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MeerKAT Spies Milky Way's Heart

Earthquakes in the Ionosphere

INNOVATIONS IN Volcanology

CREATIVE APPROACHES TO STUDYING THE WORLD'S MOST FASCINATING HOTSPOTS

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Myths, Legends, and Buried Hair

When we at *Eos* report on scientific research, we're interested in much more than new results. We are deeply curious—and we think you are too—about how science gets done. What are the clever and creative ways to approach a problem? When it's impossible to collect all the data you originally sought, how can you step back and see the problem in a different light? Or, hey, if you need to get your instrument to the seafloor, what imaginative solution can you come up with to do it simply and safely?

In our May issue of *Eos*, we take a look specifically at innovations in volcanology. We'll start by taking you to Iceland, where Sara Klaasen and her colleagues found a clever way to study Grímsvötn, as they describe in "Sensing Iceland's Most Active Volcano with a 'Buried Hair.'" The team sought to collect high-resolution data on this complex volcano system through distributed acoustic sensing—project DAS-BúmmBúmm. Turn to page 20 to read about their trek to install cables over the glacier-capped volcano, and for some great photos of their badminton tournaments in knee-high snowfields.

We'll then dive to the bottom of the sea with Pascal Pelleau and his team and a seismometer wrapped in a steel cage. Their target of study is volcanic activity near the islands of Mayotte in the Indian Ocean. Pelleau's team wanted to find a better way to get their instruments into position than tipping them overboard and letting the sea have its way with them, and without the enormous cost of a remotely operated vehicle to escort them down. Read more about their "cagey approach" on page 26.

We'll wrap the issue up with some delightful reporting on researchers who are—well, the headline says it all: "Studying Volcanoes Through Myths, Legends, & Other Unconventional Data." Painting, poetry, and oral traditions can fill the gaps left in observations. Learn how climate scientists, geologists, and historians have teamed up to match tree ring data with historical observations of dust veils. These cultural records provide context, suggest alternative causes, and confirm scientific conclusions. Turn to page 32 to learn the answer to a burning question we know you all had: How did the annals of Irish monks help sort out a mismatch of eruption dates and lead to new conclusions about climate events around the world?

Don't miss the excellent opinion on page 16 by Rebecca Haacker and colleagues on "Moving Beyond the Business Case for Diversity," in which they argue that we should pursue inclusive and equitable work spaces in service of our own humanity, not simply of the bottom line. Hear! Hear!

Heather Goss, Editor in Chief

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The Kīlauea Volcano erupts in Hawaii in 2016.
Credit: Mike Mezeul II

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Extracting Rare Earth Elements from Waste with a Flash of Heat

Rare earth elements (REEs) are vital components of everyday life, found in electronics from laptops to solar panels. The United States currently sources most of its rare earth elements from mines controlled by China, but concerns over China's dominance in the market—and the environmental costs of mining—have spurred the U.S. Department of Energy to invest millions of dollars in research into alternative sourcing options.

In a new study published in *Science Advances,* researchers at Rice University presented one promising alternative to mining (bit.ly/REE-waste). They developed a method to extract REEs from an abundant toxic waste product called coal fly ash using a jolt of electricity. By subjecting coal fly ash to extreme heat, they freed up REEs from surrounding elements without the need for harsh, corrosive chemicals. And this "flash Joule heating" method could help extract REEs from other waste materials as well.

"This is a really novel way of improving rare earth element extraction," said Laura Stoy, an environmental engineering researcher specializing in rare earth elements who recently completed a Ph.D. at the Georgia Institute of Technology. Stoy was not involved in the new research. "This method of shocking them into submission, in a way, is very cool."

Rice University chemist James Tour (left) and postdoctoral researcher Bing Deng administer a jolt of electricity to some coal fly ash. The method could be used to turn this powdery waste material into rare earth elements needed for electronic devices. Credit: Jeff Fitlow/Rice University

By subjecting coal fly ash to extreme heat, researchers freed REEs from surrounding elements without the need for harsh, corrosive chemicals.

Tricky to Get, but Essential to Modern Life

Rare earth elements are 17 metals (like neodymium and terbium, commonly used as magnets) that sit toward the bottom of the periodic table. They aren't actually rare—all are more common than gold—but they tend to be mixed up together in Earth's crust in low volumes, and extracting them traditionally requires harsh chemicals. REEs are also typically intermingled with their radioactive neighbors on the periodic table, uranium and thorium.

Between the extracting chemicals and the toxic waste, REE mining "turns out to be an environmental disaster," said James Tour, an organic chemist at Rice University and an author of the study.

As a result of the environmental challenge, the U.S. government stopped issuing permits for domestic REE mines years ago, Tour explained. China, meanwhile, ramped up production in the 1990s and came to dominate the market. For the past several years, the U.S. Department of Energy has been investing in research projects to find better ways to extract REEs from alternative sources, like acid mine drainage and coal fly ash.

Coal fly ash could be a particularly valuable source of REEs because the United States has "literal mountains" of this waste material, Tour said. Extracting rare earth elements could be a way both to reduce fly ash waste and to source REEs in a less destructive manner, but the trick is finding a way to access the elements safely and affordably.

From Waste to Treasure Trove in a Flash

Extracting rare earth elements from coal fly ash isn't a straightforward task, as coal ash particles have already "been through hell" in the combustion chamber, Stoy explained. So far, the only way to pull REEs out of coal fly ash is with strong chemical treatments. But this process, in itself, produces toxic waste.

Tour's team developed a way to reduce the chemicals needed for extraction by first treating the fly ash powder with heat. Rare earth elements in coal fly ash are trapped in microscopic glass particles that acids have a hard time breaking through, Tour explained. But just as your icy windshield will crack if you try to heat it up too fast, the ash's glass particles will crack when subjected to a sudden and intense heat change.

Flash Joule heating is a method Tour and his colleagues developed several years ago to produce graphene from a carbon source. "We

An electric current heated coal fly ash to 3,000°C in 1 second, shattering the glass and allowing for fairly easy extraction of the REEs.

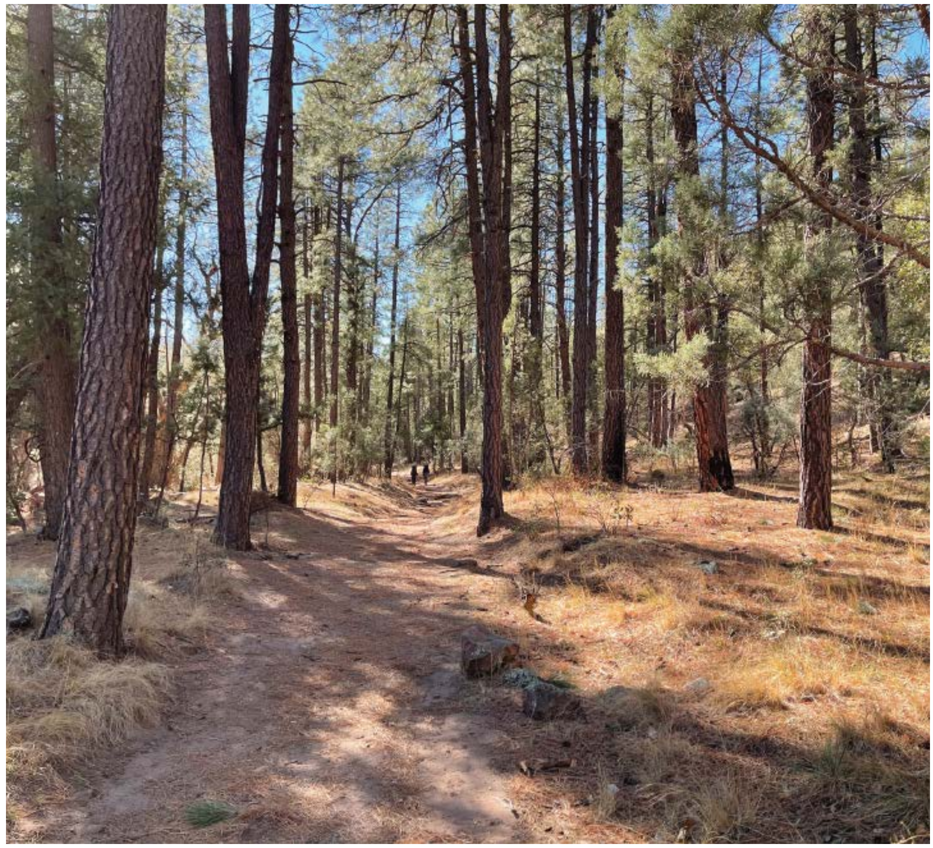
just thought, let's give it a try with fly ash," Tour said. To test their technique, the team members mixed fly ash with a material called carbon black to improve its conductivity, and put the powder mixture into a small tube with capacitors on either end. An electric current heated the ash to 3,000°C in 1 second, shattering the glass particles.

After the heat shock, the rare earth elements were in a more accessible state and could be extracted with an acid treatment so mild "you could practically drink [it]," Tour said. The researchers found that they were able to get nearly twice as much product as they could without the heat treatment. They also tested the strategy on an industrial waste known as red mud, with similarly promising results. The process seems like it could be economically viable: It requires only about $12 worth of electricity per ton of waste product.

"This paper is a good step in the direction of using fewer chemicals," Stoy said, but she cautioned that it would still produce some waste. "I would really like to see this become a closed loop," she said.

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

Tree Carbon Data That Ring True



Tree ring data combined with forest inventories showed that ponderosa pine forests in Arizona will absorb less carbon as climate warms. Credit: Richard N. Horne/Wikimedia Commons, CC BY-SA 4.0 (bit.ly/ccbysa4-0)

Forests around the world pull carbon out of the atmosphere and are crucial in the global fight to stem climate change. But figuring out how much carbon forests are storing as the planet heats up is tricky. For instance, many countries don't have a direct, systematic, and timely method for measuring how factors like drought or intense periods of rainfall might influence a forest's carbon uptake.

But now a team of international researchers has published a study that puts forth a solution for acquiring these data: gather tree ring cores from live trees in national forests (bit.ly/national-forest-trees). "Tree rings really have this remarkable annual resolution data," said Margaret Evans, a dendrochronologist at the University of Arizona's Laboratory of Tree-Ring Research who coled the study with Justin DeRose, a forest ecologist at Utah State University. "You get this decade or even century scale of the entire life span of the tree and its response to interannual climate variability and conditions."

The easiest way to collect these data, Evans and DeRose note in the study, is to include tree ring sampling in existing national forest inventory programs. The inclusion would require minimal additional investment because the cost of revisiting inventory plots is already built into the programs' budgets. And at least in North America, the foundation for such a network already exists in the form of legacy collections, totaling at least 405,092 cores from across Canada, Mexico, and the United States.

National forest inventories like the U.S. Forest Service's Forest Inventory and Analysis (FIA) program can give a broad idea of how much carbon forests absorb. But, Evans said, because such inventories are conducted only every 5–10 years, they miss many of the nuances that are becoming more important as the planet heats up. “If you only have measurements every 10 years,” she explained, “then you can’t figure out whether a particular heat wave negatively affected the forest ecosystem functioning and its carbon emissions and removals.”

“Forests are always growing. They’re dynamic,” DeRose added. “Trees grow and die; disturbances are a natural part of the system. Then you lay this increasing temperature trend on top of that, and it really complicates things. And it certainly complicates our understanding of what happens in these systems.”

Kristina Anderson-Teixeira, a forest ecologist with the Smithsonian Conservation Biology Institute and the Smithsonian Tropical Research Institute who was not involved in the research, praised the study and spoke highly of the authors’ idea to combine the two data sources (tree rings and FIA) to better understand forest climate dynamics. “There is so much potential to do more work combining tree ring research with forest ecology,” she said. “This would be a really, really good thing to do.”

Anderson-Teixeira pointed out that the framework would not work for tropical forests, however. Unlike the trees in temperate forests, which have annual periods of growth and dormancy (reflected in the alternating light and dark rings in their core), tropical trees grow year-round and do not make such rings. “So [combining dendrochronology with forest ecology is] a partial solution—it’s not going to completely answer the question” about carbon uptake in forests, Anderson-Teixeira said. “But getting this information for one continent is huge. It’s important.”

From Squishy to Solid Data

DeRose and Evans said that because tree ring data are a direct method of measuring a tree’s carbon intake, having this information would greatly improve the ability of countries to report greenhouse gas emissions and removals as required by the Paris Agreement and other international treaties. Right now, they said, scientists have to infer how much carbon sequestration is happening in forests by looking at things like fossil fuel combustion, measurements of carbon in the atmosphere, and measurements of ocean acidity levels. “It’s squishy,” said Evans.

“Forests are always growing. They’re dynamic. Trees grow and die; disturbances are a natural part of the system. Then you lay this increasing temperature trend on top of that, and it really complicates things.”

Tree core data would also sharpen models that scientists use to try to predict forest ecosystem behavior under climate warming, because researchers could compare their predictions with the annual observations in the tree rings and make adjustments. “You can look at it and say, ‘OK, where did my model go wrong? What hints does it give in terms of how my model could be improved?’” said Evans. “That’s how science marches forward.”

A recent study that Evans coauthored with Kelly Heilman, a postdoctoral research associate also at the Laboratory of Tree-Ring Research, shows how integrating the two data sources can help with forest management. Evans, Heilman, and their colleagues combined tree ring data with FIA data on Arizona’s ponderosa pines and were able to infer the size of the trees each year and see how they responded to such climate variables as rainfall and temperature.

The study predicts a 56%–91% decline in individual tree growth under future climate scenarios. It also shows that denser ponderosa forests fare worse when it’s hotter and drier—which has implications for forest managers, who could mitigate some climate stress on forests by thinning them. “If you have both an overly dense forest and climate warming happening at the same time, that’s a double whammy. But if you thin the forests, you can remove one source of stress,” said Evans.

By **Nancy Averett** (@nancyaverett), Science Writer

Black Neighborhoods Will Bear Future Flood Burden

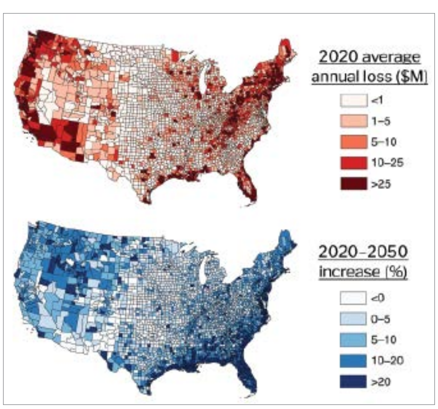
Residents of New Orleans are no strangers to floods and the losses that follow. From Katrina in 2005 to Ida in 2021, Gulf Coast hurricanes have cost the people of New Orleans hundreds of billions of dollars over the past 20 years, in addition to the loss of culturally rich historical sites and irreplaceable lives.

