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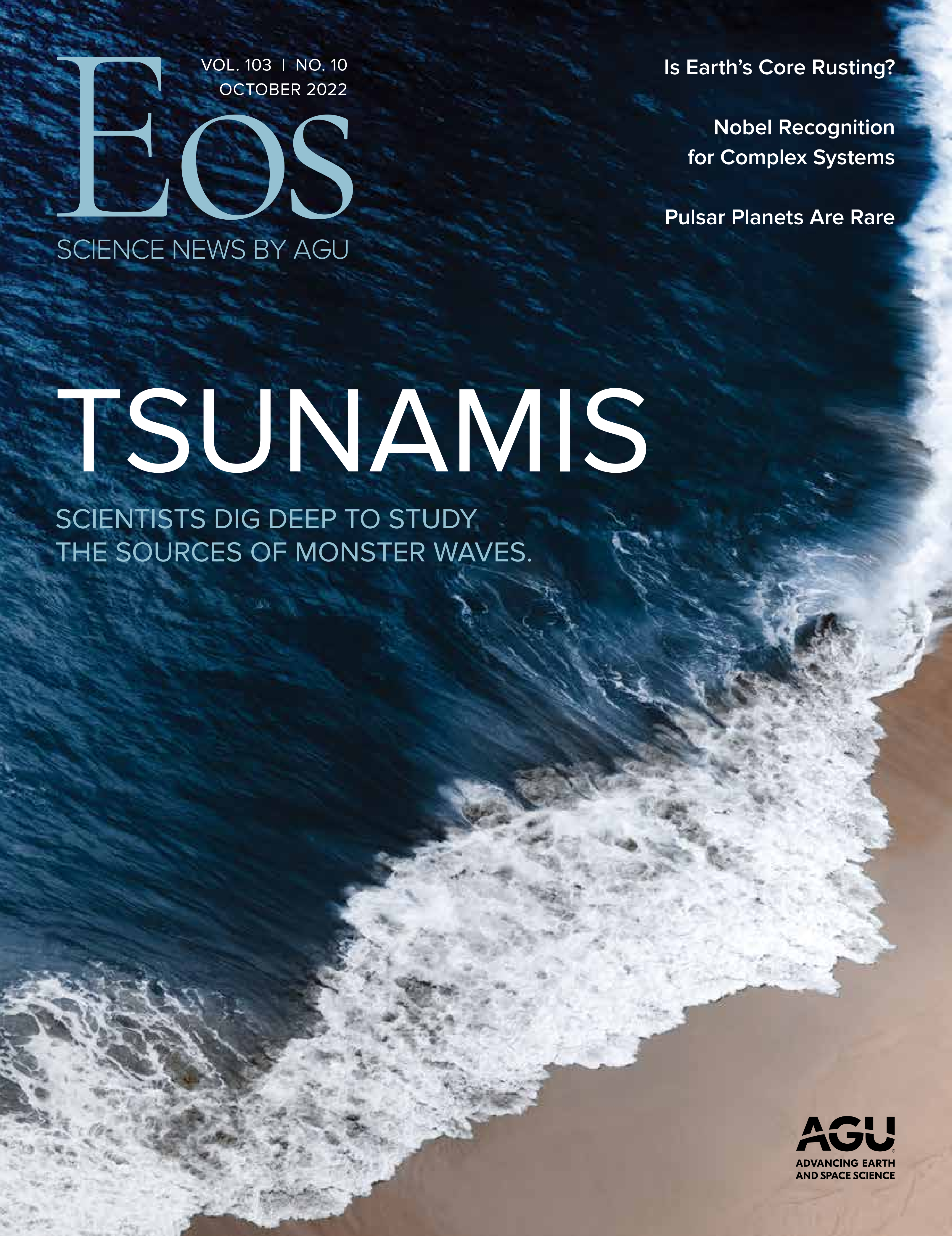
Eos

SCIENCE NEWS BY AGU

Is Earth's Core Rusting?

Nobel Recognition for Complex Systems

Pulsar Planets Are Rare



TSUNAMIS

SCIENTISTS DIG DEEP TO STUDY THE SOURCES OF MONSTER WAVES.

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Semantic segmentation for wildlife conservation.

Making Waves

Tsunamis are no ordinary waves. Their wavelengths are much longer than surface swells and are caused by a sudden displacement of water, not by wind. Studying tsunami sources can take scientists to the bottom of the ocean—and then below it. We dive deep into the sources of tsunamis in our October issue, literally from cradle to grave.

In "Seismic Sources in the Aleutian Cradle of Tsunamis," Rob Witter, Rich Briggs, Tina Dura, Simon Engelhart, and Alan Nelson remind us that tsunamis can devastate coastal communities; being better prepared for them will save lives and livelihoods around the world. In particular, tsunamis generated around the Aleutian Islands stretch far beyond their icy shores: In 1946, an Aleutian tsunami caused more than 150 deaths—in Hawaii, not Alaska. The scientists played sleuths to better understand the Aleutians' complex subduction megathrust, reassessing data from that 1946 tsunami, a mysterious 1788 tsunami, and even paleoseismic events in the region. Turn to page 20 to see how historic events are helping inform contemporary hazard preparedness.

A landslide graveyard is our next destination. Suzanne Bull, Sally J. Watson, Jess Hillman, Hannah E. Power, and Lorna J. Strachan show us how it can help us prepare for future tsunamis, on page 28. The graveyard in question lies beneath the Tasman Sea, and the scientists used a three-pronged strategy to investigate massive landslides that occurred there more than a million years ago. In addition to analyzing sedimentary basins and updating computational models, scientists sailed right into the "roaring forties" for fieldwork amid 8-meter swells. Find some firm footing and learn more in "'Landslide Graveyard' Holds Clues to Long-Term Tsunami Trends."

There's deep (seafloors and subduction zones) and then there's *deep* (Earth's core). In "Is Earth's Core Rusting?" Jiuhua Chen and Shanece S. Esdaille take one of the most familiar chemical compounds on the planet—rust—and explore how its possible presence in the outer core could result in intermittent bursts of oxygen at the surface. A rusty core could force scientists to do nothing less than reconsider Earth's interior and atmospheric evolution. Find the latest clues in one of the great unsolved mysteries in geoscience on page 34.

Speaking of intermittency, Daniel Schertzer and Catherine Nicolis make the case for "Nobel Recognition for the Roles of Complexity and Intermittency" on page 17. In 2021, the Nobel Committee for Physics bestowed landmark prizes on three giants in nonlinear geophysics. The prizes were awarded for advances in the physical modeling of Earth's climate, one of the most complex systems in a discipline built on complex systems. It's a fascinating look at a neglected, but entirely relevant, "category of mystery."

I'll close by recognizing another entirely relevant force making waves with AGU members. Heather Goss, *Eos*'s former editor in chief, is now our publisher (in addition to other duties as senior director at AGU). In her 4 years at the helm of this publication, she guided its growth in both depth and scope. We'll work to maintain the high standards she set.

Caryl-Sue Micalizio, Editor in Chief

Eos

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Randy Fiser, Executive Director/CEO

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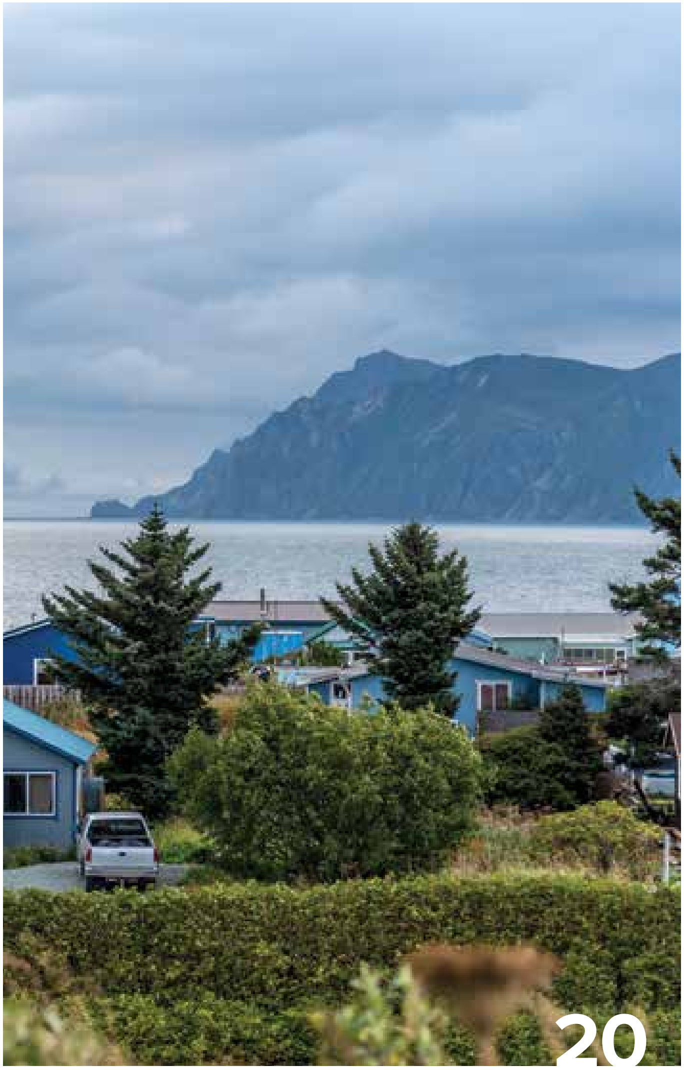

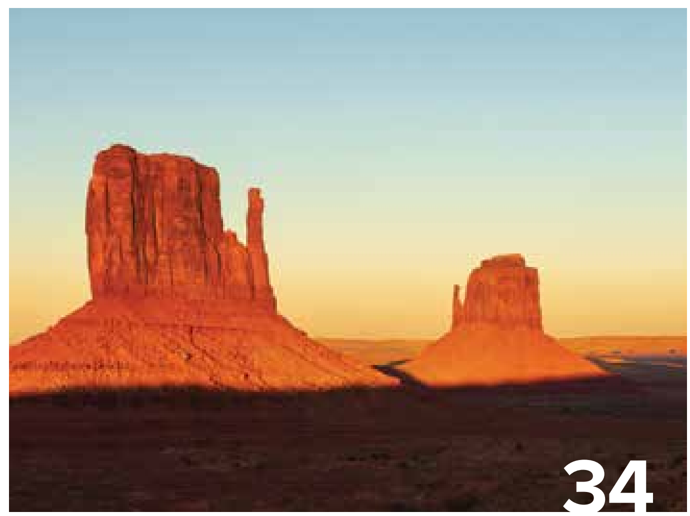

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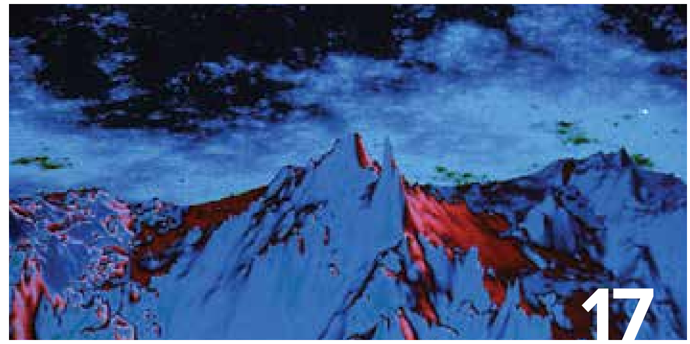

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Community Scientists Recover Micrometeorites from Lake Michigan

In the early morning hours of 6 February 2017, more than 500 people across 12 states and one Canadian province reported sightings of a bright green fireball. When weather radar data revealed the unmistakable trajectory of meteors into Lake Michigan, the hunt was on.

Researchers and nearby residents, including Chicago area teenagers, were quick to mobilize, but they failed to recover any large chunks of the extraterrestrial visitor. However, they didn't return empty-handed: The collaboration unearthed a slew of micrometeorites.

Scientists presented these findings at the 85th Annual Meeting of the Meteoritical Society in Glasgow, Scotland.

Students sift through mud from the bottom of Lake Michigan in search of meteorites. Credit: Johnny Ford/Shedd Aquarium

A group of teenagers spearheaded the design and building of a submersible sled that could be towed along the bottom of Lake Michigan. The coffee table–sized sled incorporated powerful magnets to pick up iron meteorites.

Tiny Emissaries from Space

Micrometeorites, which measure between roughly 0.01 and 2 millimeters in diameter, are relatively commonplace. Researchers have estimated that about 60 tons of cosmic dust rain down on Earth's surface each day. "This dust is everywhere," said Maitrayee Bose, a cosmochemist at Arizona State University who was not involved in the research. The trick, of course, is finding it—the vast majority of the dust on our planet is garden-variety Earthly dust, not extraterrestrial material. (Antarctica and Greenland, both relatively pristine environments, are good places to look, but even searches in urban settings have yielded micrometeorites.)

After the 2017 fireball event, a community science effort—the Aquarius Project—came together in the Chicago area to search for the culprit meteorites. The crowd grew to include team members associated with the Adler Planetarium, the Shedd Aquarium, the Field Museum of Natural History, and NASA. Guided by scientists and educators, a group of teenagers spearheaded the design and building of a submersible sled that could be towed along the bottom of Lake Michigan. The coffee table–sized sled, dubbed Starfall, incorporated powerful magnets to pick up iron meteorites.

In 2018 and 2019, Aquarius Project team members enlisted the help of a University of Wisconsin–Milwaukee research ship, R/V *Neeskay*, to put Starfall to work. While the ship cruised on Lake Michigan, the sled was lowered to roughly 60 meters below the surface and towed along the lake bottom. Not surprising, the sled's magnets picked up all sorts of rusted metal debris, but they also snagged some centimeter-scale objects that looked suspiciously like meteorites.

Ultimately, most of the candidate meteorites ended up being terrestrial rocks or bits of iron slag, but hiding within the lake sediments scooped up were what the team thought could be micrometeorites.

Spectroscopy Reveals Micrometeorites' Secrets

After encasing each candidate micrometeorite in epoxy, Maria Valdes, a cosmochemist at the Robert A. Pritzker Center for Meteoritics and Polar Studies at the Field Museum in Chicago, and colleagues hand polished them to reveal their interiors. The researchers then directed a green laser at each candidate micrometeorite and measured the different wavelengths of light the objects scattered. This technique, a type of spectroscopy, reveals chemical composition, said Valdes. "The spectral patterns are distinct chemical fingerprints of particular minerals," she said.

Five of the six candidate micrometeorites were composed largely of olivine or pyroxene, the team found. That's strong evidence that the objects really are micrometeorites, albeit the most common subtype dominated by silicate minerals, said Valdes. But the researchers were intrigued to find that the micrometeorites differed in texture: One was decidedly finer grained than its brethren. That finding said something about these objects' origins, the researchers suggested. "They don't seem to all come from the same parent body," said Valdes. Some of these micrometeorites might have been delivered by the 2017 event, but others probably weren't, the team concluded.

The micrometeorites "don't seem to all come from the same parent body."

In the future, Valdes and her team hope to analyze the isotopes of oxygen present in these micrometeorites. Such an investigation would shed light on the type of solar system object that originally shed these bits of cosmic dust, said Bose.

And in case that's not enough to keep the researchers busy, Valdes recently received a whole new batch of possible micrometeorites to investigate. "I've gotten about 50 more candidates," she said.

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

Sorting Minerals Differently Could Usher In a New Era for Mineralogy

Before Earth existed, there were minerals. Some stood witness as the solar nebula stashed stardust and meteorites coalesced to form our rocky abode. But the centuries-old system for classifying minerals focuses on what they are—missing the stories rocks can tell because of how they formed. Now, researchers have developed a new way to sort minerals—by their origins—and they've used this methodology to explore how Earth's minerals diversified across deep time.

"Minerals are information rich, but for the last almost 200 years, the way minerals have been classified is the complete opposite."

Currently, the International Mineralogical Association (IMA) categorizes minerals based on their composition and crystal structure. But minerals have more features that can be taken into account. From quotidian quartzes to dazzling diamonds, each mineral bears a wealth of characteristics: shape, color, isotopes, inclusions, magnetic properties, and more—not to mention the attributes of its geologic environment. "Minerals are information rich, but for the last almost 200 years, the way minerals have been classified is the complete opposite," said Robert Hazen, a mineralogist and astrobiologist at the Carnegie Institution for Science in Washington, D.C.

To learn about how minerals have diversified across the ages, mineralogists must consider time and mineral formation, Hazen said. So he and Shaunna Morrison, a mineralogist and planetary scientist also at the Carnegie Institution for Science, set out to mine the quarry of mineral literature for this information.

A Classification System for the Ages

Over a period of about 6 months in 2020, Hazen and Morrison dug through records on nearly 6,000 minerals recognized by the IMA, pulling entries from databases, reference books, and field studies. They tabulated the ways in which each mineral forms, sometimes making inferences based on associated minerals. It was "a labor of love," said Morrison. Their survey produced a database of 57 main methods by which nature cooked up all the known minerals on Earth, the duo reported in one of two studies published in *American Mineralogist* (bit.ly/mineral-formation).

On the basis of isotopic dating data, Hazen and Morrison also built a second database, including information about minerals from those that formed weeks ago to the oldest known samples on Earth—nearly 4.4-billion-year-old zircon crystals. The resulting timeline allowed the researchers to associate minerals with geologic milestones, such as when plate tectonics started shaking things up. Much of Earth's mineral diversity blossomed during the planet's first 250 million years, the researchers reported. (Plus, they identified 300 minerals that may predate our planet.)

The scientists concluded that more than 80% of minerals can form through water-rock interactions. "So water is the principal driver of mineral diversity," said Nathan Yee, a geochemist at Rutgers University who wasn't part of this work. Once oceans formed, lots of minerals emerged that represent most of those that we have on Earth today, he said.

Around 50% of minerals can form through biological processes, including development in living species themselves (such as corals or kidney stones), as well as through interactions like those between animal excrement and clay. "It really indicates just how intricately intertwined biology and geology and mineralogy are on our planet," Morrison said.

Some minerals can form through multiple processes. Calcite, for instance, can form in 17 different ways. Milky white calcite that forms in hot springs differs from precisely patterned calcite within a trilobite eye. Though they have the same chemical formula and crystal structure, they are different

Some minerals can form through multiple processes. The calcite specimen on the right was formed through fluctuating water levels in a cave, whereas the calcite on the right was formed by water deposition. Credit: irocks.com photo/Rob Lavinsky specimen products, Hazen said. In a second study also published in *American Mineralogist,* Hazen, Morrison, and their colleagues came up with a process to regroup the thousands of recognized IMA minerals on the basis of their formation processes and other characteristics that the current classification system misses (bit.ly/lumping-and-splitting).

Lumping and Splitting

In some cases, the team grouped several different IMA-recognized species together—for example, when species had the same structure, were compositionally similar, and were formed by the same process. In other cases, minerals that IMA combines could be split into new natural kinds, such as some types of calcite, because of the different ways they form.

"Water is the principal driver of mineral diversity."

The researchers also used a statistical approach to reveal combinations of physical or chemical properties that set minerals apart. For instance, they separated stellar moissanite, a silicon carbide formed around old stars and found in meteorites, into multiple types by considering differing isotopic signatures related to star type, Hazen said.

