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SCIENCE NEWS BY AGU

Gaining New Insights from Old Storms

South America Is Drying Up

Earth May Survive the Sun's Demise

HOW GREAT WAS the Great Oxidation Event?

Answers to existential questions are coming from a planetary perturbation billions of years in the past.

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From the Editor

The title question posed by our lead story this month has been irresistible to Earth scientists for generations: How great was the Great Oxidation Event?

Author Aubrey Zerkle and other geoscientists searched for an answer by taking a fresh look at the acidic waters of the Rio Tinto in southern Spain. What they found indicates that the Great Oxidation Event provided enough oxygen to the atmosphere for animals to have evolved nearly 2 billion years before evidence suggests they actually did. Read about it on page 18.

The banded iron formations (BIFs) that largely appeared in the run-up to the Great Oxidation Event and the large-scale perturbation that helps define it provide other clues to solving its mysteries. Learn more about BIFs and how "Bacteria Battled for Iron in Earth's Early Oceans" on page 13 and how "Planetary Perturbations May Strengthen Gaia" on page 2.

On the Cover

Iron gives a characteristic red tint to the acidic waters of the Rio Tinto in Spain. Credit: joserpizarro – stock.adobe.com

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Janice Lachance, Interim Executive Director/CEO

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Planetary Perturbations May Strengthen Gaia

New research suggests that large disruptions to living worlds may increase life's complexity in the long run. Credit: nox_box, Pixabay

Few Earth science concepts are as controversial and enticing as the Gaia hypothesis. First introduced by chemist James Lovelock and microbiologist Lynn Margulis in the 1970s, it proposes that planet Earth behaves like a self-perpetuating organism, with living creatures interacting with abiotic parts of ecosystems to maintain and even improve conditions for life.

Some experts, in contrast, have noted that large-scale planetary perturbations such as climate change and an overuse of resources can wipe out biotic progress. This thesis suggests that life worsens conditions for itself or is even inherently self-destructive.

"When you have a collapse, it gives the potential for something new to arise."

But a new study, published in *Monthly Notices of the Royal Astronomical Society* (bit.ly/Gaia-stress), uses modeling to make a different argument: that large-scale perturbations are actually a mechanism by which Gaian systems increase in complexity (defined as the number of connections existing in a network of species). The findings could eventually help planetary scientists narrow their search for life beyond Earth, according to the authors.

"I'm really glad that people are trying to experimentally test some of the most profound questions about life itself," said Peter Ward, a paleontologist at the University of Washington who was not involved in the research.

Modeling Gaia

Earth has historically behaved like a Gaian system, said Arwen Nicholson, an astrophysicist at the University of Exeter and a coauthor of the new study. "You see this trend of increasing diversity and biomass over time, and life has become more complex."

Some of that complexity seems to have arisen from large-scale perturbations to Earth. For instance, the Great Oxidation Event, a period about 2.5 billion years ago when levels of oxygen in Earth's atmosphere rose sharply, killed most anaerobic life but created the opportunity for organisms to evolve.

To test whether this may be true on other worlds, the research team used the Tangled Nature Model, meant to simulate how groups of species evolve. In this computer model, the fate of each species is tied to that of others—as it is on Earth.

The researchers simulated perturbations to these modeled worlds by temporarily lowering the carrying capacity of the world. They ran experiments with perturbations of different lengths, different numbers of perturbations, and different numbers of refugia where life could persist during a perturbation.

After thousands of simulations, the team found that though a perturbed system was more likely to completely snuff out all life, those in which life survived had higher biodiversity and abundance that persisted over tens of thousands of generations.

"When you have a collapse, it gives the potential for something new to arise," Nicholson said.

"The [systems] that survived through those events bounced back stronger," said Nathan Mayne, also an astrophysicist at the University of Exeter and a coauthor of the study. For example, during the Great Oxidation Event, anaerobic life persisted in refugia offered by deep, low-oxygen waters.