The Maldonado family travels by boat to their home after it flooded during Hurricane Ida on 31 August 2021 in Barataria, La. Credit: Brandon Bell/Getty Images News via Getty Images

No one knows this loss better than the people who live in and work with New Orleans communities. Jeff Supak is executive director of Water Wise Gulf South, a collective of community organizations in New Orleans that aims to prevent flood losses in their neighborhoods through green infrastructure. "The communities that we work in are low-lying, [are] prone to chronic flooding, and are majority Black," he said. "Climate change and a poorly maintained gray infrastructure system are wreaking havoc in these communities and will continue to do so unless change happens."

Current U.S. flood risk maps, which show regions of the country that are likely to sustain future damages from floods, are based on historical records of where flooding has occurred. But according to a recent *Nature Climate Change* study, those maps fail to account for the increasing threat of climate change, projected population changes, and infrastructure development (bit.ly/inequitable-flooding).

When those factors are accounted for, the new flood risk maps paint a stark picture: By 2050, annual U.S. flood losses are predicted to rise to $40.6 billion from today's $32.1 billion, and that increased loss will not be borne equally by all. Urban and rural areas with predominantly Black communities will see at least a 20% increase in flood risk, whereas majority white regions will see little to no change in their risk. What's more, areas with lower-income populations will continue to face more risk than affluent ones.



These county-level maps show the current average annual loss due to flooding in the contiguous United States in millions of U.S. dollars (top) and how those costs are projected to change by 2050 (bottom). Darker colors indicate a higher cost (top, red) or a greater increase in cost (bottom, blue). Credit: Fathom; Wing et al., 2022, https://doi.org/10.1038/s41558-021-01265-6, CC BY 4.0 (bit.ly/ccby4-0)

"Climate change combined with shifting populations presents a double whammy of flood risk danger," Oliver Wing, lead researcher on the study, said in a statement (bit.ly/Oliver-Wing). "The mapping clearly indicates Black communities will be disproportionately affected in a warming world, in addition to the poorer white communities which predominantly bear the historical risk." Wing is a geographer and chief research officer at Fathom Global in Bristol, U.K.

Inequitable Flood Loss Risk

Wing and his team created their projected flood loss maps under the modest Representative Concentration Pathway (RCP) 4.5 climate change scenario outlined by the Intergovernmental Panel on Climate Change, which predicts climate patterns if emissions peak in 2040 and then decline. They analyzed those data in concert with population and demographic shifts projected by the U.S. Census Bureau as well as with building and infrastructure data from the U.S. Army Corps of Engineers. Combined, these data sets allowed the researchers to predict where people are likely to live in 2050, where infrastructure is likely to develop, and where flooding (and associated damage) is likely to occur.

"If we want to understand flood risk in the future," Wing told ABC News, "the most important thing is understanding where people are going to live, more so than how weather patterns are changing."

"Climate change combined with shifting populations presents a double whammy of flood risk danger."

Under RCP 4.5, the United States will incur an additional $8.5 billion in losses from flooding in 2050, a 26.4% increase over 2020 values. Compared with regions that experience flooding losses today, future losses will be concentrated along the Gulf Coast and the Atlantic Coast north to New Jersey, whereas Appalachia and the West Coast will feel a reprieve from flood losses.

When the researchers cross-referenced the projected flood risk maps with projected demographic data for those areas, it became clear that the burden of future flood loss would not be borne equally by people of all races and economic strata. Today, impoverished white populations face the greatest flood loss risk, but by 2050 that burden is projected to shift to rural and urban Black communities, especially poorer ones, from Texas through Florida and up to Virginia.

"That raises very important social justice implications for how we ensure that the policies to deal with this address this quite severe inequity," Wing said, adding in a separate interview that "what we're seeing is that those with the least capacity to respond to these disasters are being asked to shoulder the burden. That's just fundamentally wrong."

Can't Afford to Wait

In New Orleans, one of the regions projected to bear even more flood-related loss in the future, Black communities are already working to protect their neighborhoods. "To date," Supak said, "we have installed over 160 green infrastructure installations that manage up to 100,000 gallons of stormwater per rain event, and we have planted over 500 trees to combat the urban heat island effect." The Water Wise collective has also created a network of more than 100 neighborhood leaders "advocating for more green infrastructure in their communities," comprehensive lists of green infrastructure priorities for their neighborhoods, and policy initiatives to implement them. A recent report estimated that these projects will bring up to $17.8 million annually in ecosystem services (bit.ly/green-projects-NOLA).

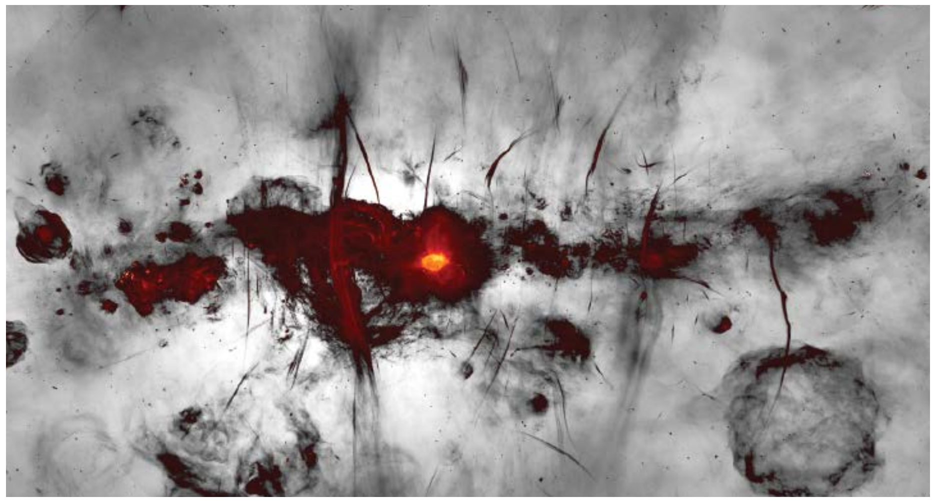
Wing and his colleagues hope that their updated maps will be used by communities and federal programs to move development away from risk-prone areas and inform equitable flood adaptation policies.

But some communities of Black, Indigenous, and People of Color (BIPOC) already feel the urgency to protect their homes and neighbors. "BIPOC communities must become engaged and educated about the risks of climate change," said Angela Chalk, executive director of Healthy Community Services, which is part of the Water Wise collective. Chalk is also an AGU Community Science Fellow.

"Community organizations across this country are becoming empowered to assist residents to make strategic adaptation measures," said Chalk. "BIPOC can no longer afford to wait for government's slow response. Community-led actions will change behaviors as well as expectations from large corporations and government."

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

With MeerKAT, Astronomers Peer at the Possibilities of Radio Imaging



This image from South Africa's MeerKAT radio telescope is a mosaic of 20 different observations. Colors indicate bright radio emissions, and fainter emissions are shown in gray scale. Credit: I. Heywood, SARAO

Between May and June 2018, the MeerKAT radio telescope observed the center of the Milky Way using 64 antennas located in the Karoo region of South Africa. After more than 200 hours of observations and 3 years of data analysis, the South African Radio Astronomy Observatory (SARAO) released spectacular images of the region near the supermassive black hole in the center of our galaxy, 25,000 light-years from Earth.

Ian Heywood, a senior researcher at the University of Oxford who led the team that analyzed the data, explained that the galactic center was chosen to demonstrate the possibilities of MeerKAT because the region "is a notoriously difficult part of the sky to image at radio wavelengths, because of the very bright emission and complicated structure.... I think it's fair to say the results exceeded everyone's expectations."

From Static to Startling Images

Radio astronomy is still emerging from its infancy. Just 90 years before MeerKAT became operational, radio engineer Karl Jansky built a 30-meter antenna while working for Bell Telephone Laboratories in New Jersey. He had been commissioned to find the cause of static in transatlantic telephone calls—and found that the radio interference came from outer space. At the time, astronomers did not pay much attention to his work. For Heywood, the first radio astronomer who made an impact was Grote Reber, who illustrated the possibilities of radio astronomy by mapping cosmic radio sources in the galaxy in 1968.

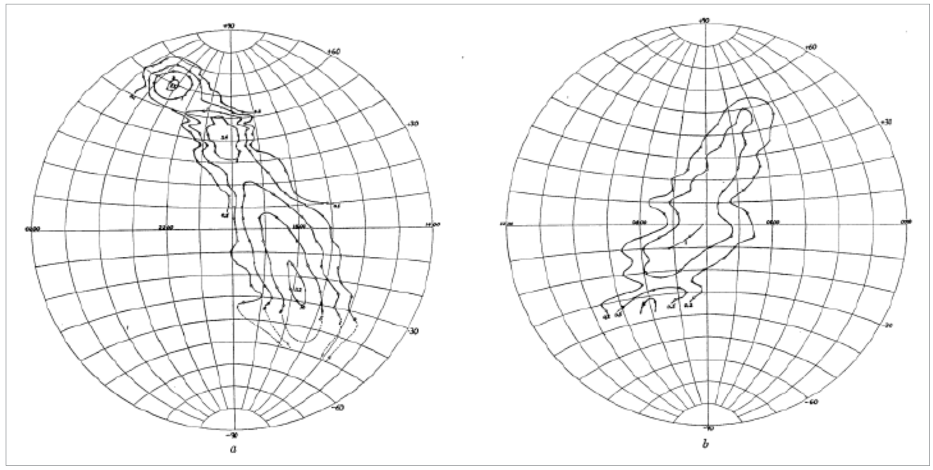
"Leaps and bounds" is how Emily Rice, an associate professor at Macaulay Honors College at the City University of New York, described current advancements in radio astronomy. "The angular resolution is so amazing, the sensitivity is so amazing," she added, "that we can turn [radio frequencies] into actual pictures."

> **"I think it's fair to say the results exceeded everyone's expectations."**

With new and more powerful radio telescopes, however, there is a need for more efficient ways to process the huge volumes of data, as well as for better calibration and imaging algorithms. Observations from MeerKAT to the galactic center produced about 2 terabytes (2,000 gigabytes) of data per day, and there are other observations at MeerKAT that produce even more data, said

Fernando Camilo, chief scientist of SARAO. (In comparison, the Hubble Space Telescope produces about 140 gigabytes of data per week.)

"Necessity is the mother of invention… [and] many novel developments in this area are being led by South African scientists," said Heywood. One of these scientists is Isabella Rammala, a Ph.D. student at the Rhodes Centre for Radio Astronomy Techniques and Technologies at Rhodes University in Makhanda, South Africa. Rammala is interested in identifying pulsar candidates in the galactic center imaged by MeerKAT. "I spent most of my time on my computer writing code," she explained, "processing the images or cleaning the data…removing things like radio interference and correcting for instrumental effects and sky effects."



This first radio map of the sky was created by American astronomer Grote Reber in 1944. Credit: Grote Reber, NRAO/AUI/NSF

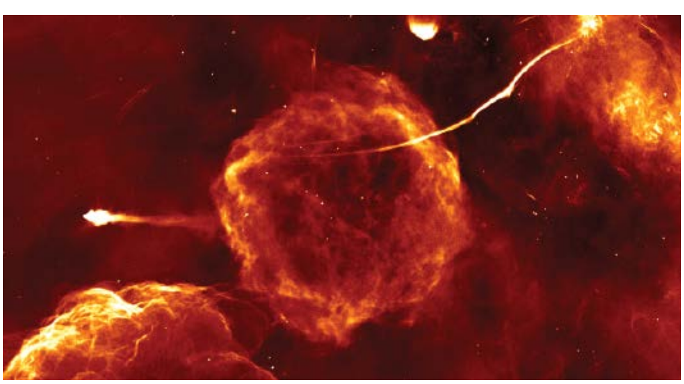
Radio Emissions from Stars and Exoplanets

Radio astronomy offers several technical and practical benefits to scientists. Its observations are not obscured by interstellar gas or dust, sunlight, or anomalies in Earth's own atmosphere. This means that unlike optical telescopes, radio telescopes can be built at sea level and observations can be made both night and day. For Rammala, studying the universe in multiple wavelengths such as radio, infrared, and gamma ray "gives us somewhat of a complete picture of what is going on."

Jackie Villadsen is a visiting assistant professor at Vassar College in New York and an astrophysicist who uses radio astronomy to study nearby stars and their interactions with planets. She said observing the universe with different types of wavelengths reveals "vastly different pictures.… Radio waves are good for studying extremes, high-energy processes, and very large objects."

According to Villadsen, new and more powerful radio telescopes with better imaging capabilities "will help [astronomers] see analogues to the Sun and Jupiter in exoplanetary systems." For example, coronal mass ejections (CMEs) are fairly easy to detect with radio astronomy. Flares can strip away an atmosphere and bake a planet's surface, and red dwarf stars, many of which likely have small, rocky planets, have a higher flare rate than the Sun. "Detecting stellar CMEs with radio telescopes will help astronomers determine whether planets around red dwarfs are habitable or friendly to life as we know it," said Villadsen.

In addition, astronomers hope to detect radio bursts produced by the aurorae of exoplanets, similar to those produced by aurorae on Jupiter. Detecting these radio waves will permit scientists to determine a planet's magnetic field strength, which "would reveal information about a planet's interior structure and how well it can hold on to its atmosphere when it's blasted by material from the star. This might even become a method for detecting new exoplanets," added Villadsen.



In the center of this image from MeerKAT is supernova remnant G359.1-0.5. At left is "the Mouse," a runaway pulsar possibly formed and ejected by the supernova event. At upper right is one of the longest and most famous radio filaments, known as "the Snake." Credit: I. Heywood, SARAO

Right now, "it's something of a golden age for radio astronomy."

Supporting Local Science

For Rice, "there's always going to be technological advancements," but the most important aspect of the development of modern radio telescopes is the effect they have in the communities in which they're located. For example, when MeerKAT made a call for open-time observation proposals in 2020, more than a third of the proposals accepted through a dual anonymous review process were from South African researchers.

According to Camilo, around 10% of SARAO's yearly budget goes to scholarships and grants to support human capital and development—from science projects in a high school in a town near the telescope to Ph.D. fellowships to more public support for radio astronomy in South Africa.

Right now, "it's something of a golden age for radio astronomy," added Heywood.

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

Lipids from Europa's Ocean Could Be Detectable on the Surface

Astrobiologists Gordon Osinski of the University of Western Ontario and Mark Fox-Powell of the Open University in the United Kingdom explore Lost Hammer spring on Axel Heiberg Island in the Canadian Arctic. Credit: Mark Fox-Powell

Jupiter's moon Europa is often lauded as one of the most promising destinations in the search for life outside Earth. Its global subsurface ocean, filled with mineral-rich salts and shielded from harmful irradiation by an icy shell, means that microbial life could flourish in its watery depths. Europa will be visited by two upcoming missions, Europa Clipper from NASA and Jupiter Icy Moons Explorer (JUICE) from the European Space Agency, both of which seek to pinpoint areas where future landers might search for life.