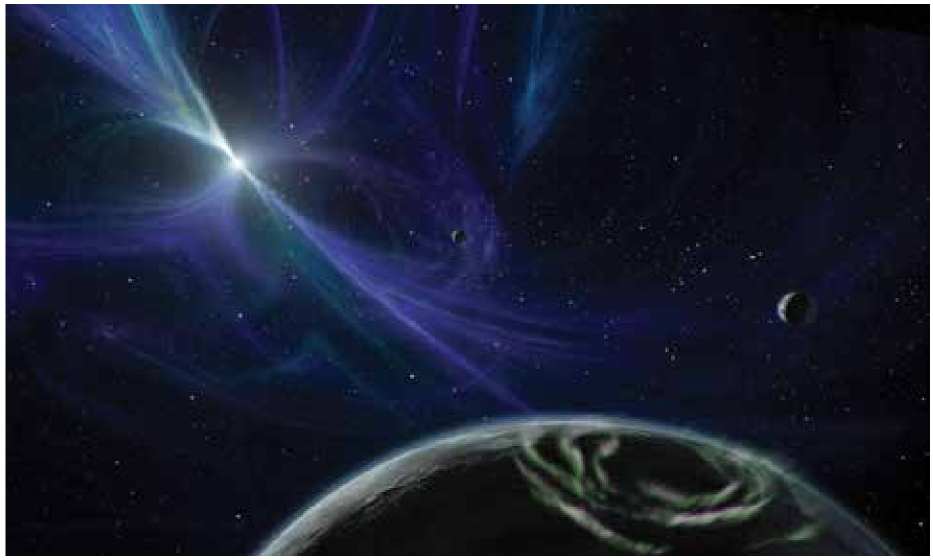
This lumping and splitting process yielded 7,816 natural mineral kinds. "It's really a big paradigm shift in the way we think about mineral classification," Yee said.

With new databases and tools, researchers could start making "incredible predictions" about where to find minerals and what minerals occur, and when, through geologic time, Yee said. Those insights could be useful in mining, studying microbial interactions with rock, and understanding the evolution of other rocky planets, like Mars. They may even allow researchers to establish a signature for whether a planet held life, Hazen said.

"If you reimagine minerals and how we describe them," Hazen said, "there's hardly an area of the Earth and planetary sciences that [classification] doesn't affect."

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

Pulsar Planets Are Exceedingly Rare



The first three known exoplanets around a pulsar, illustrated here, were surprising finds given how rare these planets are. Credit: NASA/JPL-Caltech, Public Domain

Thirty years ago, astronomers discovered the first exoplanets, a trio of Earth-sized rocky planets orbiting a dead star acting as a cosmic lighthouse. A new survey of hundreds of these lighthouses, or pulsars, revealed that the existence of those planets is the exception rather than the rule. Fewer than 0.5% of pulsars are likely to host planets heavier than 4 Earths, which deepens the mystery of how any planets exist in those systems at all.

"One of the main things about pulsar planets is we don't actually know how to get a planet around a pulsar," said Iuliana Nițu, a doctoral student at the University of Manchester in the United Kingdom and lead researcher on the new survey. "It's circular: You need to study the population to learn more about and constrain your models, which then tell you more about populations."

Planets of the Dead

A pulsar is born when a massive star dies. The star reaches the end of its atom-fusing life, goes supernova, and leaves behind a small, dense ball of neutrons spinning a thousand times per second. The neutron star continues to shed energy through energetic beams, and if the star is oriented just right, one of those beams will sweep across our field of view on Earth and appear to "pulse" at regular intervals (see video at bit.ly/Eos-pulsar-planets).

If another object—a neutron star, a white dwarf, a black hole, or, in rare cases, a planet—orbits the pulsar, the object's gravitational pull can subtly change the timing of the pulsing. The three planets around PSR B1257+12 and the five other pulsar planets later discovered were all found through pulsar timing variations that they induced.

Astronomers want to know how those planets can survive the violent deaths of their stars to begin with, and then continue to orbit the stars' leftovers. "The discovery of the first pulsar planet, and the first exoplanet, around the millisecond pulsar B1257+12 sparked some really interesting research on solar system evolution and just how much planets can take and still hang around," said pulsar astronomer Matthew Kerr of the U.S. Naval Research Laboratory in Washington, D.C. Kerr was not involved with this research.

The planets might have been there presupernova and survived, they might have formed afterward out of debris, or they might have been captured as they wandered past. The only way to narrow down the options, Nițu explained, is to find more pulsar planets and see whether they have anything in common that could point to how they formed. “There’s not really been any unbiased and big searches until now,” she said.

“Once some of the new telescopes…start to build up long data sets, we’ll be in a great place to find some planets, even if they are rare.”

To initiate the search, the team used archival observations from the Jodrell Bank Observatory in the United Kingdom and analyzed the timing regularity of nearly 800 pulsars. After searching for timing variations from objects with a wide range of masses and at a wide range of orbits, their computer algorithm flagged just 15 pulsars with irregular timing, most of which were previously known to be irregular for non-planet-related reasons.

The researchers discovered one pulsar, PSR B0144+59, with timing variations that could be consistent with an exoplanet but would need follow-up observations to confirm. On the basis of their results, they calculated that fewer than 0.5% of pulsars are likely to host exoplanets of 4 Earth-masses or larger, but that Moon-mass planets might still be possible but undetectable. (In contrast, Sun-like stars are likely to have at least one planet, on average.) The team published its results in *Monthly Notices of the Royal Astronomical Society* (bit.ly/pulsar-planets) and presented them at the Royal Astronomical Society’s National Astronomy Meeting 2022.

Out of the Ashes

For all their regularity, a pulsar’s pulses can actually be quite noisy, suggesting timing variations that aren’t really there. “That’s a bit of a spanner in the works,” Nițu said, “because how do you differentiate between the pulsars that are doing something weird and something orbiting around the pulsar?”

Despite these challenges, this is the largest survey of pulsar timing to date, and “I think the work and results are robust,” Kerr said. “In particular, because [the researchers’] sample is large and the type of pulsar is varied, I think it’s reasonable to treat their results as representative of the ‘true’ pulsar population, and thus safely conclude that terrestrial-mass planets around pulsars are quite rare, and Jupiter-mass planets are strongly excluded.”

According to Kerr, some recent supernova research has suggested that disks of rocky and dusty debris could last long enough for a new set of planets to form from the ashes of dead stars. “Identifying planets from such debris disks is a cool way to constrain those models.… And I think once some of the new telescopes—CHIME, MeerKAT, FAST, all of which have superb sensitivity—start to build up long data sets, we’ll be in a great place to find some planets, even if they are rare,” said Kerr.

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

Building Resilience in the Face of a Dwindling Colorado River

The Colorado River stretches from Rocky Mountain headwaters in Wyoming and Colorado more than 2,400 kilometers to the Gulf of California in Mexico. On its way, the river supplies water to the residents of the Colorado River Basin and millions of hectares of irrigated farmland and serves to generate affordable power for municipal and rural customers.

In the past couple of decades, however, severe drought has plagued the Colorado River Basin, and the current period is the driest in the past 1,200 years. The situation is so dire that on 14 June, U.S. Bureau of Reclamation commissioner Camille C. Touton told a U.S. Senate committee that states within the region will need to cut usage by between 2 million and 4 million acre-feet in 2023 to protect the Lake Mead and Lake Powell reservoirs.

"Right now, we find ourselves at a crossroads," said Karen Kwon, associate project director at the Colorado River Sustainability Campaign (CRSC). "We have an immediate crisis that we need to address."

In the past 20 years, various stakeholders have already been exploring pathways to resilience to dwindling water resources. Urban water authorities have increased water efficiency and are experimenting with changing city landscapes in Colorado, farmers are reducing their water use, and conservation groups are exploring how to keep fish habitat stable with reduced streamflow.

"The goal is to try and persist through the short term, adapt through the long term, and transform or transition to where we need to be," Kwon said.

Efficiency Is Key

Denver Water serves about a quarter of Colorado's population, but thanks to decades of efforts to step up water efficiency and conservation, it uses less than 2% of the state's water. The agency has curtailed outdoor watering, requires indoor fixtures to be water efficient, and is pushing for water-saving green building codes.

The city of more than half a million uses the same amount of water it did in the 1980s despite 92% growth in the past 4 decades.

The payback of such measures is that Denver, with a population of just over 715,000, has rolled back its water use by 50 years. "The customers in our service areas are using the same amount of water as in the mid-70s, despite adding half a million people and half a million jobs to our service area," said Greg Fisher, manager of demand planning at Denver Water.

Colorado Springs Utilities can boast a similar statistic: The city of more than half a million uses the same amount of water it did in the 1980s despite 92% growth in the past 4 decades. One step the utility has taken has been to rebate the conversion of nearly 167,225 square meters (1.8 million square feet) of turf grass to native species. The city's water conservation team also has two "waterwise" demonstration gardens where it tests many plant species, including 11 grasses, to determine water use and climate adaptability. "We have a large educational outreach component to all our work, which is critical to customer engagement," said Julia Gallucci, water conservation supervisor at Colorado Springs Utilities.

Although the water savings of cities have been impressive, it's the agricultural sector that uses 80% of the water in the Colorado River. Consequently, in light of prolonged drought conditions and climate change, farmers and conservation professionals have developed the Saving Tomorrow's Agriculture Resources (STAR) initiative. The goal of STAR is to encourage soil and water conservation and to provide technical and financial assistance to help farm operators and landowners evaluate their current practices and make decisions to reduce the nutrient and soil losses on their fields.

"If you increase soil health, you increase the water-holding capacity of the soil," said Les Owen, the Conservation Services Division

Soil moisture probes, useful for measuring the impact of drought on the Colorado River Basin, can be stationary or portable. Credit: Colorado Department of Agriculture director of the Colorado Department of Agriculture. Other department programs promote strategies such as improving irrigation practices to increase efficiency and reduce leaching of salts into the Colorado River.

"Looming deadlines for interstate compacts threaten the ability to irrigate a significant number of acres if we don't really adapt and be flexible," Owen said. "So agricultural producers are hungry for alternatives."

"I understand we have completely different value systems, but we all need water, and we need to do this not just for ourselves but for future generations."

Caring for the Environment

While the Colorado River community explores how to withstand the immediate crisis and navigate the "new abnormal," it is important not to overlook caring for the environment, Kwon said. Consequently, the CRSC supports conservation groups that strive to sustain healthy populations of fish and wildlife in the basin, such as Trout Unlimited (TU).

In Wyoming, a headwater state of the Colorado River, TU works with landowners and other stakeholders to protect important habitats, reconnect degraded waterways, and restore trout populations in rivers. Its focus in the state is on improving the infrastructure of irrigation—such as getting rid of the push-up dams that have impacts on the surrounding wetlands and installing more efficient structures in their place. "We do whatever we can to improve water delivery while maintaining fish passage," said Cory Toye, the TU Wyoming water and habitat program director.

TU considers the whole environment when attempting to build resilience, incorporating the needs of rivers, wildlife, and people who use river water. It's an approach modeled by the many Native American tribes that have lived sustainably in the Colorado River Basin for millennia.

In addition to providing water to more than 40 million people in two countries and seven states, the Colorado River also supplies water to 29 federally recognized Native American tribes. The river and its tributaries supply these tribes with water for domestic, commercial, and agricultural use; power generation; and cultural and religious activities. Combined, the tribes hold rights to roughly 20% (or 2.9 million acre-feet) of the water in the Colorado River Basin.

On the Hopi Reservation in northeastern Arizona, Indigenous farmers have used a myriad of techniques to preserve soil moisture in the high desert and make the most of every single drop of water. Their agriculture, like that of most Native American farmers, also preserves biodiversity. "Without biodiversity, we have no true sustainability," said Michael Kotutwa Johnson of the Indigenous Resilience Center at the University of Arizona, who is also a Hopi farmer.

This demonstration garden includes native grasses and species that thrive in Colorado and don't require watering. Credit: Colorado Springs Utilities

Soil health specialist Ryan Taylor demonstrates the installation of soil moisture probes. Credit: Colorado Department of Agriculture

Given that they have some of the oldest water rights in the basin, the tribes have the legal authority to play a significant role in balancing the water demand and supply in the region. Their extensive experience in living sustainably and stewarding the environment will be vital to efforts to ensure the future health of the Colorado River Basin in the face of climate change.

In addition, Native American communities have always talked to each other and are well practiced at trying to reach a consensus about major decisions, Johnson said. Building a resilient future for the Colorado River will require a similar approach and will involve all the different parties coming to the table and working to have a better understanding of each other's needs. "I understand we have completely different value systems, but we all need water," Johnson said. "And we need to do this not just for ourselves but for future generations."

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

Evidence of Drought Provides Clues to a Viking Mystery

It's a mystery scientists have long been investigating. Why, after more than 450 years, did a colony of medieval Norse farmers disappear from their remote Greenland settlement?

In attempting to uncover what may have happened, researchers have returned again and again to climate—and to a seemingly obvious scenario. Having turned up on the island during the centuries-long Medieval Warm Period, the settlers were then gradually ushered out by the arrival of the Little Ice Age in the 14th century.

But a new study has found that drought, not plunging temperatures, may have pushed an already fragile community to its breaking point.

"There's been a lot of focus on temperature when we think about climate change in the Arctic, and there are some good reasons for that," said Isla Castañeda, coauthor of the study, published in *Science Advances* (bit.ly/Viking-mystery). Her team, however, found little temperature variability directly at the Norse settlement sites in southern Greenland. "So we started looking at another technique to reconstruct relative humidity, which gives an indication of drought," she said, "and there we saw a pretty significant change."

Researchers have tended to extrapolate Little Ice Age climate effects in western Europe and Iceland and, perhaps erroneously, relate them to the fate of the Norse in North America.

The Viking (Ice) Age

Around 985 CE, at the height of the Viking era, a group led by exiled explorer Erik the Red sailed west from Iceland and established the first European settlement on Greenland. The Norse farmed the land and hunted walrus for the ivory trade. It's estimated that at its peak, Greenland's Norse community numbered around 2,200 inhabitants. They made their homes in the small Western Settlement, near the modern-day capital of Nuuk, and the somewhat misnomered Eastern Settlement in the south. Over the centuries, they weathered social and economic changes, agricultural challenges, and, evidence suggests, the weather itself. Though they inhabited Greenland concurrently with Indigenous Dorset and Thule populations, archaeological findings show that the Norse never adopted effective Indigenous sea ice hunting practices or tools. Other evidence indicates conflict between the two populations.

According to radiocarbon dating, by 1450, the Norse settlers were gone.

The Little Ice Age, a period of cooling temperatures, began around 1300 and affected different parts of the globe at different times until the mid-19th century. Yarrow Axford, a paleolimnologist at Northwestern University who was not involved in the new study, said researchers have tended to extrapolate Little Ice Age climate effects in western Europe and Iceland and, perhaps erroneously, relate them to the fate of the Norse in North America.

"I'm really excited to see any new data that we can bring to bear on this mystery," she said.

Going Local

There have been relatively few temperature reconstructions in Greenland, according to Castañeda, and many of those come from ice core samples taken far from the settlement sites and at a higher elevation. To figure out what happened to the Norse, she said, "we really needed records from closer to where they were living."

Castañeda is an organic chemist and an associate professor in the Department of Geosciences at the University of Massachusetts Amherst. She and her colleagues applied organic geochemical tools to reconstruct the temperature more locally, taking sediment samples from Lake 578, which is adjacent to an Eastern Settlement farming site. Some bacteria found in the lake adjust their membrane lipids in response to temperature, and analysis of these compounds in dated sediment cores provided a quantitative reconstruction of historic temperatures. The research team then extracted plant leaf waxes from the same sediment cores and analyzed their hydrogen isotope levels, which indicate moisture levels at time of growth.

In looking at both temperature and hydroclimate, the researchers made two surprise findings. "We were expecting to see this dramatic temperature drop at the end of the

The research team collects bathymetry data from a lake in southern Greenland. Credit: Isla Castañeda

Norse settlement period, if temperature was indeed the main factor that caused them to leave," Castañeda said.

Instead, the leaf waxes revealed that Greenland had experienced a relatively wet period just before the settlers arrived, and conditions became drier over time, peaking in the century after the Norse abandoned the site. According to the study authors, this long-term drying trend would have decreased summer grass yields, a critical source of winter fodder for livestock.

Supporting these findings, reported the study are two pieces of archaeological evidence: irrigation channels at a Norse farming site in Igaliku and a transition to a marine-based diet, which suggests that the Norse came to rely more heavily on seal hunts as drought limited the availability of meat from livestock.

"The real challenge is to actually draw a very close connection between what we see in terms of prevailing trends at the settlement scale and the human activities that reflect a cause-and-effect response."

To gain insight into modern Greenlandic agriculture, the team spoke with local farmers and learned that even today drought conditions are a top concern. These farmers are "living in the same spot as the Vikings," said Boyang Zhao, a paleoclimatologist and postdoctoral research associate at Brown University who coauthored the study as a Ph.D. candidate at Amherst. According to locals, he said, "it's OK if the summer is a little bit cooler. However, if there is less rainfall in summer, they won't have enough hay to overwinter [livestock]." Under these circumstances, modern Greenlanders rely on imports. The Norse could not.

Science Surprises Us

The team's study, said Axford, "highlights how important it is to look at hydroclimate, to look at changes in precipitation and evaporation...and how [they] affected societies in the past." But, she added, "I don't think it's going to be the last word. We need more data."

Boyang Zhao (left) and Tobias Schneider assemble a gravity corer at a lake in southern Greenland. Credit: Isla Castañeda

Commenting on the findings, Rowan Jackson, a geographer and archaeologist at the University of Edinburgh, agreed. "We do need more evidence locally to corroborate these records," he said. "And although we can look at evidence of climate such as this, the real challenge is to actually draw a very close connection between what we see in terms of prevailing trends at the settlement scale and the human activities that reflect a cause-and-effect response."

In considering the study's evidence of adaptive strategies, Jackson pointed to irrigation channels at the Eastern Settlement site of Gardar. "We can interpret irrigation systems as evidence of adaptation to a drier climate," he said. "But you need to infer that across other farms as well."

Jackson's research looks at whether the Norse settlers may have clung to a cultural identity that was closely tied to farming, which may explain why they apparently failed in the face of climatic challenges while the nomadic Indigenous populations survived. Combined with farming, he said, Norse hunting strategies would have become increasingly inefficient.

Marisa Borreggine, a Ph.D. candidate in the Department of Earth and Planetary Sciences at Harvard University, is studying the effects of rising sea levels on Greenland's Norse population. Their research argues that an advance of the southern Greenland Ice Sheet during the Little Ice Age led to local sea level rise and an inundation of coastal areas that would have affected Norse settlements.

"But science surprises us all the time."

"Past studies...have been focused on trying to find a singular environmental cause as to why Vikings might have left southern Greenland, and in the past, that's been really, really focused on temperature," Borreggine said. Through their research, they and the study team at Amherst are both trying to contribute a more in-depth look at the environmental factors at play, Borreggine explained. "There's a wide array of social and political and environmental factors that could have contributed to Viking out-migration, and we're able to [provide] more specific details on why a certain environmental factor could have been part of that story."

Could multiple findings on climate during the settlement period be accurate? The answer may come down to where researchers are looking. "I would be surprised if temperature trends were that spatially variable," said Axford. "But science surprises us all the time."

Zhao and his team acknowledged that many other factors were at play toward the end of the settlement period—disruptions to the ivory trade and plague in Europe among them. "We're trying to highlight that this drying trend could have been another disadvantage of being in Greenland during that time," he said.

Though deeper research into fluctuations in temperature and precipitation offers a more nuanced picture, the puzzle is still incomplete. But the pieces, when put together, may provide insight into a future in which climate and cultural adaptation are bound to increasingly intersect.

By **Korena Di Roma Howley** (@KDRHowley), Science Writer

Community Science Project Helps Track Geohazard Risks in Uganda

Senior citizens take part in a mapping workshop in the Kigezi Highlands of Uganda. Credit: Violet Kanyiginya

Senior citizens are among a group of volunteers helping to build a picture of geohazard risk in a populous mountain region in Uganda. By gathering localized data, participants in this initiative aim to identify communities vulnerable to landslides and flooding and to contribute to improved early-warning systems.

The Kigezi Highlands is a tropical region in southwestern Uganda that has undergone significant population growth in recent decades. Fertile soils attract subsistence farmers, who typically grow potatoes, climbing beans, and sorghum, used to make a popular local brew.

Landslides and floods are a part of everyday life in Kigezi, as the steep slopes of the Virunga Mountains and annual rainfall of between 1,200 and 1,300 millimeters lead to high erosion rates. Today the threat is growing as farmers cultivate hillsides that historically were pastoral land and as infrastructure expands. Landscapes are increasingly fragmented, and more people are living in the vicinity of hazards.

