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Converging Science and Grand Challenges

DART's Smashing Success

EEAGER Beavers

CHRONICLING CLIMATE IN Rings and Rocks

Scientists find fresh approaches to familiar data.

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New Discoveries in Old Records

Scientists have long known that dendrochronology and geochemistry offer substantial clues about our planet's past. In this month's *Eos*, we take a look at how innovative techniques and converging sciences are helping to yield new discoveries in old records.

So what can those records tell us about our past, present, and future climate? Here are some fascinating facts:

1. New York City has a forest of old-growth timbers in its rafters, with some beams dating as far back as the early 1500s. Timbers of trees felled from the Adirondacks to Alabama tell a story of droughts and deluges that have "great potential to support evidence-based decisionmaking in the city, in terms of both cultural heritage and climate risk." Jenessa Duncombe explores the climate database hidden in the Big Apple's attic in "Finding Climate History in the Rafters of New York City Buildings" on page 24.

2. Following the Chicxulub impact event, nonavian dinosaurs faced a future that was either bad or worse: quick death in a fiery inferno or prolonged starvation in the decades-long impact winter that followed. Turn to "A Post-Impact Deep Freeze for Dinosaurs" on page 30, in which Aubrey Zerkle shares how she and her team examined sulfur isotopes from Chicxulub crater and identified long-term effects of "the single greatest unavoidable threat to life on Earth"—an asteroid impact.

3. Colombia's known geological history is well preserved in half a dozen databases, but these resources are akin to boxes of unsorted puzzle pieces—each offering valuable, yet ultimately unassembled, fragments. In "A Puzzle Mat for Assembling Colombia's Geologic History" (p. 36), Carolina Ortiz-Guerrero tells the tale of early-career researchers who compiled the new Colombian Geochronological Database to contextualize the data, make it accessible, and identify missing pieces.

All three exercises in reevaluating climate records are transdisciplinary by nature, involving science and commerce, history and chemistry, data infrastructure and geology. They are exemplar projects in "Converging Toward Solutions to Grand Challenges," a theme Ryan McGranaghan, Adam Kellerman, and Mark Olson explore in their opinion (p. 20), which is itself concerned with the future of the U.S. power grid system.

As narrowly defined analyses of rings and rocks give way to more nuanced ebbs and flows of contextual data, *Eos* is proud to share how the geosciences are primed to address quandaries of the past and challenges of the future.

Caryl-Sue Micalizio, Editor in Chief

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Features

On the Cover

A 200-year-old oak tree was removed from a residential yard in De Pere, Wis., due to a split extending to the ground. Credit: Steven W. Lepak

Columns

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Arctic Sediments, a Peruvian Volcano, and a Russian Famine

On 19 February 1600, the Huaynaputina volcano in southern Peru erupted, in the largest such event ever recorded in South America. The eruption column was 32 kilometers tall, and an estimated 13 cubic kilometers of magma were released.

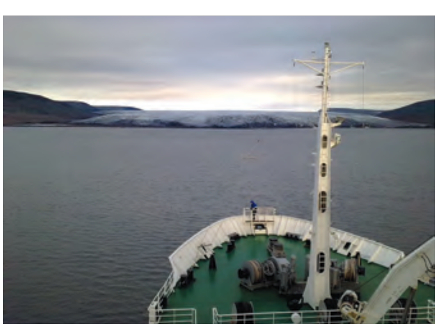
A multidisciplinary team recently published a study in *Quaternary Research* (bit.ly/volcano-famine) supporting the idea that a year after the Huaynaputina eruption, its climate effects led to global cooling and catastrophic crop failures in northern Europe. In turn, these food shortages contributed to the Great Famine that killed a third of Russia's population.

In Peru, the eruption of the Huaynaputina volcano destroyed nearby agricultural terraces like this one. Credit: Jersy Mariño

Sediment Cores from an Arctic Archipelago

In 2015 and 2017, a group of students, doctoral candidates, and professors from different disciplines participated in an expedition to Russia's Novaya Zemlya archipelago, one of the least explored regions in the Arctic and a location that can be accessed only by ship.

The expedition collected sediment core samples from seven fjords in the archipelago. All researchers had access to a workstation and laboratory on board the R/V *Akademik Mstislav Keldysh,* where the samples were cut in half lengthwise. One half was saved for scanning at an onshore laboratory, and the other half was analyzed on board the ship for factors such as grain size, mineralogy, chemistry, and biology, explained Valeriy Rusakov, lead author of the study and a geologist at the Vernadsky Institute of Geochemistry and Analytical Chemistry at the Russian Academy of Sciences.



Researchers aboard R/V Akademik Mstislavt Keldysh *made an expedition to the Russian archipelago of Novaya Zemlya in 2017 to extract sediment cores from fjords. Credit: Valeriy Rusakov*

Within the cores, the team found a sharp decrease in sedimentation rates, grain size, and biogenic remains of marine organisms starting in the 17th century. These results suggest a sudden onset of colder weather.

Global Cooling in Historical Records

The team studied historical documents as well as scientific samples and found that the "drastic decrease in sedimentation in the fjords" of Novaya Zemlya coincided with written records of both the 1600 Huaynaputina eruption and extreme cold weather around the world, from crop failures in northern Europe to a 2-week change in the blossom time of peach trees in China.

This cooling "led to the Great Famine of 1601–1603, which led to the change of ruling dynasties in Russia," said Rusakov. (The dynasty that emerged, the Romanov, led Russia until 1917.)

Heli Huhtamaa, an assistant professor at the University of Bern in Switzerland, was not involved with the new research but concured with its general findings. According to her, the Huaynaputina volcanic eruption is considered to be the most likely culprit of the cold weather experienced in 1601 because the eruption released large quantities of sulfur into the atmosphere. These volcanic gases, which damage foliage and discourage plant growth, took as long as a year to reach northern Europe.

The "coolness of the [1601] summer was a result of these volcanic aerosols high in the stratosphere…and that led to extreme harvest loss," said Huhtamaa. As an example of that loss, she pointed to church records from the municipality of Pöytyä, Finland, which document that of the 142.7 barrels of rye seeds sowed in 1601, only 1 barrel could be

Scientists on the 2017 expedition study sediment cores from Novaya Zemlya. Credit: Valeriy Rusakov harvested. (A barrel is equivalent to about 146.5 liters.)

"Historical reconstructions of unrecognized climatic processes can be extremely important for understanding the role of the nonhuman world in human affairs," said Andy Bruno, an environmental historian and professor at Northern Illinois University. But he warned that we should be wary of "claims that reduce any complicated historical event to a sole climate trigger."

The eruption of Huaynaputina and shifts in glacial dynamics in the Arctic played a role in the Great Famine in Russia, Bruno said, but were far from the only factors. The extended crop failures exacerbated an ongoing political and social conflict known as the Time of Troubles, which lasted until the establishment of the Romanov dynasty in 1613.

"Historical reconstructions of unrecognized climatic processes can be extremely important for understanding the role of the nonhuman world in human affairs."

For Jersy Mariño, research that explores the connection between the Huaynaputina eruption and historical events around the world is essential for recognizing the "cultural and geological value" of this volcano and the importance of studying it. Mariño is a geologist from the Peruvian Geological, Mining, and Metallurgical Institute who has conducted extensive research on the geological history and risk posed by this and other volcanoes in southern Peru.

During a recent expedition to Huaynaputina, Mariño and his team found evidence of six towns and several terraces used for agriculture in the 17th century that were completely buried during the 1600 eruption. (The volcano has not erupted since then.)

The scientists recommended that the Peruvian government start archaeological expeditions as soon as possible.

By **Santiago Flórez** (@rflorezsantiago), Science Writer

NASA's Double Asteroid Redirection Test Is a Smashing Success

Rocks from space have walloped Earth for eons, and it's only a matter of time until our planet lands yet again in the crosshairs of a very large asteroid. But unlike other forms of life—here's looking at you, dinosaurs—humans have a fighting chance of altering our cosmic destiny. At AGU's Fall Meeting 2022, researchers presented a slate of new results from NASA's Double Asteroid Redirection Test (DART) mission, the first demonstration of asteroid deflection.

Peering at an Orbit

DART's target, the Didymos-Dimorphos asteroid system, was first discovered in the mid-1990s. Astronomers back then spotted only its larger member, Didymos, which is roughly 800 meters (half a mile) in diameter. It wasn't until 2003 that scientists realized that a much smaller body, dubbed Dimorphos, was also present. Dimorphos is about one fifth the size of Didymos, and its orbit takes it in front of and behind Didymos as seen from Earth. That's serendipitous, because by monitoring how the brightness of the Didymos-Dimorphos asteroid system varies over time, scientists were able to determine precisely how long it took Dimorphos to complete an orbit: 11 hours and 55 minutes.

"We needed to understand the Didymos-Dimorphos system before we changed it," said Cristina Thomas, a planetary scientist at Northern Arizona University in Flagstaff, at AGU's Fall Meeting 2022.

The primary goals of the DART mission were simple, at least in concept: to hit Dimorphos with the roughly 570-kilogram (half-ton) DART spacecraft to significantly alter the orbital period of Dimorphos around Didymos, to measure that change, and to characterize the physics of the impact. If successful, it would be the first demonstration of deflecting an asteroid using so-called kinetic impactor technology. (In 2005, another NASA mission, Deep Impact, tested kinetic impactor technology with a comet.)

On 23 November 2021, a Falcon 9 rocket lifted off from California's Vandenberg Space Force Base. By then, the SpaceX-designed rocket had notched more than 100 successful launches, but for members of the DART mission, the event was anything but ordinary: Nestled within the rocket's nose cone was the spacecraft they'd spent well over a decade designing, building, and testing.

The launch went smoothly, and DART soon entered orbit around the Sun. For roughly 10 months, the spacecraft largely tracked the orbit of Earth, essentially waiting to catch up to the Didymos-Dimorphos asteroid system, which orbits the Sun between Earth and Mars. "We stayed close to Earth the entire time and just caught up with the Didymos system at its closest approach to Earth," said Elena Adams, DART mission systems engineer at the Johns Hopkins University Applied Physics Laboratory (APL) in Laurel, Md.

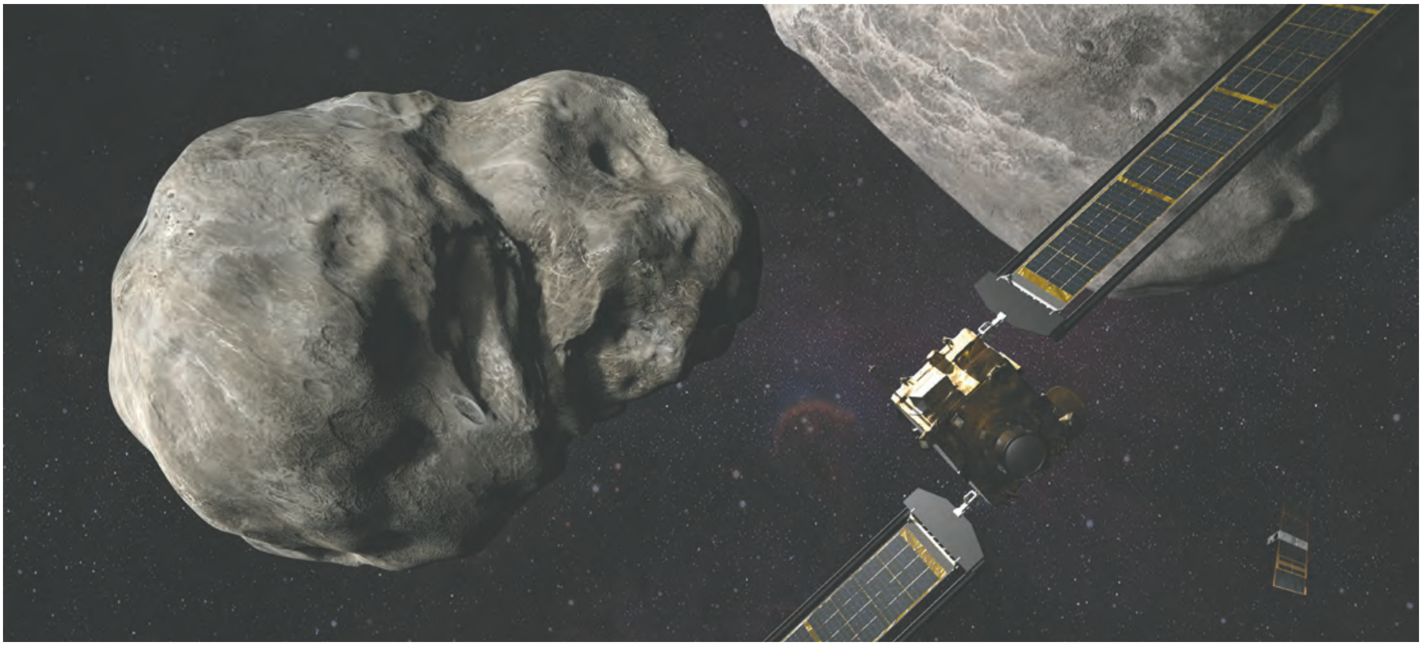
Approaching the Unknown

It was only around July 2022 that DART's onboard camera—the Didymos Reconnaissance and Asteroid Camera for Optical navigation (DRACO)—caught its first glimpse of Didymos. But Dimorphos wouldn't come into view until much, much later: Just 1 hour before impact, at a distance of roughly 25,000 kilometers, the tiny moonlet was still a mere 2 pixels across in DRACO images.

"We didn't see Dimorphos until late in the game," said Adams. To prepare for the uncertainties of striking a body they knew virtually nothing about, DART team members ran thousands of Monte Carlo simulations beforehand, in which they varied the moonlet's size, shape, albedo, and a slew of other parameters.

"We needed to understand the Didymos-Dimorphos system before we changed it."

The DART spacecraft successfully hit Dimorphos on 26 September 2022. The event was recorded by a cadre of Earth-based telescopes and also the Light Italian Cubesat for Imaging of Asteroids (LICIACube), a briefcase-sized spacecraft carrying two cameras that launched with DART and was released from the spacecraft 15 days prior to impact.



This illustration of NASA's Double Asteroid Redirection Test (DART) spacecraft (foreground) and the Italian Space Agency's LICIACube depicts them just prior to impact at the Didymos-Dimorphos binary system on 26 September 2022. Credit: NASA/Johns Hopkins APL/Steve Gribben

A Serendipitous Boost

Researchers had calculated that the impact, which occurred roughly head-on, would shorten Dimorphos's orbital period by just under 10 minutes. That was assuming the simplest scenario, in which no ejecta is produced, said Andy Cheng, DART investigation team lead at APL, at a press conference.

"The amount of momentum that you put in the target is exactly equal to the momentum that the spacecraft came in with." But if ejecta flies off the asteroid after impact, physics dictates that the asteroid can get an extra boost, said Cheng. "You end up with a bigger deflection."

That's good news when it comes to pushing a potentially harmful space rock out of the way, said Cheng. "If you're trying to save the Earth, that makes a big difference."

And ejecta there was, in spades—on the basis of detailed follow-up observations of the Didymos-Dimorphos system, scientists discovered that Dimorphos is now traveling around Didymos once every 11 hours and 22 minutes. That's a full 33 minutes shorter than its original orbital period, a finding that implies that a substantial amount of ejecta was produced. Imagery from ground- and space-based telescopes has borne that out: A plume of debris tens of thousands of kilometers long currently stretches out from Dimorphos. Researchers estimated that at least a million kilograms (1,100 U.S. tons) of material were blasted off the asteroid by the impact. That's enough debris to fill several rail cars, said Andy Rivkin, DART investigation team lead at APL, at a press conference at the Fall Meeting (bit.ly/AGU22-DART).

Follow the Debris

Of particular interest, the ejecta shed by Dimorphos has remained in distinctly more plumelike configurations than the debris shed by comet 9P/Tempel 1 when NASA's Deep Impact spacecraft intentionally crashed into it in 2005. "The Dimorphos ejecta has a lot of morphological features," said Jian-Yang Li, a planetary scientist at the Planetary Science Institute in Fairfax County, Virginia, and a member of the DART team, at the Fall Meeting.

The reason is probably the different compositions and surface features of the two bodies, he said. Tempel 1 is rich in volatiles and fine-grained dust; Dimorphos's surface, on the other hand, is littered with boulders. Scientists plan to continue to monitor Dimorphos's debris plume through at least this month.

The DART mission also has enabled scientists to investigate a fundamental question about the Didymos-Dimorphos asteroid system: Do the two asteroids have the same composition? It's a common assumption when it comes to binary asteroids, but it's never been confirmed. Thomas, leader of the DART Observations Working Group, presented new results on the subject at the press conference at the Fall Meeting. She shared near-infrared spectra of the binary asteroid system that astronomers had collected both before and after impact using a NASA telescope in Hawaii.

Observations obtained prior to impact (when the overwhelming majority of the sunlight reflected off the asteroid system came from Didymos) and after impact (when the debris shed by Dimorphos was responsible for more than two thirds of the reflected light) revealed very similar spectra, with characteristic dips at wavelengths of 1 and 2 micrometers in both cases. That's strong evidence that the two asteroids have similar compositions, said Thomas.

Scientists aren't yet finished with Didymos and Dimorphos: In 2024, researchers involved in the European Space Agency's Hera mission plan to launch a spacecraft to the system to further characterize the asteroids—including accurately measuring the mass of Dimorphos—and to study the crater created by the DART impact.

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

Glacial Ice Offers Polar Bears a Precarious Climate Refuge

Discovered in the fjords of southeastern Greenland, the world's most genetically isolated polar bear subpopulation has an unusual relationship to ice. Whereas most polar bears rely on sea ice, the bears recently found prowling Greenland's southernmost tip also hunt on glacial mélange—the jumble of floating ice that spills into fjords when glaciers come apart against the sea.

These unusual fjord dwellers might offer a glimpse of their species' future in the melting Arctic, researchers said. Ice is already as short-lived in the fjords as it is expected to be in the High Arctic by the end of the century. And as sea ice grows ever scarcer, polar bears will be driven farther back into a shrinking handful of climate change refugia, such as fjords.

A multiyear effort to study the bears and their environment was described in *Science* (bit.ly/fjord-polar-bears) and presented at AGU's Fall Meeting 2022 (bit.ly/AGU22-polar-bears).

Unexpected Discovery

The research team wasn't expecting to find a new subpopulation of polar bears hunting on fjord ice, said ecologist Kristin Laidre of the University of Washington. The team's project started in 2011 as a multiyear effort to survey the broader eastern Greenland population, which hadn't been studied closely in more than a decade.

Southeastern Greenland "definitely wasn't thought to be a place that would support a population of polar bears," said Laidre. "But we took one or two trips down there and it kind of struck me. Coming into the fjords, we were seeing a high density of bears, and I didn't really expect that."