"We can so far say that sulfate salts might be a good target to look for organics."

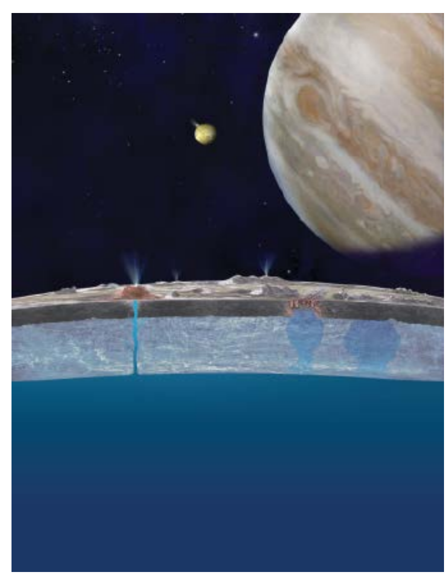
But any hypothesized life would be hidden within the ice-capped ocean and shielded from view. So how, then, could these spacecraft possibly find signs of life? New research found that if a geyser or other cryovolcanic feature brings ocean water up to the surface, any microbes within that water could be preserved as the water freezes on the surface. The organics could then precipitate out with the salts and minerals and be detectable by passing spacecraft.

From the Arctic to Europa

Planetary scientists still actively debate whether cryovolcanism—a process in which cold liquids underground migrate to the surface of a planetary body and freeze—exists on Europa. Strangely smooth patches of the moon's surface in some images from the Galileo spacecraft in the 1990s suggest freshly deposited material, and Hubble Space Telescope images from a few years ago hint at geyser-like plumes (although nothing as dramatic as those on Enceladus). Scientists also speculated that cracks in Europa's icy shell could let some ocean water escape to the surface through fissures, like mid-ocean ridges on Earth.

Any salty ocean water that reaches Europa's surface would freeze almost instantly. What would that do to biosignatures of microbial life? Past experiments have shown that when silica-rich hydrothermal fluids freeze, the minerals that the freezing process creates can trap microorganisms within them. Salts, too, can capture organics within their lattice. Those organics then precipitate out of the frozen liquid, after which scientists can detect them. But could this process work with the types of salts that are common on Europa?

Researchers went to the Canadian Arctic to find out. In 2017, they collected samples from the hypersaline Lost Hammer spring on Axel Heiberg Island. "The Lost Hammer spring is very unique, as it is anoxic, has below-zero temperatures, and [has] extremely high concentrations of sulfate and chloride—supersalty and extreme conditions," said lead researcher Arola Moreras-Marti, an astrobiologist at the University of St Andrews in the United Kingdom. The spring's salt deposits are made of "hydrated sodium sulfate and chloride, and



This illustration shows what cryovolcanism on Europa might look like. It could manifest as an effusive geyser or as a more understated fissure in the ground that connects the ice-capped ocean with the surface. Credit: NASA/JPL-Caltech, Public Domain they showed similar composition and also absorption features as Europa's nonicy materials measured by the Galileo spacecraft."

That makes Lost Hammer a great place to test what would happen to microbial life caught in a cryovolcanic eruption on Europa. The researchers tested 18 salt deposit samples from the spring by heating them and using a mass spectrometer to study the resulting gas—similar to what could be done by a lander. They also analyzed lipid biomarkers, measuring how much and which types of organic lipids they could detect within the salt deposits.

"The organic biomarker results...indicate the organics are mainly of microbial origin," Moreras-Marti said. Further analysis showed "that these organics are trapped inside the sulfate salts. This is particularly interesting, as the salts could protect the organics from oxidation, allowing for a better preservation [on Europa]." Moreras-Marti presented these preliminary results at the 2022 Lunar and Planetary Science Conference (bit.ly/Moreras-Marti).

What's in a Map

"I certainly find the idea intriguing," said Michael Brown, a planetary scientist at the California Institute of Technology in Pasadena. "Europa has several (at least) major different regions of surface composition, and trying to tease out which of these would be the best for preserving organic signatures is going to be quite important for understanding where to, eventually, land on Europa. I think their overall hypothesis—that crystallizing salts can capture and perhaps preserve organics—could be an important insight worth pursuing further." Brown was not involved with this research.

"These results from Lost Hammer will inform both future missions Europa Clipper and JUICE about how organic biomarkers are preserved in nonicy materials that have similar mineralogy to Europa's surface," Moreras-Marti said. Both missions seek to map the composition of Europa's surface, and results like these will help scientists interpret the maps and pinpoint areas more likely to contain evidence of life. Future Europa lander missions could then explore those areas. "We can so far say that sulfate salts might be a good target to look for organics."

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

Searching for Earthquakes in the Ionosphere

A magnitude 7.2 earthquake damaged roads across northwestern Mexico and Southern California, like this one in Calexico, when it struck on 4 April 2010. Credit: Adam DuBrowa/FEMA

In 2010, at 40 minutes past 3:00 in the afternoon on 4 April—Easter Sunday—northwestern Mexico started to shake. A magnitude 7.2 earthquake was rattling the Baja California region, ultimately causing three deaths and more than 100 injuries. The quake caused widespread damage in the border cities of Mexicali, Mexico, and Calexico. and made skyscrapers sway in San Diego, more than 160 kilometers west.

The earthquake sent waves through the ground around it, but high in the atmosphere, a very different sort of perturbation might have offered a forewarning of the earthquake's impending arrival, had anyone been able to see it. Subtle fluctuations in Earth's ionosphere, a region of charged particles high above the surface, preceded the Baja earthquake, said the authors of a new paper published in *Advances in Space Research*. Somehow, the fault that caused the earthquake may have been telegraphing its impending rupture, sending out a rush of electrically charged particles that resonated in the ionosphere (bit.ly/ionosphere-Baja).

The ionosphere, which begins about 48 kilometers above Earth's surface and stretches to around 965 kilometers in altitude, is where incoming energy from the Sun ionizes molecules in the atmosphere, knocking off electrons. The abundance of charged particles means the ionosphere reacts to electric and magnetic fields, something other regions of the atmosphere generally do not do.

The electron spike was located over the earthquake's epicenter, and it didn't look like anything else they'd seen in the data.

Using data from the Massachusetts Institute of Technology's Haystack Observatory on the density of electrons in the ionosphere, a team of Chinese and U.S. researchers analyzed the atmosphere above the Baja California region for 72 days both before and after the earthquake. After controlling for other things that might have been affecting the ionosphere, they said they saw a clear anomaly—a spike in the number of ionospheric electrons—on 25 March, 10 days before the earthquake. The electron spike was located over the earthquake's epicenter, and it didn't look like anything else they'd seen in the data.

We can imagine it to be something like ripples in a lake, said Chen Zhou, a researcher at Wuhan University in China and a coauthor of the paper. The electron signal looked like a brief but telling redistribution of particles from their normal movements and positions, one researchers were able to catch as it went by.

Zhou and his colleagues said their work could support a theory that faults release electrical energy in the days leading up to an earthquake. How exactly this happens isn't clear—some scientists think it's the result of radon gas released by a fault ionizing air molecules, whereas others hold that rocks under stress can release bursts of electrons.

Ripples in the Atmosphere

Scientists have been trying for decades to tie disruptions in the ionosphere to earthquakes. One day, the technique might even give scientists a way to reliably predict earthquakes days before they happen, something impossible today. A number of papers have claimed to find links between rupturing faults and the ionosphere, though the theory has also attracted its fair share of criticism.

Much of the criticism centers on the fact that the ionosphere is a noisy place, statistically speaking. Everything from solar radiation to air currents to the changing seasons leaves an imprint on the ionosphere, and it's extremely difficult amid the clamor to pick out any correlation between things near Earth's surface and an ionospheric disturbance.

We can imagine it to be something like ripples in a lake.

"The biggest problem is that [the ionosphere] is so variable that sometimes the signal due to coupling with the lithosphere could be very tiny," said Angelo De Santis, a geophysicist and director of research at the National Institute of Geophysics and Volcanology in Italy. "So you have to analyze with statistical tools to be sure the correlation you find is robust."

But the choice of which statistical tools to use can make a big difference. On that note, De Santis said he's not entirely convinced by the Baja quake paper. The authors' choice of equations may not have been nuanced enough to fully isolate the anomalies they were looking for, he said, and their choice of the mean, rather than the median, to calculate the baseline may have skewed their results.

Zhou is well aware of the difficulties of processing data from the ionosphere. "We need to be very careful about our data processing. We need to develop some very elegant algorithms to derive the very short, but certain, characteristics of these earthquake signals," he said.

Challenging Detections

Our data and knowledge may not yet be good enough to pinpoint disturbances in the ionosphere related to just one earthquake. In a similar study published in 2019, De Santis and his coauthors looked at more than 1,300 earthquakes from around the world (bit.ly/ionosphere-earthquakes). They tied similar ionospheric disturbances to earthquakes, but that work took a broader approach that was less likely to get fooled by false signals.

Another way to make earthquake hunting more precise, said De Santis, is to use more than one type of signal. Things like fluctuations in the magnetosphere, which lies above the ionosphere; seismic activity; and even ground temperature can also presage earthquakes.

It's something Zhou acknowledged as well. "The ionosphere is not the only means of prediction," he said. "We need to use all kinds of data, all kinds of monitoring."

By **Nathaniel Scharping** (@nathanielscharp), Science Writer

Did Volcanoes Accelerate the Fall of Chinese Dynasties?

The history of imperial China stretches back at least 4,000 years, from the legendary Xia dynasty established by Yu the Great. Numerous dynasties followed the Xia, claiming a "mandate of heaven" after periods of warfare. Researchers in China, Europe, and the United States, however, have found that volcanic eruptions (as well as conflict) may have contributed to dynastic collapse because they cooled the climate and affected agricultural production.

This section of the "Departure Herald" handscroll depicts horsemen traveling outside Beijing with the Xuande Emperor of the Ming Dynasty. Credit: National Palace Museum (Taiwan)

Not Just Coincidence

Cooler land temperatures caused by sunlight-blocking clouds of sulfuric acid can weaken monsoon rains, cutting crop yields. In a study published in *Communications Earth and Environment,* the researchers described how they analyzed ice cores to compare evidence of explosive volcanic activity with events in Chinese history (bit.ly/eruptions-dynasties). They determined that dynastic collapse was more likely in the years following volcanic eruptions, but the effect was especially pronounced with preexisting conflict.

"These results for the first time confirm a repeated and systematic role for volcanic climatic shocks as causal agents in the collapse of successive dynasties in one of the world's most populous and long-lasting civilizations, using the most complete and robust list of collapse dates yet compiled," they write.

The finding may sound counterintuitive because China has had few volcanoes active in recent history. Most of the volcanoes in the period studied were not active in China itself, however, researchers believed. Instead, they said that volcanic activity in Indonesia and the Philippines significantly affected temperature and rainfall in China.

Study coauthor Chaochao Gao, an associate professor in the Department of Environmental Science at Zhejiang University in China, realized that many dynastic changes had happened around the time of big eruptions, so she and her collaborators set out to see whether there was a link.

To unravel any relationship between volcanism and political events, they examined ice cores from sites in Greenland and Antarctica and looked for spikes in sulfur levels relative to background levels; the more sulfate, the greater the potential for a larger climate impact. Aided by work on a new ice chronology by coauthor Michael Sigl of the University of Bern's Physics Institute, they teased out 158 eruptions from 1 CE to 1915, a few years after the fall of the Qing dynasty (China's last), and found a pattern.

"In some of our previous and ongoing studies, we found that severe drought or flood, frost damage, [and] locust and plague outbreaks occurred in the posteruption years," said Gao. "We also found significant influence of volcanic eruptions on ENSO [El Niño–Southern Oscillation] variations, which feed back to modulate monsoon climate, which is essential for Chinese agriculture. Other studies had established links between severe weather generally and major societal stresses in China, and some had even connected specific volcanic eruptions to specific cases of dynastic collapse, such as the eruption of Mount Parker in the Philippines in 1641 and the collapse of the great Ming dynasty in 1644, though the eruption certainly didn't act alone."

Social Unrest and Climate Change

One challenge in the research was grappling with the question of why some major volcanic events, such as the massive 1815 eruption of Mount Tambora in Indonesia, did not correspond with dynastic change, whereas more moderate events (when combined with warfare) did.

"What we found was that collapses could follow small to moderate eruptions when instability was already high," said coauthor Francis Ludlow, an associate professor of history at Trinity College Dublin. "In this case you might think of the volcanic climatic shock acting as the ultimate cause of collapse, more or less as a final nail in the coffin. But larger eruptions might precede collapse even when preexisting instability was low. This suggested that these events could have enough of an impact to be thought of as more fundamental proximate causes of collapse."

"I believe that explosive volcanism might occur at any time, including [during] the flourishing age of a dynasty," said Fan Ka Wai, an associate professor in the Department of Chinese and History at City University of Hong Kong who was not involved in the study. "I do not believe that each explosive volcano would have an impact on the fall of a dynasty."

China's dynasties may be long gone, but the team's findings are relevant today in that they come at a time of both increasing social unrest and climate change.

"In the 20th and (so far) 21st centuries, we have been lucky to avoid facing eruptions of the size faced by many Chinese dynasties over the past 2 millennia," said Ludlow. "But the next big one can happen at any time, and we are also likely to be increasing the probability of extreme weather from anthropogenic climate change. How much chronic socioeconomic instability and inequality we wish to tolerate will strongly influence the level of impact these events will have. Ultimately, it is up to us to determine how prepared we wish to be."

By **Tim Hornyak** (@robotopia), Science Writer

Moving Beyond the Business Case for Diversity

Over the past few years, efforts to elevate diversity, equity, inclusion, and justice (DEIJ) in the geosciences have thankfully gained momentum as these imperatives are more broadly discussed in academic and research circles, the private sector, and professional societies like AGU. In many cases, institutions have adopted initiatives and created programs focused on DEIJ that are guided by mission statements espousing commitments to do better. These statements, which distill institutions' motivations for pursuing DEIJ, vary in their phrasing but almost universally revolve around a similar theme.

Beginning in the 1960s, proponents of efforts to diversify and broaden participation in academia, government, and private industry mostly focused on complying with affirmative action measures. These measures were spelled out in President John F. Kennedy's Executive Order 10925 in 1961 and the Civil Rights Act of 1964, which looked to ensure that employers treated people "without regard to their race, creed, color, or national origin" and to ban employment discrimination based on those attributes.

