some scientists—including us—have been investigating potential applications of petrological approaches in near-real-time volcanic monitoring to help understand what's happening underground and manage eruption responses. Questions we've considered include, for example, whether petrology can be used to study variations in magma ascent paths during eruptions and what additional information can be gleaned by combining frequent petrological analyses of

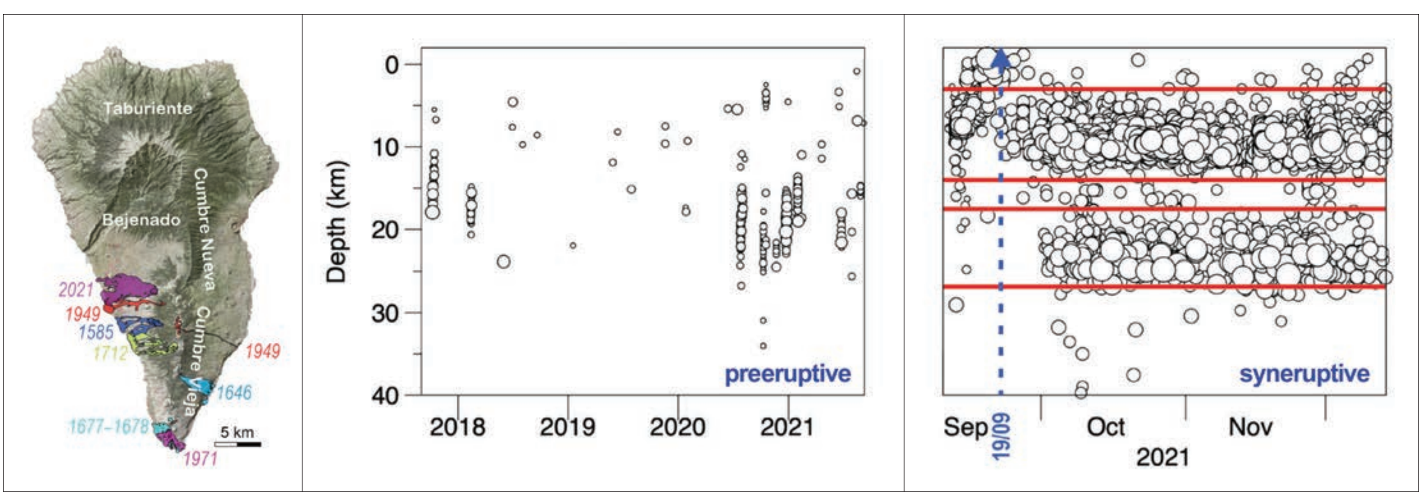


Fig. 1. Areas covered by erupted material during various major eruptions on the island of La Palma (left), which has a record of volcanic eruptions dating back to about 1500, are indicated here with different colors. Records of seismic activity from before (middle) and during (right) the 2021 eruptions were obtained from the open catalog. Credit: Adapted from Zanon et al. *[2024], CC BY 4.0 (bit.ly/ccby4-0), and* D'Auria et al. *[2022], CC BY 4.0 (bit.ly/ccby4-0)*