"Most farmers in the Kigezi Highlands have lost crops during the rainy season, and that brings a high risk of famine," said Violet Kanyiginya, a geoscientist from Mbarara University of Science and Technology in Uganda who is currently based at the Royal Museum for Central Africa in Belgium.

Kanyiginya coordinates a project to track hazard risks in the Kigezi region, which she presented at the European Geosciences Union General Assembly 2022.

In 2019, Kanyiginya's team collaborated with the district disaster management committee to identify Kigezi parishes that face the highest risks. They appointed 15 "geo-observers" from local communities who were trained to report information on eight different natural hazards using a smartphone app. In 2020 the team was expanded to include "river watchers," who record daily stream levels in eight different catchment areas.

Once geo-observers become aware of incidents—often via contacts in their communities—they travel to the site to take photos and ascertain details, including hazard type, when it happened, and the scale of the affected area. Within the first 24 months, geo-observers identified 266 natural hazards, with landslides being the biggest risk.

Each geo-observer is provided with a phone, mobile data, and money to cover transportation costs. They are not paid for their time, which is crucial, Kanyiginya said. "We want local people to own [these] data and feel like [they are] their own," she explained.

Kigezi residents cite several motives for becoming involved in the project, with the desire to become a spokesperson for the community being a common thread. "I wanted the world to know about the disasters in our community," said one geo-observer in conversation with the project team. Another shared that "being a geo-observer has made me famous in the community—this helped me to even win the recently concluded political campaigns."

"Being a geo-observer has made me famous in the community—this helped me to even win the recently concluded political campaigns."

Coproducing a Timeline of Environmental Change

In an additional part of the project, Kanyiginya's team engaged more than 100 senior citizens (most aged between 70 and 80 years) to build a picture of how the local landscape changed over the past 60 years. People who were mobile met to take part in mapping workshops. Older or less mobile members of the community received home visits.

Socioeconomic and historic information anchored participants' memories to specific periods. For instance, they were asked to describe what roads, wetlands, animals, or natural hazards existed during the rule of President Idi Amin, who led Uganda from 1971 to 1979. Common narratives from different periods emerged and were corroborated against historical photos and a series of satellite images. The exercise reinforced the findings that hazard risk is increasing with land use changes, such as cultivating hillslopes, abandoning fallowing practices, and replacing natural tree species with exotic ones.

"Memorialization of past hazardous events is so important in disaster risk reduction," said Anna Hicks of the British Geological Survey, who researches crowdsourced and community science methodologies. "Inviting older community members to share their experiences of past landscapes—both social and physical—and how they've changed over their lifetimes, is a powerful process for both storyteller and listener."

Geo-observer data are more precise than satellite-based data for landslides and floods, with fewer false positives.

Making the Data More Reliable

The Kigezi work is part of a larger program in Uganda that previously established a geo-observer network in the nearby Rwenzori Mountains in 2017. A recent analysis of the Rwenzori network found that geo-observer data are more precise than satellite-based data for landslides and floods, with fewer false positives.

Human errors do creep into the data, however. Geo-observers sometimes confuse natural wetlands with flooded regions or enter the wrong dates, and their photos do not always reveal the hazard itself. To reduce these errors, annual refresher workshops tackle common issues.

Funding has been provided for the Kigezi project to run until the end of 2023, and it will be followed by a 10-year related project covering a wider area. Jonathan Paul, a geoscientist at Royal Holloway, University of London, believes the key to long-term success in crowdsourced and community science projects is to integrate data collection into people's everyday routines, by, "for instance, using social media or WhatsApp, instead of an entirely new app that may not be very easy to use," he said.

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

Maui Endures More Drought and Drier Streams

The 122-meter Waimoku Falls, above, in the Kīpahulu District of Maui's Haleakalā National Park is fed by highland freshwater streams. Credit: Kimberly M. S. Cartier

The Hawaiian Islands have been experiencing the effects of severe drought for months. On an island like Maui, drought burdens ecosystems already under siege from invasive species, worsens water scarcity issues, disrupts agriculture and fisheries, and endangers Indigenous Hawaiian ways of living.

Recent research led by Ayron Strauch, a hydrologist at Hawaii's Commission on Water Resource Management at the Department of Land and Natural Resources (DLNR), has shown that over the past century, drought events have been increasingly common on Maui and other Hawaiian islands even during the wet season. Droughts have led to frequently dry freshwater streams, a situation that disrupts downstream ecosystems and slows groundwater recharge.

"We've had long-term decline in rainfall and long-term decline in streamflow, but we've seen acute declines in rainfall most recently.... The majority of months for the last 15 years have been below average," Strauch said.

Wai Supports Maui Ecosystems

"Water is extremely valuable on tropical islands," Strauch said. "It's used for drinking water supply, hydropower, and agricultural irrigation, and it's diverted from streams all across the state." The groundwater aquifers beneath Maui are small, thin, and vulnerable to saltwater intrusion, so "depending on your location within the island, as much as 80% of your drinking water might come from surface water."

In addition to these ecosystem services, streams help maintain the balance of biodiversity on Maui in freshwater ecosystems and transport nutrients to nearshore saltwater ecosystems like reefs. Too, fresh water, or wai, is sacred in Hawaiian culture, and a threat to streams also threatens the practice and preservation of Indigenous ways of life.

Using a combination of fieldwork, modeling, and archival information, Strauch and his team at DLNR and the University of Hawaiʻi at Mnoa examined streamflow rates and drought conditions across Maui for the past 100 years. They found that although median annual rainfall rates have declined by only a few percent per decade over the past century, the geographic and temporal pattern of rainfall has shifted.

In recent decades, some regions on Maui experienced a modest (less than 5% per decade) increase in annual rainfall, whereas other regions have seen up to a 40% decline per decade. Of more significance, the rainfall was released by only a few intense storms rather than being persistent and steady, as it was in decades past. Even during the 2022 wet season, the entire state of Hawaii experienced some state of drought; during the 2021 dry season, 29% of the state, including Maui, experienced severe, extreme, or exceptional drought.

"Our streams are very flashy," Strauch said. "They respond quite rapidly to rainfall. If the rainfall isn't distributed evenly across the year, our streams are still going to go dry, because all that water just falls right off to the shore." Moreover, Maui's groundwater aquifers recharge through persistent rainfall rather than bursts, so not only do surface water sources remain dry, but groundwater reservoirs fail to recharge as well. Strauch presented this research at AGU's Frontiers in Hydrology Meeting in San Juan, Puerto Rico.

Biodiversity Is Strength

The resilience of Maui's ecosystems lies in their biodiversity, explained Keoki Kanakaokai, natural resource manager for the Maui terrestrial program of The Nature Conservancy in Hawaii. Invasive species—plants, animals, viruses, and pathogens—are the chief threat to that biodiversity.

"Invasive species worsen the impacts of drought, and drought worsens the impact of invasive species," he said. Native plants like ʻōhiʻa lehua evolved to efficiently gather water from the air, share water among other native species, and recharge groundwater reservoirs. Invasive plants like Himalayan ginger and strawberry guava tend to monopolize and hoard water, inhibiting groundwater recharge and depriving native plants. Invasive land animals (any mammal except the Hawaiian hoary bat), and especially ungulates, like pigs, goats, and deer, disturb the soil, which worsens erosion and surface water retention. Then when drought and wildfires blight the landscape, invasive rather than native species are the first to grow back.

Dehydration of freshwater streams and increased erosion reduces the nutrients that flow to nearshore ecosystems and fisheries and increase harmful sedimentation. "As a Hawaiian growing up on the ocean, that's always been the refrigerator," Kanakaokai said. "But unfortunately, the impacts to our estuaries, our waterways, our nearshore fisheries and coral reefs, and our spawning grounds, in addition to marine invasions…all of those things combine to diminish our food security."

"That loss of biodiversity, the loss of species makes our watersheds less abundant and less resilient to other invasions, other climate changes, and other changes on the landscape," Kanakaokai said. Kanakaokai was not involved with this research.

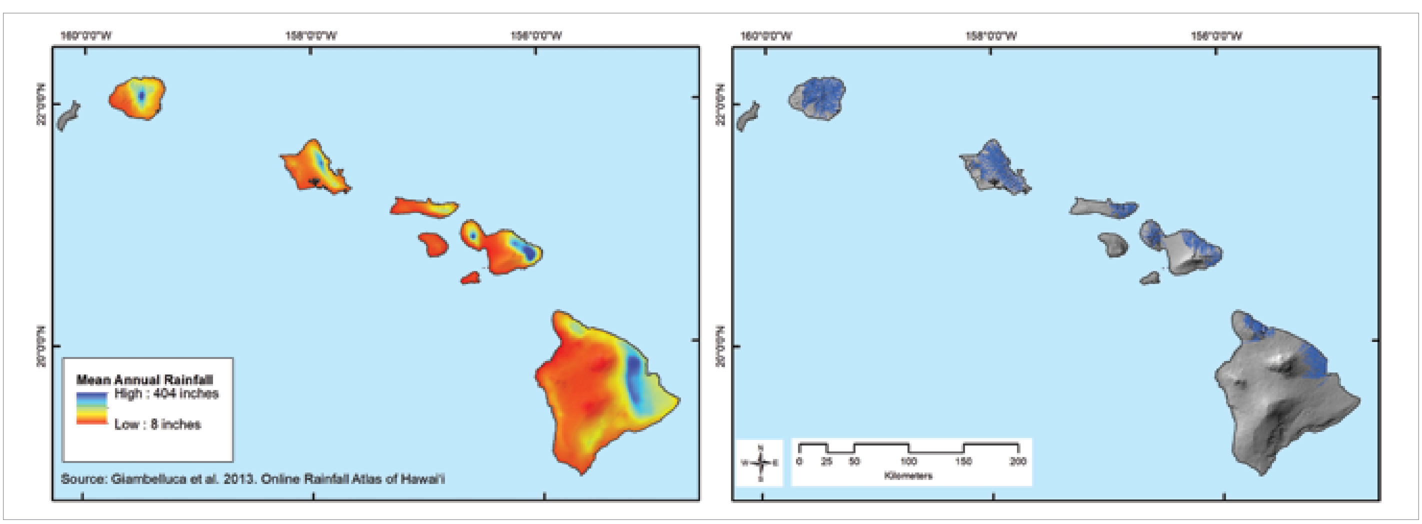
Restoration and Kilo

Ultimately, swift and robust climate action will reduce the frequency and severity of drought on Maui and other Pacific islands. But much can be done in the meantime to mitigate the impacts of drought on island ecosystems. For example, building and maintaining fences can keep invasive ungulates from damaging vulnerable ground and spreading non-native plant seeds and pathogens.

What's more, "if we controlled certain invasive [plants] and restored our native forests, we could improve groundwater recharge by 5% or 8%, which could be huge," Strauch said. "That could be the difference between major suffering from lack of water to being OK."

Conservationists like Kanakaokai and others across the islands work diligently to curb the invasion of non-native plants and restore native forests, including reestablishing many plant species that are on the brink of extinction. Although the restoration work is becoming more difficult each year, he said, "the wonderful thing is there's so much that can be done…if we control the threats, remove the threats from the landscape, then our native species can rebound. It still has that resilience built into it."

Freshwater pools and streams like this one below Waimoku Falls on Maui are a critical source of nutrients for nearshore reef ecosystems. Credit: Kimberly M. S. Cartier



Average annual rainfall on the Hawaiian Islands (left) spans a range of 2 orders of magnitude and supports the biodiverse tropical ecosystems of the islands. Perennial streams (right, blue lines) are unevenly distributed across the islands, and persistent rainfall, rather than infrequent deluges, allows them to remain wet throughout the year. Many of the islands' land-based and nearshore ecosystems also rely on fresh water from intermittent streams (not shown here) that can dry up between significant rainfall events. Credit: Ayron Strauch, DLNR Hawaiʻi

A native ʻōhiʻa lehua tree grows in a lava field (left). Invasive Himalayan ginger grows abundantly in a forest within a volcanic crater (right). These photos were taken a few kilometers apart in Hawaiʻi Volcanoes National Park. Credit: Kimberly M. S. Cartier

In addition to restoring indigenous species to the landscapes, Kanakaokai said, there has been great progress in propagating endangered native species in greenhouses, in plant nurseries, and even in suburban landscaping around houses, schools, and new developments. Communities across Hawaii are increasingly embracing sustainable agriculture and restoration of native landscapes.

"We take into consideration more than just Western empirical science; we also incorporate Traditional Ecological Knowledge [and] traditional ways of knowing. In particular, we value things like kilo, the Hawaiian concept of observation and building relationships with our resources." Hawaiian cosmogony includes recollections of life forming in an evolutionary manner, he explained, so "Hawaiians view these [ecosystems] as our ancestors. We view these as our own histories that are sacred, that need to be protected for their inherent value to us as family members."

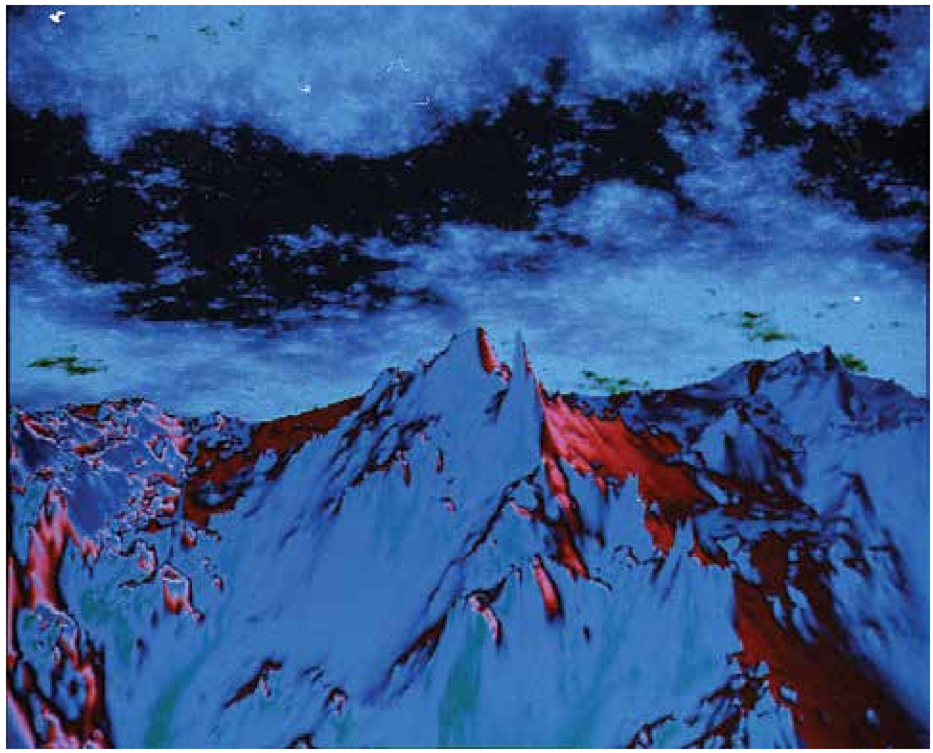
By **Kimberly M. S. Cartier** (@AstroKimCartier), Staff Writer

Nobel Recognition for the Roles of Complexity and Intermittency

Most of us would instinctually agree that Earth is a complex system, without even requesting a precise definition of this concept, and likely also that unraveling the planet's complexity is a fundamentally important role for science. Less recognized is how our understanding of this complexity greatly benefits from developments in the study of nonlinear geophysical processes as well as of exotic concepts in statistical physics.

Until recently, the Nobel Committee for Physics was more used to awarding prizes to scientists for tracking down the elementary building blocks of the universe. Yet in October 2021, the committee awarded the prize jointly to three scientists who revolutionized nonlinear physics with insights into complex systems. Specifically, Syukuro Manabe and Klaus Hasselmann were honored "for the physical modelling of Earth's climate, quantifying variability and reliably predicting global warming," and Giorgio Parisi was honored "for the discovery of the interplay of disorder and fluctuations in physical systems from atomic to planetary scales."

The diverse approaches and work of the three recipients, though groundbreaking, do not detract from the global challenges posed by complex systems [*Nicolis and Nicolis*, 2009, 2012]. And in giving these awards, the committee clearly identified the significance of understanding these systems, highlighting, for example, the importance of turbulence and, more precisely, the ubiquitous and multifaceted phenomenon of intermittency.



Both the mountains and the highly structured cloud cover in this image are characterized by strong variability that is further concentrated over small fractions of space, demonstrating intermittent behavior. Although it appears real, albeit in false color, this spectacular scene was nevertheless generated numerically using purely random multifractal processes that are basic ingredients of complexity theory. Credit: Daniel Schertzer, adapted from Schertzer and Lovejoy *[1991]*

The Nobel recognition affirms the primordial importance of these phenomena and validates the investments and work that have gone into the study of nonlinear physics and complex systems.

This recognition affirms the primordial importance of these phenomena and validates the investments and work that have gone into the study of nonlinear physics and complex systems over the past several decades.

Defining Complex Systems and Intermittency

According to the French Roadmap for Complex Systems, which was developed to coordinate and focus research on complex systems, "a complex system is in general any system comprised of a great number of heterogeneous entities, among which local interactions create multiple levels of collective structure and organization…[that] cannot be easily traced back to the properties of the constituent entities." Natural examples of complex systems range from biomolecules and cells to social systems and the ecosphere; sophisticated artificial systems, such as the Internet, power grids, and large-scale distributed software systems, also qualify.

Turbulent flows—either oceanic or atmospheric, for example—are classic examples of complex systems, as they comprise a large number of eddies with a wide range of sizes. This multiplicity of eddies causes these flows to be very agitated and to experience continuous mixing and velocity fluctuations in both amplitude and direction. Laminar flows, in contrast, are smooth, and their streamlines are easy to identify. Understanding the transition from laminar to turbulent flow is considered a prime example of the difficulties of characterizing the boundary between order and disorder in nonlinear systems (i.e., systems whose response is not proportional to the perturbation) [*Nicolis*, 1995].

A further degree of complexity in turbulent flows is called intermittency, which refers to the nonhomogeneous nature of agitation in a turbulent flow. This trait is commonly experienced by air travelers when planes are violently shaken by pockets of turbulence corresponding to clusters of strong velocity gradients. Intermittency is, in fact, a ubiquitous property of complex systems—including Earth's climate—in which increasingly high levels of activity are generally concentrated in ever smaller fractions of space.

Manabe's work laid the groundwork on which all modern climate models, known as general circulation models, are based.

Climate Models and Spin Glasses

The scientific study of climate and attempts to uncover its past and project its future behavior rely on both deterministic and stochastic models. These models can be either simple (low-order) mathematical models or detailed (high-order) numerical ones based on physical principles and developed to simulate climatic phenomena that operate over multiple time and space scales within the Earth system.

Manabe was recognized by the Nobel committee for designing and developing one of the first consistent, high-resolution, deterministic numerical global climate models. His work combining multiple climate components (e.g., displaying an ocean-continent configuration) operating at different time and space scales into a single model laid the groundwork on which all modern climate models, known as general circulation models, are based [*Manabe and Wetherald*, 1975].

Hasselmann modeled a simple climate system forced by random fluctuations (Gaussian white noise in technical terms) representing small-scale weather components (e.g., daily local temperature) that evolve much faster than climatic components averaged over longer time intervals (typically over a year). The spectral properties of the climatic variables obtained with Hasselmann's model agreed with those observed over large-scale subranges (i.e., averaged variables over time ranges of interest as obtained experimentally) [*Hasselmann*, 1976], providing a fair return for Joseph Fourier, the father of spectral analysis, who had perceived the greenhouse effect as early as 1824.

Decades of innovation in climate modeling have occurred since the groundbreaking works of Manabe and Hasselmann and their colleagues. However, the inevitably finite memory of computers used to conduct numerical experiments still forces researchers to simplify or truncate the equations modeling the full physical system at hand (as described by the laws of nature). A typical simplification involves resolving the mathematics of numerical computations at time and space scales much larger than those at which physical phenomena operate in reality. For example, the dissipation scale of turbulence is on the order of millimeters, whereas global climate models resolve system behavior over scales of at least a few tens of kilometers. As a result, one cannot access probably the most characteristic dynamic feature of the atmosphere and climate, namely, intermittency.