The more complex a living system on a planet is, the more complex species' interactions with each other are. This makes it more likely that the next iteration of an ecosystem that fills an empty niche will be made of more complex connections, Nicholson said.

Mayne stressed that the model is abstract, does not include all the details of biological life-forms, and is instead meant to reveal general principles that may play out on different worlds.

"Biology is inevitably more complicated and more subtle than the models," Charles Lineweaver, an astrobiologist at the Australian National University who was not involved in the new research, wrote in an email. "Biology is always full of surprises and unintended consequences."

"Biology is always full of surprises and unintended consequences."

Self-Destructive Tendencies

Ward was one of the first scientists to argue that life on Earth may be inherently self-destructive, calling the idea the Medea hypothesis.

He said he was not convinced by the new study because in Earth's history, "life is a major cause" of mass death. Life itself can lead to anti-Gaian feedbacks such as the Great Oxidation Event, which was caused by the evolution of a new form of single-celled organisms that could photosynthesize, he said. "You finally get life on the planet, and then what happens? It evolves to produce oxygen and kills off almost everything."

"Unlocking oxygen allowed life to become more complex...that's why we're here."

"These huge perturbations cause life to go in retrograde—they cause conditions to get worse," he said. He added that Earth's ecosystems tend to show that "diversity comes about when you have long periods of stability." For example, coral reefs tend to be more diverse if they've had a long period of stability during which to evolve.

Nicholson had a different view: "Unlocking oxygen allowed life to become more complex...that's why we're here," she said. "If you were a microbe [during the Great Oxidation Event], that would have been really bad. But in order for a biome to increase in complexity, that's going to have to involve some kind of upheaval to life."

The idea that life eventually destroys itself by spurring its own extinction events contradicts the findings of the authors' modeling experiments, which show stability arising from living systems over time even with large-scale perturbations, Mayne said. "Our idealized work does run against the Medea hypothesis," he added. "Our modeling suggests that statistically, biospheres build complexity and are not self-destructive."

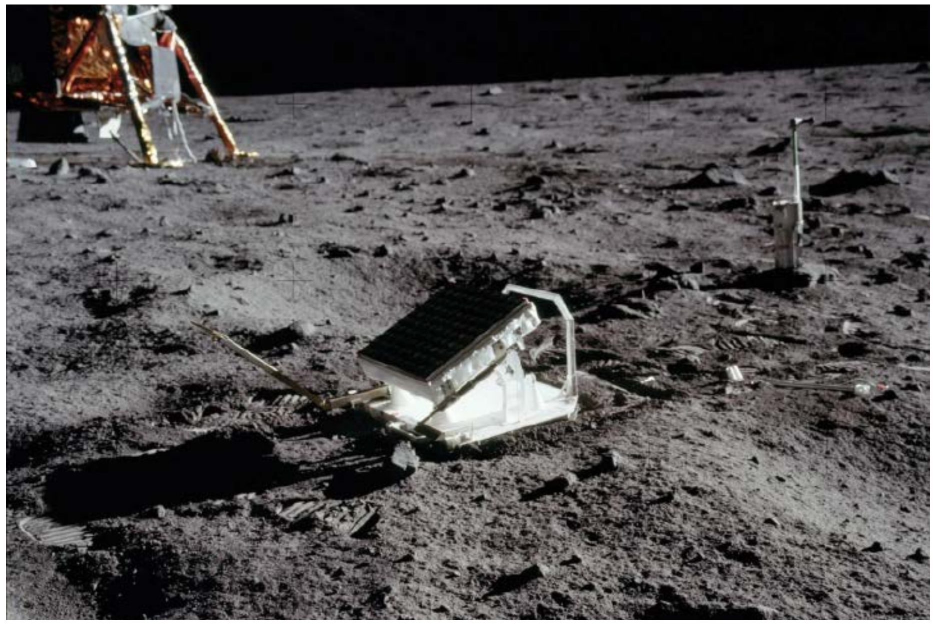
Gaias Beyond Earth

The new research could help scientists narrow their search for extraterrestrial life, according to the authors.