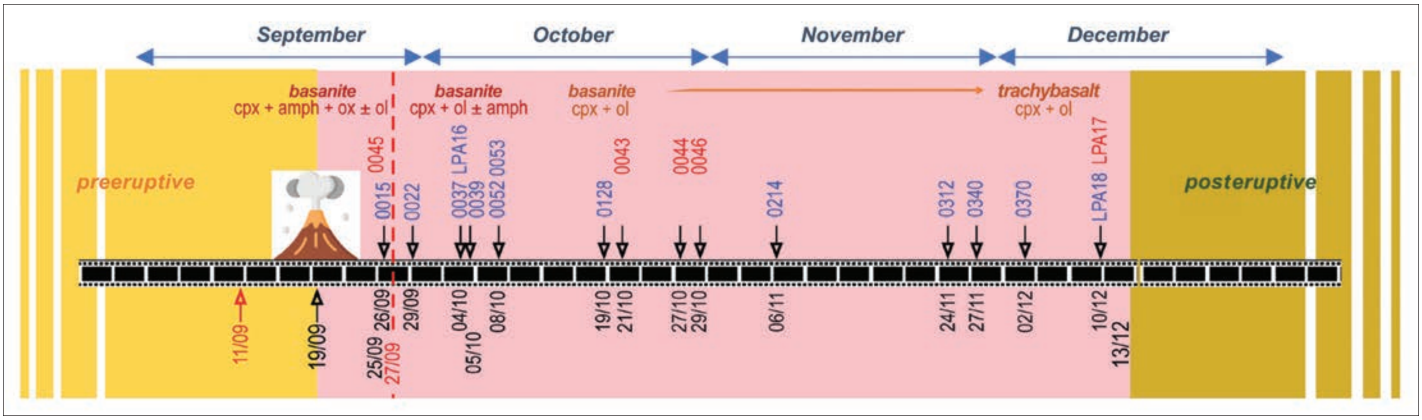


Fig. 2. Black arrows in this chronogram of the Tajogaite eruption indicate the start of eruptive activity on 19 September as well as collection times of lava (red labels) and tephra (blue labels) samples. Changes in magma composition from basanite to trachybasalt are also shown (amph = amphibole; cpx = clinopyroxene; ol = olivine; ox = oxides). The red vertical dashed line marks the timing of a temporary stop in magmatic emissions and seismicity on 27 September; the red arrow indicates the start of magma ascent from the shallow preeruptive magma ponding site at 9–10 kilometers deep. Credit: Zanon et al. *[2024], CC BY 4.0 (bit.ly/ccby4-0)*

erupted material with monitoring of syneruptive seismicity (seismic activity occurring during an eruption).

The Tajogaite eruption was an excellent opportunity to test our approach [*Zanon et al.*, 2024]. To do so, we collected samples daily from the eruptive area and sent them to a laboratory for rapid analysis of fluid inclusions within the samples (Figure 2).

Visualizing a Volcano's Interior

Petrological studies, supported by geochemistry, petrography, mineralogy, and thermodynamics, allow scientists to gain deep understanding of the conditions in which rocks form and transform. For example, they can decipher the conditions of magma formation and develop complex, accurate genetic models for volcanoes. And they can reconstruct magma ascent paths and precisely visualize volcanic anatomy.

Although these sorts of studies can be applied only after materials have been erupted, they provide a level of detail not achievable with other methods. They can also complement the work of geophysicists and geochemists, who rely upon networks of high-quality sensors distributed on volcanoes for signs of impending eruptions.

These sensors can, for instance, observe the propagation of volcanic dykes by tracking the migration of seismic swarm hypocenters, observe ground deformation caused by volcanic activity, and detect other sorts of anomalies.

Once an eruption begins, however, analyzing some geophysical and geochemical signals becomes more challenging. When magma starts flowing rapidly through the magmatic system, these signals may no longer fully capture internal processes with sufficient rapidity. As an example, the seismic "noise" of gas moving through the magmatic system and being released from it hides the signals of low-intensity seismicity. In addition, sensors can be damaged or destroyed by explosions or buried by lava flows and volcanic ash, further limiting the availability of these signals. During eruptions, real-time acquisition and interpretation of petrological data can provide missing information.

Scientific personnel in volcano observatories worldwide understand the importance of efficient and rapid petrological monitoring. This monitoring currently combines multiple analytical techniques, including basic petrographic observations using optical microscopy and other analyses to track variations in magma chemical composition and mineralogical constitution during an eruption. This approach has been applied to study several eruptions in the past 25 years, including the Etna flank eruptions in 2001 and 2002–2003, the 2011–2012 submarine eruption at El Hierro, and violent periodic explosions of Stromboli [*Corsaro et al.*, 2007; *Andronico et al.*, 2009; *Martí et al.*, 2013].

However, several obstacles to real-time petrological monitoring are challenging to resolve. Sample collection, preparation, and analysis, as well as data processing, are time-consuming. Some observatories do not possess the necessary instrumentation to perform analyses themselves and therefore must rely on preexisting scientific collaborations or commercial analytical laboratories, which may be far from the site, booked for other research, or expensive to use. In addition, analyzing single samples on a daily (or frequent) basis over an extended period—as is needed for petrological monitoring during an eruption—is never cost-effective.

Furthermore, the architecture of magmatic systems can be highly complex [*Cashman et al.*, 2017; *Sparks et al.*, 2019], and the information gathered during monitoring may not be useful immediately without an existing thorough understanding of the magma's path to the surface.

PETROLOGISTS' WORK WITH RESPECT TO VOLCANOES CAN BE LIKENED TO CONDUCTING AUTOPSIES.

Fluid Inclusions Provide a Way Forward

The 2021 eruption on La Palma occurred along a small eruptive fissure of the Cumbre Vieja volcanic ridge. This ridge consists of a roughly north–south-oriented series of monogenetic cones (each generated during a single eruptive episode) along the dominant volcano-tectonic system on the island.

Olivine and pyroxene crystals in the lavas of this volcano often contain fluid inclusions—small amounts of fluids (mainly carbon dioxide and water) trapped in minerals as they formed or as a result of recrystallization (Figure 3).