The region is incredibly remote, and doing fieldwork there was a yearslong logistical challenge, Laidre recalled. Helicopter fuel and supplies were cached years in advance, and the researchers had to get creative with campsites if they wanted to avoid a daily 4-hour commute to the fjords.

"We lived in abandoned mining camps. We lived in abandoned weather stations. We slept in a sheep farm with a couple hundred sheep," said Laidre. The scientists had to carry noisemakers, flares, and rifles to protect themselves from the polar bears they were there to study.

Striking out by helicopter, Laidre and her colleagues scouted the fjords to find and "capture" bears using sedative darts so they could safely land and approach the animals to collect health data. They'd also fit adult females with tracking collars. When capture wouldn't be safe for the researchers or for the bears, the team used biopsy darts to collect small tissue samples for genetic analysis instead.

In addition to the fieldwork, the team used satellite imagery to track the ice conditions in the bears' habitats. But because fjords are so narrow and small, the normal automated tools used to track Arctic sea ice just wouldn't work, Laidre said. The team's ice scientists had to analyze daily satellite images of the fjords by hand.

Isolated Homebodies

Polar bears need sea ice to hunt but can endure between 100 and 180 ice-free days every year. That's one reason Laidre was so surprised to find a substantial population of bears in southeastern Greenland at all: The sub-Arctic region has more than 250 days without sea ice every year.

"These bears are kind of homebodies."

The southeastern Greenland bears survive by hunting from the glacial mélange, which flows into the fjords year-round. The strategy gives the bears plenty of food to eat but also seems to restrict their movements.

"These bears are kind of homebodies," said Laidre. "[They] would stay in one or two fjords for 3–5 years. They'd move, on average, 10 or 15 square kilometers. Bears in other parts of the Arctic will move 1,000 kilometers...[these bears] really are just stuck in little pockets."

Southeastern Greenland's polar bears use glacial ice to hunt. Credit: Kristin Laidre

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This, as well as their habitat's remote location, might explain the bears' incredible isolation—the southeastern Greenland bears are the most genetically isolated polar bears in the Arctic, said Laidre.

Although other polar bear populations are genetically isolated, have small ranges, or hunt from glacial mélange, the southeastern Greenland bears are unique in having all three of these characteristics, said University of Alberta ecologist Andrew Derocher, who was not involved in the study.

Symptom of Climate Change

The discovery of this unique bear population shows that glaciers that flow into the sea offer polar bears a refuge from melting sea ice. But although it might be tempting to see the southeastern Greenland bears as a new hope for their species in our warming world, it's not that simple.

Lifestyles such as those of the Greenland bears are "a symptom of climate change," said Derocher. "In a warming Arctic, this is a scenario that we're going to see played out in many, many different places where…groups of bears become more isolated."

Sea-terminating glaciers such as those in southeastern Greenland aren't common in most of the Arctic, which includes northern Canada and Russia, where most polar bears live. And ice conditions in the Arctic can be erratic, said Derocher, adding that one or two unusually warm winters could "blink out" a small, isolated population such as the one in the study.

"Polar bears are still at risk from climate change."

So rather than being a saving grace for the bears' species, said Laidre, southeastern Greenland's fjords are better understood as a glimpse of the future—and a potential opportunity for scientists to better understand the specific challenges climate change will bring.

"Polar bears are still at risk from climate change," she said. "This small group of bears is going to teach us a lot about the future of the species, but [the way they live] is not going to save polar bears."

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

Scientists EEAGER-ly Track Beavers Across the Western United States

A cascade of beaver ponds on South Fork Middle Crow Creek in the Happy Jack Recreation Area in Wyoming cuts through a landscape of evergreens and other trees. Credit: Emily Fairfax

Beavers are among the world's most effective engineers. Members of this keystone species build dams and canals and, in so doing, create entire, multilayered wetland ecosystems. Beginning in the 1600s, however, the fur trade decimated North American beaver populations.

The species began rebounding in the early 20th century but sometimes came into conflict with the landscape, as by the 1940s and 1950s, people were aggressively modifying streams to maximize agricultural yield. Returning to their former haunts meant persecution as beavers flooded crops and felled orchards, explained Alexa Whipple, program director for the Methow Beaver Project (part of the nonprofit Methow Salmon Recovery Foundation).

Now, humans are starting to recognize that beavers, though still considered pests by some, benefit landscapes in myriad ways. For instance, beaver activity can reduce erosion, create habitat for other species, and maintain wetlands.

In fact, we often want beavers to move back in to landscapes to do the engineering for us, said Emily Fairfax, an assistant professor at California State University Channel Islands. "But how are we going to know if they are doing that," she asked, "if we don't even know where they are?" The answer lies in remote sensing imagery, which can help scientists identify the landscape-scale features created by beaver families.

Through a combination of fieldwork and remote sensing, Fairfax tracks where beavers reside across the western United States. To make the process more efficient, she's working with Google Earth Engine to develop the Earth Engine Automated Geospatial Element Recognition model—aptly called EEAGER—which uses machine learning to rapidly identify beaver dams in satellite and aerial imagery.

We often want beavers to move back in to landscapes to do the engineering for us.

In work presented at AGU's Fall Meeting 2022, Fairfax found that EEAGER decreased the time needed to map beaver dams by about 80% (bit.ly/AGU22-EEAGER). By rapidly finding beaver ponds and comparing their changing distribution over time, scientists like

Fairfax can track beaver populations to quantify the effects of their environmental engineering.

Dams Versus Cul-de-Sacs

The amount of existing and incoming imagery isn't an impediment for sky-based beaver surveillance. Beaver dams remain in place for 5–7 years on average, said Fairfax; very high resolution data that are publicly available come out at least every couple of years and sometimes more often when fires and droughts strike (which is becoming more common). Lower-resolution data sets can provide helpful imagery about once per week, filling in any gaps.

However, tracing beaver dams in such imagery is incredibly time-consuming, often taking weeks to months. With large quantities of imagery, which Fairfax noted is a pleasant problem to have, the process can become a nightmarish sea of external hard drives holding terabytes of data.

Fairfax and her colleagues at Google who specialize in neural networks, machine learning, and artificial intelligence trained the EEAGER model with 8,000 of Fairfax's manually identified beaver dams and another 5,000 from other coauthors. Because the model was convinced that cul-de-sacs were also beaver dams, they had to train the model on "not dams" as well.

EEAGER can now sort through massive amounts of satellite and aerial imagery and identify pixels that contain evidence of beaver activity. With Google Earth Engine, the data querying and processing happen in the cloud, Fairfax explained, so she doesn't need to add more hard drives to her already impressive stash.

Fairfax noted that the model wouldn't work as well as it does without extensive field mapping of beaver dams (and *not* beaver dams), which involves wading through muck and dense vegetation. But although pond-specific beaver studies are important, looking at how beavers affect entire watersheds can now be efficiently accomplished in beaver-based research.

For regions still needing ground truthing, drones now expedite this process. However, because Fairfax's research has been focused on the western United States, EEAGER may be biased. "We actually don't know how good it would do in places like Canada or Minnesota," she said, "because it hasn't been trained there."

Slowing Down Water, Speeding Up Recovery

After the results from EEAGER go through quality control, calculations can address whatever the science question at hand may be. For instance, in research currently under review, Fairfax looked at whether beaver dams became fire refuges during three Rocky Mountain megafires in 2020. In some watersheds, beavers had dammed every single stream from start to end, she said. These sinuous stretches of hydrologic connectivity resulted in fire-resistant habitats. "In these beaver complexes, everything stays wet," said Fairfax, which means that fires cannot easily burn these ponds.

"I've gone to [wildfire] sites where I fully expected the beavers to be dead," she recalled, but "the evening rolls around and the beavers come swimming out."

Channel modifications, such as straightening bends to transport logs and barges, result in water being whisked rapidly downstream, said Chris Jordan, a research fisheries biologist with NOAA's National Marine Fisheries Service who was not involved with the study. Beavers' networks of dams, canals, and felled trees do the opposite, slowing water down, which—like magic, except that it's physics—restores river systems, he said.

Given time and opportunity, beavers will engineer an entire valley floor, which could be more than a kilometer wide, said Fairfax. That seemingly magical engineering lets water seep into the soil, allowing streams to reconnect to their floodplains. Simple or degraded ecosystems can transform into riverscapes with healthy food chains.

For example, because endangered salmon and similar fish species are born and die in freshwater, they depend on healthy river conditions to complete their life cycle, Jordan said. Growing more fish requires ants, earthworms, and other floodplain-dwelling invertebrates to become fish fodder. But for that part of the food chain to exist, landscapes around rivers need to be wet at least some of the time. Beavers create the necessary wetland environments that then become biodiversity hot spots.

"In these beaver complexes, everything stays wet."

Acquiring regular snapshots of beaver ponds from space, combined with algorithms doing the tedious work of examining millions of kilometers of streams, means new ways to quantify the impact beavers are having on the landscape, Jordan said.

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

Beaver dams create a wet refuge from wildfires. Little Last Chance Creek in California burned during the 2021 Beckwourth Complex Fire. This photo was taken 1 year later. Credit: Emily Fairfax

Drones Make Weather Prediction at the Poles Easier

In February 2022, a drone flew off the deck of the Japanese vessel *Sōya* and over the ice-covered Sea of Okhotsk in the northwestern Pacific Ocean. The only difference between this uncrewed aerial vehicle (UAV) and one you could buy at any electronics store was an extra sensor that researchers had added to measure wind speed.

The flight was a test to see whether collecting wind speed measurements in remote regions could be made more accessible and less expensive. The researchers recently published their findings in *Drones* (bit.ly/weather-drones).

Adding an inexpensive, lightweight sensor to a commercial drone allowed researchers to accurately measure wind speeds in the Arctic. Credit: Jim Makos, CC BY-ND 2.0 (bit.ly/ccbynd2-0)

Drones are "reusable, they're cheap, they're portable...they're able to reach areas of the atmosphere that we don't typically have access to."

Drones have many advantages, said Brian Greene, a postdoctoral fellow at the University of Oklahoma who has used drones in the Arctic but wasn't involved in the new study. "They're reusable, they're cheap, they're portable," he said, and "they're able to reach areas of the atmosphere that we don't typically have access to with our normal, everyday sampling techniques."

"Although meteorological UAVs can [perform] wind profiling, they are usually expensive to buy or operate by a third party," wrote Jun Inoue, a researcher at the National Institute of Polar Research in Japan and lead author of the study, in an email from a research vessel in Antarctica. Lightweight and inexpensive anemometers—devices that measure wind speed and direction—attached to a smaller UAV can make the same measurements, he wrote. Inoue and his colleagues are designing a unit that fits the bill.

Where Drones and Meteorology Meet

Wind speed measurements throughout the lowest layer of the atmosphere, called the boundary layer, help to inform weather predictions and climate models. But weather stations are difficult and costly to maintain in many places around the world, particularly at the poles. "Cost-effective, frequent data acquisition at many stations is the challenge," Inoue wrote. Weather stations are also limited to collecting data at a single location. To overcome these issues, scientists have turned to drones to get weather data in hard-to-reach locations.

A Cost-Effective Option

Scientists have used custom, purpose-built drones to make observations of weather and sea ice levels at the poles before, but these units are not commercially available. In the new study, the researchers used the common DJI Mavic 2 drone and attached a thermal anemometer, which measures changes in temperature due to airflow and translates them to wind speed. Although scientists typically use a different sensor for this purpose—an ultrasonic anemometer—the thermal variety is lighter and less expensive.

The researchers wanted to collect wind speed data while the drone was ascending and descending; stopping for each measurement is a drain on battery life. However, the movement of both the drone and its propellers would create extra airflow over the sensor. For the wind speed measurements to be accurate, the researchers had to compensate for this disturbance. In a laboratory, they visualized airflow over the drone with smoke and lasers. Using videos that looked as if they could have been taken at a dance club, the researchers were able to track smoke particles and translate that information into a velocity of airflow over the drone. They could then use these measurements to correct the thermal anemometer measurements and calculate the wind speed in the surrounding environment.

Once the calibrations on the drone were accurate, the researchers headed to the Sea of Okhotsk, collecting 18 wind speed measurements over water. By comparing the drone data with the wind sensors on the ship, they determined that the drone was able to make accurate measurements of wind speed in the field.

Finding What Flies

Antonio Segalés Espinosa, a researcher at the Cooperative Institute for Severe and High-Impact Weather Research and Operations at the University of Oklahoma who designs weather-measuring drones but wasn't involved in the current work, said that in his research he's avoided using thermal anemometers because they are a bulky add-on. "Adding more extensions to the drone doesn't really help to get the drone within the performance we want for severe weather," he said. Inoue agreed, noting that a limitation of their design is that they're confined to flying the drone in clear weather.

Including a thermal anemometer on a commercially available drone has benefits.

Including a thermal anemometer on a commercially available drone has benefits. The design could be a way for people who don't have the time and money to build their own specialized drone to collect data, Greene said.

Inoue said he aims to improve the delivery of data from the drone to researchers. "We will use this system over the Southern Ocean and Antarctica to study the atmospheric boundary layer structure," he wrote. "The next step is near-real-time data transfer for numerical weather predictions."

By **Andrew Chapman** (@andrew7chapman), Science Writer

New Crowdsourced Science Project Will Study Sprites

Sprites, elves, trolls, and pixies.

No, we're not talking about fairy-tale creatures. These curiously named phenomena are all types of transient luminous events (TLEs)—bursts of red and blue light that occur high above thunderclouds and last for as little as a fraction of a second.

Eyewitness reports of strange flashes above thunderstorms were reported for more than a century before scientists accidentally caught one on film during a test for a rocket mission in 1989. Since then, scientific campaigns have captured stills and high-speed recordings of sprites and other TLEs around the world.

Scientists have many unanswered questions about the phenomena, said Burcu Kosar, a space physicist at NASA's Goddard Space Flight Center. Kosar is leading Spritacular, a community effort to build the first global database of sprites and other TLEs for scientific study.

"We need more observations to understand various aspects of sprites and other transient luminous events," said Kosar. "We may even find new types."

Spectacular Sprites

Characteristic examples of sprites include carrots, which look like bunches pulled right out of the garden, and jellyfish with dangling tendrils.

"It's an electrical zoo up there."

Sprites are generally hidden from view, occurring at an altitude of roughly 80 kilometers. "Electrical activity affects the atmosphere above [a storm], creating various optical phenomena—it's an electrical zoo up there," said Kosar, who introduced Spritacular at AGU's Fall Meeting 2022 (bit.ly/AGU22-Spritacular).

Whereas scientific efforts to document sprites have declined recently, Kosar said, amateur sky watchers known as "sprite chasers" have been sharing photos of them online for years. The largest group of sprite chasers, the International Observers of Upper-Atmospheric Electric Phenomena, started in 2013 and now has more than 7,000 members.

"Their photos are fantastic," said Kosar, but "other than a few researchers, the science community is largely unaware of their efforts and observations."

Kosar, who was previously involved in an aurora-spotting crowdsourced science project, saw an opportunity to create a community in which weather photographers and scientists could collaborate. The data and images collected by Spritacular will be used by scientists for new and ongoing research into TLEs.

Knowing Where to Look

Kosar recently had her first sprite-chasing experience with weather photographer Paul Smith in Oklahoma. "We were out night after night scouring the skies," she said.

The biggest challenge of sprite chasing is being in the right place at the right time, said Smith, who has been photographing the phenomenon for 6 years. Not every storm is going to make a sprite: "It takes experience in reading how storms evolve and the types of lightning responsible."

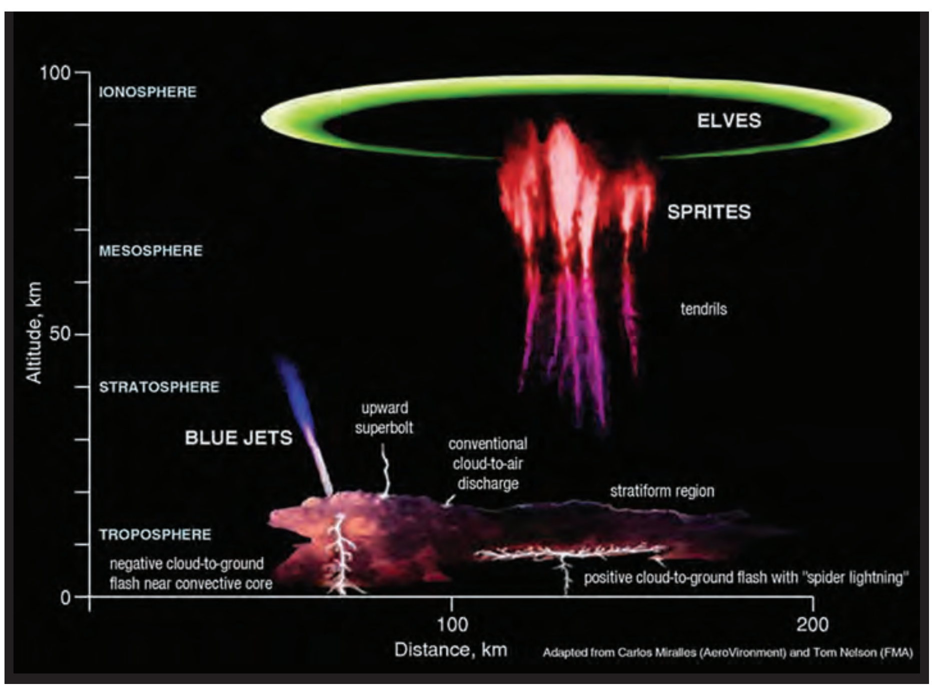
"You don't need specialized equipment to capture a sprite, though," said Smith, just a standard digital single-lens reflex camera and some practice.

Aside from collecting and collating images, a key aim of the Spritacular project is to support new observers with workshops and educational resources. In addition, Kosar is looking to explore the role of atmospheric gravity waves in sprite formation. Amateur scientists frequently capture sprites and gravity waves concurrently, but more observations are needed to support the idea that these ripples in the atmosphere may help seed sprite formation.