Parisi, in his work, further emphasized the role of fluctuations in complex systems to the point of rethinking statistical physics of nonequilibrium systems. For example, he established that magnetic fluctuations could break the "replica symmetry" of spin glasses. Spin glasses—media (e.g., metal alloys) whose magnetic spins, as well as their coupling, are randomly distributed, unlike classical ferromagnetic media in which all spins are aligned and their coupling is homogeneous—are iconic examples of systems that, like turbulence, cannot reach equilibrium. Both of these types of media generate extremely complex and rather similar energy landscapes. Statistical properties of spin glasses used to be calculated by averaging over many copies or replicas (the "replica trick"), therefore assuming a symmetry among these replicas, but that approach proved to be adequate only for high temperatures. Parisi resolved this problem for all temperatures, and he and others subsequently found that his insights and mathematical formulations regarding spin glasses could also apply to and help explain a multiplicity of other complex systems, including artificial intelligence and, indirectly, turbulence and its intermittency.

Researchers subsequently found that Parisi's insights and mathematical formulations regarding spin glasses could also apply to and help explain a multiplicity of other complex systems.

Nonlinear Geophysics Through the Years

At several stimulating conferences in 1983, scientists discussed the growing conviction that the activity of turbulence and other nonlinear systems clusters not on a single fractal set as was previously supposed [e.g., *Frisch et al.*, 1978] but, rather, over a hierarchy of multiple fractal sets corresponding to different levels of activity. Particularly notable that summer was the "Turbulence and Predictability in Geophysical Fluid Dynamics" meeting held in Varenna, Italy, and organized by Michael Ghil, Roberto Benzi, and Parisi. It was at this conference that *Parisi and Frisch* [1985] presented a first version of their multifractal formalism for turbulence—and in fact, this is when the term multifractal itself was introduced. Also raised were the first questions about the relationship of this statistical formalism with stochastic cascade models, whose paradigm can be traced back to *Richardson* [1922] and which, by way of iterated random multiplications, generate an increasingly heterogeneous flux of energy to smaller and smaller scales. In particular, it was argued that the multifractal formalism could not yield the extremes of the cascade models [*Schertzer and Lovejoy*, 1984].

Debates on these issues have continued over the years at other conferences and in publications, for example, in the "Nonlinear Variability in Geophysics" conference series [*Schertzer and Lovejoy*, 1991], in multiple sessions at AGU and European Geosciences Union meetings, and in the journal *Nonlinear Processes in Geophysics*. The advances that have come out of these debates and Parisi's work on spin glasses have served to widely extend to more abstract statistical physics the well-known role of the Legendre transform in thermodynamics to map conjugate couples of statistical variables onto each other (e.g., temperature or potential onto entropy or energy and vice versa). In the case of intermittency, the scale dependence of statistical moments maps onto that of probabilities,

Ongoing work is increasingly advancing our understanding of complex systems involved in Earth's climate and other natural and artificial processes.

succeeding in linking two apparently different statistical approaches to understanding intermittency and providing new means to measure and simulate it.

Studies of the physics of complex systems, deeply rooted in nonlinear geophysics, have matured since these pioneering works and are still going strong (for overviews, see, e.g., *Schertzer and Tchiguirinskaia* [2020] and *Lovejoy and Schertzer* [2013]), despite a lack of funding for fundamental research. Ongoing work is increasingly advancing our understanding of complex systems involved in Earth's climate and other natural and artificial processes. For all we've learned, though, much remains unknown, motivating further work.

The Nobel committee, in explaining its 2021 award in physics, was probably right to quote Philip Anderson (himself a physics Nobel laureate in 1977), who once wrote that "a real scientific mystery is worth pursuing to the ends of the Earth for its own sake, independently of any obvious practical importance or intellectual glamour." Intermittency most likely belongs in this category of mystery, regardless of the fact that its practical importance is quite obvious!

Acknowledgments

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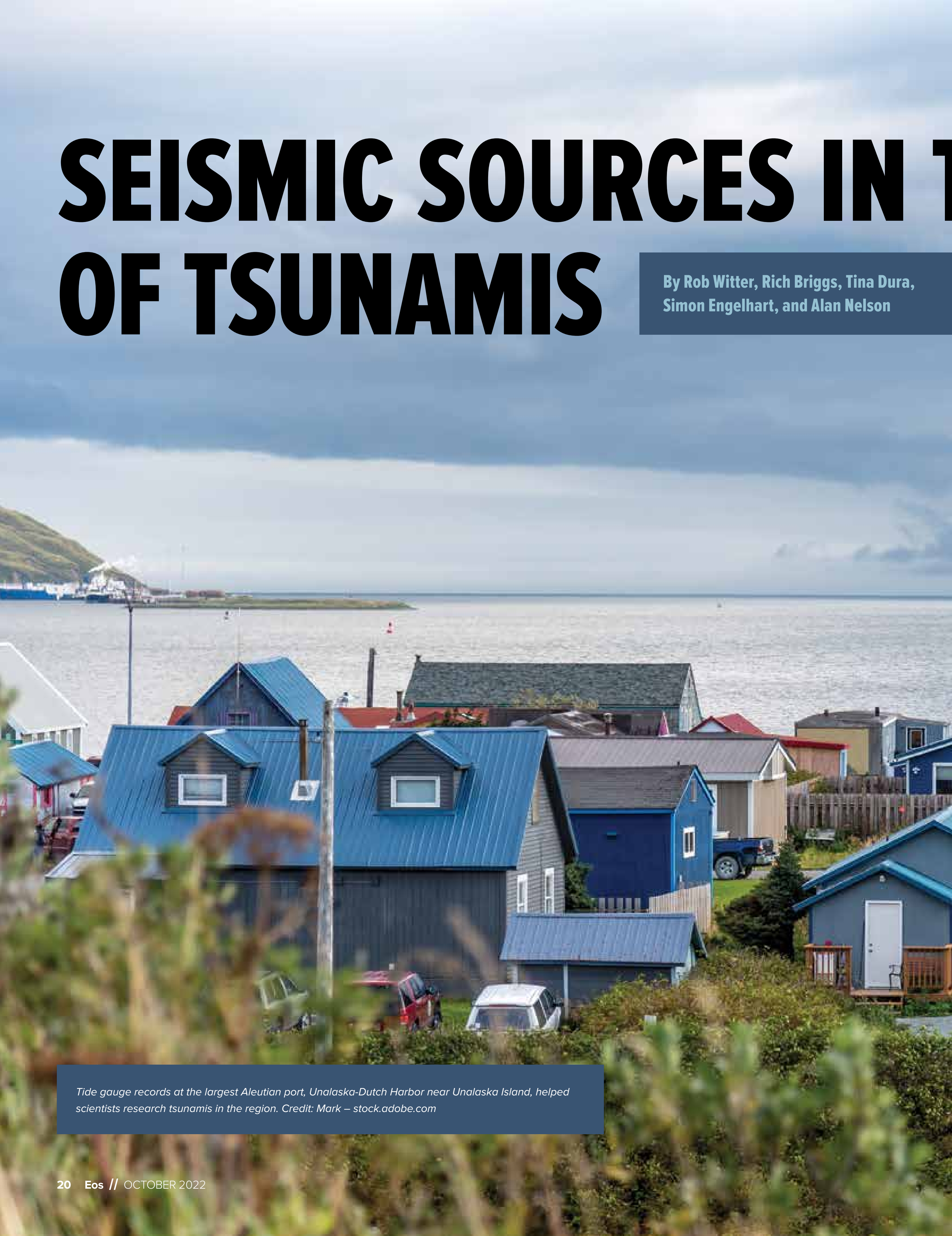
▶ Read the article at bit.ly/Eos-Nobel-recognition

SEISMIC SOURCES IN T
OF TSUNAMIS

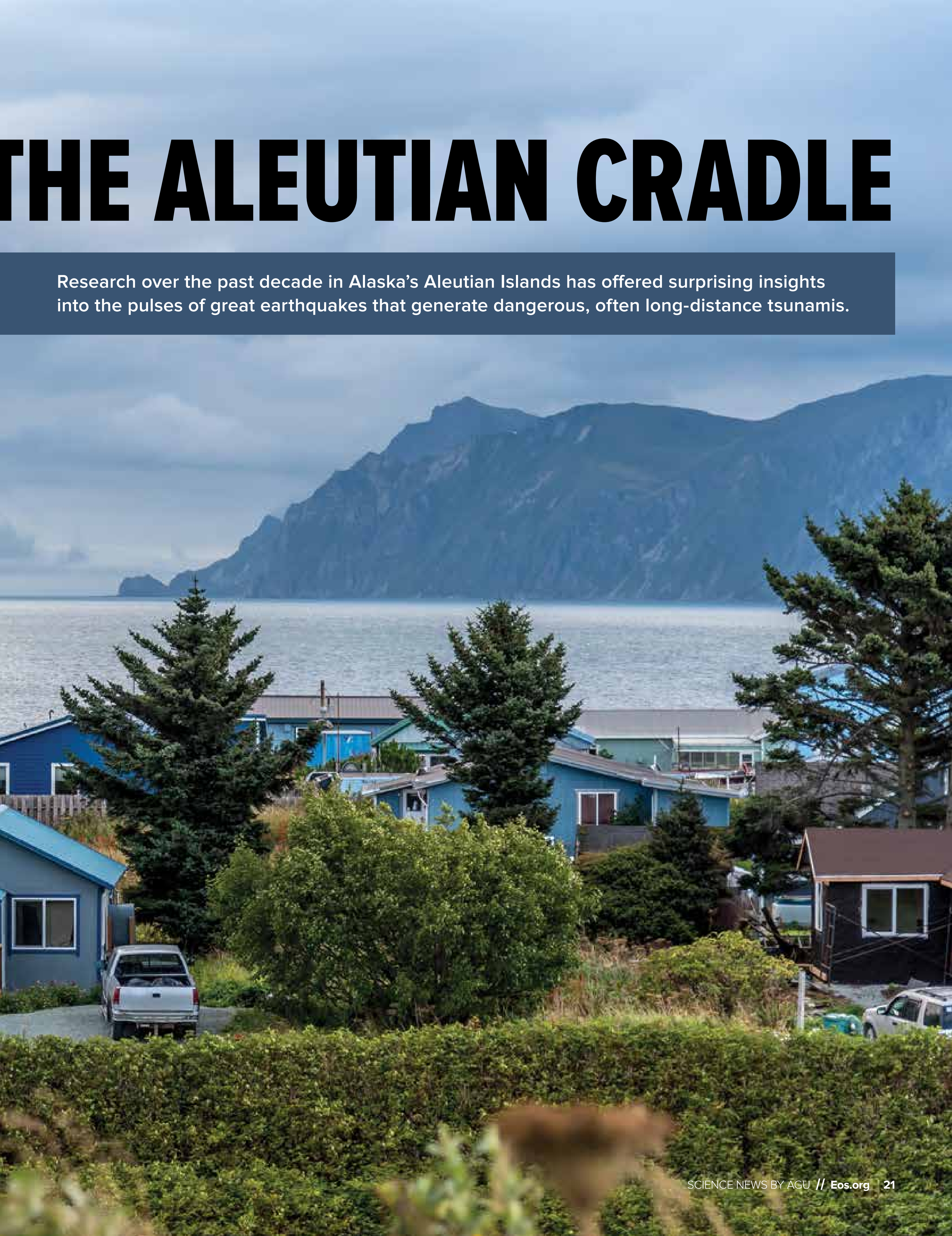
By Rob Witter, Rich Briggs, Tina Dura, Simon Engelhart, and Alan Nelson



Tide gauge records at the largest Aleutian port, Unalaska-Dutch Harbor near Unalaska Island, helped scientists research tsunamis in the region. Credit: Mark – stock.adobe.com

THE ALEUTIAN CRADLE

Research over the past decade in Alaska's Aleutian Islands has offered surprising insights into the pulses of great earthquakes that generate dangerous, often long-distance tsunamis.



Between 1938 and 1965, nearly the entire 3,300-kilometer length of the Alaska-Aleutian subduction zone ruptured in a sequence of powerful, tsunami-generating earthquakes. For example, the moment magnitude (M_w) 8.6 Unimak Island earthquake in 1946 heaved up the seafloor, generating a tsunami that reached 42 meters in height. This wave destroyed the Scotch Cap lighthouse on nearby Unimak Island, Alaska, and killed 159 people in Hawaii, 3,750 kilometers away. The unexpectedly distant and fatal consequences of the 1946 tsunami instigated the formation of the U.S. Tsunami Warning System.

Subduction zones around the world continue to surprise: For example, the 2010 M_w 7.8 Mentawai earthquake caught the world off guard because it broke the shallow portion of the Sunda megathrust fault directly above a larger rupture in 2007 and because it triggered an unexpectedly large tsunami for the size of the earthquake. A year later came an even bigger surprise: Japanese officials did not anticipate the scale and devastating impacts of the 2011 M_w 9.1 Tōhoku earthquake, or of the resulting tsunami and meltdowns at the Fukushima nuclear power plant, which together constitute the most financially costly disaster in human history. At the time, earthquake and tsunami hazard assessments in Japan relied primarily on instrumental records and written documents from time spans far shorter than the recurrence intervals (time elapsed between major events) of extreme earthquakes and tsunamis, which can span several centuries [*Sawai*, 2020]. The 2011 earthquake illustrated starkly that brief historical records alone are inadequate indicators of potential future fault behavior.

Similarly, the single century of instrumentally recorded great ($M_w > 8$) Alaska-Aleutian earthquakes is too short a period on which to base forecasts of these earthquakes and their accompanying tsunamis in the future. Yet providing hazard forecasts is crucial considering that Alaskan tsunamis endanger coastal communities around the Pacific Rim, including densely populated parts of Southern California and the shorelines of Hawaii [*Dura et al.*, 2021; *La Selle et al.*, 2020].

PROVIDING HAZARD FORECASTS IS CRUCIAL CONSIDERING THAT ALASKAN TSUNAMIS ENDANGER COASTAL COMMUNITIES AROUND THE PACIFIC RIM, INCLUDING DENSELY POPULATED PARTS OF SOUTHERN CALIFORNIA AND THE SHORELINES OF HAWAII.

So how can we get better at preventing future disasters by anticipating and mitigating the impacts of tsunamigenic earthquakes? The answer involves digging into the coastal stratigraphic record to extend our knowledge of great earthquakes and tsunamis farther back in time.

CLUES FROM PAST EARTHQUAKES

Subduction megathrusts—huge, gently dipping reverse faults that form where one tectonic plate dives below another—extend from deep-sea trenches to hundreds of kilometers beneath overlying islands or continents. Coastlines along subduction margins above megathrusts are the most accessible places to search for evidence of prehistoric subduction zone earthquakes and tsunamis.

Such evidence includes signs of sudden land uplift or subsidence caused by earthquake deformation, of scoured landforms and layered sand deposits left behind by tsunami inundations, and of landslides or underwater slumps triggered by strong shaking. The timing and pace of past events can be estimated with dating methods, like radiocarbon analyses of spruce needles or fragments of salmon vertebrae. Altogether, paleoseismic observations narrate the history of past earthquakes—their location, size, and recurrence—and validate geophysical models that simulate earthquake rupture and tsunami inundation.

From 2010 to 2021, we conducted paleoseismic studies by excavating, describing, and sampling Holocene sediments in coastal environments at 16 sites spanning 1,800 kilometers between the Fox Islands and

Clues to a history of eight Aleutian tsunamis in the past 2,000 years lie beneath the coastal lowlands of Driftwood Bay on Umnak Island, part of the Fox Islands of Alaska. Credit: USGS

Prince William Sound (Figure 1). These studies have helped reveal the long-term earthquake and tsunami potential of the eastern Aleutian megathrust. We discovered that great Aleutian earthquakes—and their towering tsunamis—have occurred more frequently than is accounted for in current seismic hazard assessments for Alaska.

Our research suggests that the upper (North American) and lower (Pacific) plates are presently locked at various locations along the megathrust, but earthquake rupture behavior at these locations varies over timescales that greatly exceed the quarter-century-or-shorter duration of space geodetic (i.e., Global Navigation Satellite System (GNSS)) data sets. Our observations also imply a prevalence of shallow megathrust earthquake ruptures near the seafloor that tend to generate high tsunamis, as well as complex, long-term patterns of ruptures whose boundaries vary from one earthquake to the next.

Fig. 1. Paleoseismic sites (colored dots) investigated in the eastern Alaska-Aleutian subduction zone since 2010 are superimposed on aftershock regions (red shading; data from Tape and Lomax *[2022]) showing the spatial extent of a sequence of 20th-century earthquakes that unzipped the megathrust. The arrow indicates the section of the subduction zone discussed in the text and the rate (70 millimeters per year) and direction of Pacific Plate motion.*

SLEUTHING A CASE FROM 1788

Historical clues about pre-20th-century Aleutian earthquakes and tsunamis are sketchy. For example, anecdotal evidence of a great earthquake and tsunami in 1788 exists in written accounts of flooding at Russian settlements at Sanak Island and at Three Saints Bay on Kodiak Island [*Lander*, 1996]. The accounts describe earthquake shaking that rattled the region between these islands and a tsunami that towered at least 30 meters above Aleutian shorelines. If the accounts are accurate, the 1788 earthquake would be the largest known event to have affected this stretch of the subduction zone.

HISTORICAL CLUES ABOUT PRE-20TH-CENTURY ALEUTIAN EARTHQUAKES AND TSUNAMIS ARE SKETCHY.

Seeking evidence of the 1788 tsunami as well as earlier events, we visited the possible western end of the earthquake rupture at Sanak Island (Figure 1), where Russian church books recount a terrible flood that year [*Lander*, 1996]. However, our investigations of the geology at the coastal sites indicated in the accounts did not confirm evidence of tsunami flooding in 1788. Instead, we found evidence on Sanak of the 1946 Unimak Island earthquake and tsunami, along with four older sand sheets deposited between 2,000 and 4,200 years ago. Despite a continuous sedimentary record, the 2,000-year hiatus in tsunamis prior to the 1946 event casts doubt on the veracity of the written accounts of the 1788 tsunami near Sanak Island. The discrepancy between the geologic record on Sanak and accounts of the 1788 tsunami remains a mystery.

Northeast of Sanak, in the Shumagin Islands, Russian documents recount “a terrible inundation on Unga Island in which many Aleuts perished but God spared the Russians.” We investigated three islands in the Shumagins (Figure 1). On one island, we identified a few thin (<1-centimeter-thick) sand sheets in coastal deposits below high tide that probably record storms or low tsunamis that occurred within the past few thousand years. These waves were likely similar to the small (<1.2-meter) tsunamis generated by the July–October 2020 earthquake sequence, which saw moment magnitudes of up to 7.8. Otherwise, we found no evidence for high tsunamis or earthquake-related land level changes, casting further doubt on the idea that the Sanak-Shumagin region marked the western terminus of a great 1788 rupture as suggested by the historical accounts [*Witter et al.*, 2014].

GAPS IN THE SEISMIC GAP HYPOTHESIS

Until the 2020 M_w 7.8 Simeonof earthquake, the Shumagin section of the Aleutian megathrust, unlike adjacent sections of the subduction zone, had not ruptured historically. The Shumagin seismic gap, labeled by seismologists in the 1970s (Figure 1), has been expected to release its accumulated strain and break in a great earthquake similar to the 1938 M_w 8.2 and 1946 M_w 8.6 ruptures. To date, however, no M_w 8 or larger earthquake,

Researchers (nearest to furthest) Simon Engelhart, Peter Haeussler, Tina Dura, Rich Koehler, and Rich Briggs climb a slope above Larsen Bay on Nagai Island in the Shumagin Archipelago, Alaska, during a field expedition to explore for evidence of past great earthquakes and high tsunamis. Credit: USGS

not even the Simeonof event, has filled the gap. What about in the geologic past?

GNSS measurements of the movement of the Alaska Peninsula and adjacent islands indicate that both large earthquakes (M_w 7–8) and gradual creep accommodate substantial plate convergence in the Shumagin gap. Creep describes the process in which converging plates slide past each other without locking, thereby reducing the buildup of elastic strain. Even though creep is considered an aseismic process, it is usually accompanied by moderate-magnitude earthquakes.