Fluid inclusions offer valuable information that can be revealed using a technique called microthermometry. A microthermometric study involves heating and cooling mineral crystals under a microscope to determine the temperatures of phase changes in fluid inclusions. These temperatures provide insights into the barometric conditions of crystallization and/or reequilibration specific to the host crystal—that is, the pressures under which these processes occurred, which relate to the depth below the surface. Microthermometric analysis of many crystals thus allows us to constrain the depths at which magma ponded and reveal the underground architecture of volcanoes.

Fluid inclusions have been used successfully to reconstruct the magma storage systems of volcanoes in various locations, including the Aeolian Islands, the Azores, the Canary Islands, Cape Verde, and Piton de la Fournaise [e.g., *Boudoire et al.*, 2019; *Hildner et al.*, 2012; *Klügel et al.*, 2000; *Zanon et al.*, 2003, 2020]. These studies used rock

MICROTHERMOMETRIC ANALYSIS OF MANY CRYSTALS ALLOWS US TO CONSTRAIN THE DEPTHS AT WHICH MAGMA PONDED AND REVEAL THE UNDERGROUND ARCHITECTURE OF VOLCANOES.

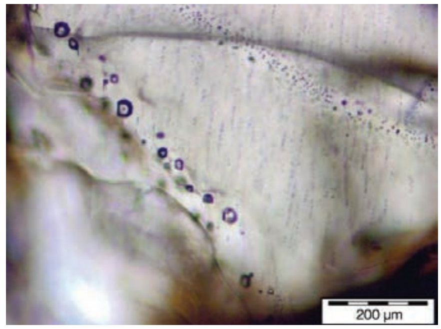


Fig. 3. Numerous fluid inclusions trapped along a fracture in an olivine crystal that erupted on 24 November can be seen in this micrograph. Credit: Vittorio Zanon

samples from different eruptions that occurred within narrow time intervals, and the resulting snapshots clearly delineated magma ascent paths, including dykes and ponding zones, during those intervals.

In our study [*Zanon et al.*, 2024], the results of petrological analyses of fluid inclusions in Tajogaite samples were promising: Estimates of the depths at which magma had ponded before erupting were consistent with the depths of the two seismically active zones that had been defined through geophysical monitoring.

Our reaction to the method's potential after the successful test was much the same as that of Gene Wilder's Dr. Frederick Frankenstein in *Young Frankenstein*: "It could work!"

Microscopy + Seismology = Success

Combining highly accurate microthermometric data from fresh lavas and pyroclastic fallouts sampled frequently during the eruption with concurrent data on the locations of seismic hypocenters was the secret to success.

Seismological imaging techniques allow us to identify lithological discontinuities and the presence of partially melted rocks beneath a volcano. Microthermometric analyses of many fluid inclusions reveal the pressures (and thus the depths) at which the magmas have ponded. In addition, tracking features of seismicity during an eruption, including hypocenter locations, energy release, and seismic wave frequency, is important for characterizing the lithology of magma ponding zones (both temporary and long-lasting accumulation zones, i.e., magma chambers) and the modality of magma extraction. Indeed, seismic wave analyses can even reveal episodes of compression of porous lithologies, such as mush layers composed of crystal aggregates, which frequently host magma.

Collecting and cross-referencing information about depths of magma ponding obtained from seismic data on subsurface discontinuities and fluid inclusion data from materials erupted by Tajogaite allowed us to define the architecture of the magmatic system with greater accuracy than we could have using either technique individually. The approach also allowed us to show the path of magma ascent in near-real time and to use changes in mineral content and in composition of trapped fluids to discriminate different batches of magma and their distinct ascent rates (Figure 4).

Using this approach, we identified five magma batches that emerged from a main accumulation zone 27–31 kilometers deep, spanning the boundary into the lithospheric mantle. This deep location is established by fluid inclusions hosting nitrogen and carbon monoxide, markers of mantle outgassing.

Magma also accumulated over different durations at depths of 22–27 and 4–16 kilometers. The deeper of those ranges comprises layers of porous rocks made of clinopyroxenes and olivines in different proportions. The shallower depth range contains a series of amphibole-bearing mush layers and crystallized magma bodies from much older intrusions.

We estimated time-integrated magma ascent velocities (including ponding times) by calculating the time between peaks of deep and shallow seismicity in clusters of earthquakes. These data showed that velocities were 0.01–0.1 meter per second. Differences in the velocities determined the partial mingling of the magma batches and, at the surface, the occurrence of changes in magma flow rate related to the speed, mobility, and size of erupted volumes.

Differences in magma ascent velocities also affected the formation of new eruptive fractures and the occurrence of cyclical explosivity during the eruption. New eruptive fractures signaled changes in eruption sites in the areas threatened, and changes in explosivity meant potential hazards for air traffic, human health (e.g., breathing problems), and infrastructure (e.g., possible roof collapses).

Considering these consequences, early recognition of the rise of new magma batches would have been very important for civil defense authorities.