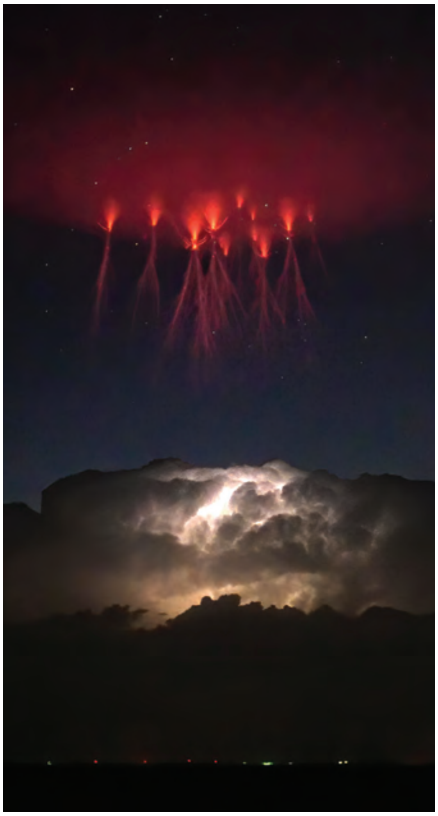
"More eyes on the skies will give us unbiased coverage across the globe."

Working Together

"More eyes on the skies will give us unbiased coverage across the globe," said Caitano da Silva, an assistant professor of physics at the New Mexico Institute of Mining and Technol-



Large thunderstorms are capable of producing lightning and other kinds of electrical phenomena called transient luminous events (TLEs). The most common TLEs include red sprites, blue jets, and elves. Credit: NOAA



A red jellyfish sprite was captured by veteran sprite chaser Paul Smith over Oklahoma in June 2022. Credit: Paul Smith/@paulmsmithphotography

ogy who is not involved in the Spritacular project. "Working together significantly increases our chances of new discoveries."

Da Silva also hopes the new project will lead to better classification of sprites and other TLEs. Classification so far has drawn on data collected by a small number of research groups.

For amateur scientists like Smith, Spritacular is a "fantastic opportunity to join forces with scientists—if we can analyze each of our shots, just imagine what we might find out."

For Kosar, the project isn't just about furthering science. "The study of TLEs, in a way, started with citizen scientists, and we want to work with them," she said, adding that there are many ways for people to get involved beyond making observations. "It's about creating a community. You don't have to be an observer—you're welcome on board even if you just want to learn more."

By **Erin Martin-Jones** (@Erin_M_J), Science Writer

Stories Scribed on Palm Leaves Help Scientists Understand Ancient Eruption

Fire rained from the sky. Avalanches coursed down a collapsing mountain. An island kingdom perished. These apocalyptic scenes describe the 1257 eruption of Samalas—the most explosive volcano you've never heard of—if historic records from the Indonesian island of Lombok are true.

In a new study, Panthéon-Sorbonne University doctoral student and geomorphologist Mukhamad Malawani and his colleagues used locally preserved historic records called *babad* to reconstruct what Lombok may have been like before, during, and after the Samalas eruption (bit.ly/palm-leaf-eruption). Investigating the changes wrought by this catastrophe may help scientists understand ancient evacuation processes, posteruption recovery, and societal resilience.

Paradise Lost

Lombok is nestled between the islands of Bali to the west and Sumbawa to the east. These islands form part of the volcano-studded Indonesian arc, largely the product of subduction as the Australian tectonic plate's northwestern oceanic edge dives below the Sunda plate. The Rinjani volcanic complex, crowned by a lake-filled caldera left by the Samalas eruption, reigns over Lombok's landscape, according to Céline Vidal, a volcanologist at the University of Cambridge. During the past 10,000 years, large eruptions have punctuated Rinjani's history, with the 1257 event ranking among the most explosive in recent times, said Vidal, who has worked on Samalas but was not involved in this study.

Like avalanches, these flows "destroy[ed] everything in their way."

After the eruption, the island morphed from a lush paradise into a dry, ash-covered landscape, according to study coauthor Franck Lavigne, a geographer at Panthéon-Sorbonne University who has worked on the Samalas eruption for the past decade.

Prior studies of the meters- to tens-of-meters-thick deposits expelled from the volcano helped scientists such as Vidal reconstruct the eruption itself. Ash, pumice, and gas rose into the atmosphere as the eruption began. The cloud spread horizontally, raining ash and pumice onto, and even beyond, the island. Once the gas sustaining the plume was exhausted, the towering column collapsed, forming clouds of hot gas, ash, and other

The palm leaf pages of Babad Lombok, *written in Old Javanese, may provide clues about a little-known 1257 volcanic eruption in what is now Indonesia. Credit: Franck Lavigne*

A cliff of pumice about 35 meters high, left from the 1257 volcanic eruption, looms above a local beach on the island of Lombok. Credit: Franck Lavigne

debris produced by the eruption that flowed along the ground, rapidly traversing the landscape.

Like avalanches, these flows "destroy[ed] everything in their way," Vidal said. Soon after, mudflows called lahars, caused when rain follows such an eruption, capped the volcanic deposits, she said.

Babad

Babad are written collections of oral traditions often transcribed in an Old Javanese script that few people can read. The sacred texts contain a mixture of legend and fact, said Lavigne. This is partly because oral traditions change as cultures do.

The researchers focused on three *babad* likely compiled in the 18th or 19th century—several centuries after the Samalas eruption. *Babad Lombok* had already been translated into modern Javanese and Indonesian and resides at the Museum of Nusa Tenggara Barat. *Babad Suwung,* also property of the museum, had yet to be translated from Old Javanese, so Lavigne and colleagues arranged for a translation to occur in a village where the person reading the *babad* sang from the palm leaves in a ceremony attended by all the residents. The third, *Babad Sembalun,* is familiar only to people who live in the Sembalun Valley on the northeastern flank of Samalas, where the original palm leaves remain.

With the translations, Malawani, Lavigne, and their colleagues examined the three *babad* for any information pertaining to an eruption. Because the *babad* provide no absolute time constraints for the Samalas eruption, the researchers had to verify that these records truly describe the event. To do so, they relied on comparisons. For instance, *Babad Lombok* specifically mentions the Old Javanese word for pumice, which helped to confirm the link between the *babads'* descriptions and the Samalas eruption. "We know that it's this eruption because it's the only [recent] eruption that produced pumice," said Lavigne. "What we see in the field corresponds to the descriptions in the *babad.*"

In that context, *Babad Lombok* and *Babad Sembalun* describe the collapse of Mount Rinjani, along with debris flows and avalanches. *Babad Suwung,* which includes the story of a group that journeyed to the nearby island of Sumbawa just before the eruption, describes "fire-rain" and burning winds—likely a surge of hot gas and ash—that seared the village across the strait.

Resilience meant resettlement away from the pumice-coated plains.

Before and After

Babad Lombok mentions Pamatan, a lost kingdom in a lowland, coastal area, said Lavigne. With a bustling population of 10,000, the fabled city boasted infrastructure, agriculture, fishing, and commerce but was wiped out by an eruption, according to the text. If Pamatan exists below Samalas's volcanic deposits, nobody knows where it lies, he said, though they have some educated guesses. Pumice quarries dot the island, trenched in deposits that can be as thick as 50 meters. Though no settlement has been found, Lavigne said he hopes that houses or temples might be unearthed in the future.

To extract what happened to the island's inhabitants after the eruption, Malawani, Lavigne, and colleagues traced the paths of refugees by matching place-names listed in the *babad* with modern geography, as well as with names taken from colonial-era maps. However, these paths could be describing either immediate evacuation or later migration, said Lavigne. "It's not always clear."

Babad Lombok also records which leaders built new settlements. For example, important people of Pamatan, such as the governor, harbormaster, headman, and royal family, each oversaw construction of a new village. On Lombok, resilience meant resettlement away from the pumice-coated plains, said Lavigne.

Timelines

For the past few decades, knowledge of volcanic eruptions in general has come from detailed studies of volcanic deposits and monitoring of those sites, said Agung Harijoko, a volcanologist at Gadjah Mada University in Yogyakarta, Indonesia, who was not involved with this study. Historical records, such as those described in the new study, may provide additional information about past eruptions and mitigation efforts that's otherwise hard to find.

In particular, said Vidal, little-studied oral histories, common in Indigenous cultures, contain invaluable information. "This study was remarkable," she said, because it uses local records, initially transmitted orally, after much of Lombok was destroyed.

However, because the *babad* do not include dates, reconstructing timelines is tricky. "Impacts immediately after an event are different from the long-term impacts, and people's understanding of that impact changes with time," said volcanologist Amanda Clarke, a professor at Arizona State University who was not involved with the study.

For instance, how long the recovery took is not mentioned in any documents from Lombok, said Malawani, who is also a lecturer at Gadjah Mada University. Fortunately, another document from Java, the Deśavarṇana, helped the researchers bracket the recovery efforts to about a century.

Many *babad* still need to be translated and studied, said Lavigne. "Some of them still may have some interesting information."

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

Were Impressionist Masters Painting a Polluted Reality?

Impressionist painters of the 19th century were famous for capturing the vitality of a scene and the fleeting nature of light, rather than meticulously reproducing every detail in a composition. But a new study presented at AGU's Fall Meeting 2022 suggested that trends toward hazier contours and whiter palettes found in works by J. M. W. Turner and Claude Monet may, in fact, be accurate representations of optical effects associated with air pollution.

The Impressionists (influenced by Turner and exemplified by Monet) were interested in contemporary scientific advances, and they often painted outdoors to capture the world in its true light. But their color palettes and painting techniques—visible brushstrokes with minimal representations of form—have been attributed largely to stylistic choice. The new research, led by Anna Lea Albright at the Laboratory of Dynamic Meteorology at Sorbonne University and École normale supérieure, suggested that Impressionists may have been more faithful to meteorological reality than previously assumed.

The study focused on Turner and Monet, iconic artists who frequently painted serialized cityscapes in London and Paris, urban areas that experienced increasing air pollution during the Industrial Revolution (bit.ly/Impressionism-pollution). "We don't want to say these artists were just instruments passively recording their environment—that would diminish their obvious creative genius. The key idea is that change to the environment provided new creative impulses, new ways of seeing," said Albright, who did the research with Peter Huybers, a professor of Earth and planetary sciences at Harvard University.

Claude Monet was fascinated by the smog of turn-of-the-century London, an atmosphere reflected in his 1904 painting of the Houses of Parliament. Credit: Musée d'Orsay

London Becomes "the Big Smoke"

Albright and Huybers first estimated air pollution levels during the periods when Turner and Monet were most active. Given that routine air quality monitoring began only in the mid-20th century, the researchers used fuel inventories as a proxy.

In Britain, the Industrial Revolution was gathering steam by the 1830s. Sulfur dioxide (SO_2) produced by burning coal was polluting the air, particularly in London, where concentrations increased throughout the 19th century. In Paris, SO_2 levels climbed only in the latter half of the 19th century, and peak levels were never as bad as those in London.

Pollution is known to affect visibility at street level, so Albright's group used image analysis to assess the clarity and color palettes in Turner's and Monet's paintings. The researchers' technique began by taking a high-resolution photo of a painting and converting it into a matrix—essentially a set of numbers corresponding to different colors. They then used mathematical wavelet analysis to determine how sharp the edges are between colors at different scales. Color models helped determine the images' "haziness."

The researchers assessed 60 oil paintings by Turner spanning the years 1796–1850 and 38 paintings by Monet dating from 1864 to 1901, after first calibrating the technique using photos of present-day cities in both clear and polluted conditions.

As pollution levels rose, the styles of both artists evolved from more clearly demarcated shapes toward blurrier edges and whiter color palettes. The trend was consistent even after the researchers accounted for factors such as subject and time of day. The same model found similar trends in paintings of London and Paris by other artists, including Camille Pissarro, James McNeill Whistler, and Gustave Caillebotte.

"Turner was born in the Age of Sail, and he died in the age of coal and steam," said Albright, who believes that industrialization influenced not only what Turner painted but also *how* he painted it. She said this influence is perhaps best illustrated in *Rain, Steam, and Speed* (1844), a frenetic scene featuring a train crossing a bridge in a golden landscape, with a hare darting along the track.

Monet, the Smog Seeker

Monet's early paintings were traditionally figurative. His style became increasingly Impressionistic as the locations in which he was painting became increasingly polluted.

Albright said Monet's work, completed generations after Turner, may actually represent an amplified version of real pollution

J. M. W. Turner's Rain, Steam, and Speed *(1844) may be a reflection of increasing air pollution in the United Kingdom as well as a stylistic precursor to Impressionism. Credit: The National Gallery (UK), CC BY-NC-ND 4.0 (bit.ly/ccbyncnd4-0)*

trends because the French artist was known to seek out the London smog for his ethereal paintings of the Houses of Parliament and other landmarks.

Peter Brimblecombe, an environmental scientist at the University of East Anglia and author of *The Big Smoke,* said some measurements of air and rainfall composition had been taken in London from the mid-1800s, but works by painters and writers can help to fill in sporadic gaps in the record. "Artistic and literary sources give clues about social perceptions that are not available in simple measurements," said Brimblecombe, who was not involved in the new study.

Donald Olson, who earned the nickname the Celestial Sleuth for investigating art mysteries using astronomical data, agreed. "Knowing the details of the place, the date, the time, the weather, and the sky conditions when artists created their artworks provides the opportunity for an imaginative experience," said Olson, an astrophysicist at Texas State University who was not involved in the new research. "The science brings the modern reader closer to the moment of creation or to the person they admire."

Albright would like to develop the scope of her research by looking at the influence of pollution on contemporary art in megacities such as Beijing and Delhi. She also said that as image analysis technologies improve, they could help to estimate pollution levels from images and video footage, providing complementary data for locations where direct air monitoring is not available.

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

Ancient Nile Tributary May Have Aided Pyramid Construction

Perhaps the most well known wonder of the ancient world, the pyramid of pharaoh Khufu was built about 7 kilometers west of the present-day Nile River, in what is now the city of Giza, Egypt. Giza lies within the Nile River delta, a 26,000-square-kilometer expanse of fertile soil. The complex, which includes two other large pyramids as well as many smaller structures, is "on the frontier between the desert and the floodplain," said Hader Sheisha, a physical geographer at Aix-Marseille University in France.

The distance between the Nile and the Giza pyramid complex has long led researchers to question how massive stone blocks were transported to the building site.

New research published in the *Proceedings of the National Academy of Sciences of the United States of America*, claims that a now abandoned channel of the Nile termed the Khufu branch once flowed freely through Giza (bit.ly/Nile-pyramid). Ancient engineers and workers, the authors said, took advantage of the waterway to easily move materials from quarries downstream to the deltaic necropolis.

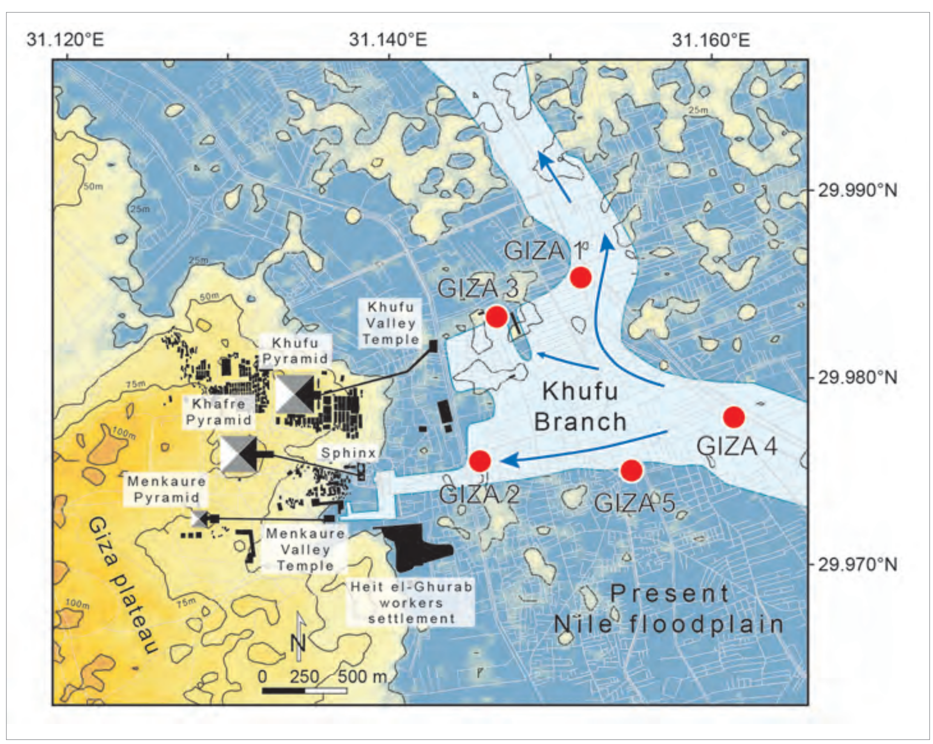
Drilling Through History

Sheisha, a doctoral student and lead author of the new paper, and her colleagues drilled nearly 9 meters beneath Giza's streets, open areas, and gardens. They collected sediment cores documenting 8,000 years of history.

Skeptical residents and onlookers assumed the researchers were looking for riches, Sheisha said. People would come to ask, "What are you looking for?" she remembered. The group was looking for a different sort of treasure: microscopic grains of pollen deposited over the millennia.

The plants that covered the ancient Nile landscape and the pollens they brushed off were not unlike those of today. Papyrus grew on stream banks, and ferns and grasses took root farther from water.

The Giza sediment cores revealed a layered history of shifting pollen species. This history indicates that the plants growing at these locations, and thus the wetness of the sediments, changed over time. The waxing and waning of the river level in the Khufu channel ultimately ended with a mostly dry streambed.



In this map, red dots identify sites where sediment cores were extracted in Giza. Credit: PNAS

Researchers extract a sediment core in Giza. Credit: Hader Sheisha

At the time the Giza pyramid complex was built—between 2670 and 2500 BCE—the channel was about 40% as high as it was during the African Humid Period, a peak wet period more than a thousand years prior. This earlier period saw relatively soggy conditions throughout northern Africa and a mostly green Sahara region. Though the core data do not constrain the Khufu branch's exact channel depth, they indicate that there was plenty of water for small boats to navigate to Giza, according to the researchers.

Other scientists were more hesitant to pin down the exact river level at that time. "This is an interesting approach, but [the study] is speculative," said Mark Macklin, a geomorphologist at the University of Lincoln in the United Kingdom. He cited limited constraints on the dates in the cores as a reason to not overinterpret the results. "It would have been good to actually relate it to the sediment and geology-based literature which exists in this region."

If accurate, the finding would support archaeological evidence that the Giza pyramid complex housed a harbor that builders used to bring supplies by water rather than transporting 2.3-ton stone blocks across the desert. From the Khufu branch, builders would have been able to dredge a short channel right up to the base of the site itself.

The sediment cores also hint at why Giza may have been chosen by Egypt's rulers, who lived 16 kilometers away in Memphis, as the site of their tombs. The Khufu branch's stable water levels made Giza an attractive site for monumental construction projects, Sheisha explained.

"It was an important factor for the builders and engineers in choosing this place because it seems to have been very suited for their needs," agreed Eva Lange-Athinodorou, an Egyptologist at the University of Würzburg who was not involved in the new research.