We found that great earthquakes and high tsunamis have not occurred in the Shumagin seismic gap over the past 3,400 years, suggesting, surprisingly, that great earthquakes may be extremely rare in the Shumagin gap, where creep has persisted for thousands of years [*Witter et al.*, 2014].

RUPTURING HISTORIC BARRIERS

Farther east, the Semidi Islands and Kodiak sections of the megathrust behave very differently than those from the creeping Shumagin section do. The Semidi section is firmly locked: Stress builds on the fault until an earthquake releases it. Here, our paleoseismic work (Figure 1) corroborated Russian accounts of the 1788 earthquake and tsunami. For example, on Chirikof Island, a stack of thin sand beds within 3–4 meters of radiocarbon-dated peat implies a recurrence interval for high tsunamis of just 180–270 years over the past 3,500 years, including the 1788 event [*Nelson et al.*, 2015]. And at Sitkinak Island, located at the southern end of Kodiak Island, we found stratigraphic evidence of sudden uplift of the island and tsunami inundation, consistent with Russian accounts of an earthquake and tsunami in 1788 [*Briggs et al.*, 2014].

Sitkinak Island also preserves clues that help define the western end of the 1964 M_w 9.2 Great Alaska Earthquake. Here, we investigated tidal exposures of peat and mud beds that contain evidence, in the form of fossil organisms too small to see with the naked eye, for five episodes of land level change accompanying earthquakes in the past 1,050 years [*Briggs et al.*, 2014]. We also tracked six continuous sand beds between 0.9 and 1.5 kilometers inland and described sedimentary properties consistent with tsunami deposits. Our field and lab findings add to a growing paleoseismic data set showing that the Kodiak section of the megathrust ruptures every 300–380 years, on average, about twice as frequently as the Prince William Sound section to the east, although both sections failed in the 1964 earthquake.

Sitkinak Island's prehistoric record suggests that the western boundary of the 1964 rupture has not been a persistent feature of the megathrust over time. The fossil organisms we studied on Sitkinak indicate that in 1964, parts of the island that had been high marsh environments suddenly subsided and became low marsh or tidal flat environments, consistent with the island's location near the western rupture boundary. However, they also indicated that the island jerked upward in the 1788 event and in older earthquakes, which implies that during these earlier events the megathrust ruptured through the 1964 boundary. Our findings, which could portend how future earthquakes will behave, will be incorporated into the 2023 update of the National Seismic Hazard Map for Alaska, which will be used, among other purposes, to improve seismic building codes.

DANGEROUS AND DIFFICULT TO DECIPHER

Some earthquakes generate much larger tsunamis than would be expected from their magnitude. Shallow earthquakes (<15-kilometer depth) with slow rupture speeds along the uppermost part of a megathrust typically produce large tsunamis because they cause large seafloor displacements in deep water. The 1946 Unimak Island earthquake is a prime example of a tsunami earthquake [*Okal and Hébert*, 2007]. Have similar earthquakes occurred elsewhere in the Aleutians?

We investigated two bays in the Fox Islands (Figure 1), located directly west of the rupture area of the 1946 earthquake, where evidence of frequent great earthquakes and unusually high tsunamis is recorded [*Witter et al.*, 2016, 2019]. Both bays face the Aleutian trench, like baseball catcher's mitts, at the eastern end of the rupture of the 1957 M_w 8.6 Andreanof Islands earthquake. Drift logs stranded inland 18–23 meters above sea level on these treeless islands, along with sheets of nearshore marine sand, record the 1957 tsunami at both sites.

Earthquake and tsunami computer simulations help us explore the nature and variability of past Aleutian tsunamis. But tsunami modeling using initial estimates of the megathrust slip that occurred in the 1957 earthquake failed to re-create conditions that account for two important observations: tide gauge records at the largest Aleutian port, Dutch Harbor, and the stranded drift logs along the islands' Pacific coasts [*Nicolsky et al.*, 2016].

Further testing demonstrated that the tsunami model that best matched the constraints posed by tide gauge records and drift log locations required a shallow (5- to 15-kilometer-depth) rupture with 20 meters of average slip and a M_w approaching 9 [*Nicolsky et al.*, 2016]. The long-term tsunami record we gleaned from the Fox Islands points to previous tsunami earthquakes that affected the area, but not all of the events mimicked the 1957 rupture. Together the Fox Island sites record nine tsunamis over the past 2,200 years with a 160- to 260-year recurrence interval—much shorter than recurrence estimates used in previous Aleutian seismic hazard assessments.

OUR FINDINGS, WHICH COULD PORTEND HOW FUTURE EARTHQUAKES WILL BEHAVE, WILL BE INCORPORATED INTO THE 2023 UPDATE OF THE NATIONAL SEISMIC HAZARD MAP FOR ALASKA.

PACIFIC-WIDE IMPACTS OF RECURRING WAVES

Underestimating the frequency of tsunamis that originate in the Aleutian Islands raises concerns about safety, not only for Alaskans but also for coastal communities thousands of kilometers away. The far reach of Aleutian tsunamis was seen during the 1964 Great Alaska Earthquake, which caused deaths and damage as far away as Crescent City, Calif. And it is evident in coastal wetlands and lagoons of Hawaii, which archive marine sand sheets deposited by Alaska-sourced tsunami waves in historic and prehistoric times [*La Selle et al.*, 2020]. Sand sheets on the islands of Hawaii, Oahu, and Kauai, dated by cesium and radiocarbon methods, chronicle inundation by Aleutian tsunamis in 1957 and 1946 and during a larger event sometime between 1350 and 1450.

Climate change may exacerbate Aleutian tsunami hazards. For example, the ripple effects of sea level rise over the next century will expose the ports of Los Angeles and Long Beach in Southern California to higher wave heights from tsunamis generated by Alaskan earthquakes [*Dura et al.*, 2021]. Worst-case predictions of sea level rise from the Intergovernmental Panel on Climate Change indicate that by 2100, M_w 8.0 earthquakes along the Alaska-Aleutian subduction zone could produce tsunamis with maximum nearshore heights of more than 1 meter at Southern California ports. Earthquakes of this magnitude are about 6.7 times more likely to occur along the Alaska-Aleutian subduction zone than the M_w 9.1 earthquakes required to produce such tsunamis with present-day sea level.

SEISMIC STUDIES FOR SAFER COMMUNITIES

The long-term record of seismic activity along the Alaska-Aleutian subduction zone that we are helping assemble has shown that this cradle of Pacific tsunamis launches dangerous waves every 60–90 years, on average. The sequence of great earthquakes from 1946 to 1965 alone generated four transpacific tsunamis—and more such ruptures are likely to occur in the 21st century.

The past decade of earthquake and tsunami research along the Alaska-Aleutian subduction zone conducted by us and by others can help bolster societal resilience and reduce losses in future events by providing updated

Researchers (left to right) Andrew Kemp, Peter Haeussler, and Alan Nelson examine salt marsh beds in a tidal outcrop on Sitkinak Island, Alaska. These beds provide evidence of earthquake-induced changes in land level, including coastal uplift during the 1788 earthquake. Credit: USGS input to strengthen hazard assessments, including the U.S. Geological Survey's 2023 National Seismic Hazard Map for Alaska. Seismic safety codes adopted by the state based on earlier seismic hazard assessments likely explain the relative resilience of the built environment to strong ground motions during the 2018 M_W 7.1 Anchorage earthquake. This work also supports more accurate inundation scenarios that aid in delineating tsunami evacuation zones and improve public safety.

THIS CRADLE OF PACIFIC TSUNAMIS LAUNCHES DANGEROUS WAVES EVERY 60–90 YEARS, ON AVERAGE.

There are several as-yet-unexplored frontiers for Alaska-Aleutian paleoseismic research, including the western Aleutians, which have yet to be investigated at all. Our investigation of tsunami evidence related to the 1965 M_W 8.7 Rat Islands earthquake at Kiska Island in the western Aleutians, planned since 2020, has been hampered by logistical challenges and pandemic restrictions, although we intend to pursue this work in the future. Lakes overlying the megathrust offer other targets for ongoing work. In summer 2022, we surveyed Karluk Lake on Kodiak Island for evidence of turbidites in lake sediments that may record strong shaking during past great megathrust earthquakes. Lake sediment studies can provide greater precision for earthquake age estimates and potentially differentiate past megathrust events from earthquakes with shallow crustal or deep slab sources.

By digging into the Holocene stratigraphic record, these and other paleoseismic studies enrich our knowledge of past subduction earthquakes and tsunamis in the Alaska-Aleutian region by allowing us to better understand the range of seismic behavior and better forecast future tsunami hazards to coastal communities around the Pacific rim.

Geologist Rich Koehler examines layers, or sheets, of beach and nearshore sands deposited in a freshwater peat bog on Sitkalidak Island, Alaska, near Kodiak Island. The bog lies beyond the reach of Gulf of Alaska storm waves. Such evidence of marine inundation indicates that large earthquake-generated tsunamis flooded the coast repeatedly in the past millennium. Credit: USGS

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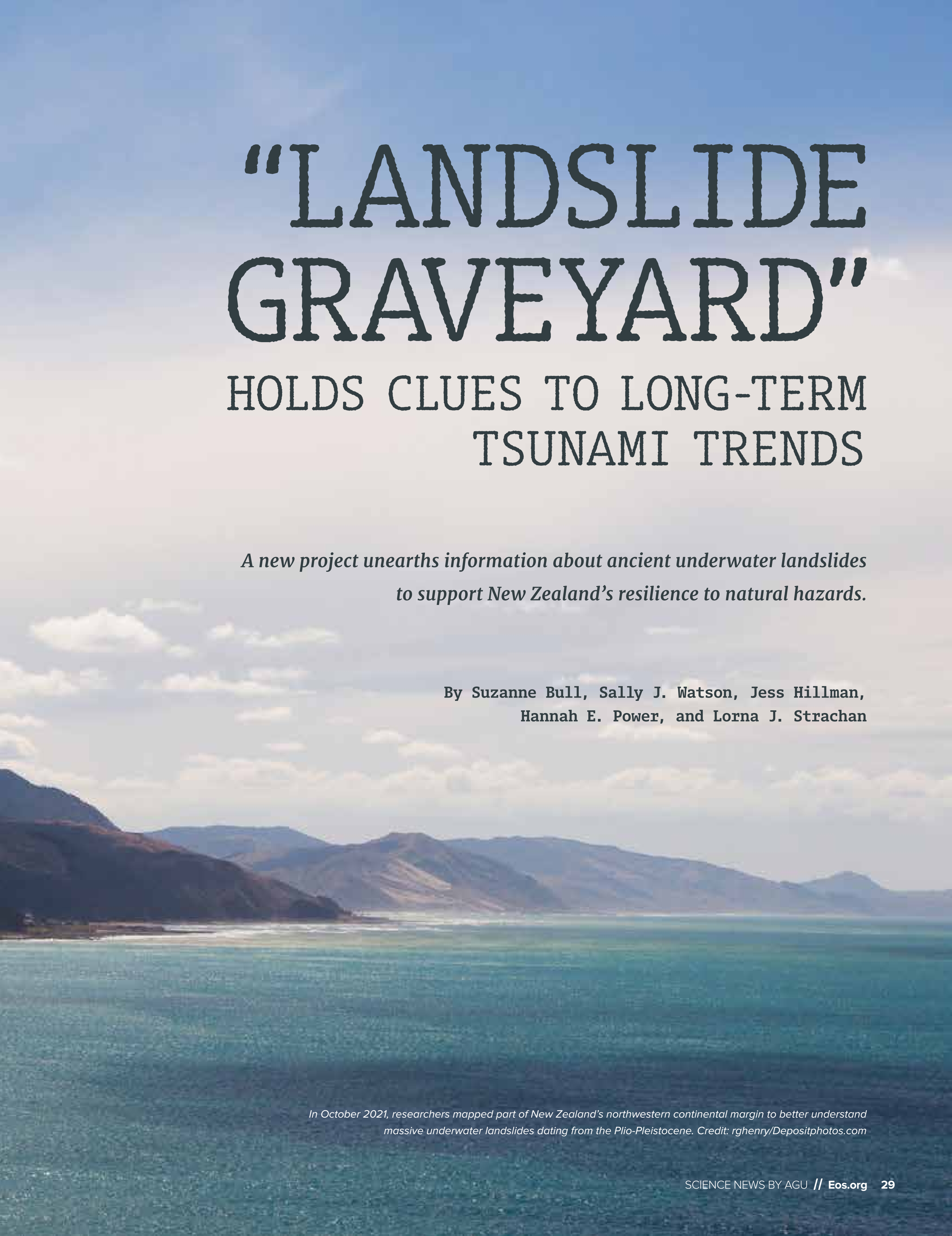
"LANDSLIDE GRAVEYARD" HOLDS CLUES TO LONG-TERM TSUNAMI TRENDS

A new project unearths information about ancient underwater landslides to support New Zealand's resilience to natural hazards.

By Suzanne Bull, Sally J. Watson, Jess Hillman, Hannah E. Power, and Lorna J. Strachan



In October 2021, researchers mapped part of New Zealand's northwestern continental margin to better understand massive underwater landslides dating from the Plio-Pleistocene. Credit: rghenry/Depositphotos.com

"*Ka mua, ka muri.*" We walk backward into the future, with our eyes on the past. This *whakataukī* (proverb) represents a New Zealand Māori perspective that has much in common with the way Earth scientists study natural hazards. Understanding and learning from historical events inform our preparedness for and increase resilience to future disasters. Studying past tsunami events, for example, is an important part of better understanding the diverse and complex mechanisms of tsunami generation and of improving natural hazard assessments.

Tsunamis are dangerous natural hazards and are most often caused by earthquakes. Consequently, researchers and hazard planners have focused mostly on co-seismic tsunamis. However, several recent tsunamis have been attributed to other sources on which less research has been done, including underwater landslides, as in the case of the 2018 event in Palu, Indonesia, and volcanic eruptions in the case of the tsunami originating from Hunga Tonga-Hunga Haʻapai in early 2022.

The Tasman Sea, located between Australia and New Zealand and notorious for its storms amid the "roaring forties" latitudes, may have witnessed a series of devastating tsunamis during the past 5 million years (i.e., in the Pliocene and Pleistocene, or Plio-Pleistocene, epochs). These tsunamis likely originated near New Zealand's west coast and traveled more than 2,000 kilometers to also affect Australia, yet intriguingly, there is little easily observable evidence of these events. This tumultuous history is surprising considering that western New Zealand is not especially exposed to subduction zone processes and their associated seismic activity; such exposure is often the main indicator of how vulnerable a coastline is to a tsunami. However, New Zealand is surrounded by steep and, in some cases, tectonically active submarine slopes, where landslides can occur.

In the past few decades, evidence of six giant underwater landslides dating from the Plio-Pleistocene has been discovered beneath the modern seafloor in the eastern Tasman Sea (Figure 1). The most recent, thought to have occurred about 1 million years ago, is the largest documented landslide in New Zealand, covering more than 22,000 square kilometers—an area larger than Wales. With a volume of about 3,700 cubic kilometers, this landslide was bigger than the famous tsunamigenic Storegga Slide, which involved massive collapses of the continental shelf off the coast of Norway roughly 8,200 years ago.

Can scientists use these landslide deposits to derive credible indications of past tsunamis? If so, how can we assess the modern potential for hazardous tsunamis based only on these ancient, buried remnants? Underwater landslides are not comprehensively included as tsunami sources in New Zealand's hazard assessments. This data gap exists largely because of a lack of research into underwater landslide return rates (a statistical measure of how often these events are likely to recur) and tsunamigenic mechanisms, as well as of uncertainties introduced by errors in available dating methods and the difficulty and expense of obtaining samples. These key questions and issues are currently being addressed by a trans-Tasman team of researchers, including us, from Australia and New Zealand under the Silent Tsunami project (officially named Assessing Risk of Silent Tsunami in the Tasman Sea/Te Tai-o-Rēhua), which began in 2021.

> **The unstable sediment piles, perched precariously at the interface between the Pacific and Australian plates, inevitably collapsed in catastrophic fashion several times over.**

Search Strategy for Landslide Evidence

Throughout the Plio-Pleistocene, a vast volume of material was eroded from the rapidly uplifting Southern Alps, on New Zealand's South Island, and delivered to the coast by river networks. Powerful ocean currents then transported the sediment north to the country's northwestern continental margin. The ocean basin duly accommodated the relentless influx of material, and the margin rapidly prograded (built outward toward the sea) via a series of spectacular, steeply dipping depositional surfaces (up to 1,500 meters tall) called sigmoidal clinoforms, which are the building blocks of deltas and basin margins. The unstable sediment piles, perched precariously at the edge of the tectonically hyperactive interface between the Pacific and Australian plates, inevitably collapsed in catastrophic fashion several times over.

However, evidence of these Tasman Sea landslides cannot be readily observed, in part because of a lack of detailed seafloor mapping in

The Sun rises over the Tasman Sea and Mount Taranaki (at left on the horizon), as seen from R/V Tangaroa *during research voyage TAN2111 in October 2021 to map part of New Zealand's northwestern continental margin. Credit: Jess Hillman*

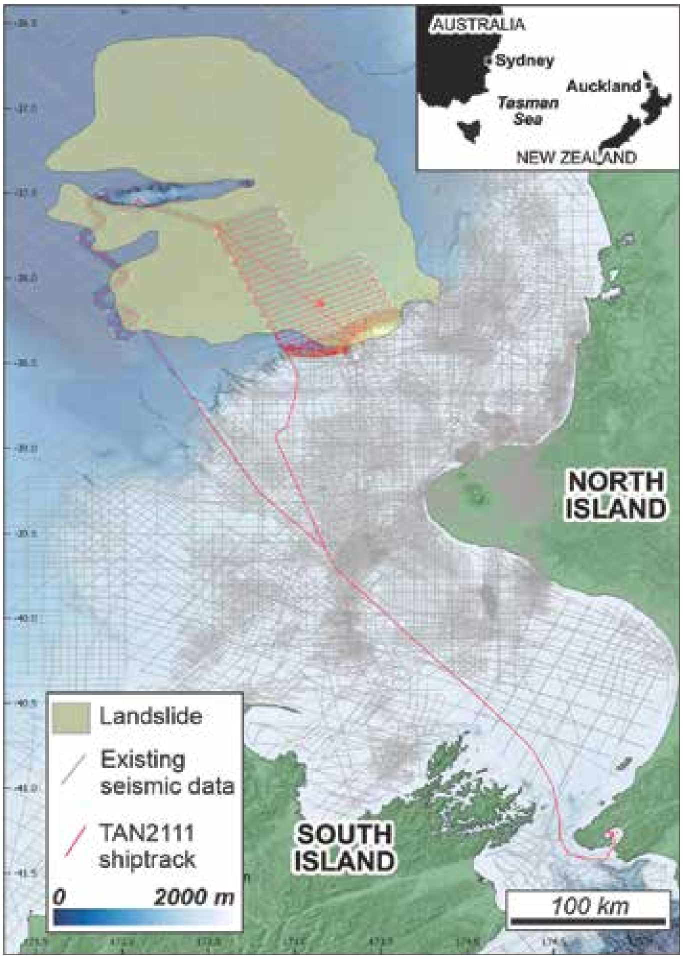


Fig. 1. The study area of the Silent Tsunami project is shown here, along with seafloor bathymetry and existing seismic reflection data. The outline of the most recent giant landslide from the Pleistocene is also shown and is overlain by the ship track from voyage TAN2111 in October 2021.

the area but also because the slides were quickly buried under other sediment. Compounding the difficulty are the erosion and uplift of New Zealand's dynamic coastline, which have erased potential land-based geological evidence in the form of tsunami deposits. Only past seismic reflection surveying in the area enabled the discovery of evidence for these events (Figure 1), with geologists documenting the landslide deposits while mapping New Zealand's offshore sedimentary basins.