This study represents the first time a result blending seismological and petrological data was obtained, and it demonstrates how integrating these two fundamentally different methodologies can set a new standard for monitoring volcanic activity.

Improving and Integrating Petrological Monitoring

Unfortunately, this new methodology is not applicable for monitoring all volcanoes because not all magmas contain crystals with trapped fluid inclusions. In large active magma reservoirs below some volcanoes, fractionation processes (e.g., gravitational settling of minerals contained in magmas) filter out heavier crystals that form first and mostly trap fluid inclusions.

For example, it is unlikely to work for silicic volcanoes, in which viscous magmas are rich in silica and gas—making them prone to dangerously explosive eruptions—but devoid of early-formed crystals likely to host fluid inclusions. However, the approach might apply to any volcano that erupts mafic (olivine- and pyroxene-rich) magmas, which typically rise rapidly through the crust without pausing for long in ponding zones, thus limiting how many inclusion-bearing crystals settle out.

Improving on our method will involve accelerating the workflow, from sample collection and preparation to interpreting the data. If a volcano erupts at a location without research infrastructure, logistics may become problematic, and days may be lost transporting samples. The best solution in such cases could be to develop a mobile laboratory equipped with the necessary instruments for microthermometric fluid inclusion analysis and interpretation.

Furthermore, as more people collaborate, more time is saved during sample preparation and analysis. At best, it will always take at least a day to perform the necessary petrological analyses on a single sample. However, this time lag is short enough to allow the approach to be applied during the scientific management of a volcanic eruption.

Challenges aside, we are confident that the developments in petrological analysis techniques demonstrated recently add petrology to the disciplines that can be used for near-real-time eruption monitoring, greatly enhancing our ability to understand internal volcanic dynamics while they are still in action.

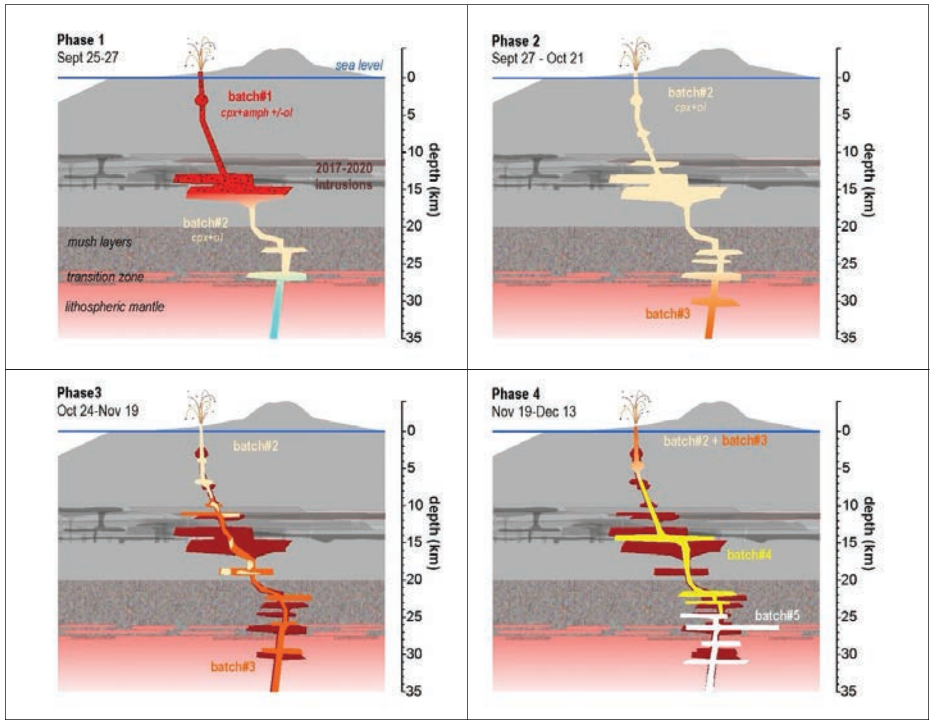


Fig. 4. This conceptual model shows the path followed by different batches of magma (represented with different colors) during the eruption. Two main depth ranges where magma stalled during the eruption were 22–31 and 11–16 kilometers, in agreement with recorded seismicity. Periodic magma ponding at about 4-kilometer depth was also observed. Features of the crust are shown with gray patterns, and the lithospheric mantle is in light red. This model also shows how physical interactions occurred among the various batches of magma. Credit: Zanon et al. *[2024], CC BY 4.0 (bit.ly/ccby4-0)*

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How Rivers Carved the Canyons of the Central Colorado Plateau

The Colorado River, as seen from Dead Horse Point State Park in Utah, has been shaping the features of the Colorado Plateau for millions of years. Credit: Natalie Tanski

Long after tectonic plate movement has created mountains, forces such as weathering and river erosion can continue to shape a landscape. One example is the Colorado Plateau, which spans more than 336,000 square kilometers across four states and encompasses iconic sites such as the Grand Canyon and Arches National Park.