"It is fascinating to see that…environmental change was a deciding factor [in pyramid building]."

Geography Is Destiny

For a thousand years, the Nile River flooded its surrounding plains with a tonic of nutrients that fed the industrious civilizations dotting its banks. In the otherwise arid landscape of the eastern Sahara desert, communities relied on the predictability of the annual flood levels to sustain agriculture and move goods.

The fluctuating Nile documented by the new sediment research corresponded to a fluctuating social and political system in Old Kingdom Egypt, although many Egyptologists are hesitant to draw conclusions. Following the Fourth Dynasty, when Khufu was pharaoh, leaders started building their pyramids away from Giza. The subsequent period saw pharaohs lose much of their power to local governors. Archaeological records show that instability in Egypt was accompanied by widespread famine and conflict across northeastern Africa and Mesopotamia and as far east as the Indus Valley.

The shift in funerary construction away from Giza was an odd move in a culture that emphasized continuous familial succession of leaders, Lange-Athinodorou said. Previous theorized explanations for the shift included royal feuds and changes in religious beliefs. "The timeline is a bit fuzzy," she said, but the new core data show that around the end of the Fourth Dynasty, water levels in the Khufu branch dropped, potentially making construction at Giza more difficult.

"It is fascinating to see that…environmental change was a deciding factor [in pyramid building]," she said.

By **Jennifer Schmidt** (@DrJenGEO), Science Writer

Geohazard Education Trainings Foster Resilience in Rural Alaska

Leola Rutherford, the sole sixth-grade teacher at Girdwood PreK–8 School near Anchorage, Alaska, has walked teachers, emergency managers, Alaska Native middle school students, and her own classroom through a seemingly silly activity: tugging one sandpaper-covered wooden block across a sandpaper runway.

It sounds like fun and games, but exercises like these hold important lessons. That activity, called the earthquake machine, simulates the geology behind earthquakes. As learners pull one block with a rubber band, they mimic tectonic plate movement. When the block lurches across the sandpaper in a jerking, stop-and-go rhythm, it mimics an earthquake. And by pairing that basic science with practical safety tips, Rutherford and other educators hope to build geohazard resilience in Alaska.

Rutherford learned many science fair–like activities, including the earthquake machine, in 2019 during an educator workshop put on by a National Science Foundation–funded education program called ANGLE, which stands for Alaska Native Geoscience Learning Experience. "It's definitely one of the best trainings I've ever attended," Rutherford said. "I can guide discussions with my students a lot better because I've actually experienced it with other teachers and heard their Aha! moments."

"The work that ANGLE is doing is very important and is often overlooked. When you're looking at things like grants or promotion in academia, this type of work should be encouraged and rewarded."

ANGLE began in 2018 with the goal of fostering disaster resiliency through education, particularly in rural Alaskan and Native coastal communities. The project was modeled after previous Washington and Oregon programs (Cascadia Earthscope Earthquake and Tsunami Education Program (CEETEP) and Teachers on the Leading Edge (TOTLE)) that brought educators together for similar workshops. In December, as ANGLE drew to a close, the team behind 5 years of community-focused training presented its work at AGU's Fall Meeting 2022 (bit.ly/AGU22-ANGLE).

Leola Rutherford (right) masters the earthquake machine with other participants at ANGLE's 2019 educator workshop. Credit: Beth Pratt-Sitaula, ANGLE

Community Resilience Through Education and Networking

Thousands of Alaskans live at risk of earthquakes, tsunamis, landslides, and volcanoes. In particular, because of their locations and distance from emergency services, rural coastal communities are particularly vulnerable to earthquakes and tsunamis, said ANGLE organizer Beth Pratt-Sitaula of Central Washington University.

The earthquake machine was just one activity of many at ANGLE's 4-day educator workshops, which taught Alaskan K–12 teachers, emergency managers, and park and museum interpreters more than they could learn from a textbook, Rutherford said. They networked with different types of educators, practiced activities in a judgment-free learning space, and grew curious about Earth's inner workings.

In addition, ANGLE organizers have modified these workshops to bake them into preexisting programs for middle and high school students from rural Alaska Native villages. ANGLE supported about a dozen Alaska Native Science & Engineering Program (ANSEP) academies for students that ranged from 1.5-hour virtual sessions to weeklong career explorations. In one such workshop, for example, middle schoolers learned how GPS works and designed tongue depressor structures to withstand an earthquake.

After attending those academies, some ANSEP students said they wanted to be geologists, said Beth Spangler, the program's senior director. ANGLE materials remain a part of ANSEP programs today, she noted.

Lasting Impact

"The work that ANGLE is doing is very important and is often overlooked," said Elizabeth Vanacore, a seismologist at the University of Puerto Rico at Mayagüez who is not involved with the team. "When you're looking at things like grants or promotion in academia, this type of work should be encouraged and rewarded."

The educator workshop participants almost doubled their geohazard knowledge, according to surveys collected by ANGLE. Before each workshop, educators didn't feel very confident about helping to prepare their community for disasters. Afterward, their confidence and optimism had increased.

ANGLE workshop participants also returned home with a box of materials, including the earthquake machine, to continue sharing these lessons in their communities.

Vanacore has witnessed similar ownership of disaster preparedness in Puerto Rico, where she and the local TsunamiReady program equipped community leaders with tsunami resources. Those same leaders now run annual tsunami evacuation exercises on their own.

Although ANGLE funding expired at the end of 2022, the network it built will remain. "We're a small town in Alaska, so we're going to see each other, and we're going to be able to continue these relationships," Rutherford said. "Anyone can go online and watch YouTube videos, but nothing replaces meeting people face to face and physically being able to play. I mean, it's science. It should be fun."

By **Anna Marie Yanny** (@annamarie_yanny), Science Writer

A Day in the Life Used to Be 17 Hours

Since its creation, the Moon has been receding from Earth, and attempts at reconstructing the slow trajectory of the lunar exodus have reached very different conclusions. As a result, for much of its history, the location of the Moon in relation to Earth has been a mystery.

Now, new research has calculated the distance of the Moon from Earth 2.46 billion years ago, nearly doubling the age of the previous estimate. Because the length of the day is tightly, tidally tied to the location of the Moon, the research has also calculated how long a day lasted at the time: 17 hours.

To determine the distance between Earth and the Moon, scientists studied rhythmic patterns in Earth's orbit and axis called Milankovitch cycles, explained Margriet Lantink, a geologist at the University of Wisconsin–Madison and lead author of the new study in the *Proceedings of the National Academy of Sciences of the United States of America* (bit.ly/Moon-distance).

The idea of looking at Milankovitch cycles to learn about the history of the Earth-Moon system is not new, said Lantink, who conducted the research as a doctoral candidate at Utrecht University in the Netherlands. "But until recently, people have been applying them only to the youngest part of the geological record, where changes are very small," she said.

In determining the way solar radiation is distributed on Earth, Milankovitch cycles influence changes in climate over very long periods of time. These changes can be captured in the geologic record, which Lantink investigated in banded iron formations (BIFs) at Joffre Gorge in Western Australia's Karijini National Park.

By examining alternating layers of iron and clay in the BIFs, Lantink was able to identify patterns recording two key elements of Milankovitch cycles: orbital eccentricity and axial precession. Earth's circular-to-elliptical orbital eccentricity cycle lasts about 100,000 years. Earth's precession cycle, which describes wobbly changes in the direction of Earth's rotational axis, currently lasts almost 26,000 years.

The BIFs showed a smaller repeating pattern inside a larger repeating pattern. Uranium-lead dating helped Lantink determine that the larger pattern was likely guided by eccentricity, whereas the smaller pattern recorded precession.

The idea of looking at Milankovitch cycles to learn about the history of the Earth-Moon system is not new, "but until recently, people have been applying them only to the youngest part of the geological record, where changes are very small."

The 2.46-billion-year-old banded iron formations in Western Australia's Karijini National Park helped provide researchers (from left, Margriet Lantink, Joshua Davies, Frits Hilgen, and Paul Mason) with more robust data on both the Moon and the length of an ancient day. Credit: Greg Jack

Using the precession cycle recorded in Joffre Gorge's BIFs, which was closer to 11,000 years, Lantink and her colleagues calculated that at the time of the earliest deposits (2.46 billion years ago) the Moon was 321,800 kilometers from Earth—only 84% of its current distance. The precession analysis also indicated that Earth was spinning much faster at this time, resulting in 17-hour days.

"It turns out that the rate at which precession happens…depends on the Earth's rotation rate and the distance to the Moon," said Alberto Malinverno, a geophysicist at Columbia University who was not involved in the study.

"We showed that in very old rocks…you can recognize these Milankovitch cycles, and they are of high enough quality to say something about the Earth-Moon system," said Lantink. "There's a lot more possible than we thought."

By **Emily Shepherd** (@emilyshep1011), Science Writer

Converging Toward Solutions to Grand Challenges

Electrical power grids, on which we all depend, comprise numerous interconnected components, including generators, transformers, and transmission and distribution lines, as well as the operating processes required to keep these components functioning. These massive and truly complex systems function at the whim of myriad natural forces and the vicissitudes of human behavior that can reduce grid reliability or knock out operation altogether. Creating a power grid that is resilient to these forces is a national-scale societal challenge, one that cannot be addressed by a single sector or discipline.

Meeting this and other grand, sociotechnical challenges requires convergence, the merging of innovative ideas, approaches, and technologies from a wide range of sectors and expertise. With convergence comes a new spectrum of challenges involving how we work across disciplinary lines, collaborate meaningfully in large groups, and develop healthy—meaning open, participatory, and resilient—connections among diverse stakeholders. Indeed, tackling the problems we face as a society, whether pandemics, climate change, or complex systems, requires new levels of cooperation, facilitation, and synthesis.

The Convergence Hub for the Exploration of Space Science (CHESS) is a research project working to develop best practices for convergence research in the context of studying and predicting space weather. Recently, members of the CHESS team and others held a three-part workshop involving a simulated extreme space weather storm with impacts on power grid resilience and socioeconomic conditions, activities designed to highlight knowledge gaps apparent from the simulation, and group work to develop potential solutions to the gaps identified. In the workshop, we also learned actionable lessons for developing healthy gatherings and relationships among participants spanning a range of disciplines.

An Essential but Vulnerable System

The current flowing through a power grid can be affected by innumerable factors, from weather to details of the grid's operation to user demands on the system. The supply of current must be balanced at all times with demand, and this balancing is accomplished by maintaining a stable system frequency for the alternating current and voltages produced by synchronized generators. Keeping the frequency close to 60 hertz—the nominal alternating current frequency in the United States—is critical to coordinating a national-scale grid, keeping power plants online, and preventing widespread blackouts.

The failure of Texas's power grid in February 2021 reawakened the world to the precarity of power grids, whose complexity is only growing.

In February 2021, three major winter storms hit Texas within a span of 2 weeks. As the second storm descended, bringing with it record-low temperatures, Texas's power grid failed. In the middle of the night, the Electric Reliability Council of Texas (ERCOT) declared an Energy Emergency Alert Level 3—the most severe level—as officials nervously watched the frequency of Texas's power grid drop below the narrow 60-hertz band. The resulting blackouts affected millions of Texans for several days as freezing temperatures settled in and yet another storm approached.

This event reawakened the world to the precarity of power grids, whose complexity is only growing as new power sources and technologies are incorporated and their interconnectedness, digitization, and dependencies on weather and the changing climate increase. Operators use vast sets of sensors and tools to observe, control, and operate electrical grids, yet grid resilience to natural and human-induced hazards is anything but guaranteed.

Against this foreground of earthly challenges for power grids is another continual hazard: the constant flow of solar plasma and energy known as space weather, which alters Earth's space environment and can adversely affect human infrastructure. Space weather on its own can produce massive geomagnetic storms that result in power fluctuations and blackouts. It can also compound the effects of other threats, such as extreme temperatures, combining to push the power grid beyond critical thresholds.

As we head toward another solar maximum and the Sun's activity ramps up, awareness of the imminent threat to power grids from space weather, which could have global repercussions, is growing. According to the 2020 U.K. National Risk Register, the annual likelihood of extreme (i.e., "reasonable worst case scenario") consequences of space weather occurring is similar to that of "high consequence infectious disease outbreaks."

Progress toward a more resilient power grid is precluded by artificial separations among experts in relevant disciplines. To reimagine grid resilience, traditionally disparate communities must be connected and data from diverse fields must be open and broadly usable.

Since 2019, CHESS has been using a transdisciplinary approach to understanding and improving grid resilience and to building an open knowledge network (OKN) to achieve it. OKNs enable integration of vast amounts of diverse, publicly accessible data in service of a broad range of uses across society. In April 2022, the CHESS team, in cooperation with others in the convergent "Sun-to-power-grid" community, took the next step in growing the OKN with our three-part workshop, which centered community participation and collaboration.

Simulating a Grid Catastrophe

The first stage of our workshop involved participants playing out a space weather simulation game. This approach provided a low-risk, cost-effective environment in which to bring together researchers, decisionmakers, and operators to assess the U.S. electrical power grid's preparedness for hazards posed by space weather.

To bring the imagined world and scenario in the simulation to life, we consulted the North American Electric Reliability Corporation (NERC) Electricity Information Sharing and Analysis Center. This organization has been running North America's largest tabletop power grid security exercise, GridEx, biennially for more than a decade. We followed its design of mapping out our simulated scenario into three phases and an epilogue. The phases included observation of a large solar event days ahead of its arrival at Earth, communication and grid posturing hours ahead of arrival, and the onset of severe space weather impacts on Earth. The epilogue considered ongoing disturbances to the power grid and society 18 hours after onset.

Lighting along the U.S. Gulf Coast, as seen from space, illustrates the complexity and interconnectedness of the electrical power grid. Credit: NASA/Unsplash, Unsplash License

To instigate our simulation, we needed to create extreme yet geophysically realistic space weather conditions that participants had not seen before. We turned to a massive eruption from the Sun on 23 July 2012 that narrowly missed Earth but that struck a solar wind monitoring spacecraft in interplanetary space. We reconstructed solar wind time series during that event from the available data, used them to drive three of the main geospace models used by the space weather community, and incorporated Earth conductivity models to calculate the resulting electric field at Earth's surface. Then we worked with the Electric Power Research Institute to determine how the simulated geoelectric field would affect currents induced on a realistic power grid network.

We simulated the entire northeastern United States but focused on impacts to the Washington, D.C., area, where the workshop was held. Finally, in what we believe was a significant first for such a system-wide simulation, we used U.S. Department of Homeland Security data to tie in business and population models and state-of-the-art interactive visualizations to understand the socioeconomic impacts of the event.

Social Science Concepts Inform Interactions

The simulation game became a community-wide exercise to run models and trace lines of communication among participants (both individuals and institutions) representing a complete cross section of the Sun-to-power-grid information flow. Institutions involved included the National Science Foundation (NSF), NASA, Department of Energy, Federal Emergency Management Agency, Federal Energy Regulatory Commission, NERC, U.S. Geological Survey, NOAA, several national space weather programs, and numerous academic and private institutions. Whereas this event focused on the resilience of the power grid to space weather, the lessons learned in convening a group to cultivate multidisciplinary understanding and fluid exchange across domains are relevant in any effort to build resilience in complex systems.

In designing workshops, conferences, and other meetings, physical scientists and engineers can learn much from social science, psychology, and team science research looking into creating more generative and healthy exchanges [*National Research Council*, 2015].

We used the simulation game as a "boundary object," a tool that facilitates cross-disciplinary communication among disparate communities, allowing them to collaborate on a common task and develop a shared language [*Star and Griesemer*, 1989; *Lee*, 2007; *Wenger*, 1998]. The game served to structure interactions and enhance connections and information exchange, or "idea flow" [*Pentland*, 2015], among participants beyond what would have been possible through traditional presentation formats. These interactions involved interleaved exploration (brainstorming) and engagement (coordinating) activities.

Workshop participants were sequentially presented with a narrative for each simulation phase, along with data visualizations, model outputs, and other elements to bring the scenario to life (e.g., news headlines, social media, etc.). After each phase was presented, they convened separately in four discussion groups to work through a list of prompts carefully designed to facilitate a common group effort and shared language. These prompts included, for example, questions about uncertainties in space weather models and how quickly model updates are produced and shared, and about how decisions by grid operators to take action in light of risks to power supplies are coordinated.

In addition to the predetermined prompts, group leaders also facilitated open-ended discussion to further promote idea flow and connections among participants. And following each discussion session, group leaders wrote up summaries of key ideas, questions, and recommendations to share and integrate with those of other groups.

Synthesizing and Prototyping

Following the simulation game, the final two stages of the workshop involved sensemaking and system building, which together were

High-tension power transmission lines stretch across part of North Texas. The failure of Texas's electrical power grid in February 2021 demonstrated the precarity of these systems, which are growing more complex and facing increased hazards from weather and climate change as well as from the effects of space weather. Credit: David R. Tribble/Wikimedia Commons, CC BY-SA 3.0 (bit.ly/ccbysa3-0)

intended to synthesize insights and research, as well as development gaps identified during the simulation, and to create recommendations for researchers and policymakers.

Led by applied complexity scientists and philosophers, the groups used sensemaking techniques to reflect on the simulation game. Specifically, we used What? So What? Now What?, a critical reflection model designed to help groups assess the facts of what happened during a shared experience, make sense of what was learned, understand implications of the experience, and propose goals or solutions to problems. In our case, the exercise helped participants more clearly understand each other's roles and perspectives, and it revealed numerous insights. For example, space weather researchers learned how power grid operators determine grid reliability as well as what space weather information is most useful to operators in helping protect the grid during a real event.

Finally, we put the new understanding into practice, holding a full day of system building that teamed domain scientists, engineers, and data scientists in hackathon-like activities. The purpose was for the groups to develop and test rapid "prototype" solutions to address identified research and development gaps, especially with respect to the data and information systems that are needed but lacking. For example, there is a need to better understand the physical mechanism driving geomagnetically induced currents (GICs) and to model this process using real and synthetic data. The prototyped recommendation was to invite space weather researchers to help create software used to analyze power grid data, such as NERC's GIC database, so that the analysis better connects space weather and power grid data.

Participants also recognized the risk to the power grid from potentially compounding events, indicating a need to be able to overlay various hazard maps to better visualize and assess compound risk. The solution that emerged from this gap is to develop data integration systems (e.g., knowledge graphs) that allow research and information about multiple hazards—space weather, floods, and wildfires, for example—to be integrated and overlain.

Facilitation Is Essential

The increasingly complex challenges that society faces, including power grid resilience, require wider collaboration and clearer communication among scientists, engineers, and many others. So the role of facilitation—too often underappreciated—in solving these challenges is becoming ever more essential, requiring that the scientific and engineering communities learn, apply, and value facilitation skills.