Since those early days of affirmative action, the primary reasoning of companies and institutions of higher education or research has evolved into what is often referred to as the business case, or the instrumental rationale, for diversity [*Starck et al.*, 2021]. This rationale makes the argument, correctly, that a variety of perspectives and backgrounds improves the quality of research, contributes to solving big scientific challenges, helps institutions attract more students and scientists, and improves employee happiness, among other benefits. Such justifications have been necessary to convince institutional leaders to buy in to the idea of investing in and supporting measures meant to broaden diversity and inclusion. And as the business case for diversity has gained popularity, we have seen references to it multiply, appearing in countless scholarly papers, on institutional websites, and in funding solicitations and subsequent grant proposals.

We found that nearly all of the diversity statements focused solely or primarily on the business case.

The business case for diversity may thus seem sound. But it is not enough and is potentially even harmful. Put another way, it is inappropriate as the driving motivation for DEIJ work because it fails to acknowledge the paramount moral rationales for this work; more important, it can create unintended negative impacts, particularly for students and scholars who identify as Black, Indigenous, and People of Color (BIPOC) and for other marginalized groups. We therefore argue that institutions should reframe their views of DEIJ and their approaches to diversify their institutions.

The Widespread Use of the Business Case

A study by *Starck et al.* [2021] examined both instrumental and moral rationales for diversity in U.S. universities and how different populations reacted to the different arguments. The researchers found that the business case is the most commonly applied argument for diversity efforts in higher education. Further, they found that white students and their parents reacted positively to those arguments, whereas Black students and their parents preferred moral arguments for diversity.

The *Starck et al.* [2021] study inspired us to conduct an extensive review of diversity statements from all 42 Federally Funded Research and Development Centers in the United States. Like that study, our analysis showed the prevalence of the business case throughout this research community. In fact, we found that nearly all of the diver-

sity statements issued by centers or their managing organizations focused solely or primarily on the contributions of diversity to productivity, creativity, and employee satisfaction—in other words, the business case.

For example, a statement by the National Renewable Energy Laboratory (NREL) reads, "At NREL, we believe that fostering an inclusive work environment maximizes the unique talents and innovative ideas of every employee. Our diverse backgrounds and expertise from across the globe enable the laboratory to create clean energy solutions built upon a wide range of experiences and viewpoints." Similarly, a statement by the Southwest Research Institute (SwRI), which manages the Center for Nuclear Waste Regulatory Analyses, says, "Diversity and inclusion are key ingredients in the advancement of technology, and this is why SwRI aims to attract, develop and retain a highly diverse workforce at all levels." The managing organization of the National Center for Atmospheric Research, the University Corporation for Atmospheric Research, is one of only two examples we found whose diversity statements mentioned moral reasons, such as that it's "the right thing to do."

We don't dispute the validity of the business case; indeed, many studies have borne out its arguments. Diverse teams that bring a wider array of knowledge and experience to the table are more creative and set high bars for research and scholarly excellence, producing ideas that are both more innovative and more feasible than those produced by homogeneous groups [*McLeod et al.,* 1996]. However, although the business case makes valid points, it is ethically flawed.

A Flawed Approach

The business case is problematic because it focuses on the needs and goals of the institution rather than on addressing exclusion as a justice issue. It's a utilitarian approach, justifying the inclusion of BIPOC and other marginalized people by their transactional benefits to the majority instead of by acknowledging the individual humanity of people. We see this focus in the private sector as well when companies try to reach new consumer populations. *Thomas* [2004] described how the chief executive officer of IBM saw the company's diversity efforts: "'We made diversity a market-based issue.... It's about understanding our markets, which are diverse and multicultural.' By deliberately seeking ways to more effectively reach a broader range of customers, IBM has seen significant bottom-line results."

In addition to being ethically flawed, the business case relies heavily on making arguments for why an institution should invest in BIPOC and people from other marginalized backgrounds. This approach forces people from these groups into the position of having to explain why they should be seen, heard, and hired. Constantly having to justify one's value or worthiness as a result of systemic biases and racism can cause highly capable people to second-guess themselves [*Tulshyan and Burey*, 2021]. BIPOC, for example, should not have to convince people to allow them into different spaces, whether in science, technology, engineering, and mathematics (STEM) or in other fields, and they should not have to constantly second-guess the reasons they are in these spaces.

Emphasizing the business case can be unfair and even harmful for BIPOC and people from other marginalized groups, and it can unintentionally build unreasonable expectations for individuals.

Thus, emphasizing the business case can be unfair and even harmful for BIPOC and people from other marginalized groups, and just as affirmative action efforts often led to unjust assumptions that some people were hired on the basis of quotas, not qualifications, it can unintentionally build unreasonable expectations for individuals. Under the assumption that scientific output and innovation will improve with more diverse teams, BIPOC and other marginalized scholars are implicitly expected to overperform and overcontribute in their work. These same unreasonable expectations are not placed on scholars in the majority, even when their work or productivity is mediocre. In addition, it is often assumed that BIPOC and other marginalized scholars will lead diversity efforts without asking whether they are interested in taking on such roles.

These are significant problems across STEM fields. Research has shown that women and people of color must outperform men, especially white men, to achieve the same recognition or reward. Women in leadership roles are all too familiar with this phenomenon, facing heightened attention on their performance and expectations that their hiring would quickly translate into higher sales, improved company performance, or better science output. Along with the unfair performance standards women have long experienced, they have also faced harsher judgments for mistakes [*Coury et al.*, 2020]. *Pew Research Center* [2015] found that although gains have been made with more women in leadership roles, progress has been slowed by the burden of higher expectations.

Fewer than 6% of STEM faculty in academic institutions are people of color, which *Watson* [2019] claims is because "faculty hire faculty." In other words, people hire people like themselves. If they do hire a person of color, they often must convince other faculty that the person has the right "pedigree" to be part of the institution. Once a person of color is hired, tokenism and isolation can set in because of heightened expectations for performance—which are reinforced by instrumental rationales for diversity—and because the person may well be one of only a few people of color in the department. *Watson* [2019] further suggests that faculty of color leave academia in search of fulfillment elsewhere because the academic environment is not welcoming and because the bias of the majority becomes especially apparent in recruitment and hiring practices. Of course, not retaining individuals who are outside the demographic majority defeats the goal of increasing institutional diversity.

Focusing on Equity over Expectations

We call for a new approach and a reframed rationale for DEIJ work in the geosciences, indicative of a commitment to creating institutional environments that are inherently equitable, where all members are heard, seen, and valued without having to provide justification for their inclusion. Institutions should make intentional efforts to recruit and retain people with a variety of backgrounds, experiences, and perspectives because they are seeking to be equitable, not because of the benefits these people are expected to bring to the institution.

To help with transitioning to an equity-focused approach, we recommend that institutions and individuals reflect on their reasons and motivations for supporting the recruitment and retention of a more diverse workforce and student body and how those motivations drive expectations of recruitment and retention. Words matter, so institutions should review their diversity and inclusion statements and update them to include moral rationales. Understanding and acknowledging the historic responsibility of an institution are often first steps. Land acknowledgments, for example, although performative as stand-alone actions, can be starting points for establishing authentic and equitable partnerships with Indigenous and local communities and can move institutions toward conducting science in more just and inclusive ways.

If your institution subscribes to the business case justification for diversity, question whether that approach creates inequitable or unrealistic expectations. Specifically, are there heightened expectations of new BIPOC hires? Are you expecting colleagues or students from BIPOC and other marginalized backgrounds to overperform? Do you have heightened expectations that hiring a few individuals will rapidly change the output of the group? Are all students and colleagues allowed to be average at times?

Creating and nurturing a transformative culture require institutions to embody DEIJ as a foundational component to support their community and workforce. No institutions are doing this perfectly, but there are examples of institutions working toward transformational change. At Colorado State University, faculty performance reviews and tenure and promotion packages in many departments now include, as an evaluation component, evidence of incorporating DEIJ efforts into research, teaching, and service.

Positive and productive changes in institutions come with structural change at all levels, and these changes can take time. The benefits of diversity for science and for organizations are not immediate. They also do not depend only on the contributions of BIPOC and marginalized scholars and so won't be realized simply by augmenting numbers. Instead, the benefits come from systematically creating inclusive and equitable spaces that allow all scholars to be productive, to contribute, and to be valued and evaluated fairly.

Words matter, so institutions should review their diversity and inclusion statements

It is time for institutions to create transformational and equitable cultures by recognizing everyone's humanity and no longer treating efforts in diversity, equity, inclusion, and justice as a business decision.

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▶ **Read the article at bit.ly/Eos-DEIJ**

SENSING Iceland's MOST ACTIVE VOLCANO WITH A "BURIED HAIR"

By Sara Klaasen, Sölvi Thrastarson, Andreas Fichtner, Yeşim Çubuk-Sabuncu, and Kristín Jónsdóttir

The May 2011 eruption of Grímsvötn, the most active volcano in Iceland, was the largest in the country in half a century, spreading ash over the local landscape and impairing air quality and visibility. Credit: AFP/Stringer, via Getty Images

DISTRIBUTED ACOUSTIC SENSING OFFERED RESEARCHERS A MEANS TO MEASURE GROUND DEFORMATION FROM ATOP ICE-CLAD GRÍMSVÖTN VOLCANO WITH UNPRECEDENTED SPATIAL AND TEMPORAL RESOLUTIONS.

Icelandic legend tells of an outlaw named Grímur who hid in the highlands of the island after avenging the murder of his father. A widow assisted him, directing him to some remote lakes where he could sustain himself by fishing. However, there was already a giant living near the lakes. Grímur fought and killed the giant, so upsetting the giant's daughter that she laid a curse on the landscape. From then on, fires would burn in the lakes, and the surrounding woods would vanish.

To this day, Grímur's lakes, Grímsvötn in Icelandic, continue to spit fire, even as they are buried under hundreds of meters of the ice of Europe's largest glacier, Vatnajökull. In fact, since the settlement of Iceland, Grímsvötn has been the island's most active volcano—and it may be due for another major eruption.

In spring 2021, researchers from ETH Zürich and the Icelandic Meteorological Office (IMO) set out for Grímsvötn to take a closer look at its activity, using an emerging geophysical technology called distributed acoustic sensing (DAS; Figure 1). DAS can yield unprecedentedly high resolution data in hazardous and difficult-to-access environments. In addition to measuring previously unobserved seismic activity at the volcano, the experiment also indicated the presence of continuous seismic tremor and a variety of other signals at Grímsvötn not observed before in such detail.

GRÍMSVÖTN IS A COMPLEX VOLCANIC SYSTEM GOVERNED BY BOTH GEOTHERMAL HEAT FROM BELOW AND THE ICE OF THE OVERLYING GLACIER.

The Hazards of Grímur's Lakes

Grímsvötn is a complex volcanic system governed by both geothermal heat from below and the ice of the overlying glacier. The heat melts the underside of the glacier, creating runoff and forming a subglacial lake within the caldera of the volcano. This lake occasionally drains during major outburst floods called jökulhlaups, which inundate the coastal plains south of the ice cap. Past jökulhlaups from Grímsvötn have destroyed bridges and cut off transit between western and eastern Iceland.

Recently, Grímsvötn again showed such increased activity. Around 20 November 2021, GPS measurements recorded the ice shelf above Grímsvötn starting to subside slowly, marking the beginning of a jökulhlaup as water flowed out of the subglacial lake. The jökulhlaup peaked on 5 December in the Gígjukvísl glacier river, and more than 0.8 cubic kilometer of water in total drained from below the volcano.

In addition to the flood hazard, ash clouds pose threats to humans and livestock when direct interaction between magma and meltwater causes Grímsvötn to erupt explosively. Recent eruptions occurred in 1998, 2004, and 2011, each of which sent plumes of ash and debris into the atmosphere (the 1998 and 2004 events were also associated jökulhlaups). These plumes can spread heavy layers of ash over the local landscape, cause intense lightning, and reduce air quality and visibility, conditions that can create hazards for aircraft and vehicles. If winds are unfavorable during an eruption, ash clouds can also cause major shutdowns and economic damage in the air traffic industry, as happened during the 2010 eruption of Eyjafjallajökull, located about 140 kilometers southwest of Grímsvötn.

Rapid and substantial pressure decreases, such as that seen beginning in late November, have previously caused Grímsvötn to erupt (in 1922, 1932, and 2004). IMO, which is responsible for providing warnings about impending eruptions, was thus on full alert and raised the aviation alert level from yellow to orange as seismicity started to pick up at Grímsfjall, peaking with a magnitude 3.6 earthquake on 6 December. However, the seismicity quickly subsided that same day, and on 8 December, IMO lowered the code back to yellow.

Instrumenting the Ice

Conducting a large-scale field experiment in the middle of 7,900-square-kilometer Vatnajökull was challenging. After months of planning, the effort began with our team of nine traveling by truck from Reykjavík to the glacier's edge. From there, we continued aboard snowmobiles, superjeeps (trucks specially equipped with large tires for traversing ice), and a snowcat, following a carefully selected route to Grímsvötn to

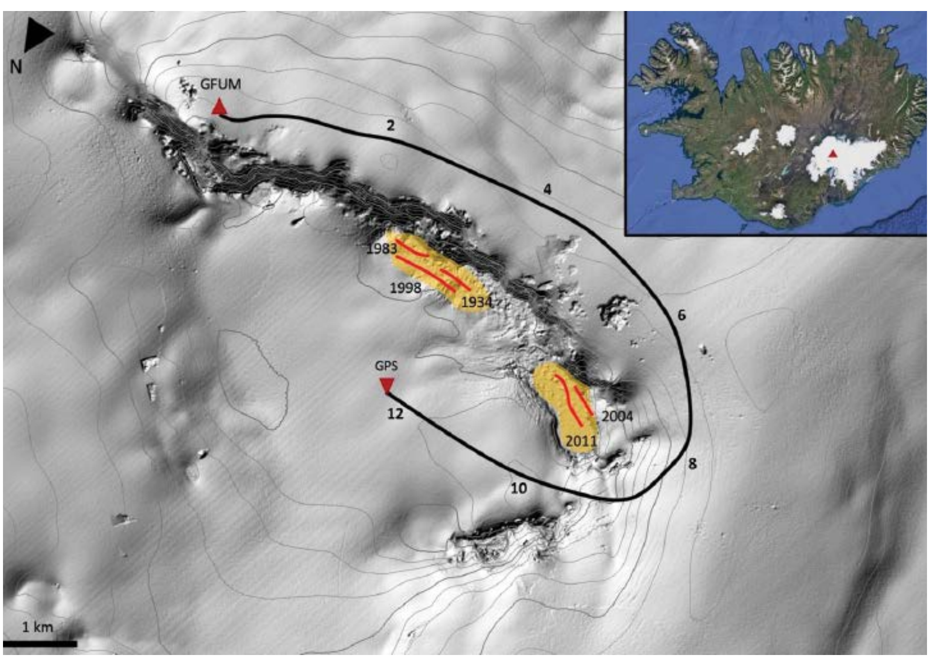

Fig. 1. This map of Grímsvötn shows the layout of the fiber-optic cable (black line with numbers indicating distance in kilometers) deployed in the DAS-BúmmBúmm experiment in spring 2021. Locations of the research huts (GFUM) near one end of the cable and a GPS station at the other end are also shown, as are the years and approximate locations of previous fissure eruptions (orange and red). The site of Grímsvötn (red triangle) amid the Vatnajökull ice sheet in Iceland is indicated in the inset. Topographic information in this figure is based on ArcticDEM.