Dramatic sites such as these are created when a river incises the rock below over millions of years. The rate of river incision in the Colorado Plateau has varied over time and is not well understood.

Tanski et al. looked at two reaches of the Colorado River to determine how and why incision varied during the Pleistocene, dating fluvial gravel deposits that form river terraces, which are steplike features that mark the former floors of river valleys.

To constrain the ages of the river terraces, they used luminescence dating, which measures a mineral's release of photons to determine the last time it was exposed to sunlight or intense heat, and isochron dating, a form of radioactive dating that, in this case, measured the changing relative abundance of beryllium and aluminum isotopes.

They then simulated how and when a wave of incision may have migrated up through a drainage basin in response to a change in baselevel, the lowest point that a river can erode. They compared the results to their terrace ages to determine whether drops in baselevel could have contributed to unsteady incision rates.

The researchers found that in the Moab region of the central Colorado Plateau, river incision paused from 1.8 million years ago to about 350,000 years ago. This pause was followed by a period of rapid incision lasting to the present, during which the river systems carved 200 meters deeper into the plateau. These shifts can be linked to baselevel changes as the Colorado River established its path, eventually contributing to the shape and iconic chasm of the Grand Canyon and its tributaries.

However, this particular period of rapid erosion represents only about a quarter of total exhumation that took place in the central Colorado Plateau over a much longer time period, suggesting that yet-unknown events occurring millions of years earlier may have also shaped the landscape. (*AGU Advances*, https://doi.org/10.1029/2024AV001359, 2025)

—Rebecca Owen, *Science Writer*

Tracking Some of the World's Fiercest Ocean Currents

In 2022, researchers aboard R/V Marion Dufresne II*, seen here in 2020, studied ocean currents in the Mozambique Channel. Credit: Antoine Lamielle/Wikimedia Commons, CC BY-SA 4.0 (bit.ly/ccbysa4-0)*

The Mozambique Channel, between Mozambique and Madagascar, is home to some of the most turbulent waters in the ocean. Swirling at a rate of more than 1 meter per second, currents in the channel can form structures known as anticyclonic rings that spread up to 350 kilometers across—about the width of Missouri—and extend 2,000 meters below the surface.

The currents carry nutrients and marine life such as shrimp, the basis of a major industry in Mozambique. Information about the movements of shrimp larvae and their food is crucial for managing fisheries. Yet currents in the Mozambique Channel remain poorly understood.

Penven et al. characterized currents in the channel as part of a study called RESILIENCE (Fronts, Eddies, and Marine Life in the Western Indian Ocean). In 2022, the research team set off aboard a vessel towing a Moving Vessel Profiler, which measured water conductivity, temperature, and turbidity in the region with unprecedented spatial resolution. Meanwhile, an instrument on the ship's hull, called the RDI Ocean Surveyor Acoustic Doppler Current Profiler, measured water velocities.

Specifically, the researchers traversed a prominent type of current in the Mozambique Channel known as an eddy-ring dipole. In this feature, an anticyclonic ring—in which water swirls counterclockwise in the Southern Hemisphere—pairs with a cyclonic eddy—in which water swirls clockwise in the Southern Hemisphere. Using the profiling instruments, the team took high-resolution measurements of several cross sections of the current down to a depth of 300 meters.

The fierce central current formed by the eddy-ring dipole whisked nutrients and sea life away from the continental shelf and the Mozambican coast at speeds of up to 1.3 meters per second, the researchers found. Conditions varied significantly between the current's two parts. In the cyclonic eddy, patches of either high or low salinity exist and photosynthetic life is abundant. In the anticyclonic ring, on the other hand, conditions are homogeneous and photosynthetic life is largely absent.

The study is among the first to characterize these complex currents, and it provides a basis for future research on this turbulent region, the researchers say. (*Journal of Geophysical Research: Oceans*, https://doi.org/10.1029/2024JC021913, 2025) **—Saima May Sidik,** *Science Writer*

"Thirstwaves" Are Growing More Common Across the United States

As the climate warms, the atmosphere is getting thirstier. Scientists define this atmospheric thirst, or evaporative demand, as the amount of water that could potentially evaporate from Earth's surface in response to weather.

Standardized short-crop evapotranspiration (ET_{os}) is a metric that estimates how much water would evaporate and transpire across a uniform, well-watered grass surface. It is used to measure the evaporative demand experienced by land covered by agricultural crops.