Before, during, and after the workshop, we focused on successful facilitation as a cornerstone of the effort. In addition to effective time management, meeting scheduling, and communication support, numerous qualities are needed to support convergence research. Primary among them are the following: understanding and capability with the mediums of exchange that different communities use (i.e., beyond in-person interaction), understanding information flows within a group (i.e., the network of relationships), demonstrating and supporting emotional intelligence to increase mutual understanding, creating safe and inclusive environments, and adapting to changing conditions.

Meaningful and generative social interactions require facilitation across many small transactions between individuals [*Pentland*, 2015]. This effort begins with promoting relationships and helping establish common vocabulary among individuals from different communities—which is a long process. We needed participants to develop rapport and trust with each other prior to the 3-day workshop so that our limited time together in person could be used more efficiently. To that end, we held a preworkshop "microlab" to introduce participants to one another and allow them to identify commonalities in their expectations for the event. We also created numerous communication channels for them, including through live virtual activities and through unstructured asynchronous online collaboration (e.g., via Slack and Discord), to support different preferences for interaction.

The role of facilitation—too often underappreciated—in solving complex challenges that society faces, including power grid resilience, is becoming ever more essential.

These activities were mirrored during our in-person event, which included both the structured interactions and unstructured discussions to create more diverse exchanges and, ultimately, denser collaborative networks across scales (i.e., individuals, small groups, the whole community).

Conversations among workshop participants via the platforms set up before the meeting have also continued beyond the workshop. But facilitating further exchange and enhanced connections within and outside the workshop cohort requires more sophisticated digital spaces. To that end, we created an open knowledge commons to continue fostering relationships [*McGranaghan et al.*, 2021], and we suggest that this commons be a focus for the scientific community to sustain and amplify progress toward improving grid resilience.

The collective value of these facilitation efforts is exemplified by the prototype solutions that emerged from the workshop as products of close, trusted collaboration across groups, as well as by the strong, ongoing discussions among participants and between participants and other stakeholders and groups.

A Convergence of Many Voices

We recognize that other communities of experts and stakeholders are pursuing similar goals with respect to power grid resilience. The Institute of Electrical and Electronics Engineers Power and Energy Society, for example, provides forums for information sharing about technology development in the electric power industry, developing relevant standards, and educating experts and the public. Following our ethos of openness and convergence, we believe that all efforts and voices are important in solving this grand challenge and that progress will come from cooperative, not competitive, attitudes. We also believe that integrating social science techniques, emphasizing synthesis activities, and practicing effective facilitation will help stakeholders and experts across multiple communities better connect and will amplify progress toward solutions.

Scientists and engineers must value the skills of organizing and facilitating interactions and connections. These are traditionally "silent" skills that go unrecognized and undervalued in individuals, yet they are inextricably linked to the success of efforts to advance research and solutions. No longer are our scientific and engineering challenges—and indeed the most significant societal challenges—solvable without them.

Acknowledgments

The workshop discussed above was funded by NSF (award AGS-2131047). Those interested can read the Quick-Look Report (bit.ly/quick-look-report) from the April 2022 workshop, which includes a link to sign up to receive notification when the full report is published, as well as a database produced by the workshop steering committee of lessons learned from the experience of designing and hosting the workshop (bit.ly/lessons-learned-database).

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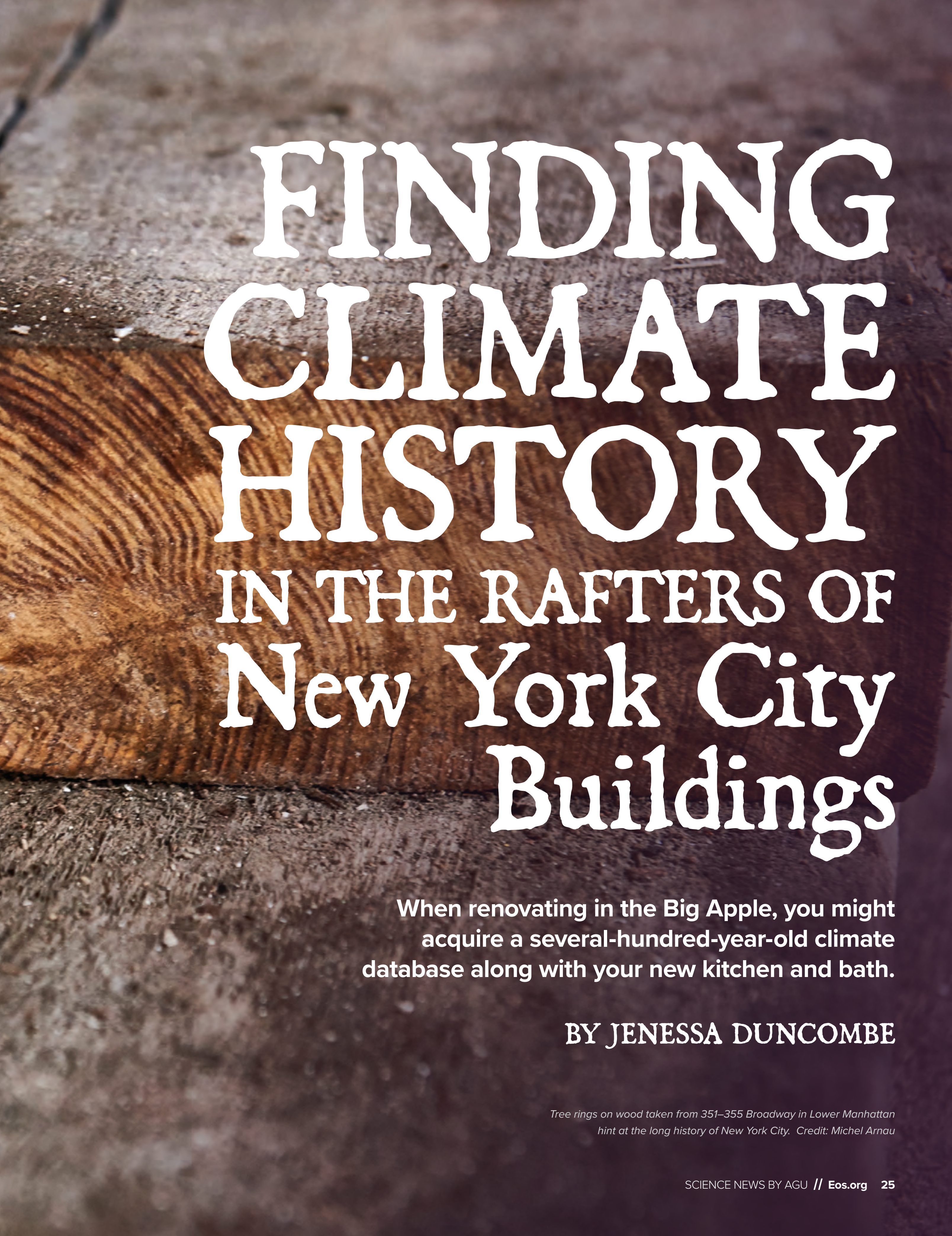
FINDING CLIMATE HISTORY IN THE RAFTERS OF New York City Buildings

When renovating in the Big Apple, you might acquire a several-hundred-year-old climate database along with your new kitchen and bath.

BY JENESSA DUNCOMBE



Tree rings on wood taken from 351–355 Broadway in Lower Manhattan hint at the long history of New York City. Credit: Michel Arnau

Mukund Palat Rao prefers the quiet of a forest grove, but on a winter day in Lower Manhattan, the ecoclimatologist was surrounded by buzzing chainsaws just blocks from Wall Street. He was there to rescue a piece of New York's heritage from a six-story residential building at 142 Fulton Street.

Hidden in wooden joists and beams in New York City's oldest buildings is the largest repository of old-growth timber in the eastern United States, said Rao. These timbers can hold valuable information about past climates—but it can be uncovered only if scientists can get their hands on the timbers before they go to a landfill.

Scientists and engineers estimate that 14,000 cubic meters of old-growth wood are removed from buildings in New York City (NYC) each year during demolitions or renovations; the city is continuously being remade. Rao, a scientist at Lamont-Doherty Earth Observatory's Tree Ring Lab at Columbia University, wants to ensure that the history locked in this valuable old growth isn't lost.

The Advent of Tree Ring Science

Each spring, a tree begins growing a new ring. This early growth is light colored and often contains larger cells; the wood turns darker in the fall, and new cells are smaller. An entire ring includes both light and dark wood, and its thickness is an excellent marker of how wet the environment was during its year of growth. A skinny ring denotes a dry year; a thick ring indicates a wet year.

Scientists extract samples of mixed old-growth conifers from 40 West 29th Street in Midtown Manhattan. Credit: Mukund Palat Rao

Dendrochronology emerged as a tool for studying past events in the late 1800s, when an astronomer, Andrew E. Douglass, recorded the patterns of wide and narrow rings on ponderosa pine stumps near the Lowell Observatory in Flagstaff, Ariz.

Since then, tree rings have become a popular proxy to estimate past meteorological conditions. Ice cores, speleothems, and even bat guano have all revealed Earth's ancient and historical secrets, but tree rings are unique because trees are so widespread. Since Douglass's first observations, scientists have measured tree rings in forests, violins, and shipwrecks. The International Tree-Ring Data Bank at NOAA has more than 5,000 tree ring measurements from six continents.

Scientific findings from tree rings can advance climate science and inform regional policies. In 2004, an influential paper in *Science* suggested that the U.S. Southwest was in the midst of a long-term drought on the basis of tree ring records from the West spanning 600 years. Today, knowledge of this 22-year-long "megadrought" has prompted the widespread adoption of sustainable water practices.

Records like these also shed light on how climate change alters the planet. Rings in trees from the British Isles and the Mediterranean suggest that the North Atlantic jet stream has become less stable since the 1960s.

Unfortunately, some of the United States' longest tree ring records have been lost. "Because of the history of deforestation, it's hard to find old-growth forests," said Rao.

New York City is a kind of national park of salvaged lumber.

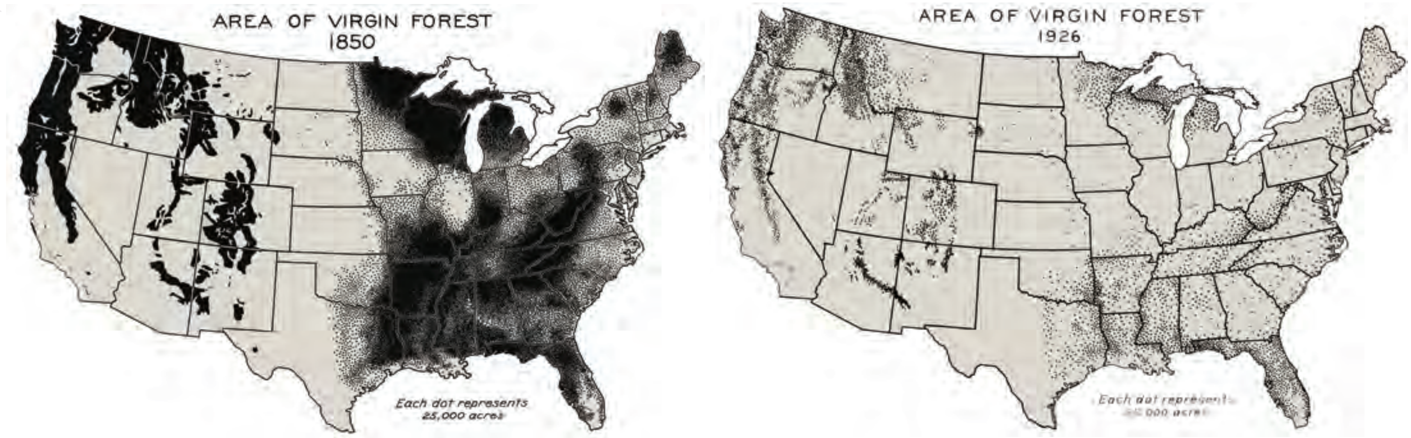
By the mid-20th century, logging had felled huge swaths of old-growth longleaf pine forests in the Southeast and eastern white pine forests in the Northeast—two of the most popular species of wood for building at the time. Longleaf pine forests once stretched for more than 36 million hectares (90 million acres) across the southern United States, but only 1.8 million hectares (about 4.5 million acres) still stand.

New York City's rapid urbanization in the late 1800s stoked a hot market for timber. NYC has the third-highest number of skyscrapers of any city in the world (behind Hong Kong and Shenzhen, China), and 95% of its buildings are believed to have wood framing and materials.

Saving a Gilded Age Landmark

In 2019, dendrochronologist Ed Cook, who leads the Tree Ring Lab at the Lamont-Doherty Earth Observatory, was contacted by the new owners of the Terminal Warehouse in Chelsea, Manhattan. The owners were renovating the building into a hub of office space, restaurants, and shops. They recognized the value of its giant wooden joists and reached out to Cook to learn more about the timbers.

Taking up a whole city block, the Terminal Warehouse was a signature feature of the Chelsea neighborhood. It provided nearly 92,000 square meters (1 million square feet) of retail space and had offered some of the city's only cold storage in its early days. Railroad tracks once ran straight into the building, and its pier sat on the Hudson River. In its more-than-a-century-long existence, the building housed Broadway sets, a nightclub, and untold numbers of goods such as furs, rugs, wines, liquors, and rubber.



Virgin forests have been slowly disappearing across the United States. Credit: William B. Greeley/U.S. Forest Service, Public Domain

No stranger to cold calls like this, Cook agreed that the Tree Ring Lab would study the warehouse's timbers. He has studied such timbers in more than 150 structures in the eastern United States, including Philadelphia's Independence Hall, as well as wood from an 18th-century shipwreck found under the World Trade Center.

Rao and another dendrochronologist at the Tree Ring Lab, Caroline Leland, took on the assignment.

A Search for the Timber's Origins

In the summer of 2019, Rao and Leland went to the Terminal Warehouse, where the timber that had been removed from renovated sections of the building sat stacked under low-hung ceilings in the basement. They sawed off wood from 22 joists and cored wooden columns. Comparing these samples with tree samples from across the United States would reveal where they once grew, before New York City gobbled them up.

Leland and Rao noticed that some timbers still had sapwood, the soft outermost layers of a tree that separate the inner heartwood and the bark. This sapwood would help the two decipher precisely when the trees had been cut down.

Back at the lab, they identified the wood as longleaf pine. It had all the species' telltale characteristics: substantial amounts of resin; high color contrast between the dark latewood and light earlywood in the tree rings; and a pencil-sized pith, or center of the tree.

Under a microscope, the scientists measured the width of each ring from pith to outer edge. Once they were done, they had a string of numbers from each sample—a "barcode" of the tree's growth history.

Comparing these barcodes with others published by scientists from trees around the country, Leland and Rao found that the Terminal Warehouse timbers were likely chopped down in the late 1800s in western and central Georgia and eastern Alabama, where they'd probably grown on dry mountainous slopes. One timber from the Terminal Warehouse had rings from as early as 1512.

The team hypothesized that the 110-kilogram (250-pound) joists came from the Sample Lumber Company near Hollins, Ala., and likely traveled by rail to a port in Savannah, Ga., before making the final leg of the journey on a schooner up the Hudson. The group published its findings in the *Journal of Archaeological Science: Reports*, adding to the growing recognition of Southern pine trees as an essential foundation of NYC's expansion during the Gilded Age.

Striking It Rich

The research would have stopped there without help from a Brooklyn wood salvager, Alan Solomon.

Solomon grew up at his father's junkyard in Boston and now runs a wood salvaging company, Sawkill Lumber, in Brooklyn. He travels to demolition sites around New York City, collecting wood to repurpose into furniture, floor-

One timber from the Terminal Warehouse had rings from as early as 1512.

The Terminal Warehouse held the "only stores in New York at which railway cars, steamships and trucks are in close communication," wrote guidebook author Moses King in 1892. Credit: King's Handbook of New York City/Internet Archive, *Public Domain* ing, and paneling. The city is “a kind of national park of salvaged lumber,” he said.

Solomon’s work intersected with the dendrochronologists’ in the 2000s, when an 1831 warehouse at 211 Pearl Street originally commissioned by the entrepreneur William Colgate was scheduled to be torn down. Solomon fought against the demolition of the property, but the building was eventually removed to make way for a skyscraper. Still, he saved several chunks of the building’s eastern white pine.

The team has collected wood from 26 buildings, including stables, a firehouse, and churches.

An analysis of the salvaged timber revealed that it hailed from New York’s Adirondack Mountains, a mere 480 kilometers (300 miles) north of the city. A few old-growth trees still live in the mountains, and the tree ring barcode of 211 Pearl matched some in the stand.

Remarkably, the oldest tree ring in the building’s timbers dated from 1532. The oldest known living tree in the Adirondacks reaches back only to 1690.

Solomon first reached out to Cook while writing a handbook on reclaimed wood to better understand how dendrochronology reveals hidden stories of timber. Solomon went on to assist with research for the Terminal Warehouse.

The warehouse experience piqued the whole team’s interest. Where else might genuine old growth be hiding? About 10,000 buildings are demolished in the city annually, but it’s challenging for the team to get much warning, and not all buildings have old-growth wood.

Solomon became a natural partner for Leland and Rao. “He is in touch with the pulse of the demolition market in NYC,” said Rao, and a whiz with the city’s construction history.

“If we can get [more] samples, it may allow us to develop a better understanding of the long-term climate in the regions these trees come from,” said Leland. “There’s the possibility that we can get further back in time.” So far, the team has collected wood from 26 buildings, including stables, a firehouse, and churches.

Giuliano Maselli Locoselli, a scientist at the University of São Paulo who specializes in urban dendrochronology, called the approach by Columbia’s Tree Ring Lab “brilliant.”

Men load planks of wood onto the schooner H. J. Smith *in Louisiana between 1900 and 1906. Credit: Detroit Publishing Company photograph collection/ Library of Congress*

Caroline Leland, a scientist at Lamont-Doherty Earth Observatory’s Tree Ring Lab at Columbia University, extracts a thin slice of timber from a Terminal Warehouse column. Credit: Mukund Palat Rao

“All the knowledge produced by these tree ring records will have great potential to support evidence-based decisionmaking in the city in terms of both cultural heritage and climate risk,” said Locosselli.

More tree ring records from rescued timber could help scientists better understand the megadroughts of yes-

A piece of longleaf pine from the Terminal Warehouse shows off its rings. Credit: Mukund Palat Rao teryear. One such parched period is thought to have occurred across North America during the 16th century, according to tree rings as well as English, Native American, and Spanish records. The year 1580 was the driest of the past 1,200 in much of North America.