A superjeep and a snowcat used by researchers atop Grímsvötn are seen in this drone-captured photo, with the caldera in the background. Credit: Hildur Jónsdóttir

avoid the largest crevasses. Over roughly 80 kilometers of ice, we hauled all the equipment we needed for our 5-day expedition, including three large cable drums, each weighing roughly 50 kilograms and holding 4-kilometer-long segments of fiber-optic cable, until we reached three huts near the highest point of the caldera rim at Grímsfjall. Built in 1957, 1987, and 1994 to conduct scientific research, the huts—geothermally heated by the volcano, and collectively housing a small kitchen, bunks, and even a steam sauna—served as our base of operations.

The fiber-optic cable was the core component of our experiment. DAS makes use of a standard fiber-optic cable together with an instrument called an interrogation unit (IU), which sends laser pulses through the fiber and receives them back. Inhomogeneities in the fiber cause backscattering of the light, which is measured by the IU. Small shifts in the return timing of the backscattered signals can be related to localized deformations of the fiber caused by seismicity or other sources of vibration.

Thus, long lengths of fiber can be used to create a dense seismic network, collecting measurements in the millihertz to kilohertz range every few meters with lower labor and financial costs compared with those from conventional seismic arrays covering areas of similar sizes. The high spatiotemporal sampling is especially beneficial in remote and harsh environments, such as Grímsvötn, where the installation of conventional arrays either would require substantially more personnel and time or is altogether infeasible. (In populated areas exposed to volcanic hazards, unused "dark" fibers in existing fiber-optic communications networks coupled with edge computing—data analysis that happens in real time at an instrument—may have great potential for noninvasive volcano monitoring and other applications of DAS.)

To build our detection network at Grímsvötn, we set up the IU in one of the huts, where electricity and Internet are available, and from there, we laid out our 12 kilometers of fiber-optic cable in a hook-shaped pattern along much of the caldera rim and atop the subglacial lake (Figure 1). Using the snowcat equipped with a custom-made plow, we trenched the cable 50 centimeters deep into the snow, thereby protecting it from atmospheric influences. Because the cable was delivered on three separate drums, the different segments had to be spliced, which was a surgical task given that each fiber is about as thin as a human hair. This surgery was complicated by the fact that it had to be performed during the trenching, and thus in the back of a cold,

Sara Klaasen conducts a hammer test to create a seismic signal that the distributed acoustic sensing cable can record. To increase the strength of their hammer blows, the researchers pounded on the metal plate on the plow used to deploy the cable. Credit: Sölvi Thrastarson cramped superjeep rather than in the relative comfort of the huts.

Badminton and a Bad Connection

Deploying the entire length of cable took 2 days, a process that ran smoothly overall despite the difficult conditions of working atop an active, glacier-capped volcano. During the deployment, we were always in direct contact with the volcano monitoring room at the IMO. At the first signs of volcanic unrest, we would have evacuated immediately.

On the third day, we conducted hammer tests to locate the DAS channels and to provide first glimpses of seismic wave propagation in the ice. This entailed pounding a sledgehammer on the ice in different places so the fiber-optic cable would record the signals at those locations. In the data, we could then see exactly where along the cable the signals were recorded, allowing us to link the data with their geographic location. From these initial tests, the experimental setup—our "buried hair," as we jokingly called it—appeared to work as expected. This success gave us reason to celebrate, and the team was excited to have a good time amid the challenging days of fieldwork.

Among our supplies, we had packed a badminton set—not at all standard equipment because the glacier is notoriously windy—hoping for an opportunity to spice up the expedition in the event of low-wind conditions inside the caldera, which is partly shielded by Grímsfjall mountain. We were extremely lucky to experience such a day inside the caldera. We set up a net amid the snow and enjoyed a sunny break for badminton—albeit wearing snowsuits instead of shorts and T-shirts—surrounded by the hills of the caldera rim. With the help of a large speaker we had brought up the glacier, the celebration turned into a small party, and because both the speaker and the party were referred to as "búmmbúmm" in Icelandic, we named our experiment DAS-BúmmBúmm.

After our celebrations, however, we learned the experiment would not be without hiccups. Our original plan included collecting 2 months of continuous measurements, but upon arrival back in Reykjavík, we found that the connection to our instruments was lost. A week later, after waiting for a storm to pass, we returned to Grímsvötn a second time and diagnosed that the lack of communication occurred because of a broken drive in the instrument. The problem prevented it from recording, and we could not repair it atop the glacier—unfortunately, the DAS system was more "broke-broke" than "búmmbúmm." Once we arranged for a replacement instrument, we went to Grímsvötn a third time and corrected the problem, and in the end we still managed to collect 1 month of measurements.

Andreas Fichtner (left) and Sara Klaasen splice fiber-optic cables in the back of a superjeep during the deployment at Grímsvötn, a task that required safety gear and surgical precision. Credit: Sölvi Thrastarson

EXPERIMENTS ON VOLCANOES ARE A RELATIVELY NEW APPLICATION OF DISTRIBUTED ACOUSTIC SENSING (DAS), SO THE SCIENCE IS STILL EXPLORATORY. OUR GOAL IS EVENTUALLY TO DEVELOP DAS AS A REAL-TIME VOLCANO MONITORING TOOL.

Experimental Expectations

Experiments on volcanoes are a relatively new application of DAS, with only a few examples to date, such as an experiment on Mount Meager in 2019, so the science is still exploratory. Our goal is to develop DAS as a real-time volcano monitoring tool. To achieve this, we need to conduct several DAS experiments in different volcanic settings to develop algorithms that can identify, locate, and characterize volcanic signals on the fly.

We are still analyzing the data from this first-ever DAS deployment at Grímsvötn. So far, they reveal an unexpected level of seismic activity. Prior to the DAS-BúmmBúmm experiment, there had been one seismic

Sunset over the caldera of Grímsvötn, as seen from the research huts near the caldera rim. Credit: Sölvi Thrastarson

station at Grímsvötn to record seismic signals, whereas we effectively recorded ground motions every 8 meters along the fiber-optic cable. With a single station only, it is hard to distinguish smaller signals from background noise, but in our DAS data, we can see the propagation of even the smallest signals. We recorded previously unknown tremor inside the caldera, for example, as well as frequently occurring small, local events that were detected all along the fiber-optic cable. These events may have been caused by a wide range of phenomena, such as volcanic and geothermal activity, icequakes, snow avalanches, and resonance of the subglacial lake and the overlying ice sheet (Figure 2). Because the cable loops closely past fumarole fields, their activity is likely recorded as well.

In our initial analyses, we are locating the detected events, carefully accounting for the rough topography and the presence of the ice and the lake, which affect seismic signals differently than the bedrock below. This work will be followed by a process of iteratively inverting the data to help determine the internal structure of Grímsvötn, including its magma chamber and conduits. We hope that our results and experiences from this experiment—and from future experiments planned for a range of volcanological settings in Santorini, Tenerife, and Indonesia—will shed light on hidden processes at hazardous active volcanoes and bring us closer to enhanced volcano monitoring using versatile fiber-optic cables.

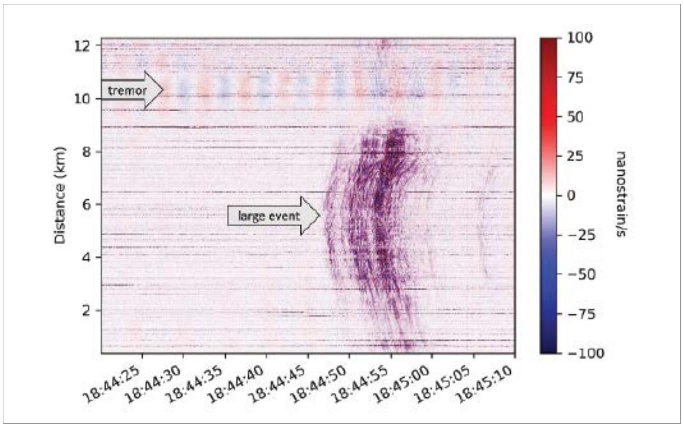

Fig. 2. This sample data plot shows ground deformation along the fiber-optic cable deployed at Grímsvötn over about 50 seconds. A large event arrived near the middle of the cable at about 18:44:50 on this day as it propagated through the glacier. The signal observed around kilometers 10–12 of the fiber, which sat on top of the subglacial lake, oscillated with longer periods than the large event and may have been caused by bending of the ice sheet on top of the lake.

Acknowledgments

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A Cagey Approach

TO SPEEDY AND SAFE SEAFLOOR DEPLOYMENTS

By Pascal Pelleau, Ronan Apprioual, Antony Ferrant, and Daniel Aslanian

Researchers devised a simple way to deliver ocean bottom seismometers accurately to the seafloor to study ongoing seismic and volcanic activity near the islands of Mayotte.

HENADZ/Adobe Stock

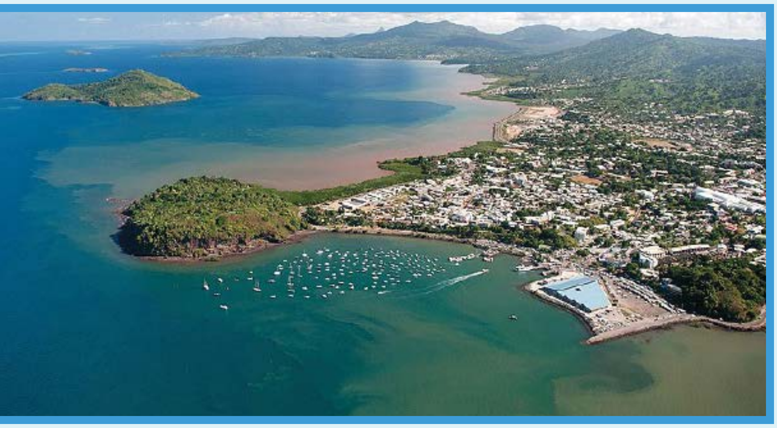
On 10 May 2018, an unprecedented bout of earthquake activity began in the vicinity of Grande-Terre, the main island in the French overseas region of Mayotte, located in the Indian Ocean between northern Mozambique and Madagascar. The ensuing seismic swarm, which shook the island repeatedly, included events of up to magnitude 5.9 as well as long-lasting very low frequency earthquakes [*Lemoine et al.*, 2020; *Cesca et al.*, 2020]. More than 3 years later, the nearly 300,000 residents of Mayotte still cannot rest easy as the intense offshore activity continues to be unpredictable.

Adding to the hazard facing Mayotte (a name often used to refer to the island of Grande-Terre as well as the surrounding region) is a new volcano rising more than 820 meters from the seafloor 50 kilometers east of Grande-Terre. The volcano formed when some 5 cubic kilometers of fresh lava, almost 9 times the volume of Sydney Harbour, began erupting onto the seafloor in July 2018. This volume is equivalent to about a quarter of the long-term average amount emplaced annually from the entire mid-ocean ridge system; the eruption therefore emitted a considerable amount of carbon dioxide [*Feuillet et al.*, 2021]. As a result of the eruption—and the emptying and deflation of magma chambers deep below the volcano—the island underwent major subsidence and shifted eastward [*Lemoine et al.*, 2020; *Cesca et al.*, 2020].

A puzzling observation was that the concurrent seismic activity was not near the birthplace of the new volcanic edifice, as scientists initially expected, but was instead several tens of kilometers west of there, nearer to Mayotte [*Saurel et al.*, 2022]. This region of seismic activity has shown evidence of degassing from the seafloor since the main eruption, indicating that subsurface magmatism is ongoing [*Feuillet et al.*, 2021].

Naturally, there has been great interest recently in studying and monitoring the area, out of concern for the safety of local residents [*Devès et al.*, 2021] and to gain a better scientific understanding of what's happening belowground [e.g., *Aiken et al.*, 2021]. Ocean bottom seismometers (OBSs) are valuable tools for imaging subseafloor structure and monitoring internal activity, particularly during seismic or volcanic crises. Even under the best conditions, though, ensuring that OBSs land safely at target positions on the seafloor is difficult. Conventionally, the instruments are dropped from a ship into the ocean, where they free-fall through the water column. In deep waters, strong currents can carry them long distances from their targeted positions, and they may settle on unfriendly or hazardous terrain.

With the intense seismic and volcanic crisis near Mayotte, the area offers significant challenges, to say the least, for deploying an underwater seismic observatory. However, in April 2021, we successfully tested a ballasted metal cage that allowed us to position six OBSs on the seafloor safely, precisely, and quickly to ensure that they could collect optimal recordings of ongoing seismic activity. The work was part of an unprecedented effort to turn the unexpected events near Mayotte since 2018 into a major scientific opportunity.



Mamoudzou, on the eastern coast of the island of Grande-Terre in the Mozambique Channel, is the seat of government of the French overseas region of Mayotte. Credit: Bebetot/Wikimedia Commons, CC BY-SA 4.0 (bit.ly/ccbysa4-0)

A NEW CAMPAIGN TO STUDY THE SEISMICITY

Mayotte is part of the Comoros archipelago, an east-west oriented cluster of volcanic islands in the Mozambique Channel. The islands are south of the Somalia Basin, which opened during the Mesozoic as Madagascar detached from Africa and drifted southward. However, the volcanism of the Comoros archipelago is much younger—no older than Miocene in age—and is thought to have occurred along the transfer zone, where deformational strain is transmitted between the East African and Madagascar rift systems [*Feuillet et al.*, 2021].

Although we have broad knowledge of this region's geologic history, there is much that we do not know about its crustal structure, magmatic systems, and seismic constraints, all of which build the area's landscape and are connected to natural hazards.

In spring 2019, several French research organizations—including the Institut Français de Recherche pour l'Exploitation de la Mer (IFREMER), Bureau de Recherches Géologiques et Minières, Institut de Physique du Globe de Paris, and Centre National de la Recherche Scientifique—launched the Mayotte Ocean Bottom Seismometers (MAYOBS) oceanic surveying campaign under the multidisciplinary Réseau de Surveillance Volcanologique et Sismologique de Mayotte (REVOSIMA) initiative.