Past studies have shown that ET_{os} has increased over time in response to factors such as air temperature, solar radiation, humidity, and wind speed. But that research doesn't cover patterns and trends over prolonged periods with exceptionally high atmospheric thirst.

Kukal and Hobbins designate a new term for extreme ET_{os} events: thirstwaves. A thirstwave is a period of extremely high evaporative demand that, like its cousin the heat wave, can wreak havoc on a growing season. To be called a thirstwave, the ET_{os} must be above the 90th percentile for at least 3 days.

The researchers studied ET_{os} measurements for the contiguous United States during the 1981–2021 growing seasons, examining the intensity, duration, and frequencies of the thirstwaves they identified at the county level. They then grouped the results into nine regions.

The researchers' analysis showed that thirstwaves occurred an average of 2.9 times throughout the growing season of April through October and had an average duration of 4 days. The longest duration was 17 days, and the greatest frequency was 20 events per season. Across the nation, the High Plains experienced the most intense thirstwaves; the South, Upper Midwest, Pacific Northwest, and West Coast experienced the longest average duration (~4.5 days), and the West Coast and South experienced the highest frequency (~3.5 events per season).

Thirstwaves have become more widespread and are affecting regions such as the Southwest, Northern Plains, and Northern Rockies, which might not have experienced them in previous decades. The likelihood that a region won't experience a thirstwave at all during the year has also decreased. Continuing to measure and track thirstwaves will be crucial for crop and water management in the coming years, especially as the climate continues to warm, the researchers say. (*Earth's Future,* https://doi.org/10.1029/2024EF004870, 2025)

—Rebecca Owen, *Science Writer*

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Forecasting the Future of Southern Ocean Ecosystems

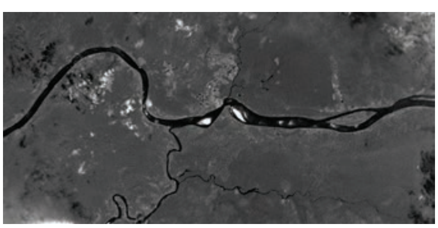
Ecosystems in the Southern Ocean, the body of water surrounding Antarctica, are under threat from climate change. The species native to the region, from whales to krill to phytoplankton, face changes such as a loss in sea ice and rising ocean temperatures. A decrease in the population of endemic species, such as the Antarctic toothfish, could affect fisheries and lead to cascading socioeconomic and geopolitical consequences.

Scientists use marine ecosystem models to understand how fragile regions such as the Southern Ocean will respond to changing climate, as well as to develop management and conservation plans. The Fisheries and Marine Ecosystem Model Intercomparison Project (FishMIP) combines results from an ensemble of marine ecosystem models, but it includes relatively few models that focus on the Southern Ocean. Though scientists have made progress in understanding this area's food webs and biogeochemical processes in the past decade, work remains to be done on assessing how the ecosystem may evolve under different climate change scenarios.

Murphy et al. are developing a new suite of models to complement FishMIP called the Southern Ocean Marine Ecosystem Model Ensemble (SOMEME). By consulting experts in fields such as ocean and biogeochemical modeling, the team determined that the variables used across FishMIP (sea surface temperature, sea ice concentration, and phytoplankton biomass) made it a sufficient framework for their new suite. The SOMEME effort seeks to address some of the gaps in FishMIP by better representing regional elements, including sea ice, species such as Antarctic krill, the historical impacts of whaling, and the connections between fisheries and climate.

These additions will help scientists understand how climate change can affect the region and how those effects can be mitigated, the researchers say. The team expects the model will grow more capable as they incorporate artificial intelligence into the approach and as the project gains more collaborators. (Earth's Future, https://doi.org/10.1029/2024EF004849, 2025) **—Rebecca Owen,** *Science Writer*

The Rivers That Science Says Shouldn't Exist



In a new paper, scientists call the Casiquiare River (running north to south in the center of this image), which connects the Orinoco River (running east to west) with the Rio Negro, "the hydrologic equivalent of a wormhole between two galaxies." Credit: Coordenação-Geral de Observação da Terra/INPE, CC BY-SA 2.0 (bit.ly/ccbysa2-0)

Rivers join downstream, flow downhill, and eventually meet an ocean or terminal lake: These are fundamental rules of how waterways and basins are supposed to work. But rules are made to be broken. *Sowby and Siegel* lay out nine rivers and lakes in the Americas that defy hydrologic expectations.

All exhibit instances of bifurcation, in which a river splits into branches that continue downstream. But unlike typical bifurcations, these examples do not return to the main waterway after branching off.

South America's Casiquiare River, for example, is a navigable waterway that connects the continent's two largest watersheds, the Orinoco and Amazon basins, by acting as a distributary of the former and a tributary of the latter. It's "the hydrologic equivalent of a wormhole between two galaxies," the authors write.