Getting more data points from 16th-century trees will help scientists understand the intensity and reach of the drought currently affecting the U.S. Southeast, said Rao. "A longer data set also helps us understand decadal- to centennial-scale cycles that are inherent in the climate system."

Longleaf pine can even be used to reconstruct fire history, windstorms, and other disturbances to the forest, such as tropical cyclones, according to Leland. They also reveal exceptionally wet spells, such as the past half century in the northeastern United States.

Any new records would enrich the NOAA tree ring data bank as well. The thousands of records currently stored there support the Intergovernmental Panel on Climate Change's past climate variability information and ultimately serve as benchmarks and validation for climate models.

Alan Solomon, a wood salvager based in Brooklyn, N.Y., uses a saw to cut through history in Midtown Manhattan. Credit: Milagros Rocio Rodriguez Caton

Saving Timber from the Landfill

Other efforts echo Rao and Leland's project, including Cornell University's New York State and NE North American Dendrochronology Project, which has amassed more than 600 samples from upstate New York timbers to reconstruct climate from as early as the 1400s.

German scientists have dated construction timbers to reconstruct building activity in Europe from 1250 to 1699, a time period that includes the Black Death and the Thirty Years' War. Going back even further, dendroarchaeological finds have revealed insights into early human societies during the Neolithic and the Bronze Age.

Each building is like a little safety deposit box.

Rao dreams of someday making a compendium of sorts, a website of all the historical information from the group's tree ring research across the city for all to reference. For the time being, however, the group will keep collecting samples, although they have "more than we know what to do with," said Leland. Securing funding to support laboratory analysis of the samples is critical. Each new chunk of timber offers a window into the past and builds on the tapestry of tree ring data collected worldwide.

Solomon is lobbying for New York City to enact a deconstruction ordinance requiring valuable wood to be saved from certain buildings. Each building is like a "little safety deposit box," he said. The city is estimated to hold 14 million cubic meters of lumber, or about 74,000 subway cars' worth of wood.

The ordinance would require demolition crews to stack wood from reconstruction projects on flatbed trucks destined for salvage rather than directly into trash containers. It's supported by the New York Circular Construction Working Group, a group of built-environment professionals, including Solomon, working to promote the circular economy through policy and legislation change.

The idea has precedence: In 2016, Portland, Ore., was the first U.S. city to require buildings constructed before 1940 or deemed historical to be deconstructed rather than demolished. Other cities have similar guidelines.

"Because of the churn and continuous development of cities like New York, a lot of these buildings are being torn down and being replaced by high-rise towers," said Rao. "These timbers represent a very finite resource."

After leaving the Fulton Street construction site, Rao returned home with dozens of slices of timber, their rings clearly visible, and laid them out on his own hardwood floor. The timbers literally helped frame New York's past. The next day, he'd take them to the lab, where they'd have a new job to do.

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A POST-IMPACT DEEP FREEZE FOR DINOSAURS

New research supports the hypothesis that dinosaurs were done in by climate change after an asteroid impact kicked up a massive plume of sulfur gases that circled the globe.

An artist's rendering of North America in the weeks following the Chicxulub impact shows freezing conditions and skies hazy with sulfate aerosols. The pair of T. Rex *chicks in the foreground survived the impact but will soon succumb to the cold. Credit: @JamesMcKay-Creative Commons*

BY AUBREY ZERKLE

One balmy spring day 66 million years ago, a space rock 100 times the size of the International Space Station hurtled into what is now the southeastern tip of Mexico. The impact vaporized massive amounts of seawater and sulfur-rich marine rocks, creating a cloud of dust and aerosols that blanketed Earth and obscured the Sun.

This event, the Cretaceous-Paleogene (K-Pg) asteroid impact, remains one of the highest-profile cosmic disasters in Earth's history—it coincided with a planetwide extinction event that decimated nonavian dinosaurs and wiped out more than three quarters of life on Earth. The long-term biological consequences of this event are well established—the ecological reorganization that followed signified an end to the Mesozoic Age of Reptiles and ushered in the Cenozoic Age of Mammals.

The long-term environmental consequences of asteroid impacts remain foggy, but new fingerprints from atmospheric sulfur may help cut through the haze. Isotopic analyses of rock samples from Texas yielded clues to the history of the sulfur they preserved for posterity. Did the sulfur reach the stratosphere, and if so, did it stay there long enough to severely affect the climate?

The Chicxulub Impact

In 1980, geologist Walter Alvarez and his father, Luis, a Nobel Prize–winning physicist, first proposed that a collision with an extraterrestrial object wiped out the dinosaurs. The father-son team discovered up to 160 times the normal amount of iridium, an element sourced from cosmic dust, in deep-sea sediments formed at the same time as the extinction event. They suggested that the dust originated from a massive asteroid that smashed into Earth, explaining both the astonishingly high iridium levels and the coinciding extinction.

This sensational theory was met with skepticism for more than a decade, until 1991, when geophysicists discovered a circular structure about the size of Hawaii buried beneath the seafloor of the Yucatán Peninsula (Figure 1). Geochronologists dated melted glass in the walls of the structure and confirmed that it was roughly the same age as the mass extinction event. The crater was named Chicxulub, after the town closest to its center.

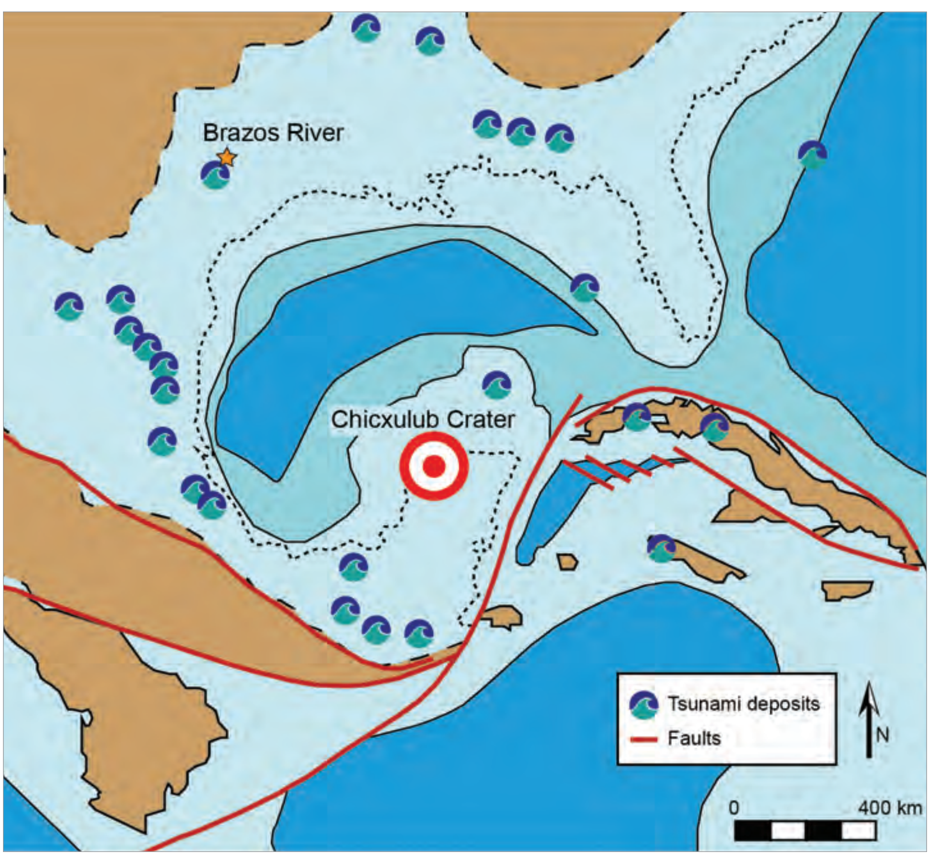

Fig. 1. A map of the Gulf of Mexico at the end of the Cretaceous, showing the relationship between the Brazos River deposits (orange star) and the Chicxulub impact site (bull's-eye). Modified from Vellekoop et al. *[2014]*

Paleontologists and geochemists set to work over the ensuing decades, scrutinizing the crater and impact ejecta in search of clues to the events that followed. They concluded that the impact caused a shock wave that wiped out everything in its immediate path, followed by devastating tsunamis and extensive wildfires. Tsunami waves propagated up rivers and onto land, producing landslides that buried anything in their path, including intact fish with well-preserved ear bones that constrained their time of death to Northern Hemisphere spring [*During et al.*, 2022].

These studies paint a terrifying picture of the devastation that occurred in the first few hours to days after the impact, but the immediate effects appear to have been too short-lived and localized to permanently alter Earth's biosphere. Some additional form of rapid and profound environmental disturbance must have occurred to cause widespread ecosystem upheaval in the decades that followed. But what are the long-term global consequences of a high-velocity planetary collision?

Impact Winter

Extreme cooling associated with an "impact winter" has been proposed to explain the severity of the K-Pg mass extinction. In this hypothesis, the impact produced a cloud of dust and soot that temporarily blocked out the Sun, shutting down photosynthesis and sending global temperatures plummeting. Life on a frozen, desolate tundra would have been particularly challenging for land-based creatures acclimated to the warm, stable climate of the Late Cretaceous.

Calculations have confirmed that dust and soot could have blocked sunlight almost entirely, but these heavier particles would have rained out of the atmosphere in months to years rather than decades [*Tabor et al.*, 2020], limiting their effects to several chilling summers. The key to sustaining a long-term impact winter might lie in where the asteroid hit.

The Yucatán in the Late Cretaceous was like it is today, with warm, shallow seas overlying a sulfur-rich carbonate platform. Volatilization of these rocks during the impact would have injected massive loads of carbon dioxide,

(left to right) Linda Ivany, Christopher Junium, and James Witts examine the main K-Pg boundary deposit at Darting Minnow Creek near the Brazos River in Texas. Credit: Shiv Das

sulfur, and other climatically active gases into the atmosphere. In particular, atmospheric sulfur rapidly forms sulfate aerosols, which can reflect incoming solar radiation and cool the planet for many years after an impact-generated plume has dissipated.

Geochemists recently confirmed that rubble collected from the Chicxulub crater contained virtually no sulfur [*Gulick et al.*, 2019], meaning that all the sulfur in these rocks, with an estimated mass of more than 10 million times that of the Eiffel Tower, must have been vaporized into the atmosphere. However, sulfate aerosols have long-term climatic effects only when they form in the stratosphere, where they can remain for years to decades.

This altitude dependence complicates attempts to model the global cooling effect of the Chicxulub impact because the height of the plume depends on unknowns like impact angle and velocity. Direct, empirical data are needed to test how much sulfur reached the stratosphere, where it would have caused the maximum disturbance.

Atmospheric Fossils

Fortuitously, the interaction of sulfur gases with ultraviolet (UV) light produces a unique geochemical signature, termed mass-independent fractionation of sulfur isotopes, or MIF. As the name suggests, MIF refers to chemical or physical processes that separate the isotopes of an element. “Mass independent” indicates that the amount of difference in the masses of the isotopes does not determine the degree of isotope separation.

DIRECT, EMPIRICAL DATA ARE NEEDED TO TEST HOW MUCH SULFUR REACHED THE STRATOSPHERE, WHERE IT WOULD HAVE CAUSED THE MAXIMUM DISTURBANCE.

Until recently, sulfur MIF signatures have been found only in rocks that formed more than 2.3 billion years ago, when Earth’s atmosphere was devoid of oxygen. The reason is that today, molecules of oxygen in our atmosphere combine to produce a stratospheric ozone layer, which blocks most harmful UV rays from reaching Earth’s surface, preventing them from burning our skin and damaging our DNA. This protective shield also blocks UV light from interacting with any sulfur gases emanating from volcanoes and hot springs, which rain or fall out of the lower atmosphere with no MIF.

I’ve spent much of my career examining these rocks, with their isotopic signatures preserved like ancient atmospheric fossils, to determine how and when oxygen built up on Earth. If the Chicxulub impact thrust huge amounts of sulfur above the ozone layer and into the stratosphere, the sulfur in these rocks should contain similar MIF signatures. A collaboration with my close friend and colleague Christopher Junium, from Syracuse University, provided some valuable insights.

In early 2019, Chris, along with James Witts and Linda Ivany, visited the Brazos River area, in Texas, to sample a section of rocks across the K-Pg boundary. The team's original goal was to collect the shells of Late Cretaceous ammonites (now extinct sea creatures with spiral shells) to reconstruct their diets, but the researchers also collected a full suite of samples across the section.

THESE DATA DEFINITIVELY SHOWED THAT SULFUR FROM THE IMPACT EVENT WAS THRUST INTO THE STRATOSPHERE, WHERE IT WOULD HAVE PROLONGED GLOBAL COOLING AND INTENSIFIED THE EXTINCTION.

This careful sampling proved key to our later work. The K-Pg event deposits that they collected in the Brazos River area constitute an expanded sequence of tsunami or storm deposits with exceptional temporal resolution, perfect for capturing such a geologically fleeting event. And most exciting, the rocks contained oodles of sulfur, with up to 10 times more sulfur in the impact deposits than in the rocks formed just prior to impact!

Chris had already received a fellowship to visit my lab at the University of St Andrews later that spring, and we decided to have a go at analyzing MIF in his samples to search for evidence of stratospheric sulfur. More serendipity followed, as the first sample we measured contained the largest MIF signal we found, spurring us on.

In fact, all the impact deposits that we analyzed showed signs of MIF. Perhaps more important, none of the samples from before or after the impact did. When the COVID-19 pandemic shut down labs in early 2020, I set about testing various mixing models to see whether any normal marine processes could explain the sulfur isotope data from the Brazos impact deposits. In the end, the only way to reproduce these signals was by dropping a massive load of MIF-bearing sulfur onto the Late Cretaceous continents and ocean [*Junium et al.*, 2022].

These data definitively showed that sulfur from the impact event was thrust into the stratosphere, where it would have prolonged global cooling and intensified the extinction. Further MIF analyses of additional K-Pg rocks from around the world should help confirm the extent of the sulfur plume and the duration of the resulting impact winter. Comparison with a more recent event offers additional clues. In 1991, the eruption of Mount Pinatubo released sulfate aerosols into the stratosphere. This event released about 100,000 times less sulfur than the Chicxulub impact, but it still caused global temperatures to decrease by 0.5°C for 2 years.

The Next Big One

Asteroid impacts constitute the single greatest unavoidable threat to life on Earth—the K-Pg event was the most recent, most deadly point of comparison. As of June 2022, NASA's Near-Earth Object Wide-field Infrared Survey Explorer (NEOWISE) has detected 849 near-Earth asteroids with a diameter of 1 kilometer or greater. The full list of near-Earth objects (NEOs) currently contains 13 objects with an impact probability of 1 in 10,000 or higher, the largest of which is a half kilometer in diameter, about 5% the size of the Chicxulub asteroid.

In 2021, NASA launched its first large-scale planetary defense test mission, the Double Asteroid Redirection Test (DART). The DART mission became the first to successfully alter the path of an NEO in space as it completed a collision course with the asteroid Dimorphos in September 2022. DART laid the groundwork for the development of similar technology for defending Earth against small-scale impacts.

But what will happen when the next big one approaches our humble planet? For *Tyrannosaurus rex* and its feathered friends, it seems that survival options were limited—they either died quickly in a fiery inferno or slowly froze and starved to death in the harsh decades-long winter that followed. If "forewarned is forearmed," perhaps humanity's new knowledge will offer us a broader range of options.

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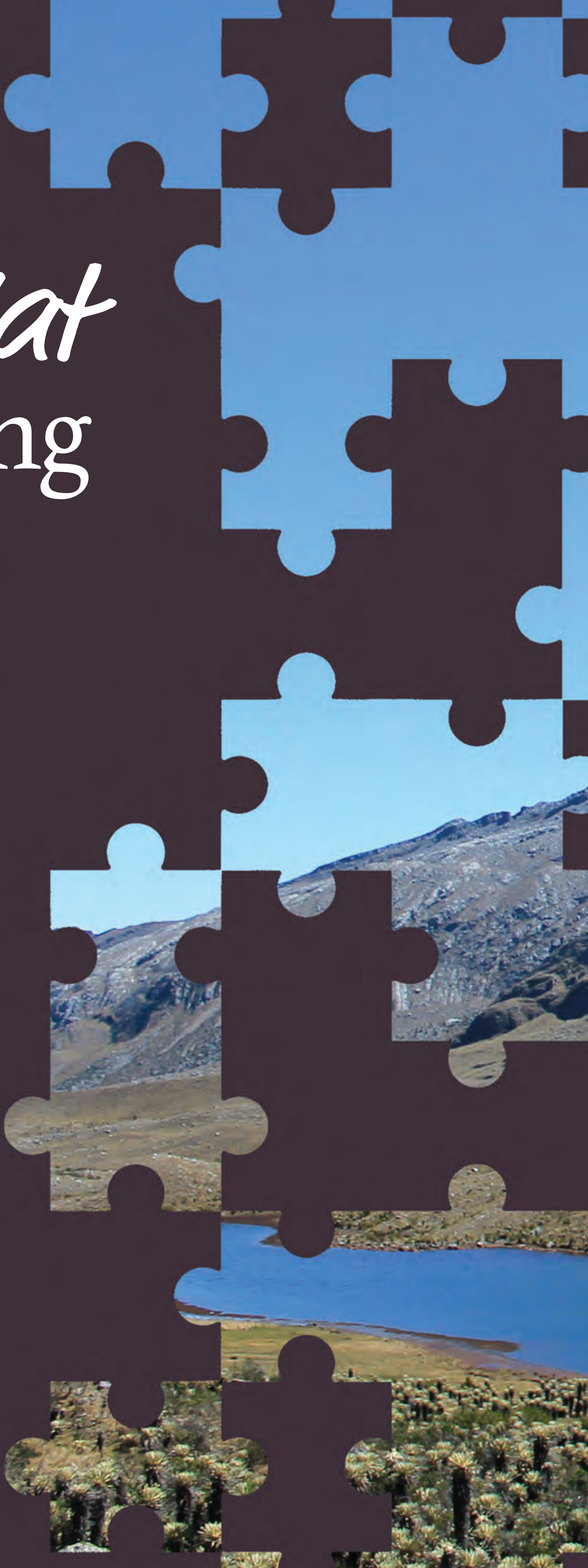
A Puzzle Mat for Assembling Colombia's Geologic History

A new database compiles all available information about Colombia's geochronology, offering scientists a consistent framework in which to study the data in a broader context.

By CAROLINA ORTIZ-GUERRERO



The rocky landscape of Sierra Nevada del Cocuy National Park, seen here, is in Colombia's Eastern Cordillera. Credit: Lina C. Pérez-Angel

Earth's deep history might be the biggest puzzle geologists try to put together.