Over its 21 MAYOBS cruises so far, the research consortium has repeatedly monitored the seismic and volcanic activity near Mayotte with the goal of holistically studying its causes and consequences. The group is specifically interested in illuminating how magma, ascending through volcanic plumbing networks and recharging reservoirs, reaches the seafloor [e.g., *Berthod et al.*, 2021a, 2021b; *Foix et al.*, 2021], where it shapes new relief, spreads chemical volatiles like carbon dioxide into the water column, and affects surrounding ecosystems. A dramatic example of such effects has been shown by discoveries by local sailors of dead deepwater fish rising to the surface.

The MAYOBS 18 cruise in April 2021 targeted the highly active Horseshoe area, just 10 kilometers offshore eastern Mayotte, to study weak seismic signals generated by fluids, magma, and gas circulating inside the local volcanic plumbing system (Figure 1). These signals are essential to helping us understand the system's architecture and how it operates, and they may allow us eventually to forecast future volcanic events. To record these faint drumbeats, we planned to deploy six OBSs during the cruise to water depths of 1,470–2,130 meters.

A first step, though, was to overcome logistical and health protocols imposed because of the COVID-19 pandemic, which were particularly strict for those embarking on oceanographic missions. All participants had to self-isolate at home for 15 days before their flight to Réunion Island, where, upon arrival, they boarded a bus that transported the scientific staff and sailors directly to the ship without any contact with the local population. Once on board, a further 7-day precautionary period of wearing masks and limiting interactions among personnel was strictly imposed. Finally, at the end of this period, normal operations resumed—a beautiful moment of tension release and relief (although we had to repeat the process in reverse on the return home). Despite the complications, we completed our operations within the planned time frame.

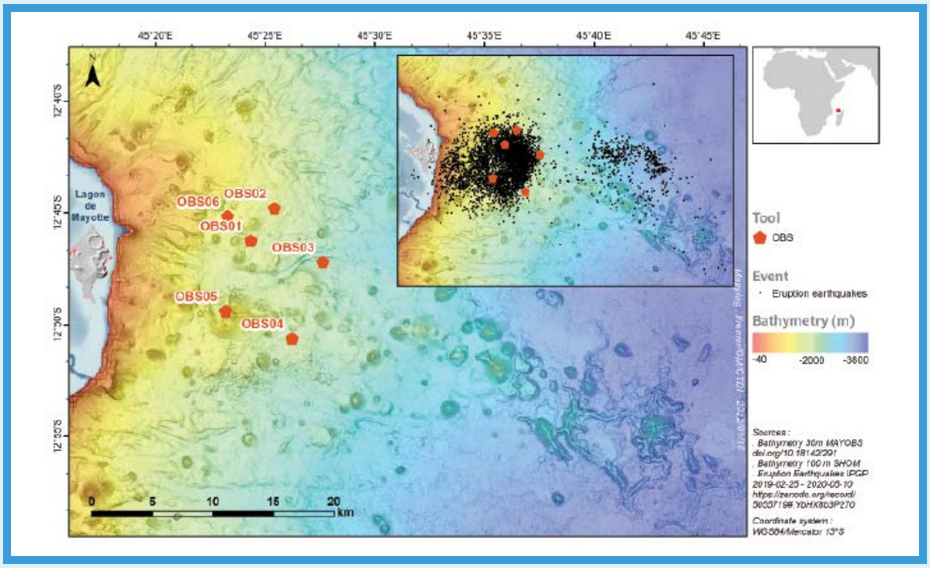


*Fig. 1. Locations of the six ocean bottom seismometers (OBSs, orange hexagons) deployed during the 18th Mayotte Ocean Bottom Seismometers (MAYOBS) cruise in April 2021 are shown amid the bathymetry of the Horseshoe area offshore Mayotte. The small island at left is Pamanzi, just east of Grande-Terre. The newborn volcano appears at bottom right on the map. The inset shows the same map overlain by the epicenters of earthquakes from 25 February 2019 to 10 May 2020 located using MAYOBS data [*Saurel et al.*, 2021] and showing the concentration of seismicity near the island and about 35 kilometers northwest of the newborn volcano.*

HITTING A DEEP, DARK TARGET

Before deploying the OBSs, the onboard team carefully analyzed high-resolution bathymetry of the area to find sites where the ground slope was less than 5° (Figure 1), the maximum inclination allowed by instrumentation (specifically, the horizontal geophones) in our OBSs. The team also looked for sites that were not at high risk of new volcanic eruptions and where the seafloor topography was not rough from previous lava flows, to ensure the instruments would record properly and remain safe. Even with such planning, positioning these instruments precisely was a huge challenge.

Remotely operated vehicles (ROVs) are generally used for this task in offshore industries (e.g., in the petroleum and cable-laying industries), but this option is often too expensive and time-consuming in academic research. On oceanographic cruises, researchers usually opt for the fastest way to deploy OBSs, dropping the instruments from the ship and letting them free-fall to the bottom of the ocean, with the understanding that highly variable ocean conditions, weather, currents, and eddies can cause trouble.

Further, the risk that instruments will land on undesired terrain is increased in areas of rough or steep seafloor, such as at subduction zones, mid-ocean ridges, and volcanic islands like Mayotte. Rough terrain may directly affect the instruments' ability to operate correctly if they don't settle properly. There is also a high risk of simply losing instruments in dark waters.

In the past, our team tried deploying OBSs attached to a cable. This technique offers more control over the final position of an instrument, but as with allowing an OBS to free-fall, the instrument's relatively light weight in water slows its descent and means that this option is still very time-consuming. To overcome these difficulties, our team designed a ballasted cage and tested it during the MAYOBS 18 cruise. The cage encloses the OBS, increasing the weight and descent speed of the instrument. An added benefit is that the cage's steel fabrication is inexpensive and can easily be adapted to work with any oceanic instrument.

The cage was further equipped with an Ultra Short Baseline (USBL) underwater positioning system—like those often used on ROVs and autonomous underwater vehicles—featuring real-time tracking with a horizontal accuracy of 0.1% of the water depth (e.g., 1-meter accuracy at a depth of 1,000 meters).

Our USBL system also included a removable acoustic transmitter—a feature that would prove important in our deployments—and a release function. Together with the dynamic positioning capabilities of our ship, R/V *Pourquoi Pas?*, the communications package on the cage allowed us to control precisely in real time the horizontal positioning of the cage as it was lowered on its cable from the ship's winch and to remain above the target during its descent. The OBSs were released from their cages to free-fall from about 10–20 meters above the seafloor, and the cages were then quickly returned to the ship at the maximum speed of the winch (1.5 meters per second).

FINER, FASTER, AND SAFER DEPLOYMENT

Our first three deployments were a little erratic. The real-time positioning indicated many communication interruptions and uncontrolled jumps in the estimated positions of the cage during these descents. Although we ultimately released the OBSs at the correct locations, it took us longer than expected because we sometimes had to wait for the position of the cage to stabilize and we did not use the winch at full speed.

It turned out that the steel frames of the cage interfered with the USBL communications because the acoustic transmitters were located at the center of the cage. To mitigate this effect, during the next three deployments, we affixed the acoustic transmitters to an outer

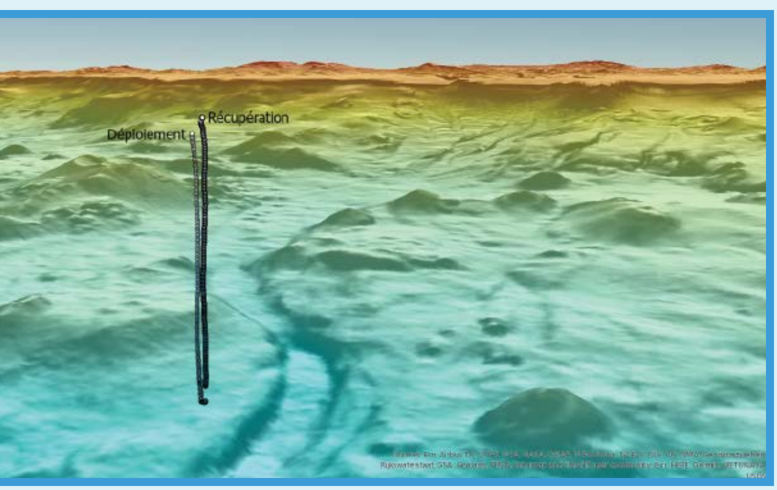
Even under the best conditions, ensuring that ocean bottom seismometers (OBSs) land safely at target positions on the seafloor is difficult.

The ballast cage (left) is deployed over the side of R/V Pourquoi Pas?. *The cylinder mounted to the top center strut is the acoustic transmitter of the Ultra Short Baseline (USBL) positioning system. For the last three OBS deployments, the acoustic transmitter of the USBL positioning system (right) was decoupled from the metal cage using a wooden plate and was moved from the top center to a corner of the cage for better communication with the ship. Credit: Pascal Pelleau*

corner of the cage. We also separated them from the metal frames with a wooden plate, which provided important acoustic and mechanical decoupling from the cage and further attenuated interference. With this setup, our communication with the USBL was unimpeded, and we could deploy the OBSs faster and more smoothly.

Considering the accuracy of the USBL system and assuming instrument drift during its final 10- to 20-meter free fall of about 10%, we estimated the accuracy of the final measured positions of the deployed OBSs to be ±5 meters at water depths between 1,470 and 2,130 meters. An instrument's final position on the seafloor with respect to the targeted position strongly depends, however, on the ability of the ship to control its position and keep the cage at the needed location.

During our experiment, using accurate dynamic ship positioning and with calm seas and moderate winds, we dropped each of our six instruments to within 5–35 meters of the targeted positions. By comparison, letting an OBS free-fall through the entire water column, which doesn't allow any control once it is released, often leads to final positions several hundreds of meters—or even more than a kilometer when currents are strong—from targeted sites. Our precise and safe deployments took about 45 minutes each, including the descent to 1,500- to 2,000-meter water depth and the retrieval of the empty cage back on deck, an improvement of roughly 1 hour compared with conventional OBS deployments.



Shown here are the tracked positions of one OBS during deployment (déploiement) and recovery (récupération) off Mayotte. The ballasted cage reduced drift during the deployment of the OBSs, which assisted with precise positioning and made the instruments easier to locate when it was time to recover them.

THE STEADFAST SEISMOMETER

During the subsequent cruise of the Geochemistry, Fluids, Acoustic Anomalies, and Magmatic Activity Following the Mayotte Eruption (GEOFLAMME) program (April through May 2021), which was dedicated to exploring for and sampling lava, fluids, and gas emitted at the seafloor near Mayotte, IFREMER's *Victor 6000* ROV dived to the location of one of the MAYOBS 18 OBS deployments. The ROV photographed the OBS standing on flat, smooth seafloor, out of danger, as expected, and in the same position as when it was released from the cage.

The six instruments were recovered a few months after their deployment during the MAYOBS 20 cruise. The OBSs are made of buoyant, hermetically sealed glass spheres that enclose sensors, batteries, data recorders, and all the necessary electronics. We need that sphere to come back to the surface to download and process the recorded data.

During the MAYOBS 20 cruise, acoustic signals were sent to the instruments, causing them to detach from their anchors and allowing the glass spheres to rise to the surface. After a tense half hour to hour of waiting on the ship for each instrument, all of them were recovered with the valuable data they had collected. The successful deployment and 100% retrieval of the OBSs, combined with the decreased deployment times, confirmed our overall data collection strategy as well as the usefulness of the ballasted cage we designed.

Although the cage was developed for OBSs, only minor adjustments would be required for its use in accurately deploying other scientific instruments to the seabed. Moreover, real-time tracking of the cages could provide supplemental ocean data, helping us to measure and understand local deepwater currents. Deployment times could also easily be reduced further (which would reduce drift), either by increasing the weight of the cage with additional ballast or by using a state-of-the-art winch capable of operating at higher speeds.

The successful deployment and 100% retrieval of the OBSs, combined with the decreased deployment times, confirmed our overall data collection strategy as well as the usefulness of the ballasted cage.

In the wake of the expedition in spring 2021, scientists at IFREMER and partner institutions are analyzing and making use of the data collected. They are working to understand how underwater ecosystems are adapting to brutal changes wrought by volcanism, from the massive lava flows reshaping the seafloor to the emitted volatiles altering oceanic chemistry. They are also tracking seismic signals that could help them to better characterize the shape and functioning of the volcanic plumbing system as well as the risks it poses to humans.

The January magmatic event at the Hunga Tonga–Hunga Ha'apai seamounts provided a fresh reminder of such risks. This activity led to an explosive eruption and the collapse of a large part of the volcanic edifice, which triggered a tsunami that quickly reached the populated islands of Tonga before progressing to islands and coasts farther away. Fortunately, tsunami warnings were issued, and few casualties were reported, although damage in Tonga was extensive.

We hope, of course, that there will be no catastrophic effects from the ongoing activity near Mayotte. But to help ensure safety, this activity is still being carefully monitored, and regular reports are made available through REVOSIMA to locals and the global public. Additional MAYOBS campaigns are also planned for the near future to continue addressing both safety concerns and scientific questions in the region.

ACKNOWLEDGMENTS

We thank Gaelle Lamarque and Mikael Evain for fostering the development of the cage. We also thank the captain and crew of R/V *Pourquoi Pas?* and the scientists mobilized during the MAYOBS 18 cruise who made these deployments possible. We gratefully acknowledge Mathilde Pitel Roudaut, Nina Tangy, and Alison Chalm from IFREMER for creating illustrations used in this article and for help writing in English. We thank Emmanuel Rinnert, Nathalie Feuillet, and Cécile Cathalot, principal investigators of the GEOFLAMME cruise, for providing the underwater photograph of one of our OBSs taken from ROV *Victor 6000*. Since June 2019, all activities on Mayotte have been supported by the Ministère de l'Enseignement Supérieur, de la Recherche et de l'Innovation, the Ministère de la Transition Écologique, the Ministère des Outre-Mer, the Ministère de l'Intérieur, and the Ministère des Armées with the support of the Direction Interministérielle aux Risques Majeurs en Outremer. All marine operations are performed as part of the MAYOBS set of cruises, and we thank the captains and crews of R/V *Pourquoi Pas?*. Data from these cruises are available at campagnes.flotteoceanographique.fr/series/291/.