The Casiquiare splits from the Orinoco River and meanders through lush, nearly flat rainforests to join the Rio Negro and, ultimately, the Amazon. The study's authors point out that the slight slope (less than 0.009%) is enough to send large volumes of water down the river and that this unusual instance results from an incomplete river capture. They note that understanding of the Casiquiare is still evolving.

Dutch colonists first mapped the remote Wayambo River in Suriname in 1717. This river can flow either east or west, depending on rainfall and human modifications of flow using locks. It is also near gold and bauxite mining as well as oil production sites, and its two-way flow makes predicting the spread of pollutants difficult.

Of all the rivers they reviewed, the researchers described the Echimamish, high in the Canadian wilderness, as the "most baffling." Its name in Cree means "water that flows both ways." The river connects the Hayes and Nelson rivers, and by some accounts, the Echimamish flows outward from its middle toward both larger rivers. However, its course is flat and punctuated by beaver dams, leading to uncertainty, even today, about the direction of its flow and exactly where the direction shifts.

The authors also explored six other strange waterways, including lakes with two outlets and creeks that drain to both the Atlantic and Pacific oceans. In doing so, they highlighted how much there is still to learn about how our world's waters work. (*Water Resources Research*, https://doi.org/10.1029/2024WR039824, 2025) **—Rebecca Dzombak,** *Science Writer*

Water Stored in the Mantle for Millions of Years May Be Linked to Continental Volcanism

Lunar Crater in Nevada and the volcanic field that surrounds it came about via intraplate volcanism. Credit: Ken Lund/Flickr, CC BY-SA 2.0

The mantle transition zone (MTZ), which occurs 410–670 kilometers below Earth's surface, may store several oceans' worth of water. This water, which is carried to such depths by subducting tectonic slabs, is stored in minerals like ringwoodite and wadsleyite.

The distribution of water in the MTZ, both today and in the past, is not fully understood or mapped. However, because hydrated slabs enter the mantle in different locations and with different speeds, shapes, and sizes, researchers expect that water isn't distributed evenly throughout the zone.

Intraplate volcanism, or volcanism occurring away from plate boundaries, can provide clues about which areas of the MTZ are the most hydrated. Some of this volcanism occurs when water-rich mantle upwellings trigger the melting of mantle rocks, forming magma that can erupt.

Wang et al. used plate reconstructions from the past 400 million years to estimate where subducting slabs may have helped transport water into the MTZ. The researchers then compared these maps of mantle water to locations where intraplate volcanism occurred over the past 250 million years.

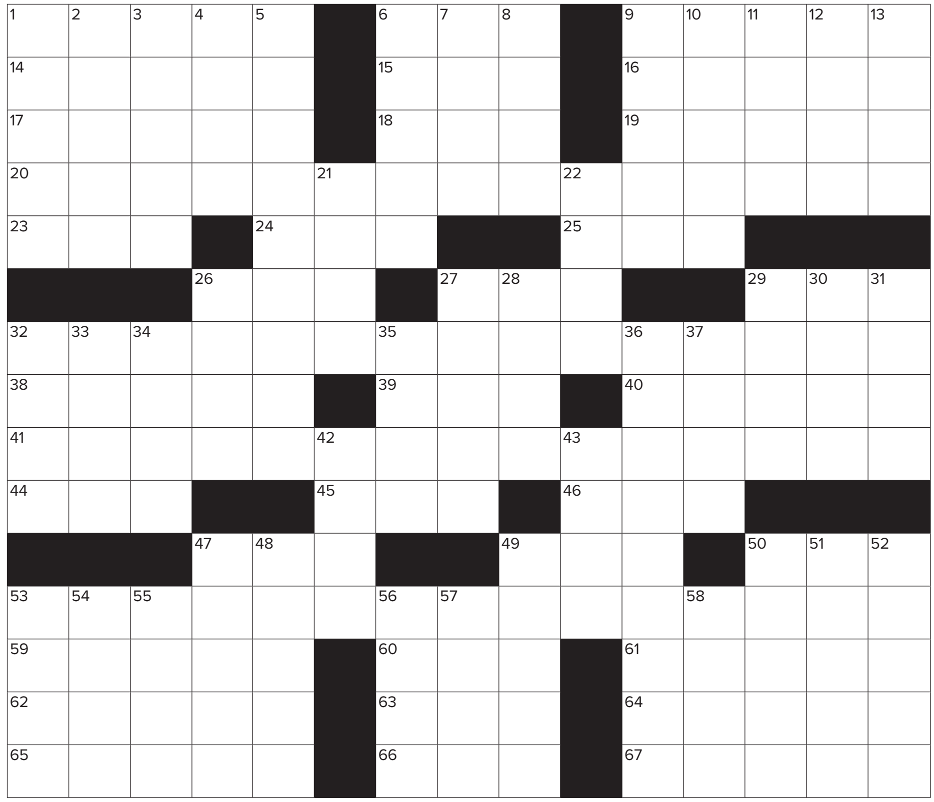
Their findings showed a strong correlation between wet areas of the MTZ and continental intraplate volcanism, with 42%–68% of intraplate volcanism occurring over more-water-saturated MTZ locations around the globe. The correlation is stronger in locations where water has remained in the MTZ for 30–100 million years; thus, the researchers suggest, a long timescale with multiple subduction events is needed to hydrate the MTZ and possibly trigger intraplate volcanic activity.