If you have ever assembled a large jigsaw puzzle, you know how difficult the task can be, especially if the picture you are putting together is unclear or if pieces are missing. The process becomes even harder without a table or puzzle mat to display and support all the pieces during the building process.

Earth's deep history might be the biggest puzzle geologists try to put together—and it's not an easy job. Geologists use isotope geochronology, a method that relies on the predictable decay of radioactive elements, to determine when a particular rock formed, and they apply this information to establish the timing of past geologic events. However, isolated pieces of rock do not tell the complete picture of Earth's history. Just as each piece of a puzzle has a shape and color pattern matching the pieces around it, in geochronology, dated rocks must be matched with other rocks of similar age and isotopic composition to tell the history of Earth clearly and accurately. It is much easier to make these matches when you have an appropriate puzzle mat on which to reconstruct the geologic history.

Over the past few years, a group of early-career Colombian scientists from the Semillero de Geocronologia Uniandes (Geochronology Incubator at the University of the Andes) have collected all known pieces of geochronological information about Colombia's rocky landscape to build the Colombian Geochronological Database (CGD). This database serves as a mat for geochronologists interested in fitting the geology of Colombia, which spans more than 1.1 million square kilometers, into the puzzle that is the geologic history of the northern Andes [*Rodriguez-Corcho et al.*, 2021].

A Box of Unsorted Pieces

Colombia comprises a mosaic of five major geographic regions: the Amazon, Andean, Caribbean, Orinoco, and Pacific. Although these regions share common biological and geographic features, they do not necessarily share the same geologic history.

Figure 1 shows a different layout, delineated on the basis of distinct rocks, the result of different geological events that took place (and are still taking place) not only at the surface but also in the crust and mantle. For example, the eastern and southeastern regions (the Amazon and Orinoco geographic regions) contain rocks from the Guiana craton, which extends to Venezuela and Brazil, and group together the oldest rocks (roughly 1 billion years old) in northern South America. The Western Cordillera region (Pacific geographic region) comprises a collage of rocks, some of them formed in the bottom of the sea, which crashed against the South American continent and were elevated above sea level by geological forces. When each of these events took place and how long each lasted are big-picture questions that isotope geochronology can answer.

In 2017, undergraduates at the Semillero de Geocronologia Uniandes in Bogotá began investigating the status of the geochronological research in Colombia, motivated by the question of how much is known about the ages of Colombia's rocks. This group of students, most of whom graduated during the development of the project but continued working on it, was led by Yamirka Rojas-Agramonte and assisted by Colombian graduate students at universities all over the world.

The team found that the existing geochronological information had been previously compiled in published geochronological databases [*Gómez-Tapias et al.*, 2015; *Millward and Verdugo*, 1981; *Restrepo*, 1983; *Maya*, 1992; *Calvache*, 1988]. These databases had worked for specific research objectives, but the CGD team intended to fill several gaps in the existing databases. First, some of the older databases did not provide clear insights on the regional geology and tectonics of Colombia and the northern Andes region through all geologic time. Second, not all of the databases were contained in a digital format, and not all of them were available for easy public access or organized under a consistent format (e.g., in some of the databases, the locations of some samples were described by colloquial names for businesses or other landmarks that no longer existed). Also, none of the databases had enough data to construct representative statistical figures for use in regional-scale geologic interpretations.

In other words, although these databases preserved the geochronological information of Colombia, they were like boxes of unsorted puzzle pieces. What was needed was a resource in which pieces that fit together—rocks of similar ages—could be kept in place, showing where most of the available information is concentrated and where the gaps are.

The Need for a Puzzle Mat

The lack of a common framework in which to view Colombia's geologic history motivated the creation of the CGD. The CGD allows geochronologists to recognize significant events in Colombia's geologic past that may have regional or even global tectonic and geodynamic significance.

For example, by providing a peer-reviewed timeline for major tectonic events recorded in the rocks of Colombia, the CGD allows geologists to understand when plate tectonic processes along northwestern South America have resulted in the creation of new crust (through processes like arc magmatism, crustal melting, and continental rifting), the preservation of old crust (through processes such as continent-continent or arc-continent collision), or the destruction of crust. These are relevant questions for researchers studying the evolution of mountains and active tectonic processes.

The CGD also aids in assessing the effects of societal events on geological research. For example, the long-lasting, violent conflict between Colombia's government and guerilla forces has hindered access to places in the southern (Amazonia), western (Pacific), and eastern (Llanos) regions of the country, resulting in data gaps in those areas. The only way to collect samples for geochronological studies is to gather them during fieldwork. The CGD enables scientists to visualize where the conflict has left these gaps and to plan future fieldwork to fill them. Although the internal conflict persists (and even worsened in certain areas), with the signing of a 2016 peace agreement and now with the development of the CGD, the new generation of geoscientists is optimistic about the challenges and opportunities to come.

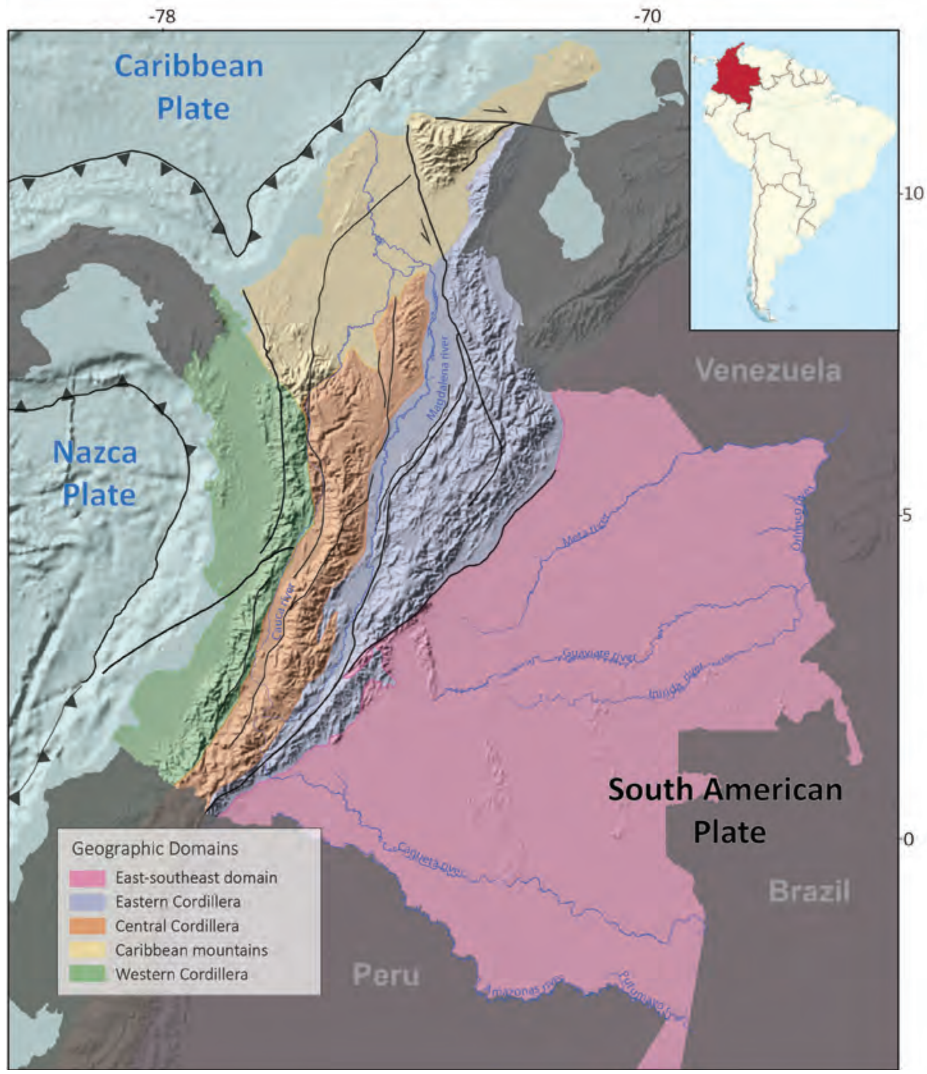


Fig. 1. The geological regions of Colombia and the surrounding areas reflect their common tectonic history and rock formations. The boundaries of these regions differ from regional definitions based on biodiversity and geographic, sociological, and other factors. Credit: Rodriguez-Corcho et al. *[2021], reprinted by permission of Taylor & Francis Ltd.*

An Example of ICON Science

The CGD is an example of global and regional scientific collaboration fulfilling the values of ICON science. ICON, a term coined in 2019 by the U.S. Department of Energy, refers to the principles that integrate processes across disciplines and scales (I), coordinate consistent protocols to produce interoperable data (C), openly exchange data (O), and network data collection (N) across projects.

The CGD was designed primarily by following the approach used by Bruce Eglington in developing DateView, a user-friendly freeware geochronology database system that offers well-organized data storage and easy retrieval [*Eglington*, 2004].

Project members also developed a consistent workflow to compile, filter, and interpret all geochronological data related to Colombia's geology published between 1962 and 2021. This task required the team to review each of the available data sets and analyze the type and quality of data they contained, an effort led by Rojas-Agramonte and carried out by students at different stages in their early careers with assistance from expert scientist mentors. In total, this work amounted to reviewing 342 references, of which 283—including peer-reviewed papers and bachelor's, master's, and doctoral theses—met the minimum criteria to be included. References were discarded if they lacked geological information related to the samples studied or if samples didn't have the correct coordinates.

In August 2021, the CGD launched a public web page featuring an interactive map and other useful tools for data accessibility

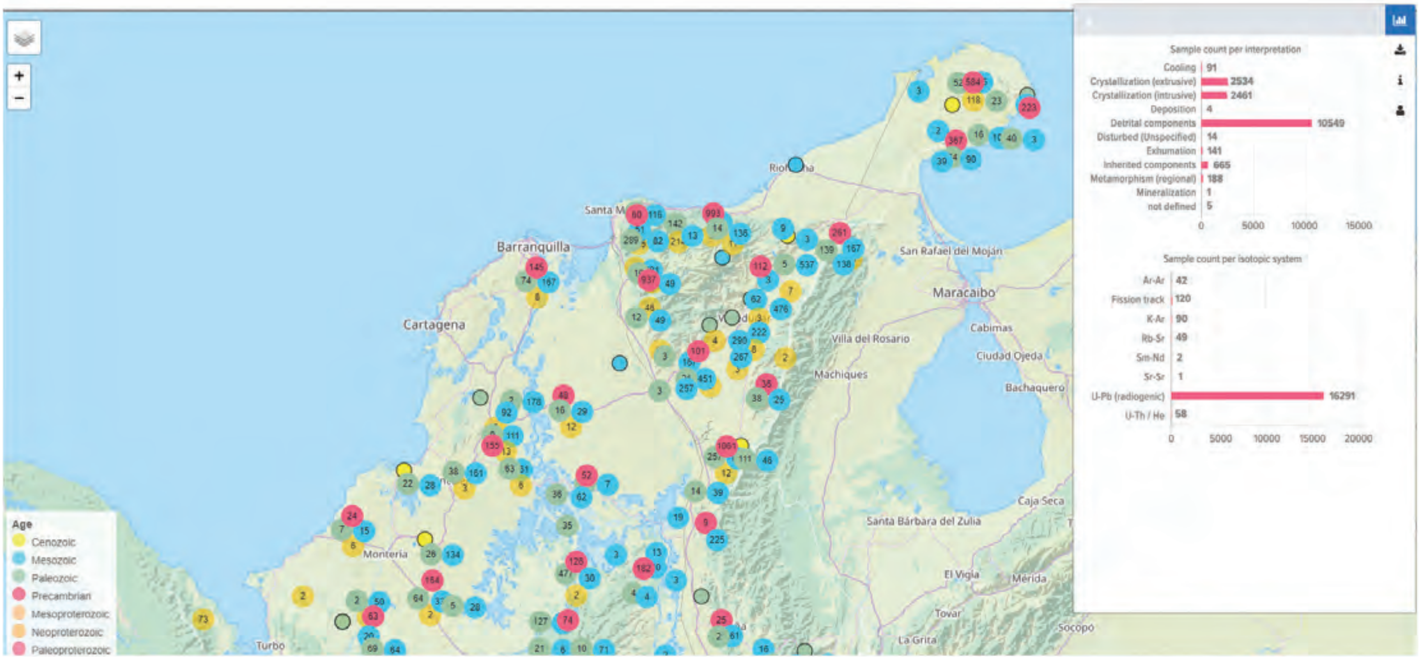


Fig. 2. The Colombian Geochronological Database web page (bit.ly/CGD-visualization) features an interactive map and other data accessibility tools. Researchers can upload their geochronology data to the site, which is updated routinely.

The CGD team plans to expand its network and include data from other Latin American countries.

(bit.ly/CGD-visualization; Figure 2). The site is updated routinely and allows researchers to contribute by uploading their geochronology data. Behind the website is a team of volunteer scientists and experts in geochronology and Colombian geology who review and assess the quality of the contributions, using the criteria mentioned above.

For the moment, the database includes data from Colombia exclusively, but the CGD team plans to expand its network and include data from other Latin American countries by training scientists from those countries to compile their data in the CGD. To further network and to increase the usefulness and accessibility of the data in the CGD, these data will be uploaded into global data sets, such as the PANGAEA data repository.

With the creation of this Colombian geological puzzle mat, researchers can easily see their data in a larger context, and they can see where their efforts are most needed to fill in the gaps. Furthermore, seeing all available data assembled in one place may yield new insights into the big picture of Colombia's geological history.

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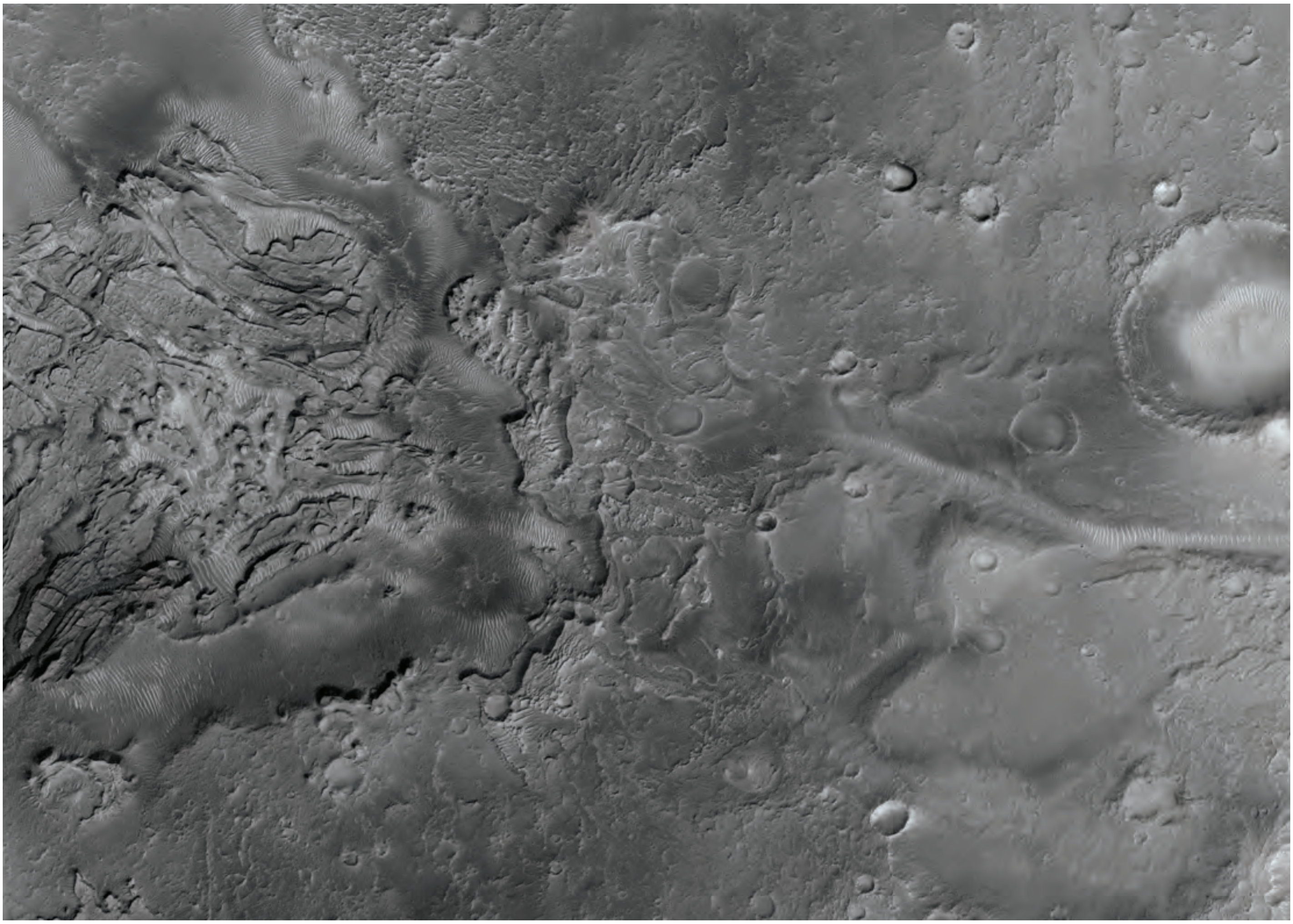
Long-Lived Lakes Reveal a History of Water on Mars



An inlet valley (sinuous feature at right), a sediment fan, and the layered sediments within a newly identified paleolake (left) in the Arabia Terra region of Mars are visible in this image taken by the High Resolution Imaging Science Experiment camera aboard the Mars Reconnaissance Orbiter. Credit: NASA/JPL-Caltech/UArizona

Mars is divided into two broadly distinctive areas: the smooth northern lowlands and the pockmarked southern highlands. The region of Arabia Terra sits along the transition between these two regions and is thought to contain some of the planet's oldest rocks, at more than 3.7 billion years old.

Among the craters in the southern highlands, valleys and paleolakes abound, exposing sedimentary and geomorphologic evidence of liquid water. However, relatively few paleolakes have been identified in Arabia Terra. *Dickeson et al.* used imagery and data from NASA's Context Camera (CTX), High Resolution Imaging Science Experiment (HiRISE), and Thermal Emission Imaging System (THEMIS) to study a roughly 22,000-square-kilometer area of Arabia Terra in detail. From this imagery, the team created high-resolution maps and digital elevation models to study the area's geomorphology, which allowed them to identify and describe seven new paleolakes in the region.

The researchers focused on paleolake features including lake levels, drainage catchments, fans, and lake outlets. They found that the shapes of the lakes were irregular in comparison with the circular lakes found in craters in the southern highlands. There was evidence of surface water inflows that filled the lakes as well as outlet streams that drained them, forming a cascading chain of lakes. The team also observed multiple past water levels within each of the paleolakes, indicating that the lakes persisted over long periods of time during the Noachian, rather than forming and disappearing quickly.