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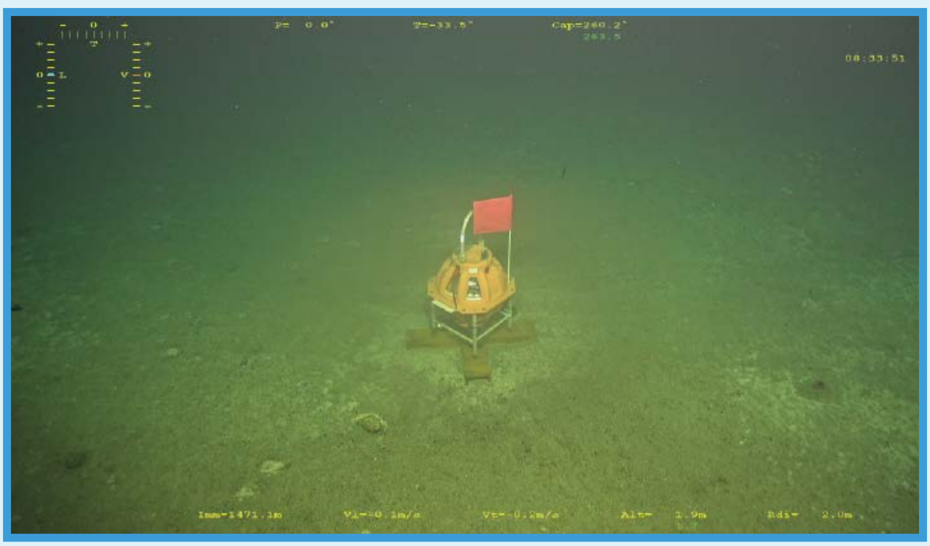

During the 2021 cruise of the Geochemistry, Fluids, Acoustic Anomalies, and Magmatic Activity Following the Mayotte Eruption (GEOFLAMME) program, the Institut Français de Recherche pour l'Exploitation de la Mer's Victor 6000 *remotely operated vehicle took this photo of one of the OBSs deployed with the ballast cage during the MAYOBS 18 cruise. The OBS was found within about 5 meters of where it was expected on the basis of the position provided by the USBL system. Credit: Rinnert Emmanuel (2021)/IFREMER, CC BY 4.0 (bit.ly/ccby4-0)*

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Island.
Bay of

Studying Volcanoes *through* Myths, Legends, & Other Unconventional Data

BY NANCY AVERETT

Studying historic eruptions through a storytelling lens often improves our understanding of and ability to prepare for such events.

Historic depictions of New Zealand's Whakaari/White Island help contemporary volcanologists better understand patterns in eruptions. Credit: (photo) gérard/Flickr, CC BY-SA 2.0 (bit.ly/ccbysa2-0); (drawing) State Library of New South Wales (PXA 2073), CC BY-SA 3.0 AU (bit.ly/ccbysa3-0AU). The photo and illustration—from an album of drawings in Australia and New Zealand, 1844–1866, compiled by T. E. Donne—have been modified to blend together. The right portion of the photo and left portion of the drawing are not shown.

In Native Hawaiian Pelehonuamea chants, several verses describe a fight between Pele, goddess of fire and volcanoes, and her youngest sister, Hiʻiaka: In a jealous rage, Pele burns the forest that Hiʻiaka loved, then kills her lover and throws him into the Kīlauea volcano. Jumping in, Hiʻiaka starts digging to find him—but carefully; if she digs too deep, water will bubble up and put out the fire of Pele.

Native Hawaiians view such stories as important and instructive and have passed them down through generations. But when white missionaries came to the islands in the 19th century, they dismissed such chants and stories as primitive narratives. Not long after Hawaiʻi was colonized, the modern academic discipline of geology developed, and Western scientists began chipping away at the islands' old lava flows, studying rift zones and escaping gases. Through these and other methods, they "discovered" what had already been reported in the chants: Sometime during the 15th century, a huge lava flow covered Wao Kele O Puna, a lowland tropical rain forest along Kīlauea's East Rift Zone, and groundwater interacting with hot magma caused a steam explosion that helped form the volcano's current caldera.

As ecologist and Hawaiian Volcano Observatory volcanologist emeritus Don Swanson said at a U.S. Geological Survey (USGS) workshop in 2017, "Recent evidence that we've acquired scientifically is entirely consistent with what I think the chants are telling us."

Chants, mythologies, and popular stories about eruptions and their aftermath are often not top-of-mind for geologists and volcanologists, but that is starting to change. In some cases, researchers are teaming up with Indigenous experts to better understand volcanology embedded in oral traditions. In other cases, they're working with historians to find and interpret eyewitness accounts of eruptions and associated data in archives, newspaper articles, journals, telegrams, and different sources.

Undertaking such work is critical, not just to illuminate (and, in some cases, correct) accounts of the past, but also because many volcanoes are not actively monitored and stories and chants can sometimes provide the only clues to past behavior. What's needed to better mitigate risk is a more complete understanding of how the world's volcanoes transition from "repose to unrest, and unrest to eruption," argues a 2020 *Nature Reviews Earth and Environment* commentary from volcanologists David Pyle of the University of Oxford and Jenni Barclay of the University of East Anglia.

Stories and other historical records, therefore, may be some of the best sources from which to gain more robust knowledge about these phases of volcanic activity. Consider, Pyle and Barclay write, this line of poetry, written by jazz musician Shake Keane, about the rapid transition of the La Soufrière volcano on the island of Saint Vincent in Saint Vincent and the Grenadines on 13 April 1979:

> That thing split Good Friday in two
> and that good new morning groaned
> and snapped
> like breaking an old habit.

The next stanza of "Soufrière" chronicles the subsequent evacuation:

> Within minutes
> people
> who had always been leaving nowhere
> began arriving nowhere
> entire lives stuffed in pillow cases
> and used plastic bags.

Such perspectives, Barclay said, are invaluable. "To understand the complete history of a volcano is a piece of detective work.... And the historical aspects of that can be incredibly insightful."

SOLVING A MYSTERY

Painting, not poetry, is what helped excite volcanologist Katharine Cashman about teaming with Caroline Williams. Williams, who died in 2019, was an expert in Latin American history who had come across a painting depicting the 1773 eruption of Tungurahua volcano in Ecuador. She shared the image with Cashman, who was

That thing split Good Friday in two
and that good new morning groaned
and snapped
like breaking an old habit.

intrigued by its depiction of mudflows that blocked a river.

"It showed that the river was dry on one side and not on the other," Cashman said.

Eventually Cashman, Williams, and graduate students published three papers. One looked at the eruption of Guatemala's Fuego volcano in 1717, relying on a 250-plus-page report prepared by the Spanish colonial government. The report contained drawings of magma flow, documentation of building damage, and numerous eyewitness accounts that described sounds ("rumbling"), physical sensations ("ground shaking"), and sights ("tall flames of fire") during both the initial eruption and a subsequent series of earthquakes and mudflows that occurred afterward. "To my knowledge, it's the first social science survey of the impact of a volcanic eruption," Cashman said.

She and Williams also delved into the 1902 eruption of Guatemala's Santa María volcano. Although it was one of the volcano's largest eruptions ever, it's been poorly studied. In part, this is because Manuel Estrada Cabrera, Guatemala's president at the time, gagged the media out of concern that news of the disaster would curtail international investment in Guatemala's coffee farms—there's no mention of the eruption in local newspapers for a full week after the event. The researchers consulted telegrams and newspapers from Argentina, Mexico, Spain, the United Kingdom, and the United States to piece together the event. In those newspapers, they found eyewitness accounts that allowed them to calculate the deposited volume of ashfall as well as estimates of fatalities.

Cashman and Williams's third paper didn't chronicle a known eruption but tried to solve a mystery using icy evidence of the historic atmosphere. Large volcanic eruptions inject sulfur dioxide directly into the stratosphere, where the gas forms a sulfate aerosol layer that reflects solar radiation and cools the atmosphere. (After the 1815 eruption of Mount Tambora in Indonesia, e.g., the world went through "the year without a summer.") Layers of snow record the changing chemical composition of the atmosphere, and on the basis of the level of sulfur in ice core records, scientists can determine the times when large eruptions occurred.

Cashman knew that ice cores indicated that a big eruption occurred sometime in the early 19th century, so she asked Williams for help in tracking it down.

Williams found two clues in the historical record. The first was an observation by Francisco José de Caldas, who ran the astronomical observatory in Bogotá, Colombia. The "natural fiery colour [of the Sun] has changed to that of silver, so

"The Irish love to record these grim, grim things: plagues and famines and other uplifting kinds of stuff."

much so that many have mistaken it for the moon," Caldas wrote in the publication he edited, *Semanario del Nuevo Reyno de Granada*. He also noted colder than normal temperatures. The second clue was a similar observation by a physician in Lima, Peru.

Meanwhile, Cashman analyzed the rates of stratospheric aerosol dispersal from satellite monitoring of more recent eruptions and other types of scientific data to better understand how the aftereffects of a large eruption might be seen in two countries almost 2,000 kilometers apart.

Cashman, Williams, and their coauthors concluded that the mysterious eruption occurred in late November to early December 1808. They located the event somewhere in the tropics (because sulfate clouds blocking the Sun were seen on both sides of the equator) but eliminated Latin America because Williams knew that the Spanish, with their meticulous record keeping, would have noted such an important event in their archives. "My best guess is Indonesia," said Cashman of where the eruption occurred, adding, "It was a fun little detective story to undertake."

A NEW ICE CORE CHRONOLOGY

The Spanish weren't the only scribes with a penchant for noting strange weather and atmospheric conditions.

Medieval Irish monks also wrote about "veiled suns" and colder than normal climates. "The Irish love to record these grim, grim things," said Francis Ludlow, an associate professor of history at Trinity College Dublin, "plagues and famines and other uplifting kinds of stuff."

Francisco José de Caldas, often recognized as the "first Colombian scientist," recorded atmospheric changes that hinted at a volcanic eruption in 1808. Credit: Ministerio de Cultura de Colombia/Wikimedia, Public Domain

The daily events chronicled by monks in Irish annals helped historians and scientists identify global climatic events like volcanic eruptions. Credit: The Annals of. Ulster/Wikimedia, Public Domain

While working on his doctorate, Ludlow undertook the first systematic survey of the Irish annals, records (often kept by monks) of daily events from about 400–1600 CE. Ludlow classified the many climatic events within the annals and showed them to be reliable for reconstructing the Irish climate during those years and also for understanding how extreme weather events affected Irish society.

“What is it about a story that makes it last for thousands of years? What resonates with people? How do we use analogy and context and anecdote, embellishing details, but also the true essence of the event to get a broader perspective of what happened?”

Through that work, Ludlow noticed that when he compared some major Irish climatic events during the first millennium with ice core dating of volcanic events, the two did not line up. Then, during a poster session at AGU’s Fall Meeting 2012, he met Michael Sigl of the University of Bern’s Physics Institute, who was also questioning the accuracy of volcanic eruption dates in ice core chronologies. The two teamed up and recruited other experts in climate science, geology, and history. Together the transdisciplinary team compared the chronologies with historical tree ring data (reduced tree growth is a proxy for a prolonged period of cool weather), written historical observations of dust veils, and ice core tephra evidence. Their conclusion, published in *Nature* in 2015, offered a new ice chronology—one that aligned with Ludlow’s collection of Irish climatic events and would soon give context to other historical climate events around the world.

“All of a sudden,” said Ludlow, “anywhere I turn to that has good written records, I’m finding climatic events and the fallout from them—drought, flooding—that can be traced back to eruptions.”

In 2017, for instance, he, Sigl, and others published a paper showing that four closely timed volcanic eruptions around the world may have helped end the Ptolemaic Kingdom, whose dynasty ruled Egypt from 305 to 30 BCE. Atmospheric changes from the eruptions, they wrote, suppressed the annual monsoons in Ethiopia and subsequently diminished flooding in the Nile River valley, which Egyptian farmers depended on to irrigate their crops. By also examining written records of “priestly decrees” and hereditary land sales, the group was able to make a case that the societal stressors from reduced flooding contributed to a series of revolts in the kingdom (Roman conquest ultimately ended Ptolemaic rule).

Just last year, Ludlow, Sigl, and another group of coauthors published a paper looking at patterns in their new ice chronology to show that volcanic eruptions and subsequent climate cooling contributed to the collapse of a number of Chinese dynasties from 1 CE to 1915.

Ludlow and Sigl’s wide-ranging work illustrates how a changed climate can have catastrophic effects on civilizations, especially if the society is already in disarray or if the government is not in tune with the local population. Ptolemaic leaders, for instance, gave tax breaks to Greeks living in the kingdom, which angered local Egyptians. Still, said Ludlow, some leaders, most notably Cleopatra (the last Ptolemy), were smart enough to make sure the people they ruled did not starve; when the reduced Nile flooding harmed agriculture, she banned the exportation of grain. “Cleopatra had the worst eruption, I would say in 43–44 BC, but she didn’t have any revolt,” Ludlow said.

"So she was obviously pretty good at managing the population and the economy."

Although much of Ludlow's work seems to portend grim news for how nations will fare under climate change, he said there are historical examples of countries making themselves more resilient to disaster. He cited the response to the Great Lisbon earthquake in 1755, which was followed by a tsunami and fire that demolished Portugal's capital city. Government leaders used the disaster to justify such infrastructure changes as widening the streets. This redevelopment left more room between buildings, so they were less likely to catch fire from one another. Portuguese leaders also began constructing more earthquake-resilient structures. "So they're much more resilient today," Ludlow said, "because of how they deliberately built things back better after that disaster."

SCIENTISTS WITH FEET IN BOTH WORLDS

Although Ludlow and his coauthors' work ponders how nations and communities grapple with climate change and catastrophes, others focus their effort on a more intimate scale, thinking about how historical records can help them find better ways to communicate risk among the fraction of the world's population that lives near active volcanoes. For geologist Heather Wright, who works for the USGS Volcano Disaster Assistance Program at the Cascades Volcano Observatory in Washington State, that has meant starting a reading group for herself and colleagues that looks at how Indigenous groups historically communicated volcano hazards.

"Here in the Pacific Northwest, there are Klamath Indian stories of Mount Mazama (the remnants of which are now Crater Lake) that happened 7,000 years ago," she said. "So what is it about a story that makes it last for thousands of years? What resonates with people? How do we use analogy and context and anecdote, embellishing details, but also the true essence of the event to get a broader perspective of what happened?"

Wright said she and others in her line of work have learned that having a personal connection to a previous eruption is the best way to understand risk, but that's often not possible because volcanoes can go 500 or more years between explosions. Indigenous communities incorporate such events into oral traditions, which are passed down and repeated frequently, Wright said. Today, she continued, people are looking for additional ways to get the information to stick. For example, every year administrators and teachers in Washington's Orting School District lead students in evacuation drills in case a massive mudflow triggered by an eruption on nearby Mount Rainier comes barreling down on their schools—even though the volcano's last major eruption was in 1894. "It's become this really rich sense of community identity to talk about those evacuation drills," said Wright, "and everybody knows about it, because it's something that's part of the schools, it's something that's part of education from a very young age, and it's an experiential thing, because they literally have to walk the distance to the safe zones every year as a school group."