The link between water storage in the MTZ and continental intraplate volcanism could provide an explanation for minor volcanic activity across eastern Asia, western North America, and eastern Australia, as well as global intraplate volcanism patterns over the past 200 million years. By contrast, the Indian Ocean, southeast Africa, and the south Atlantic Ocean sit above swaths of the MTZ that have been dry for the past 400 million years, which may have contributed to the lack of volcanic activity in these regions, the researchers say. (*Geochemistry, Geophysics, Geosystems,* https://doi.org/10.1029/2024GC011901, 2025)

—Rebecca Owen, *Science Writer*

In the Field

By Russ Colson, Minnesota State University Moorhead



ACROSS

1 Oui, peas are _____ pois
6 Batch (e.g., of gum)
9 One often must _____ hills, in 32 across
14 Furious
15 The Pleistocene ended <7 down>_____, three to be exact
16 Exceptionally fab volcanic moon of Jupiter?
17 Characteristic of chipping sparrow song
18 *Last Chance to* _____ (1990 book on fieldwork by Adams and Carwardine)
19 "Friendship _____ nations...calls for constructive efforts to muster the forces of humanity." —Franklin Roosevelt
20 In the field, a scientist does this in environmental, paleontological, and other studies
23 Time units (abbr.)
24 Comes before, text, vent, and face
25 Location syst. important in 41 across
26 Eureka!
27 Locale of Aleppo (abbr.)
29 On the _____ (fleeing)
32 Fieldwork done to establish substrate, especially in the past
38 A healthy economy should minimize _____ needs
39 Burger, computer, or pasta
40 It's like this sentence the clauses are improperly connected
41 Fieldwork in seismic, ocean, climate, and other studies
44 Middle of both sides, or an older spelling of Chinese "Xi"
45 Toward the sunrise in Northern Hemisphere (abbr.) winter
46 A bad _____ ; when you knock on the door improperly?
47 North, South, Red, or Black
49 Photo
50 Home of the Burj Khalifa
53 Field measurements important in remote sensing studies
59 What high-spirited, boisterous field excursions should be?
60 Word before tide, cord, or saw
61 Machu Picchu architects
62 "Frankly, my dear, I don't give a damn" in Dijon
63 SF trope that is not quite science, like FTL or time travel
64 Delight
65 Unit of distance in France
66 _____ location for a marine field school
67 *Brassica napus*, canola, and mustard

See p. 28 for the answer key.

DOWN

1 One feature scientists may monitor when studying environmental acoustics
2 Dropped ball, e.g.
3 Follows
4 No worries, _____ be fine!
5 Lens common in remote sensing
6 The Resource Conservation and Recovery Act governs solid _____ management
7 The Pleistocene ended _____ <15 across>, three to be exact
8 Buck's mates
9 Charley horse
10 Lava and Aladdin's are two examples
11 Billy, American, or teen
12 Extract, or "not yours"
13 Slows (with "down")
21 Rocky prominence
22 Famous for the Taj Mahal
26 Ginger, pale, and Adam's
27 What one must do to measured values in completing 53 across
28 Family rec center, and disco hit
29 Follows chorus, clothes, or property
30 Your byline as a flame-war participant (abbr.)?
31 Like some schools or Earth's core but without vowels
32 What an artesian well might do when first opened
33 Directions 45 degrees from 45 across, or an ending for "hex"
34 "Everything" start for bus, present, or science
35 Mythological mischief-makers, a Mars Pathfinder camera, and certain volcanic features on the Moon
36 More prone to pontification
37 It's usually needed to extract well water
42 No doubt, you _____ the previous issue of *Eos*
43 Writing grp feedback
47 Great!
48 Follow, as in "one should avoid inflammatory rhetoric lest violence _____"
49 Word before love, dog, or chow
50 What one must do to a water bottle, when one does 20 across
51 Banded quartz
52 The beginning and end of soil surveys
53 Unit of mass
54 What one did with a bicycle
55 Exclude
56 Journey
57 What hot air and machines in *Terminator 3* do
58 At Santa Monica State Beach, e.g.