The new project takes a three-pronged approach to carry earlier findings forward. First, we're combining tools and techniques from the playbook used to analyze the formation and evolution of sedimentary basins, especially how the basin filling process interacts with tectonic processes. These methods include the conversion of time series seismic reflection data into depth measurements using seismic wave velocities measured from drill holes (meaning that the depth for each data point is known) and virtually stripping away overlying sediments (back-stripping) using computational models. This approach allows us to unearth accurate original volumes (areal extent and thickness) of the landslides before their burial and compaction.

Second, we're applying these new physical descriptions of landslides, along with knowledge of where they occurred, to inform computational models. The models, run using the cutting-edge fluid dynamics modeling tool Basilisk, simulate landslide motion, tsunami generation, and hazard metrics like inundation extents, wave amplitudes, wave arrival times, and current velocities.

Third, during two research voyages, we collected new geophysical data—multibeam bathymetry, subbottom profiles, and high-resolution multichannel seismic reflection profiles—and sediment samples from rock dredges and sediment cores from the site of the landslides. Data from the voyages are perhaps most critical to the outcomes of the project. The modeling builds a picture of the likely impacts of the Tasman Sea landslides, but probing the sites of their origin in the real world draws tangible ties between these ancient events and the present day.

So what about the present day? During sea level highstands, when sea levels rise above the edge of a continental shelf, as is the case today, delivery of sediment to the deep ocean is thought to decrease. However, a paucity of information from the Tasman Sea region means that no one knows how much, how fast, and exactly where sediment is accumulating at present. It is not clear whether the conveyor belt of northward sediment delivery is still operating or what could trigger a future landslide event.

Setting Sail

In October 2021, on the first of the two research voyages, a small science party of five boarded R/V *Tangaroa* for an 11-day voyage to map some 5,000 square kilometers of the Tasman Sea for the first time and to identify targets for a sampling campaign to be conducted during the second voyage (Figure 1). The preexisting seismic reflection data set for the region (Figure 2), comprising data gathered during numerous explorative surveys over several decades, appeared to show evidence of "megablocks" peeking up through the modern seabed from within the most recent Tasman Sea landslide deposit. These megablocks are large clasts or "rafts" of material that were transported within a landslide and that have remained mostly intact. Such blocks often form highly irregular seafloor topography in the immediate aftermath of an underwater landslide and can create localized sediment traps when normal sedimentation resumes. As we headed into the voyage, it was uncertain whether these features would be visible or prominent on the seafloor or whether we could identify viable targets for sampling.

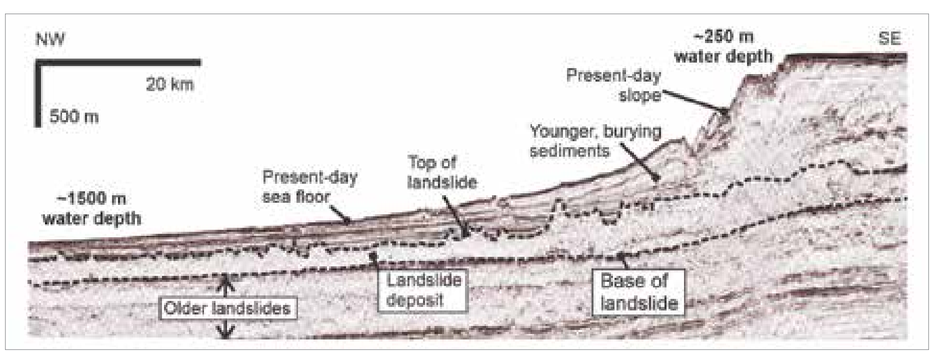


Fig. 2. Ancient landslide deposits beneath the modern seafloor are evident in this seismic reflection profile produced from data collected prior to the Silent Tsunami project.

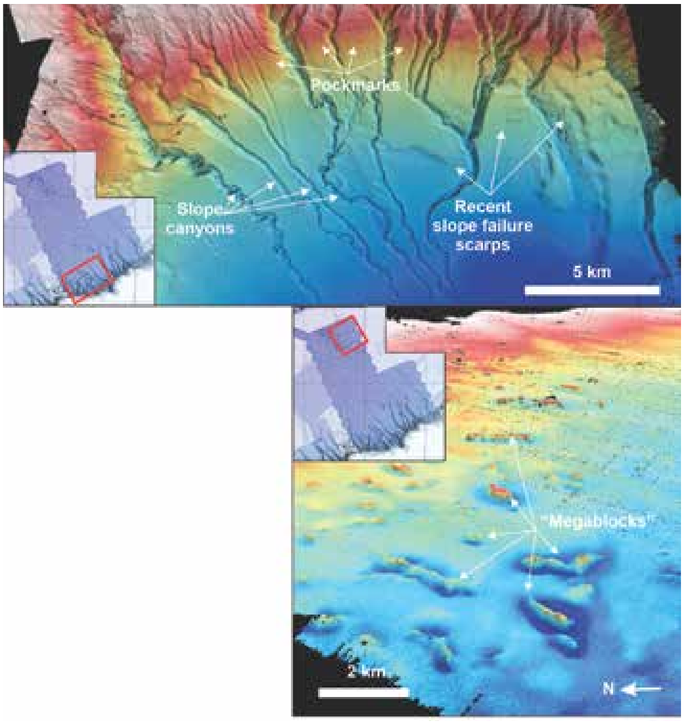


Fig. 3. Perspective views from the newly acquired bathymetric data set show shelf-slope canyons, pockmarks, and evidence of small, recent slope failures (top), as well as the tops of megablocks from the most recent ancient landslide rising above the modern seafloor of the continental rise at water depths of 1,500–1,700 meters (bottom).

True to form for the Tasman Sea, after we left the shelter of Wellington Harbour, a howling southerly wind and 8-meter swells pummeled our ship during the 20-hour transit. Once on site about 100 kilometers off New Zealand's North Island, above the continental shelf break and rise, however, conditions calmed, allowing the ship's multibeam echo sounders to run—and map the seafloor at high resolution—uninterrupted.

As the data came in, we spent long hours poring over them in the bathymetry lab aboard the *Tangaroa.* The time was highly rewarding. First came images of canyons and numerous pockmarks and evidence of recent small-scale slope failures as the ship passed over the shelf break and traversed the continental slope (Figure 3). Then we saw an astonishing area of deep seafloor littered with numerous angular, often elongated ridges and peaks up to 100 meters in relief, some with surrounding "moats" winnowed by the action of recent ocean currents. These ridges are the exposed tops of megablocks from the most recent Tasman Sea landslide, still making their mark on the seafloor roughly 1 million years later.

We decided that the megablocks, now that we'd observed them firsthand, were viable targets for rock dredging, offering the tantalizing possibility of sampling landslide material itself. If we could achieve it, this sampling could allow us to characterize the sedimentology and physical properties of the landslide and thus to refine our fluid dynamics models. In addition, areas between blocks would be good targets to sample covering sediments to help constrain the minimum age of the most recent and largest landslide and to determine the rate and patterns of modern sediment accumulation.

We set off on the 3-week-long second voyage, again aboard the *Tangaroa*, on 15 March 2022. Taking advantage of a spell of calm weather, we deployed the ship's brand-new 96-channel solid seis-

Jess Hillman of the Institute of Geological and Nuclear Sciences Limited (left) and University of Auckland student Georgia Warren (right) examine the contents of a dredge sample from one of the landslide megablocks on the trawl deck of the R/V Tangaroa. *Credit: Suzanne Bull* mic streamer then waited anxiously for the first reflection data it would collect. Our worry was unnecessary, as the data looked beautiful, with much-improved resolution compared with the preexisting data set.

The biggest highlights from this voyage came as we turned our attention to sediment sampling and targeted several megablocks with the rock dredge. We recovered a lot of sticky mud thought to be the “mud drape” formed by the continuous rain of fine-grained sediment that accumulates normally over many years. We also recovered fist- to paving slab–sized clasts of more consolidated mud and fine sand, which we cautiously assumed to be landslide material.

After deciding to target a flat-topped megablock at roughly 1,500-meter-depth for coring, we again waited nervously to see what, if anything, we’d recover. To the team’s excitement, we indeed recovered a 4-meter core from the megablock. Does it contain landslide material, or is it all mud drape? Time will tell. Now back on dry land, we are awaiting the results of nondestructive preliminary scanning before we split and subsample the core to determine in detail what we recovered. In all, 79 meters of core were successfully recovered on the voyage, including from the areas between megablocks, which we are confident will enable us to characterize modern sediment deposition and properties.

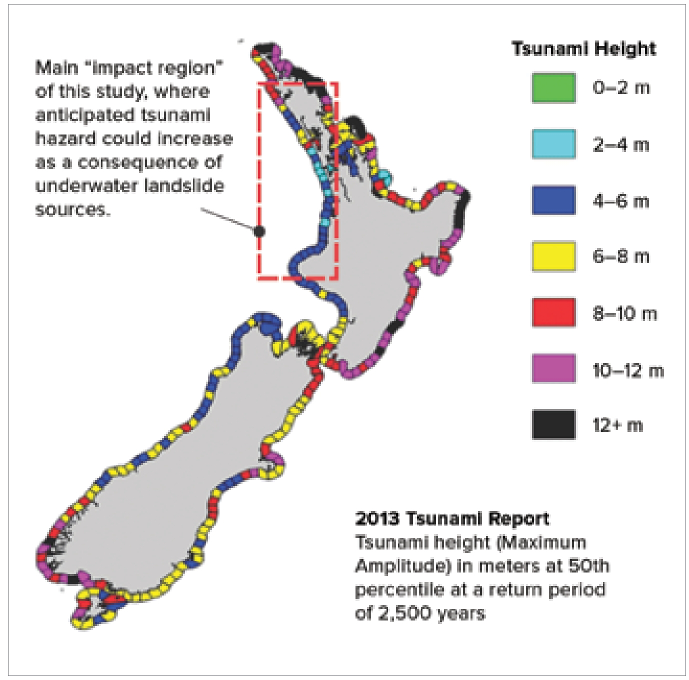


Fig. 4. This depiction of the New Zealand National Tsunami Hazard Model shows expected tsunami heights along the country’s coastline. Although formally published in 2013, the model is continually updated as more information becomes available.

From Data to Knowledge to Application

We expect our project to generate new knowledge that builds a picture of modern-day conditions at the site of the Tasman Sea landslides, to refine our understanding of the return rate of large, potentially tsunami-generating landslides, and to develop credible scenarios of the specific hazards related to them. Pathways to assessing the usefulness of the information gained and to guide its uptake in national hazard assessments involve working with a hazard scientists’ advisory group, territorial authorities, and civil defense agencies.

> We deployed the ship’s brand-new 96-channel solid seismic streamer then waited anxiously for the first reflection data it would collect. Our worry was unnecessary, as the data looked beautiful.

The most likely conduit to implementation in New Zealand is the Review of Tsunami Hazard in New Zealand, a probabilistic risk assessment that quantitively estimates maximum tsunami heights along the country’s coastlines (Figure 4). The model underpins more detailed site-specific hazard assessments and emergency management planning and is continually refined and updated with new information. In Australia, new information from this project could be incorporated into state-based hazard assessments and education programs led by the country’s emergency management authorities.

An exciting prospect is the potential to apply the same approaches used in our project to other areas of Australia, New Zealand, and elsewhere. Many of the world’s continental margins have been imaged using seismic reflection surveying—often during exploration for offshore energy resources—creating a vast repository of information about the subsurface. Most of what is known about tsunamis generated by underwater landslides comes from computational models, with few observed examples of such slides to validate them. But existing data sets may hold a wealth of data related to numerous examples of ancient underwater landslides now buried beneath the seafloor.

Translating knowledge from examples of subsurface landslides into information to support hazard assessment is rarely done because of a lack of information on the ages of the landslides and the complexities of assessing their size caused by their burial, compaction, and incomplete preservation. We hope that results and learning from our early-stage research will help scientists better understand regional tsunami hazards. We also hope that these results will pave the way for future endeavors to develop constructive tools to support refined tsunami hazard assessment and emergency management planning, helping safeguard people around and beyond the Tasman Sea.

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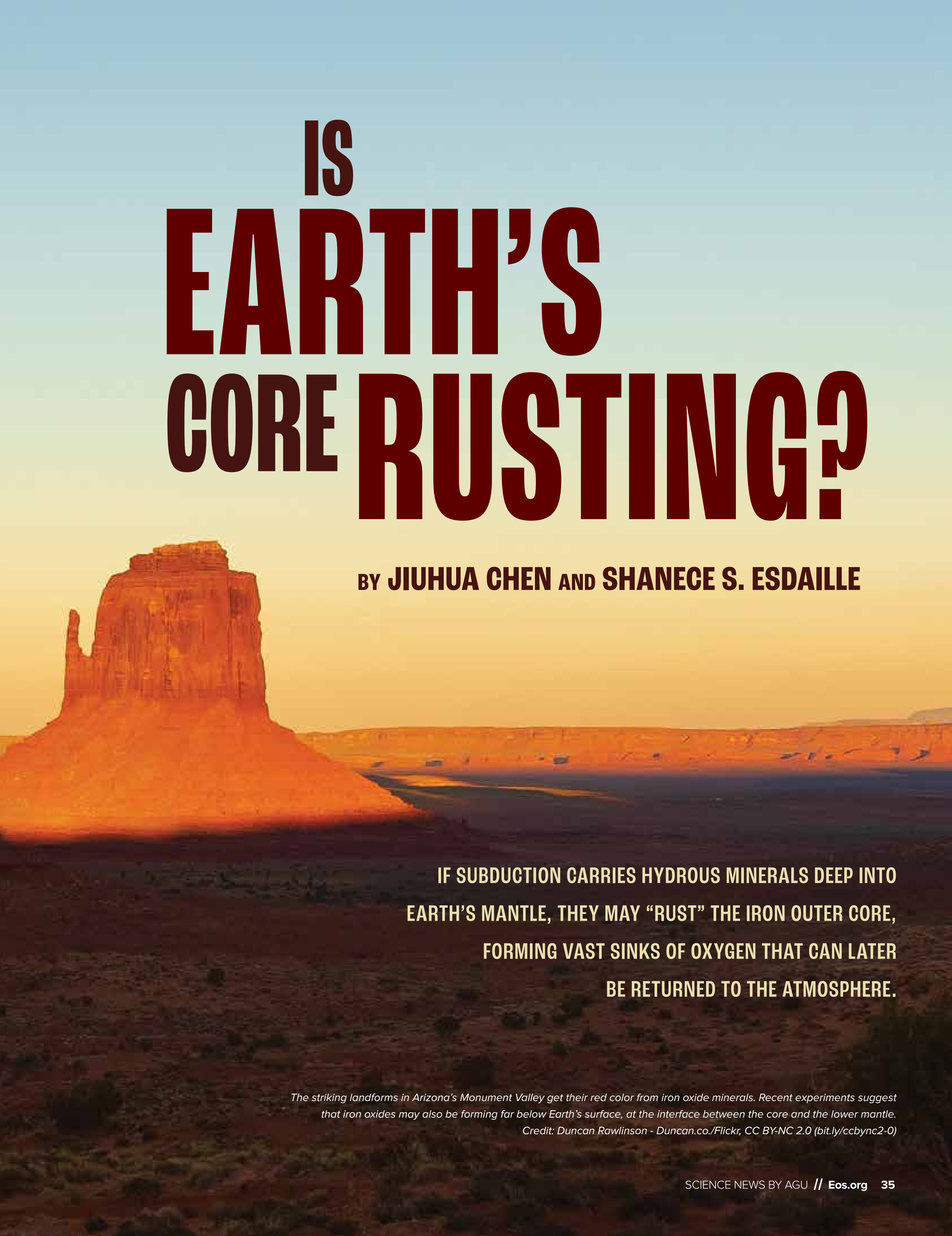
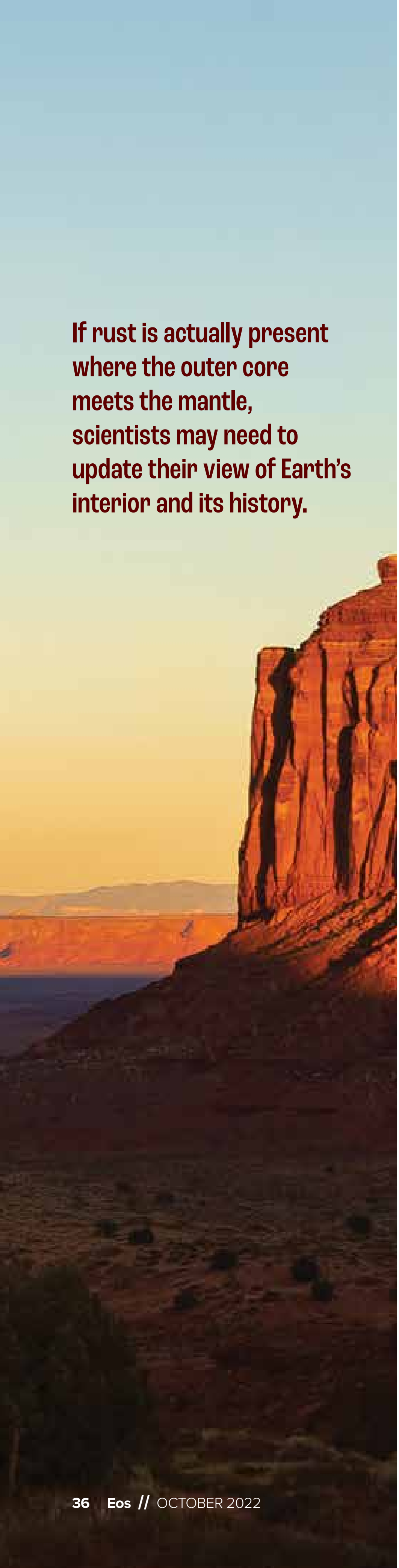
IS EARTH'S CORE RUSTING?

BY JIUHUA CHEN AND SHANECE S. ESDAILLE



IF SUBDUCTION CARRIES HYDROUS MINERALS DEEP INTO EARTH'S MANTLE, THEY MAY "RUST" THE IRON OUTER CORE, FORMING VAST SINKS OF OXYGEN THAT CAN LATER BE RETURNED TO THE ATMOSPHERE.

The striking landforms in Arizona's Monument Valley get their red color from iron oxide minerals. Recent experiments suggest that iron oxides may also be forming far below Earth's surface, at the interface between the core and the lower mantle. Credit: Duncan Rawlinson - Duncan.co./Flickr, CC BY-NC 2.0 (bit.ly/ccbync2-0)



If rust is actually present where the outer core meets the mantle, scientists may need to update their view of Earth's interior and its history.

Iron on Earth's surface—whether in simple nails or mighty girders—is altered gradually when exposed to moist air or oxygenated water through a chemical reaction known as oxidation. The reddish-brown product of this reaction, rust, can consist of various forms of hydrous (water-bearing) iron oxides and iron oxide–hydroxide materials. In nature, the red rocks found in the arid climes of the southwestern United States and elsewhere similarly owe their color to the iron oxide mineral hematite, whereas in wetter environments, iron ore minerals like hematite weather to form the iron oxide–hydroxide mineral goethite (FeOOH).

Deep below Earth's surface—2,900 kilometers deep, to be precise—is a mass of mostly molten iron forming the planet's outer core. Could it rust as well?

In experiments, scientists have recently shown that when iron meets moisture—as water or in the form of hydroxyl-bearing minerals—at pressures close to 1 million atmospheres, similar to pressures in the deep lower mantle, it forms iron peroxide or a high-pressure form of iron oxide–hydroxide with the same structure as pyrite (i.e., pyrite-type FeOOH) [*Hu et al.*, 2016; *Mao et al.*, 2017]. In other words, the oxidation reactions in these experiments do, indeed, form high-pressure rust.

If rust is actually present where the outer core meets the mantle (the core-mantle boundary, or CMB), scientists may need to update their view of Earth's interior and its history. This rust could shed light on the deep-water cycle in the lower mantle and the enigmatic origins of ultralow-velocity zones (ULVZs)—small, thin regions atop Earth's fluid core that slow seismic waves significantly (Figure 1). It could also help answer questions about the Great Oxidation Event (GOE), which marked the beginning of Earth's oxygen-rich atmosphere some 2.5 billion to 2.3 billion years ago, and the Neoproterozoic Oxygenation Event (NOE), which brought atmospheric free oxygen to its present levels 1 billion to 540 million years ago.