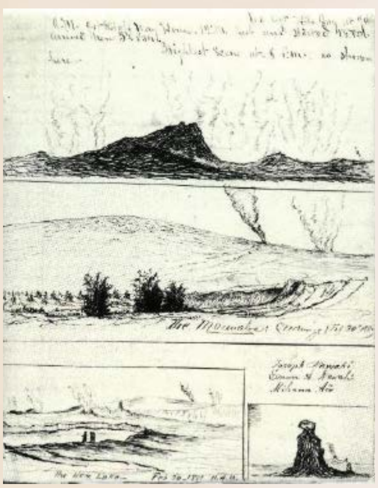
Wright, herself a member of the Tlingit Tribe, said that learning about Indigenous volcanic knowledge can also help scientists form more trusting relationships with tribal members when they are doing research on tribal lands. For instance, she said, the Cowlitz Indian Tribe has always lived in the shadow of Mount St. Helens, one of the most well monitored volcanoes in the United States. The Cowlitz have a tradition of collecting the wool that mountain goats rub off on nearby plant life to use for tribal rituals. "It's important to know how precious that [tradition] is to them," Wright said, "so if you're up there doing research, you don't disturb [the wool]."

The catastrophic earthquake experienced in Portugal in 1755 led to major infrastructure improvements in Lisbon, including wider streets and more resilient buildings. Credit: Archiv für Kunst und Geschichte

Jonathan Procter, a professor of natural hazards at Massey University in New Zealand, agreed that geologists and volcanologists need to show cultural sensitivity when doing research, and he has seen improvement in that area. For example, scientists know they must follow the prayers of a Maori guide when studying volcanic lakes on Whakaari/White Island. But the two entities don't always come to complete agreement. For example, Maori leaders have requested scientific monitoring of several lakes, including Rotokura, for potential signals of an impending eruption.

"Maori histories tell them that whenever those lakes change to a certain color, there's likely to be an eruption," said Procter. "The scientists say, 'Well, we can't determine whether the lakes are connected to the volcanic system or not. So we're not going to invest any time or funding into monitoring them.'"

"Most of the volcano histories available today are heavy on what foreigners observed and interpreted with maybe a passing reference to some aspect of Hawaiian reaction."



Volcanologists consulted eyewitness accounts from letters, magazines, newspapers, and even hotel registries (like the Volcano House) to better understand an 1881 eruption of Kīlauea. Credit: Guest Register/Wikimedia, Public Domain

Procter himself straddles both worlds, being both of Maori descent and a scientist who studies eruptions, and has written about the balance. In one instance, he explained how one Maori community, the Ngāti Rangi, who live on the southern flanks of their ancestral mountain, Ruapehu, view it as intimately connected to their own identity. He noted the Ngāti Rangi don't like the word hazard used to describe Ruapehu. "The perspective is that [an eruption] is a natural event that should not be restrained, diverted, or withheld.... This position is communicated throughout the generations and therefore is widely accepted."

Combining Indigenous Knowledges and Western science is something that Jim Kauahikaua, a geophysicist with the Hawaiian Volcano Observatory, also thinks about. Kauahikaua, who is part Native Hawaiian but does not speak the language fluently, has used Native Hawaiian sources as well as white missionary writings to better understand eruptions. To analyze eyewitness accounts of three different Kīlauea eruptions, for example, he combed through written observations that appeared in scientific journals, letters, magazines, newspapers, and even hotel registries. He and his coauthors then used that material to better locate the eruption rifts and direction of the lava flow.

Kauahikaua also teamed up with a Native Hawaiian speaker to translate 19th-century Hawaiian language newspaper articles, some of which appeared in a USGS publication about the 1880–1881 Mauna Loa eruption. "One of my goals is to include how Hawaiians view volcanoes and eruptions, earthquakes, and other environmental effects through examples in old newspapers, journals, et cetera," he said.

"Most of the volcano histories available today are heavy on what foreigners observed and interpreted with maybe a passing reference to some aspect of Hawaiian reaction," Kauahikaua said. He compared the two communities' responses to the 1880–1881 eruption of Mauna Loa. The Rev. Titus Coan, a missionary from New England, thought intensive mass prayer would stop lava from flowing into the town of Hilo, whereas Hawaiians asked Princess Luka Ruth Keʻelikōlani, a direct descendent of King Kamehameha I, to intervene with Pele to spare the town. When the lava flow stopped just a few days after the princess arrived in Hilo, it was a big deal for Hawaiians, Kauahikaua said. "But today it's mostly passed off as a 'cute' story."

Such cultural dissonance, he and other scientists have said, is one part of geologic history that needs to stay in the past.

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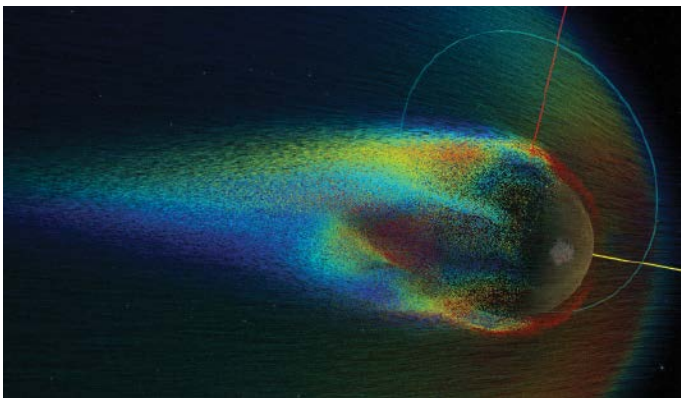
Measuring Carbon Ion Loss from the Martian Atmosphere

In recent decades, planetary scientists have developed ample evidence that Mars was home to a relatively thick atmosphere and hosted liquid water on its surface during the Noachian, around 4 billion years ago. Since then, significant climate change occurred, resulting in the loss of much of the planet's atmosphere and all of its surface water.

What remains of the atmosphere today is a thin envelope consisting largely of carbon dioxide. Without a protective planetary magnetic field, this, too, is being stripped away by the solar wind. Since its arrival in 2014, NASA's Mars Atmosphere and Volatile Evolution (MAVEN) spacecraft has tracked the escape of the atmosphere's most abundant ions, those of atomic and molecular oxygen.



A computer simulation shows ions escaping the Martian atmosphere due to interactions with the Sun's solar wind. Credit: NASA's Scientific Visualization Studio

In a new study, *Pickett et al.* attempt to extend these observations to carbon, the second most abundant element in the atmosphere. A complicating factor in observing the atmosphere's carbon (C) ion loss is that carbon is similar in mass to the dominant species, oxygen (O). For this work, the authors used 40 orbits of data collected by MAVEN's Suprathermal and Thermal Ion Composition (STATIC) instrument, which records the charge, mass, and velocity of incoming ions.

Because of instrumental uncertainties, STATIC registers particle impacts with a small range of masses; the distribution is centered on the true mass of a given ion. Because C^+ and O^+ have similar masses, these distributions overlap. Thus, contributions from the oxygen ions must be modeled and removed before the C^+ population can be ascertained. The authors developed a multistep process to accomplish this.

The researchers applied their method to data collected by STATIC in April 2018 as an initial assessment of the technique and a first approximation of the escape rate of C^+. They estimate that C^+ flows away from Mars with a flux on the order of 10^4–10^5 per centimeter squared per second down the magnetotail. This finding is broadly consistent with previous model-derived estimates of carbon loss from the atmosphere and lower by 1–2 orders of magnitude than the observed loss rate for oxygen ions.

In aggregate, STATIC found detectable C^+ fluxes in about a quarter of all observations during the study period. This finding illustrates the persistent difficulty of disentangling the two most abundant components of the Martian atmosphere. The stories of carbon and oxygen in the current atmosphere remain a task for the future with implications for the history of the Red Planet's climate. (*Journal of Geophysical Research: Space Physics*, https://doi.org/10.1029/2021JA029635, 2022)

—Morgan Rehnberg, *Science Writer*

Climate Change Could Reshape Pathogen Profile of Diarrheal Disease

More than half a million children under 5 years old die of diarrheal disease every year, according to the World Health Organization. Deaths and serious illness are most common in regions without access to clean water. Local climate fluctuations can be tied to outbreaks, but researchers have struggled to predict how climate change will affect diarrheal disease prevalence because diarrhea does not have a single root cause. Bacteria, viruses, and protozoa are all potential culprits of the underlying intestinal infection. Each potential cause can react differently to changes in rainfall, temperature, and other climate variables.

New research by *Colston et al.* aims to shed light on how different pathogens could respond to climate change. Researchers analyzed how 10 different diarrhea-causing bugs—including bacteria like *Escherichia coli* and *Campylobacter*, as well as viruses like adenovirus, norovirus, and rotavirus—responded to eight climate variables. The researchers collected stool samples and satellite data from communities and hospitals in 19 countries across southern Asia, sub-Saharan Africa, and Central and South America. Polymerase chain reaction (PCR) tests identified target pathogens in 65,000 stool samples from more than 20,000 children in regions where diarrhea is a substantial threat. The team used data from satellites and Earth system models to gather daily information about climate variables at each site, including humidity, soil moisture, temperature, and rainfall.

They found evidence that the impact of climate change on diarrhea outbreaks may vary depending on the underlying source of infection. In general, bacterial infections increased in areas with warm, moist conditions, whereas viruses became less prevalent in these regions. For instance, *E. coli* infection risk increased as temperatures warmed, whereas rotavirus became more common in colder weather. Just one variable—soil moisture—was associated with an increase in all 10 pathogens. The authors conclude that bacteria-caused diarrhea in children and adults could become more dominant as warm, wet places get even warmer and wetter because of climate change. Conversely, rotavirus—one of the leading causes of diarrhea—might become less prevalent as the climate shifts. (*GeoHealth*, https://doi.org/10.1029/2021GH000452, 2022) **—Rachel Fritts,** *Science Writer*

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If you need assistance and/or a reasonable accommodation during the application or the recruiting process, please submit a request via our **https://www.llnl.gov/join-our-team/careers/accessibility**.

CALIFORNIA PRIVACY NOTICE
The California Consumer Privacy Act (CCPA) grants privacy rights to all California residents. The law also entitles job applicants, employees, and non-employee workers to be notified of what personal information LLNL collects and for what purpose. The Employee Privacy Notice can be accessed **https://www.llnl.gov/join-our-team/careers/privacy-statement**.

For full application instructions and position description, visit **https://apptrkr.com/2859644**

UC DAVIS
JOHN MUIR INSTITUTE OF THE ENVIRONMENT

INDUSTRY ALLNS SPEC 3 (ASSOCIATE DIRECTOR OF STRATEGIC INITIATIVES)

DEPARTMENT DESCRIPTION

The John Muir Institute of the Environment (JMIE) is an Organized Research Unit (ORU) within the Office of Research fostering solutions-based environmental and climate-related research that crosses boundaries among disciplines and departments, professional schools and colleges at UC Davis. JMIE is the campus flagship for environmental research, addressing complex interdisciplinary real-world issues at the environmental nexus of people and the environment that cannot be effectively accomplished within a single academic unit.

JOB SUMMARY

The **Associate Director of Strategic Initiatives** will play a critical role in the leadership of JMIE and its internal and external programs. Under direction of the Director of JMIE, the Assoc. Director will be responsible for engagement, outreach, and development of large-scale strategic initiatives. The Assoc. Director will collaborate with the other JMIE directors, the Assoc. Director of Environmental and Climate Justice, and faculty and researchers campus-wide to identify and foster new activities in relevant research areas at the intersection of climate impacts, mitigation, and adaptation, and to develop and support fundraising plans. This role is key in supporting the One Climate Initiative (Big Idea) that addresses climate change impacts and efforts to mitigate and adapt to them through transdisciplinary research efforts. One Climate involves large collaborations between campus researchers and with external partners in government, academia, NGO's and corporations. Under the direction of the Director of JMIE, the Assoc. Director will be responsible for co-leading the design, implementation, and oversight of multiple diverse activities that support the JMIE and One Climate community at UC Davis, including:

- Strategic planning and management
- Developing strong relationships with faculty across campus and external stakeholders, and organization of workshops, symposia, seminar series, and other events related to One Climate.
- Involvement in strategic communications, marketing and outreach, including co-supervising the Strategic Communications Manager at JMIE.
- Working with the external advisory board and the JMIE Director on external fund-raising and development efforts.

POSITION INFORMATION

Salary Range: $68,200/yr. - $136,900/yr.
No. of Positions: 1
Appointment Type: Contract (3-Years, with the possibility of extension)
Percentage of Time: 100%
Shift Hours: Monday – Friday
Location: UC Davis
Union Representation: No
Benefits Eligible: Yes
Apply by Date: 3/4/2022

PHYSICAL DEMANDS

Lift and move office materials weighing up to 30 lbs.
On occasions work evenings and weekends to meet operational needs and deadlines.
Restricted vacation during peak periods.

WORK ENVIRONMENT

UC Davis is a smoke and tobacco free campus effective **January 1, 2014**. Smoking, the use of smokeless tobacco products, and the use of unregulated nicotine products (e-cigarettes) will be strictly prohibited on any UC Davis owned or leased property, indoors and outdoors, including parking lots and residential space.

MINIMUM QUALIFICATIONS

Minimum Education/Experience:

- Advanced research degree or equivalent education and research experience.
- Experience in planning and in project management in environmental and/or climate sciences research and/or policy.
- Networking experience to identify and collaborate effectively with appropriate individuals at universities, national laboratories, educational and public institutions, state and federal agencies, NGOs, and/or industry.

Minimum Knowledge, Skills, and Abilities (KSA):

- Scientific or technical writing skills to produce professional correspondence, documents, and presentations and/or related scientific peer reviewed articles and/or op eds.
- Knowledge and experience developing state and federal grant proposals.
- Knowledge of best practices and models for successful partnerships between academia and other entities.
- Time management and organizational skills to prioritize and effectively manage multiple, simultaneous projects with conflicting deadlines and follow tasks to completion with a high level of independence.

Continued on next page

Dear *Eos:*

We are on Muskegon Lake in Michigan on board the NOAA Great Lakes Environmental Research Laboratory's buoy tender R5503. In November 2021, at the end of the growing season, before ice sets in, we retrieved the Muskegon Lake Observatory buoy (www.gvsu.edu/buoy/). The observatory collects weather and water quality data at high frequencies—around 1 million data points each year. The urban Great Lakes estuary is affected by eutrophication, harmful algal blooms, and bottom water hypoxia. Our findings have relevance to coastal ecosystems everywhere that are similarly afflicted by anthropogenic disturbance and ongoing climate change.

This 11-year-long lake project keeps track of ongoing ecosystem changes in a model freshwater estuary; provides open-access environmental data in near-real time for advancing science, education, and outreach; and exemplifies a fruitful collaboration between a regional university, Grand Valley State University, and a national laboratory.

—**Bopi Biddanda,** Robert B. Annis Water Resources Institute, Grand Valley State University, Muskegon, Mich.; and **Todd Roetman, Andrew Yagiela,** and **Dan Burlingame,** Lake Michigan Field Station, NOAA Great Lakes Environmental Research Laboratory, Muskegon, Mich.

Send us your postcards at bit.ly/Eos-postcard