To maintain the filling and drainage of the lakes, liquid water must have been common, with steady inputs into the lake system from precipitation and groundwater, the researchers concluded. The potentially habitable environment in Mars's distant past indicated by these paleolakes offers an ideal location for future astrobiology and paleoclimate studies, they suggest. (*Journal of Geophysical Research: Planets*, https://doi.org/10.1029/2021JE007152, 2022) **—Sarah Derouin,** *Science Writer*

When the Aral Sea Dried Up, Central Asia Became Dustier

In 1959, officials in the Soviet Union decided to divert river flows feeding the Aral Sea to the deserts of Central Asia, where the water irrigated farms supplying a growing cotton industry. As the cotton blossomed, the lake's level dropped. Today only slivers remain of what was once the world's fourth-largest lake.

As the Aral Sea has become a desert, known as the Aralkum, soil from the dry lake bed has added to the dust that swirls above Central Asia. This dust carries hazards beyond those typically associated with natural particulate matter: It's mixed with salt as well as with residues from agricultural pesticides and fertilizers introduced into the sea. How much and where dust from the former Aral Sea spreads across the surrounding region are therefore important public health questions.

In a new study, *Banks et al.* used an atmospheric transport model known as COSMO-MUSCAT (Consortium for Small-scale Modeling-Multiscale Chemistry Aerosol Transport) to quantify how much dust the dry lake bed contributes to the region, where the dust is most prevalent, and how much of the dust can be measured by satellites. The modeling revealed that the dry lake bed of the former Aral Sea added about 7% more dust over Central Asia in the 2000s to 2010s compared with the 1980s and 1990s. Dust emissions from the Aralkum appear to peak twice per year, in spring and early winter. When the researchers focused on a 1-year period from spring 2015 to spring 2016, they found that among the region's major cities, Tashkent, Uzbekistan, and Ashgabat, Turkmenistan, were hit hardest by this dust, with levels exceeding World Health Organization recommendations 2–3 days per year. However, substantial year-to-year variability in winds means that different areas likely bear the brunt of the dust in different years.

A fishing boat lies rusting on what was once the bottom of the Aral Sea. Credit: Gilad Rom/Wikimedia Commons, CC BY 2.0 (bit.ly/ccby2-0)

The researchers also found that dustiness in the region often coincides with cloudiness. They estimate that more than two thirds of dust storms are obscured by clouds, a condition most pronounced in winter and spring, meaning that satellites may struggle to quantify dust emissions from the dry lake bed during these times. In light of this observation, the authors suggest that complementing modeling studies with ground-based observations will be particularly important for continuing to reveal how dust from the former Aral Sea is affecting Central Asia. (*Journal of Geophysical Research: Atmospheres*, https://doi.org/10.1029/2022JD036618, 2022) **—Saima May Sidik**, *Science Writer*

If There Is Phosphine on Venus, There Isn't Much

In the absence of direct observations of extraterrestrial life, scientists often focus on searching for biosignatures, chemical by-products of life, that can be detected with remote sensing. Although Mars has received the most attention in this regard, other solar system worlds with atmospheres also have been investigated.

In 2021, planetary astronomers reported detecting phosphine gas in the atmosphere of Venus using ground-based radio observations. The concentration of the gas was initially reported to be 20 parts per billion but was later revised to 7 or fewer parts per billion on the basis of improved calibration and analysis of the data. On Earth, phosphine can be associated with biological processes, and researchers are studying whether the gas may be used as a sign of life on other planets.

The purported phosphine detection has been met with skepticism because of difficulties with calibration and analysis of the ground-based observational data. Follow-up attempts to detect phosphine in Venus's atmosphere using other ground- and space-based telescopes also have produced no definitive detection. *Cordiner et al.* contribute another set of measurements from a unique observational platform: the Stratospheric Observatory for Infrared Astronomy (SOFIA).

The SOFIA aircraft flies at a height of 13 kilometers, which is above the majority of Earth's atmosphere, greatly reducing the risk of contamination of the phosphine signal from terrestrial sources. The researchers used SOFIA's German Receiver for Astronomy at Terahertz Frequencies (GREAT) instrument, which has very high spectral resolution, to collect far-infrared spectroscopic data from 75–110 kilometers above Venus's surface, which is very close to the altitude range measured by the earlier study.

Data collected by GREAT during three observing flights revealed no clear evidence of phosphine, the researchers report. If any phosphine is present in Venus's atmosphere, and assuming that the abundance is constant in time, the new observations indicate an upper limit on its concentration of 0.8 part per billion. This level is the most stringent upper limit presented to date for the entire Earth-facing hemisphere of Venus.

Many intricacies of Venus's dense atmosphere remain puzzling for planetary scientists. The next big breakthrough may arrive when NASA's DAVINCI probe (Deep Atmosphere Venus Investigation of Noble Gases, Chemistry, and Imaging) plunges to the planet's surface, which is scheduled to occur in the early 2030s. (*Geophysical Research Letters*, https://doi.org/10.1029/2022GL101055, 2022) **—Morgan Rehnberg**, *Science Writer*

Mapping Street-Level Pollution Estimates to Reveal Safer Routes

Hong Kong is seen by satellite here in January 2018. Credit: Axelspace Corporation/Wikimedia Commons, CC BY-SA 4.0 (bit.ly/ccbysa4-0)

The United Nations has identified improving the walkability and bikeability of cities as key goals in efforts to reduce dependence on greenhouse gas–emitting automobiles and promote routine exercise for public health. However, increased walking and cycling can come with their own health risks.

Time spent in the open air, in addition to other factors, increases exposure to airborne pollutants, for example. The most harmful category of pollutants to human health includes inhalable particles smaller than 2.5 micrometers, referred to as $PM_{2.5}$. It has been estimated that more than 4 million premature deaths worldwide each year are attributable to these pollutants.

To help reduce health risks from this pollution, *Tong et al.* developed a new approach for estimating ground-level $PM_{2.5}$ concentrations from satellite observations and incorporated it into a mobile mapping application that identifies routes through Hong Kong that minimize pedestrians' exposure to $PM_{2.5}$.

The researchers combined several data sources to build their framework, which accounts for city-specific factors that produce and concentrate $PM_{2.5}$. Sixteen air quality monitoring stations provided hourly $PM_{2.5}$ estimates across the city. Landsat 8–derived data products provided maps of vegetation, impervious surfaces, and aerosol density. Weather data were incorporated through the use of NASA's Goddard Earth Observing System-Forward Processing (GEOS-FP) forecasts, and road data from OpenStreetMap helped quantify the contributions of automobile and bus traffic.

The input data were used to estimate real-time $PM_{2.5}$ concentrations on a grid across the city. That grid was then overlaid by a graph with nodes representing street intersections and edges representing the streets themselves. Each edge was assigned a pollution "cost" based on the $PM_{2.5}$ in the grid cells it crosses. The pollution breathed during a journey between two nodes is the sum of the costs of the edges that most efficiently connect them.

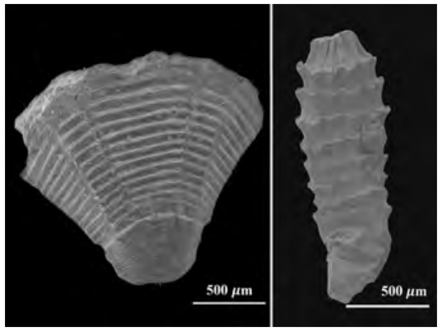
The Hong Kong case study included $PM_{2.5}$ estimates for 70,788 roads. Using the developed app, which is visually similar to commercial mapping apps, a user can find the fastest and healthiest routes between two points. The researchers observed that healthy route planning could reduce $PM_{2.5}$ exposure by 5%–25%. In one highlighted example, the app indicated that choosing a route between two Hong Kong universities that was 100 meters longer than the shortest available route would result in a 5%–10% reduction in breathed pollution.

The researchers note that the generalizability of their approach for estimating high-resolution $PM_{2.5}$ levels means that it may be applicable in other cities and useful in other route planning applications and services to minimize people's pollution exposure. (*GeoHealth*, https://doi.org/10.1029/2022GH000669, 2022) **—Morgan Rehnberg,** *Science Writer*

Fluid Dynamics of Tiny, Ancient Marine Animals

About 536 million years ago, in the early Cambrian period, an abundance of different species of millimeter-scale marine organisms thrived in continental shelf habitats around the world. Today their fossils yield clues to ancient ocean conditions and animal evolution.

Many of these tiny fossils are sedentary medusozoans, a subgroup of the phylum Cnidaria, which now includes free-swimming jellyfish. New research by *Liu et al.* reveals for the first time how the exoskeletal shapes of ancient, minuscule medusozoans may have interacted with flowing water in their marine shelf environment.



A study of specimens of the early Cambrian sedentary medusozoans Hexaconularia *sichuanensis (left) and* Quadrapyrgites quadratacris *(right) points to potential imbalances in the evolutionary fitness of different ancient species. Credit: Ping Liu*

The researchers collected fossils of two species, *Hexaconularia sichuanensis* and *Quadrapyrgites quadratacris*, from the 535-million-year-old Kuanchuanpu Formation in southern Shaanxi Province in China. The fanlike shape of *Hexaconularia* exhibits biradial symmetry, whereas *Quadrapyrgites* is tetraradial.

The researchers used microcomputed tomography data of the fossils to create virtual 3D models of each species, then applied computational fluid dynamics to simulate how the flow of seawater would have dragged and contorted the organisms when they were living. The simulation results suggest that the two species—and most other sedentary, millimeter-scale medusozoans from the same time—likely lived in the viscous flow layer, a less turbulent layer of seawater just above the seafloor. In addition, the biradial shape of *Hexaconularia* proved to be more structurally stable in the simulations than the tetraradial *Quadrapyrgites*, suggesting that *Hexaconularia* may have been better adapted to survive in the strong-flow conditions of the ancient marine shelf.

The findings are in line with fossil records suggesting that tetraradial sedentary medusozoans, as well as those with triradial, pentaradial, or hexaradial symmetry, went extinct about 529 million years ago but that *Hexaconularia* and other biradial medusozoans survived.

This study marks the first application of computational fluid dynamics to early Cambrian microfossils living in the viscous flow layer. The authors suggest that future research could introduce more details into such simulations, such as seafloor roughness and the presence of neighboring organisms, to further explore this ancient medusozoan community. (*Journal of Geophysical Research: Biogeosciences*, https://doi.org/10.1029/2022JG006854, 2022) **—Sarah Stanley,** *Science Writer*

Tracking Water in the Tongan Volcano's Massive Eruption Plume

The 15 January 2022 eruption of underwater Hunga Tonga–Hunga Ha'apai volcano triggered a tsunami that flattened buildings, displaced residents, and resulted in at least four deaths across the islands of Tonga. The powerful blast sent waves rippling throughout Earth's oceans and atmosphere, with tsunami waves causing additional damage and casualties thousands of kilometers away, including two deaths in Peru.

Researchers around the world have been studying and learning from the catastrophic event. Now *Schoeberl et al.* shed light on the fate of a record-breaking amount of water vapor—up to 150 teragrams, or 150 billion kilograms—shot into Earth's stratosphere by the eruption.

The water vapor was part of a huge plume of ash, gas, and steam that at its highest, billowed 58 kilometers into the sky. Months after the eruption, elevated levels of water vapor and sulfur-rich aerosol particles remained layered in the stratosphere.

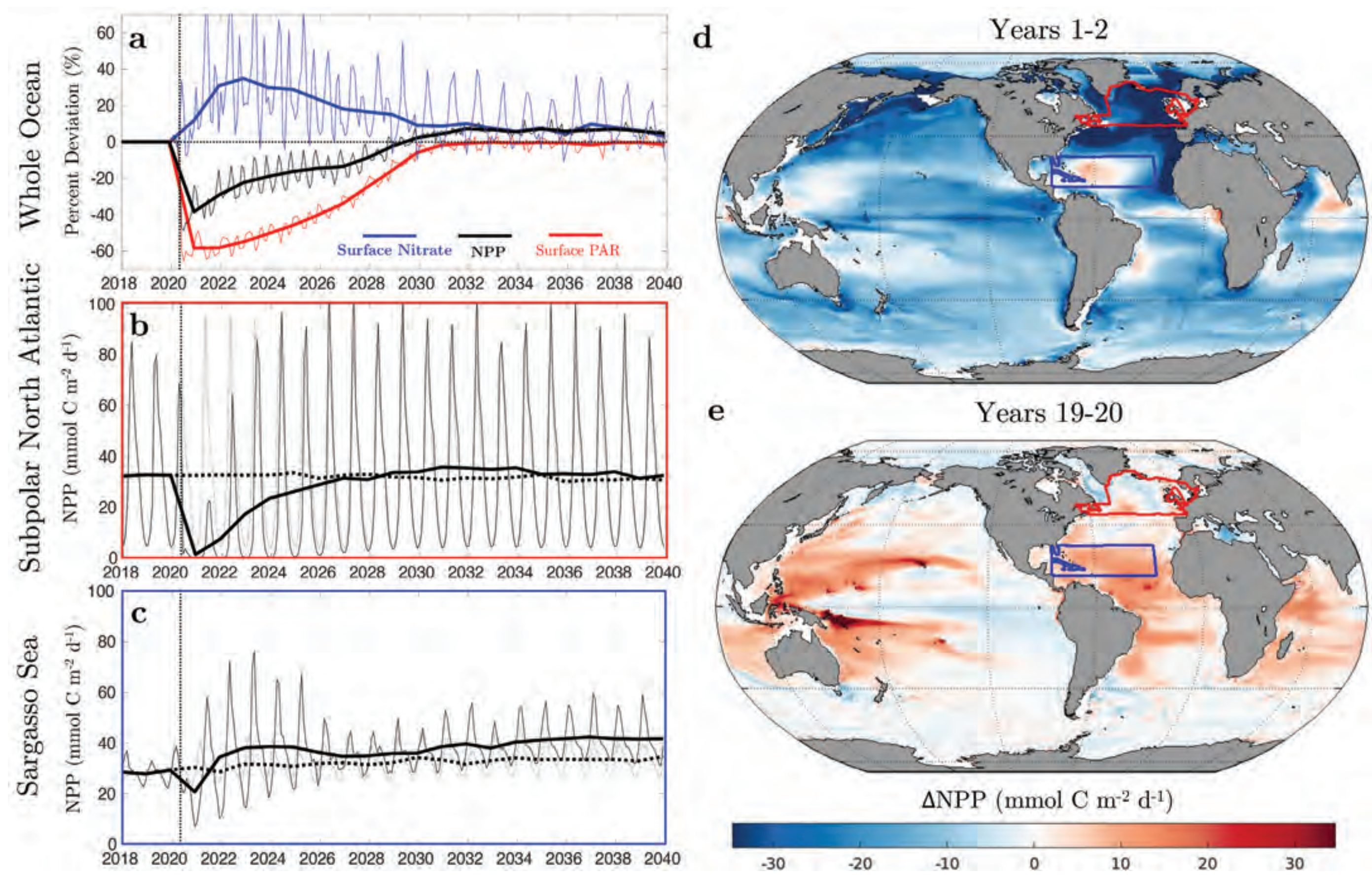
To clarify how these water vapor and aerosol layers formed and evolved over time, the researchers used data collected from 15 January through 1 July 2022 by NASA's Microwave Limb Sounder instrument aboard the Aura satellite. They also developed a model incorporating several factors, including tropical atmospheric temperatures, to simulate the posteruption fate of the water vapor.

Their analysis suggests that after the eruption, the stratospheric water vapor and sulfate aerosols began to separate from each other, forming two distinct but overlapping layers by mid-February. These layers continued to separate through the end of June, with the water vapor rising in a manner consistent with normal upwelling residual velocity and the aerosols settling gravitationally. A surprising result was that the midstratospheric eruption aerosols and water stayed in the Southern Hemisphere for 5.5 months, with very little material moving north of the equator.

The data also revealed the development of an anomalous 3K–4K temperature decrease in the midstratosphere through March and April, which appears to have been caused by the infrared cooling effects of the lofted water vapor.

The researchers suggest that the high altitude of the eruption plume helps explain why other recent volcanic eruptions have not sent nearly as much water vapor into the stratosphere as Hunga Tonga–Hunga Ha'apai did. (*Geophysical Research Letters*, https://doi.org/10.1029/2022GL100248, 2022) **—Sarah Stanley,** *Science Writer*

Long-Lasting Impacts of Nuclear War on the Ocean



Shown here are model-simulated changes in (a) global ocean surface nitrate, net primary production (NPP), and surface photosynthetically active radiation (PAR)—and regional changes in NPP in the (b) subpolar North Atlantic and (c) Sargasso Sea—after a simulated nuclear war in 2020 deposited 150 teragrams of black carbon into the atmosphere (thin and thick curves represent monthly and annual estimates, respectively). The resulting global sea surface cooling and reduction in surface PAR causes a rapid reduction of roughly 50% of NPP in the first few months after the conflict. In some regions such as the subpolar North Atlantic, outlined in red (d and e), NPP collapses completely. Global NPP rebounds after about a decade, but it does not return to the initial, prewar state. Instead, ocean productivity is reorganized, with some tropical and midlatitude regions, such as the Sargasso Sea, outlined in blue (d and e), experiencing higher productivity. Credit: Harrison et al.

As the talk of global leaders during the war in Ukraine reminds us, the threat of a nuclear conflict is real. What consequences would such a war have for life in the ocean? *Harrison et al.* highlight both immediate and long-lasting effects of nuclear war acting through nonlinear responses of the ocean.

The researchers report on results from model simulations they conducted to investigate impacts of nuclear conflicts of different scales, including a large-scale war depositing 150 teragrams (150 billion kilograms) of sunlight-absorbing black carbon into the atmosphere. This largest scenario in the simulations causes a global-scale cooling of sea surface temperature of nearly 6°C. Even though the associated deepening of the mixed layer brings additional nutrients to the surface, the lack of light initially reduced net primary production (NPP) by roughly 50% globally, with some regions experiencing a complete collapse of biological productivity. Global NPP gradually recovers after about a decade, alongside sea surface temperature, but it is shifted compared with prewar conditions, with some regions experiencing higher or lower levels. (https://doi.org/10.1029/2021AV000610, 2022) **—Nicolas Gruber**

Dear AGU:

The White River watershed offers a clear view of its source—the snows of Mount Hood, in Oregon. Montana State University students Behnaz Hosseini (foreground) and Megan Harris walk the drainage looking at both pyroclastic and debris flow deposits.

—**Madison Myers,** assistant professor, Department of Earth Sciences, Montana State University

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