But how do we know whether rusting has been happening at the CMB?

SEISMIC SIGNATURES AT THE CORE-MANTLE BOUNDARY

Although we can't mine the minerals at the CMB, we can examine them in other ways. If the core rusts over time, a layer of rust may have accumulated at the CMB, exhibiting certain seismic signatures.

Laboratory studies indicate that iron oxide–hydroxide core rust (i.e., FeOOH*x*, where *x* is 0–1) may cause significant reductions in the velocities of seismic shear waves (*Vs*) and compressional waves (*Vp*) that pass through it, much like the rocks (or partial melts, if present) in ULVZs do [*Liu et al.*, 2017]. In fact, core rust could slow seismic wave velocities by as much as 44% for *Vs* and 23% for *Vp*, compared with the average seismic velocities as a function of depth represented in the preliminary reference Earth model. These large velocity reductions would make the core rust recognizable in seismic tomography if it accumulated into piles thicker than 3-5 kilometers.

The difficulty lies in distinguishing whether seismic anomalies in ULVZs are

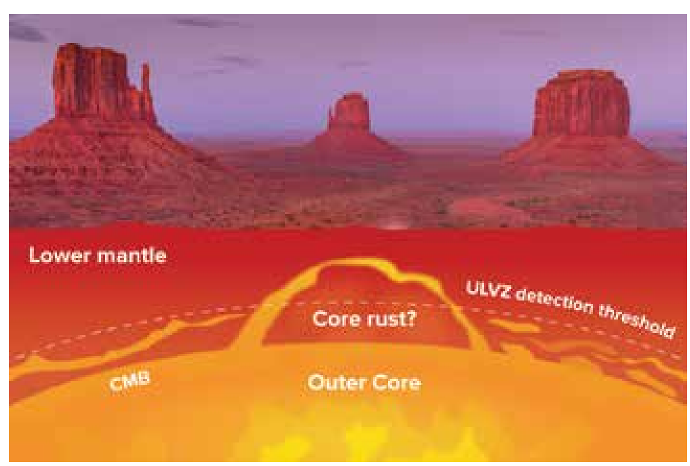


Fig. 1. The coloration of red rocks on Earth's surface—as seen here near West Mitten Butte, East Mitten Butte, and Merrick Butte in Arizona—mainly results from the oxidized iron minerals hematite and goethite. Possible core rust deposits at the core-mantle boundary (CMB), 2,900 kilometers below Earth's surface, could be made of iron oxide–hydroxide minerals with a pyrite-like structure. This rust material could explain the detections of ultralow-velocity zones (ULVZs) in seismic data. The ULVZ detection threshold indicates the resolution of current seismic tomography. Credit: Top: Ken Cheung/Pexels; Bottom: Mary Heinrichs/AGU

caused by core rust or whether they have other origins. For example, partial melting, which is commonly believed to occur at the base of the lower mantle and to be responsible for ULVZs [*Williams and Garnero*, 1996], could give rise to seismic velocity reductions similar to those caused by core rust.

Scientists should be able to use seismic tomograms to differentiate between core rust and partial melting at the CMB. A seismic tomogram is normally produced through a mathematical inversion process that matches calculated and observed seismic waveforms. The inversion process requires determining possible mathematical solutions that fit the data and then choosing a "best" solution from among these on the basis of additional considerations.

Each possible mathematical solution corresponds to a distinct set of model parameters related to the physical properties of the materials involved—for example, the relative differences in *Vs*, *Vp*, and density between a material of interest and the average of the mantle surrounding that material.

These differences can vary with the amount of the material in the mantle, but each material usually exhibits a characteristic range of values for the differential logarithmic ratio of *Vs* to *Vp* (δln*Vs*:δln*Vp*) [*Chen*, 2021], which can be used to distinguish materials in seismic tomograms (Figure 2). It's known from mineral physics experiments that this ratio ranges from a lower limit of 1.2:1 to an upper limit of 4.5:1 for all possible materials explaining the origin of ULVZs. Within this broader range, ratios for core rust (pyrite-type FeOOH*x*) fall between 1.6:1 and 2:1 and are distinct from the other materials.

EVIDENCE OF CORE RUST ORIGINS

So far, seismologists have sampled about 60% of the CMB in their search for ULVZs, and they have identified nearly 50 locations of seismic anomalies, accounting for as much as 20% of the CMB area, that could represent ULVZs. Most of these areas are coupled with large low shear velocity provinces (LLSVPs) in the lowermost mantle and display a δln*Vs*:δln*Vp* of around 3:1, which suggests partial melting (Figure 2).

However, some of them, located at the margins of or outside the LLSVP beneath the Pacific, display a best fit ratio of about 2:1 [*Chen*, 2021]. For example, a ULVZ at the northern border of the Pacific LLSVP (at about 9°N, 151°W) [*Hutko et al.*, 2009] and a cluster of ULVZs beneath northern Mexico (at about 24°N, 104°W) [*Havens and Revenaugh*, 2001] each have δln*Vs*:δln*Vp* ratios that suggest the presence of pyrite-type FeOOH*x*.

A common feature of these ULVZs is that they are located in a region of the CMB where temperatures are relatively low—a few hundred kelvins lower than average temperatures within the LLSVP. The low temperatures suggest that these zones were produced by a mechanism other than melting. Of note, the region beneath northern Mexico has been identified as comprising the remnants of deep subduction deposited roughly 200 million years ago to the west of North and Central America, which supports the notion that water released from the subducting slab could have rusted the outer core at the CMB.

Scientists should be able to use seismic tomograms to differentiate between core rust and partial melting at the core-mantle boundary.

THE CONSEQUENCES OF A RUSTED CORE

It is thought that the dominant mineral in Earth's lower mantle, bridgmanite, has little ability to host water. However, rusting of the core could produce a high-capacity water reservoir at the CMB—the FeOOH*x* rust may contain about 7% water by weight [*Tang et al.*, 2021]. Because core rust is heavier than the average mantle, this water reservoir would tend to stay at the CMB. Thus, water can theoretically be transported and stored just outside the core, at least until mantle convection carries it away from the cooler regions near the remnants of subducted slabs and makes it thermally unstable (Figure 3).

Whether and when this deep water cycles back to the surface would depend largely on the thermal stability of the core rust. Some scientists, on the basis of experimental work, have claimed that FeOOH*x* can survive only up to 2,400 K under the pressure at the CMB [*Nishi et al.*, 2017], whereas others have observed the presence of FeOOH*x* at 3,100–3,300 K at a similar pressure [*Liu et al.*, 2017]. But whatever the maximum temperature FeOOH*x* can withstand, it's likely that when core rust migrates to hotter regions of the CMB, following the flow of mantle convection, it would decompose into hematite, water, and oxygen. This process offers a possible alternative explanation for the oxygenation history of Earth's atmosphere.

Geological, isotopic, and chemical evidence suggests that Earth's atmosphere was mostly or entirely anoxic during the Archean eon. Following the Archean, the first introduction of molecular oxygen into the atmosphere began about 2.4 billion years ago in the GOE. The second major rise in atmospheric oxygen, the NOE, then occurred about 750 million years ago, bringing concentrations close to today's level.

The causes of these oxygenation events remain uncertain. One possible explanation of the GOE is the emergence of cyanobacteria, the early photosynthesizing precursor to plants. The NOE, occurring almost 2 bil-

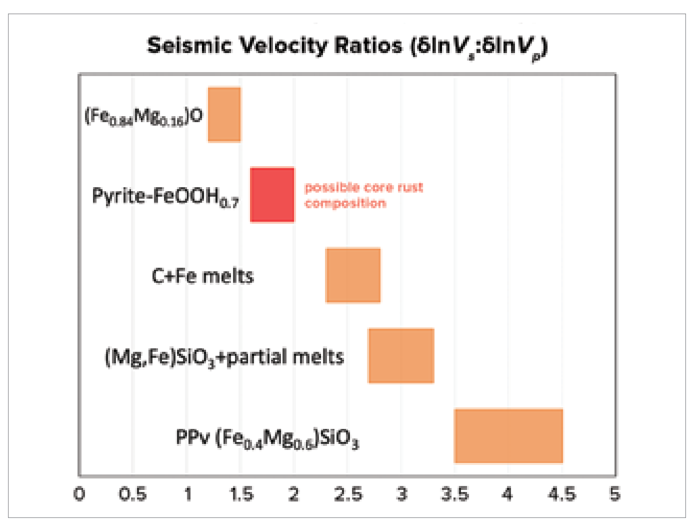


Fig. 2. The ranges (orange and red) of seismic velocity ratios (δlnVs:δlnVp) for different materials proposed as sources of ULVZs are shown here: iron-rich oxide, ($Fe_{0.84}Mg_{0.16}$)O; pyrite-type $FeOOH_{0.7}$ (possible core rust composition); carbon-iron melts, C+Fe melts; silicate perovskite and mantle partial melts, (Mg,Fe)SiO_3+partial melts; and postperovskite solid silicate, PPv ($Fe_{0.4}Mg_{0.6}$)SiO_3.

lion years later, has been attributed to a rapid increase in marine photosynthesis and to an increased photoperiod (i.e., longer daylight hours) [*Klatt et al.*, 2021].

But these explanations are far from impeccable. For example, besides a large mismatch in timing between the appearance of cyanobacteria on Earth and the GOE, several studies have indicated the possibility that a large increase in atmospheric oxygen at the beginning of the GOE was followed by a deep plunge to lower levels that extended over a few hundred million years. So far, there is no convincing explanation for this rise and fall based on cyanobacterial photosynthesis.

Furthermore, although it is widely accepted that the GOE raised atmospheric oxygen concentrations only modestly compared with the rise during the NOE, laboratory experiments investigating the influence of photoperiod on the net oxygen export from microbial mats that host competitive photosynthetic and chemosynthetic communities suggest a contradictory result [*Klatt et al.*, 2021]. Instead of more oxygen emerging from such mats as a result of longer daylight in the NOE, the experiments indicated that the increase in day length, from 21 to 24 hours, during the NOE may have led to only about half the rise in oxygen seen when the day length increased to 21 hours during the GOE.

Changes attributed to cyanobacteria and the length of the photoperiod thus do not provide a complete or consistent explanation for the atmospheric oxygen increases during the GOE or NOE, and alternative mechanisms for the origins of these events cannot be ruled out.

SUBDUCTION, MIGRATION, CONVECTION, ERUPTION

Decades of research have not produced conclusive evidence about when plate tectonics began on Earth. However, some recent studies indicate that subduction began bringing hydrous minerals down to the deep mantle before 3.3 billion years ago. And experimental studies have shown that hydrous minerals in subducting slabs are capable of relaying water all the way to the CMB [*Ohtani*, 2019]. If so, rusting might have happened as soon as the first ancient slab met the core. The core rust could have piled up gradually at the CMB, giving rise to ULVZs. As the pile migrated away from the cooler subduction region atop the molten outer core, driven by mantle convection, it would have heated up and likely become unstable when it reached a hotter region where a mantle plume was rooted (Figure 3).

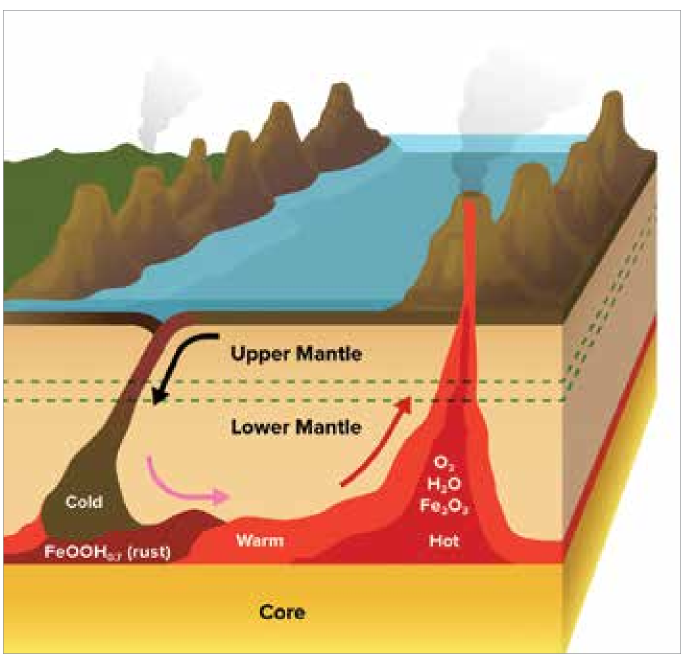


Fig. 3. Core rust ($FeOOH_{0.7}$) could form when a relatively cold subducting slab carrying hydrous minerals meets the outer core. Driven by mantle convection, core rust deposits from this cold region could then migrate along the CMB to a hotter region at the root of a mantle plume, where it could become unstable and decompose into hematite (Fe_2O_3), water (H_2O), and oxygen (O_2). Credit: Mary Heinrichs/AGU

Just as typical volcanic eruptions occur intermittently, the temperature-driven decomposition of core rust could result in fitful bursts of oxygen at the surface. In contrast to the gradual increase in oxygen from cyanobacterial photosynthesis, such a burst might have released oxygen faster than the surface environment could respond and consume it, causing a rapid initial rise and a subsequent fall of atmospheric oxygen levels.

The accumulation of a large core rust pile and its migration to the site of thermal decomposition could take a much longer time compared with the duration of eruptions of magma at the surface. Indeed, some piles that were formed may not have reached a region hot enough to cause decomposition, and their negative buoyancy amid the surrounding deep mantle would have kept them at the CMB. The geologic record suggests that Earth's surface was entirely covered by ocean until about 3.2 billion years ago. Net removal of water from the surface and storage in the deep mantle in core rust could have contributed to the emergence of continents in the Archean, although changes in surface topography driven by plate tectonics and the growth of buoyant continents also contributed to this emergence.

A POTENTIAL PARADIGM SHIFT

Although everyone can see that iron rusts at Earth's surface, unfortunately, no one can directly prove that Earth's liquid iron core 2,900 kilometers below the surface is similarly rusting. However, continuing studies will help scrape away layers of uncertainty and answer major questions, such as whether core rusting is responsible for the GOE and the NOE.

In particular, more laboratory experiments are needed to determine the precise limits of the thermal and compositional stability of core rust in equilibrium with molten iron at the conditions of the CMB. For example, we need to investigate the equilibrium between core rust and liquid iron at high pressure and high temperature. Other studies could examine core rust thermal stability at high pressures. These experiments are challenging but doable with the current experimental capabilities of laser-heated diamond anvil cells.

Furthermore, additional work is needed to resolve when subduction began and, specifically, when "wet subduction," which takes hydrous minerals into the deep interior, started. Geochemical evidence suggests that wet subduction did not start until 2.25 billion years ago, instead of 3.3 billion. This late a start of wet subduction may challenge the hypothesis that core rusting was the origin of the GOE.

Moreover, whether mantle convection involves layered circulations (i.e., separate convection cells in the lower and upper

Owl Rock in Arizona's Monument Valley gets its red color from iron oxide minerals. Recent experiments suggest that iron oxides may also be forming far below Earth's surface, at the interface between the core and the lower mantle. Credit: G. Lamar/Flickr, CC BY 2.0 (bit.ly/ccby2-0)

mantle), whole-mantle circulation, or some hybrid of these scenarios still requires clarification. If layered circulation prevails in the mantle, then subducting slabs would be prevented from entering the lower mantle. Thus, either whole-mantle or hybrid convection [*Chen*, 2016] must exist for slabs—and the hydrous minerals they carry—to reach the CMB and potentially cause rusting.

If the pieces of the puzzle fall into place, then rusting of the core may, indeed, be a massive internal oxygen generator on Earth—and the next great atmospheric oxygenation event could be on its way. The possibility of such an event would raise all sorts of questions about the effects it could have on environments, climate, and habitability in the future. In the near term, confirming that Earth's core rusts would cause a paradigm shift in our understanding of the planet's deep interior and how it has fundamentally influenced conditions and life at the surface.

ACKNOWLEDGMENTS

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How Forest Structure Drives Productivity

The woods and wetlands in the Chequamegon-Nicolet National Forest in Wisconsin are heterogeneous in nature. Credit: Jeff Miller, UW-Madison

Forests make large contributions to Earth's climate, from releasing water vapor to pulling in carbon dioxide from the air, which mitigates global warming. The arrangement of trees affects how forests use light and water for photosynthesis, and more complex forests have higher productivity, or rates of photosynthesis. But our knowledge of the specific factors driving this relationship is lacking.

In a recent study, *Murphy et al.* link two types of data to address this knowledge gap. Data were collected at nine sites in the Chequamegon-Nicolet National Forest in northern Wisconsin using a first-of-its-kind very high density eddy covariance flux tower network. Instruments on the towers measured the exchange of carbon, water, and energy between forest sites and the atmosphere, which then was used to calculate productivity. The researchers also characterized forest structure using lidar. This method collected 3D details, such as canopy roughness and tree height variation.

In addition, the scientists developed mathematical models to identify key structural factors underlying productivity. They found vertical heterogeneity metrics to be the most influential drivers. These metrics reveal the height distribution of vegetation at a site—low vertical heterogeneity indicates trees of similar height, such as after clear-cutting, whereas high vertical heterogeneity reflects trees distributed across heights. Yet the relationship between forest structure and productivity is not direct. Instead, it is mediated by how efficiently trees use resources—especially water—to produce biomass.

According to the authors, these results will improve mathematical models for how forest ecosystems respond to management. Such analyses could lead to better strategies for addressing climate change. (*Journal of Geophysical Research: Biogeosciences*, https://doi.org/10.1029/2021JG006748, 2022) **—Jack Lee,** *Science Writer*

A Unified Atmospheric Model for Uranus and Neptune

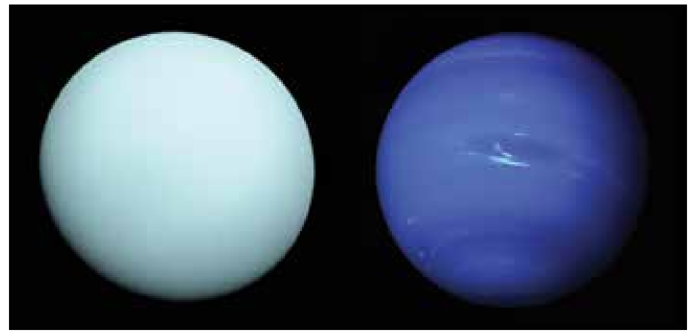
The ice giants, Uranus and Neptune, are the least understood planets in the solar system. They remain the only worlds that an orbital spacecraft has not visited. Our limited understanding of them derives largely from the flyby of NASA's Voyager 2 probe and subsequent observations with the Hubble Space Telescope. Yet the ice giants may be most representative of the extrasolar planets in our vicinity.

Why these planets appear so different in color despite having very similar physical properties, including vertical temperature profiles and atmospheric compositions, is a mystery. Past investigations have attributed Neptune's deeper blue largely to excess absorption in the red and near infrared from atmospheric methane. But the two planets have always been treated independently despite their similarities. Without a comprehensive atmospheric model, direct comparisons between them remain difficult.

Irwin et al. attempt to fill this gap by developing a single atmospheric model consistent with the spectral observations of both planets. They fit near-infrared spectra collected by Hubble, as well as by the ground-based Gemini and NASA Infrared Telescope Facility (IRTF) telescopes, to a three-layer aerosol model.

The topmost layer of this structure consists of haze resulting from photochemistry involving unknown atmospheric constituents. This haze is then somehow concentrated into a stable layer spanning from 1 bar down to approximately 2 bars. This main haze layer is roughly twice as thick on Uranus as it is on Neptune, giving Uranus a distinctly paler blue color.

In addition, at the base of the intermediate layer, the haze particles serve as condensation nuclei for atmospheric methane. These now heavy methane ice particles snow downward to a depth of 5–7 bars, where they heat up enough for the methane to evaporate. In this deepest layer, surviving haze particles become nucleation sites for another round of condensation, this time involving hydrogen sulfide.

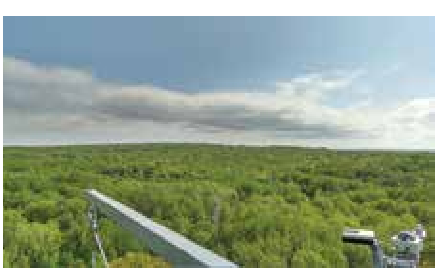


These images of Uranus (left) and Neptune were taken by NASA's Voyager 2 probe in flybys in 1986 and 1989. Credit: NASA/JPL-Caltech, Public Domain

This combined model mirrors the significant similarities that appear to exist between the two ice giant planets. Yet much about the mechanism and its constituent molecules remains unknown. This issue is likely to persist until the arrival of a Uranus orbiter, the development of which has been identified as a primary goal in the most recent planetary science decadal survey. (*Journal of Geophysical Research: Planets*, https://doi.org/10.1029/2022JE007189, 2022) **—Morgan Rehnberg,** *Science Writer*

Using Sap Flow to Infer Plant Hydraulic Properties

A foundational element of plant metabolism is the transport of water from the ground to the leaves. In most plants, this task is facilitated by xylem, a tissue whose structure provides hydraulic pathways that aid the water's upward movement. As plants face stressors such as drought, they respond by modifying their transport characteristics. Thus, an accurate understanding of their hydraulic properties is critical to modeling the effects of climate change on plant populations as well as to providing insight into how plant populations' water use will affect the global water, energy, and carbon cycles.



To understand the effects of climate change on forests, scientists analyzed data from measurements taken in northern Michigan. Credit: Gil Bohrer

However, experts have been challenged by individual plants' hydraulic variability, even among members of the same species. Plus, direct measurement of internal plant structures requires significantly more time and resources than external observables, such as leaf size.

Lu et al. attempt to sidestep these difficulties by constructing a model reliant on a more easily obtained alternative: sap flow rates. After developing a model that predicts sap flow on the basis of hydraulic properties, they used the Markov chain Monte Carlo methodology to invert it such that real-world observations of sap flow can be used to infer the underlying hydraulic characteristics. They derived their input data from measurements taken in 2015 in northern Michigan.

In addition to a series of synthetic tests, the authors used sap flow observations from four tree species: red maple, paper birch, bigtooth aspen, and white pine. Their approach successfully predicted sap flow trends from environmental data, such as atmospheric conditions, and it can distinguish a unique response from each species of tree.

This new method opens the way for better understanding of interspecies and intraspecies variation in the response to large-scale climate events. According to the authors, the approach could be further improved through the integration of additional environmental observations. (*Journal of Geophysical Research: Biogeosciences*, https://doi.org/10.1029/2021JG006777, 2022) **—Morgan Rehnberg,** *Science Writer*

Living near Fumigant-Using Farms Could Increase Cancer Risk

Every year, farmers around the world coat their fields in hundreds of millions of kilograms of herbicides, insecticides, fungicides, and fumigants. These chemical treatments effectively take care of crop-damaging pests, but many have negative side effects for people and animals in the ecosystem. Over the past half century, many pesticides, such as DDT, have been banned because of their health and environmental impacts. However, farmers in the United States still use dozens of chemicals that have been outlawed in other countries.

Previous studies have found a likely link between cancer rates and some of the pesticides that are still applied today. Most of this research, however, has focused on specific case studies of exposed agricultural workers. *Joseph et al.* study how simply being at risk of pesticide exposure affects people's health. The team looked at cancer and pesticide data across the 11 westernmost U.S. states to see whether any connections might emerge between higher cancer rates and the use of certain types of agricultural chemicals.

Farmers in the United States apply more than 450 million kilograms of pesticides to their crops each year. Credit: Tamina Miller/Flickr, CC BY-NC 2.0 (bit.ly/ccbync2-0)

The study revealed a connection between cancer rates and fumigants. The higher the mass of fumigants applied in a region, the higher the rate of pediatric cancer. Two widely used soil fumigants—metam sodium and metam potassium—were also linked to an overall higher prevalence of cancer. The carcinogenic influence of metam salts could happen after their application to the soil, when they break down into more toxic chemicals and spread through the air. Conversely, the researchers did not find a connection between cancer risk and amount of herbicide applied.

Although the results of this study represent only correlations, they demonstrate a need for further investigation, according to the authors. These results could be used to identify areas in the West that require more public health attention. The authors also suggest that future studies investigate the link between metam, the chemicals it breaks down into, and cancer. (*GeoHealth*, https://doi.org/10.1029/2021GH000544, 2022) **—Rachel Fritts,** *Science Writer*

Tracing Water Particles Back in Time

Low-oxygen conditions in oceans negatively affect marine life and ecosystems. Although many coastlines experience regular low-oxygen periods, the phenomenon is becoming more common as dissolved oxygen decreases globally. Deciphering how oxygen levels fluctuate throughout the year can help scientists better understand marine ecosystem dynamics.

In a new study, *Sahu et al.* dive deep into the waters off Vancouver Island, where every summer a low-oxygen pool of water settles over the continental shelf. The region is part of the Juan de Fuca Eddy—which sits at the northern end of the California Current System—and spans the bathymetrically complex continental shelf.

The researchers analyzed the potential sources of water that contribute to the low-oxygen summer pool. They populated an oceanic numerical model for the region using data collected during a scientific cruise in August 2013. The model depicts how ocean properties like temperature and salinity vary over time. In the model, they traced water particles backward in time using Lagrangian particle tracking. In addition, they used kernel density estimation to determine the geographic origin of the low-oxygen pool's source water.

The results showed that deep low-oxygen waters arrive from the south in early summer. Specifically, the models showed that 45% of the low-oxygen pool derives from the California Undercurrent and an additional 20% originates in deeper, offshore waters. The low-oxygen waters weave through a maze of submarine canyons in the Juan de Fuca region to arrive at Vancouver Island. This movement is opposite the summer currents on the continental shelf, which typically flow from the north.

Researchers analyzed the seasonally oxygen-poor waters off the coast of Vancouver Island, seen here in the distance above a marine layer. Credit: Keith Ewing/Flickr, CC BY-NC 2.0 (bit.ly/ccbync2-0)

According to the authors, elucidating this movement of water reveals critical mechanisms driving one of the most biologically productive coastlines in the world. (*Journal of Geophysical Research: Oceans*, https://doi.org/10.1029/2021JC018135, 2022) **—Aaron Sidder,** *Science Writer*

Impact of Climate on River Chemistry Across the United States

Rivers flow across many kinds of terrain, interacting with soil, rocks, microbes, and roots. River water therefore carries signatures of everything it interacts with, and its chemistry reflects the response of the critical zone—the region of the planet stretching from the tops of trees to the bottom of groundwater—to changing climate. River chemistry is likely to change with a warming climate, yet most climate-related research studies have focused on changes in river flow.

Now, *Li et al.* focus on changes in river chemistry and water quality under a changing climate. They investigated the influence of climate on the long-term chemistry of rivers in the contiguous United States, compiling more than 400,000 data points from 506 rivers with minimal human impacts to identify patterns of 16 common river chemistry constituents (solutes).

For all geographic areas of the United States, the team found that concentrations of 16 solutes decrease with increasing mean river discharge, which is the amount of precipitated water (both rainfall and snowfall) that ends up in streams and rivers. This finding contradicts the common perception that river chemistry is controlled primarily by the abundance of local materials in the critical zone. Instead, river chemistry is controlled first by river discharge, then by the abundance of materials the water interacts with.

Changing climate conditions—including higher temperatures—can influence not only river discharge but also the types of critical zone materials that interact with and dissolve in waters. The authors say that in places that become drier, such as western parts of the United States, mean solute concentrations are expected to increase, and the magnitude of the increase hinges on the solutes' sensitivity to changes in discharge. In places that become wetter, mean concentrations likely decrease, but the loads, or the rates of solute export leaving rivers, can increase with more water.

As the climate changes, increasing solute concentrations will have implications for water management and treatment efforts and may require renovated or augmented treatment infrastructure. These changes can also have significant impacts on aquatic ecosystem health. (*Earth's Future*, https://doi.org/10.1029/2021EF002603, 2022) **—Sarah Derouin,** *Science Writer*

Constraining Martian Crustal Thickness with InSight Seismology

An artist's rendering of InSight on the surface of Mars. The lander has a seismometer that captures measurements of seismic waves on the Red Planet. Credit: NASA/JPL-Caltech, Public Domain

A planet's geologic history is locked up in its crust, but a fundamental challenge in planetary science is deducing the subsurface composition and structure of other worlds. In studying Mars, efforts to infer the thickness and composition of the planet's crust have combined available spacecraft data with reasonable geologic assumptions. These efforts have yielded a wide range of estimates. In recent years, however, a critical new source of data has emerged: NASA's InSight lander.

Since 2018, InSight has provided the first meaningful measurements of seismic waves on the Red Planet. By analyzing these observations, recent work has deduced the presence of several significant crustal layers beneath the lander. However, because InSight is the only seismic station on Mars, its results are particular to its location in the planet's northern lowlands.

Wieczorek et al. work to overcome this limitation by combining the seismic observations with gravity and topography data obtained by previous missions. The authors constructed three possible models for Martian crust: The first is of a spatially uniform composition, the second includes a near-surface low-density layer, and the third uses different compositions and density for northern lowlands and southern highlands. Each model also accounts for the low-density ice caps at the north and south poles. Then—as in past work—these models are fit to the best available gravimetric data, considering the visible surface topography.

The structure inferred by InSight's seismic observations forms a new, more specific constraint. The researchers considered the three different models and estimated the average crustal thickness to be between 30 and 72 kilometers. In addition, the implied density of 2,850–3,100 kilograms per cubic meter is lower than that of most rocks studied by the rovers, and of most Martian meteorites.

On the basis of this density estimate, the authors conclude that most Martian crust is left over from the planet's creation, having formed as the planet's differentiated surface cooled. While there remains some ambiguity in the overall structure, the placement of a second seismometer far from the location of InSight could provide some answers, according to the authors. (*Journal of Geophysical Research: Planets*, https://doi.org/10.1029/2022JE007298, 2022) **—Morgan Rehnberg,** *Science Writer*

Atmospheric Rivers Help Coastal Wetlands Build Up Sediment

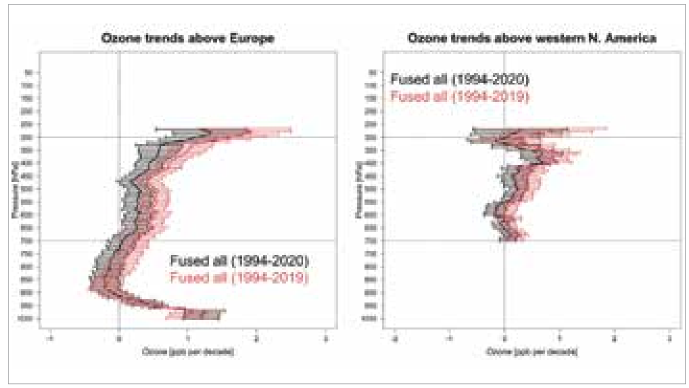
Extreme precipitation from hurricanes and atmospheric rivers can lead to increased flooding in the world's coastal zones, where more than 630 million people reside. Tidal marshes act as important buffers in these areas, absorbing the initial impact of storm surges and strong winds. In addition, tidal marsh ecosystems rely on storm events to deposit sediments that help with marsh accretion.

In a new study, *Thorne et al*. focus on tidal marsh accretion and elevation change in the San Francisco Bay after an atmospheric river event in 2016–2017. The authors installed deep rod surface elevation table instruments and feldspar marker horizon plots at five marsh sites differing in salinity and tidal range to determine vertical accretion and elevation changes.

They discovered that in response to the storms, different landscape characteristics played important roles in sediment deposition and flooding. For example, sites that were closest to rivers had the highest accretion and surface elevation gains. According to the authors, these data could provide important insights for offsetting sea level rise and thwarting habitat loss. Incorporating marsh accretion responses to storm events into wetland evolution models could also help predict marshes' long-term response to sea level rise. (*Journal of Geophysical Research: Biogeosciences*, https://doi.org/10.1029/2021JG006592, 2022) **—Alexandra K. Scammell,** *Associate Editor*

Air Pollution Was Reduced During the COVID-19 Pandemic

In the Northern Hemisphere, levels of ozone in the free troposphere increased each year since the mid-1990s—until 2020. *Chang et al.* examine the association between negative anomalies in tropospheric ozone observed in 2020 above Europe and western North America and the economic downturn brought on by the COVID-19 pandemic, as well as the resulting effects on long-term trends. The team developed a statistical framework to better quantify regional-scale ozone anomalies throughout the depth of the troposphere and stratosphere by combining multiple sources of vertical profile records, such as ozonesonde, lidar, and commercial aircraft data. The authors show that regional anomalies, and their associated estimation uncertainty, can be consistently and systematically quantified. Their findings indicate that the increasing ozone trends from 1994 to 2019 above Europe and western North America are diminished when the large negative anomalies in 2020 are included. Further, 2020 is the only year in which both regions show coincident and profound negative anomalies since the benchmark year of 1994. (https://doi.org/10.1029/2021AV000542) **—Donald Wuebbles**

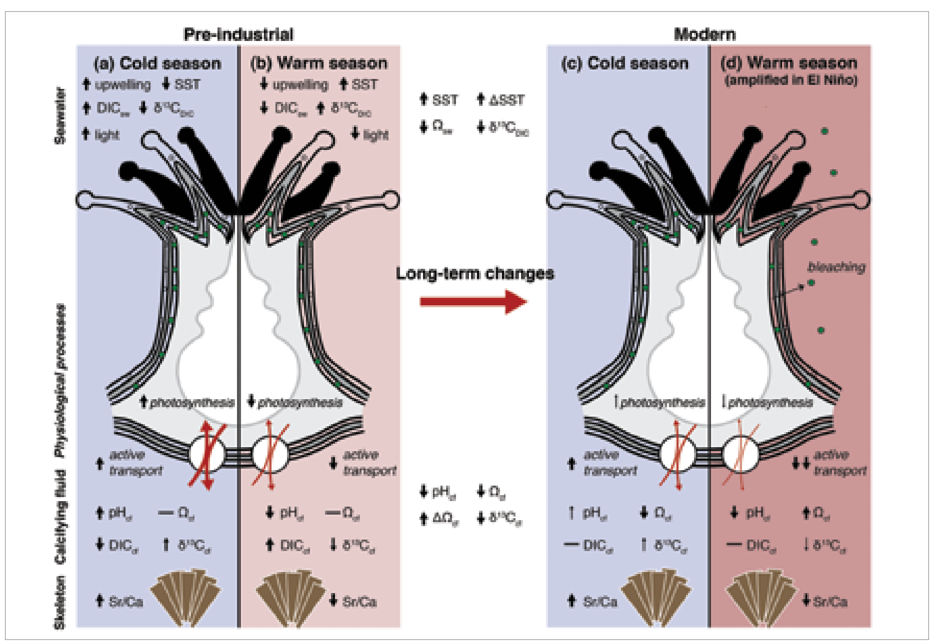


Profiles of ozone mean trends above Europe and western North America (in parts per billion by volume per decade) derived from the final fused product over 1994–2019 and 1994–2020 demonstrate the significant decrease in ozone over these regions in 2020. Credit: Chang et al.

Reef-Building Corals at Risk from Ocean Warming, Acidification

Environmental stress imposed by ocean warming and acidification has important implications for the growth of organisms, especially those with carbonate skeletons, such as reef-building corals.

Thompson et al. use coral geochemistry and results from Earth system modeling to examine the effects of these stressors on calcification and resiliency in corals around the Galápagos Islands. Their analysis of calcifying fluid geochemistry in preindustrial and modern corals suggests that physiological limits to coral buffering capacity affect growth. The implication is that the capacity of corals to buffer ocean acidification may be more limited than indicated by previous experimental studies. The reduced buffering capacity has consequences for calcification, which affects reef structure, function, and resilience, especially in marginal environments, such as the Galápagos. (https://doi.org/10.1029/2021AV000509) **—Eileen Hofmann**



This diagram shows seawater and physiological controls for cold and warm seasons on calcifying fluid and skeletal geochemistry for 18th-century (preindustrial) fossil corals and modern corals. The reduction in active transport (red arrows, with thickness indicating relative magnitude), critical for regulating the geochemistry of the calcifying fluid, is enhanced in modern corals by thermal stress such as that which occurs during El Niño conditions. Credit: Thompson et al.

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TAMPA BAY WATER
Supplying Water To The Region

WATER RESOURCES SYSTEM ENGINEER

Under administrative direction, performs functions of the agency involving analysis and modeling of environmental, production, and water quality data, forecast/simulation modeling of short-term and long-term water supply, modeling of surface and ground water flow systems at various spatial and temporal scales, and participates in long-term water supply planning activities. Employees in this category have knowledge and understanding in the areas of surface-water, groundwater, hydrogeology, water quality, water resources management, hydrologic and hydraulic modeling, numerical, analytical, and statistical concepts and methods, uncertainty and risk analysis, and water supply planning principles. Knowledge on systems optimization and stochastic hydrology is highly desirable.

Essential function (70%) Delivery System, Optimization and Master Water Plan Evaluation

- Support implementation and continuous improvements to Tampa Bay Water's decision support tools based on simulation-optimization approaches. Tampa Bay Water uses these tools to support long-range (at the time scale of 2-3 decades) water supply planning by evaluating delivery system performance under current and future conditions/configurations.
- Support implementation and continuous improvement to a multi-objective optimization model that facilitates allocating water production from a diverse portfolio of water supply sources at monthly to seasonal time scale
- Conduct large scale Monte-Carlo based simulation-optimization modeling using an in-house computational platform that supports parallel and distributed computing
- Conduct hydraulic modeling of large pipe municipal systems with multiple water supply sources.
- Participate in the Agency's long-term water supply planning activities including assessment updates for future water supply needs and water supply alternative evaluations.
- Provide support for Tampa Bay Water's Optimized Regional Operations Plan (OROP) that ensures water production (at weekly to monthly time scale) simultaneously meets demand and protects ecosystem health.

Essential function (30%) Integrated Hydrologic Modeling Program and Water Use Permit Support

More information about essential functions and how to apply can be found at: https://www.tampabaywater.org/careers

Dear AGU:

Flying over southern Greenland on a transatlantic commercial flight at an altitude of approximately 11,000 meters, we were amazed by the large number of meltwater lakes and the extensive network of stream channels crisscrossing the ice sheet. As scientists who study temperate lakes and their watersheds, we were struck by the similarity of these polar lakes to those in temperate latitudes (e.g., glacial lakes of the Sierra Nevada in Spain and the Laurentian Great Lakes in North America) in terms of their random distribution and interconnecting streams. With these chance observations made from the cabin porthole—before the flight attendant asked us to pull the shade so passengers could sleep—we were left with many questions.

Assuming that these lakes and streams form on the glacier's surface every summer, how has their distribution, abundance, volume, and expanse changed over the years? How much of these relatively warm and dense glacial lake waters bore their way through the ice down to bedrock, lubricating the ice sheet on its path to the sea? What role do the interconnecting streams play in fragmenting the ice sheet over the long term? How are these ongoing changes affecting the ice-albedo climate feedback? Are satellites and sensor-equipped overflights adequately mapping and keeping a close watch on the dynamics of these ephemeral glacial lakes and streams and quantifying their influence on the world's glaciers—including mountain glaciers?

In an increasingly warming world, gaining a better handle on such nonlinear processes as abrupt continental ice loss and the resulting sudden sea level rise are in the public interest. Clearly, much more than the good night's sleep of a planeload of passengers depends on the fate of these seemingly permanent continental glaciers that are unevenly melting away.

—**Juanma Medina-Sánchez,** Departamento de Ecología and Instituto del Agua, Universidad de Granada, Granada, Spain; and **Bopi Biddanda,** Robert B. Annis Water Resources Institute, Grand Valley State University, Muskegon, Mich.

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