For example, planets near the edges of the habitable zone—the window of distance from a planet's star that allows for the existence of liquid water—may be more likely to have experienced perturbations to their climates, which could have spurred more complex life. Orbital shifts and asteroid impacts could similarly perturb a planet.

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

The Relatively Messy Problem with Lunar Clocks



Apollo 11 astronauts placed the Laser Ranging Retroreflector on the surface of the Moon. This device was designed to test Einstein's theory of general relativity, which is necessary to understanding the different rates at which clocks run on the Moon versus Earth. Credit: NASA; scan by NASA Johnson

What time is it on the Moon?

In April 2024, the White House issued a challenge to scientists to establish a lunar time standard, looking ahead to increased international presence on the Moon and potential human bases as part of NASA's Artemis initiative.

The real question isn't "What time is it?" but, rather, "How quickly does time pass?"

The time that a clock reads can be set by any timekeeper, but physics determines how quickly time passes. In the early years of the 20th century, Albert Einstein theorized that two observers won't agree on how long an hour is if they aren't moving at the same speed in the same direction. That disagreement also holds between a person on Earth's surface and another in orbit or on the Moon.

"If we are on the Moon, clocks are going to tick differently [than on Earth]," said theoretical physicist Bijunath Patla of the National Institute of Standards and Technology (NIST) in Boulder, Colo. He noted that the Moon's motion relative to ours should make clocks run slower than Earth standard, but its lower gravity leads to clocks running faster.

"So these are two competing effects, and the net result of this is a 56-microseconds-per-day drift," he said. (That's 0.000056 second.)

Patla and his NIST physicist colleague Neil Ashby used Einstein's theory of general relativity to calculate this number, an improvement over previous analyses. They published their results in the *Astronomical Journal* (bit.ly/Moon-clocks).

Though a 56-microsecond difference is small by human standards, it's significant when it comes to guiding multiple missions with pinpoint accuracy or communicating between Earth and the Moon.

"The fundamental thing is safety of navigation in the context of a lunar ecosystem when you have lots more activity on the Moon than you have now," said Cheryl Gramling, a systems engineer at NASA's Goddard Space Flight Center. "When it comes to navigation, a drift of 56 microseconds over a day between a clock on the Moon and [a clock] on Earth is a big difference, so you have to accommodate that."

Modern precision navigation relies on synchronizing clocks. This involves coordination using radio waves, which travel at the speed of light. Gramling noted that light travels 30 centimeters (11.8 inches) in 1 nanosecond (0.001 microsecond)—an unbelievably short amount of time by human standards—so failing to account for the 56-microsecond discrepancy could potentially result in navigational errors as large as 17 kilometers per day. Even a fraction of that is unacceptable when it comes to Artemis missions, which will require knowing the position of every rover, lander, or astronaut to within 10 meters at all times.

"When it comes to navigation, a drift of 56 microseconds over a day between a clock on the Moon and [a clock] on Earth is a big difference, so you have to accommodate that."

Free Falling

A key result of the theory of relativity is that there's no such thing as absolute time. A clock on Earth's surface will tick more slowly than one in orbit because of gravitational effects, which is why GPS satellites have to take relativity into account. (Coordinated universal time and other standards on Earth use networks of clocks that correct for tiny gravitational differences at various elevations, too.)

Determining the difference in timekeeping between Earth and the Moon adds extra complications. The Moon is moving relative to any spot on Earth's surface because of our rotation and its orbit around us, which means any lunar clock will appear to run slower from our point of view. In addition, any clock on the Moon is affected by the Moon's gravity and Earth's. (Artificial satellites aren't large or massive enough for their own gravitational effects to matter.)

Properly handling these effects of relativity requires picking an appropriate frame of reference. Ashby and Patla tackled the problem by acknowledging that the Earth-Moon system is in free fall—moving only under the influence of the Sun's gravity—with each orbiting their mutual center of mass. That enabled them to formulate the contributions from each complication: the rotation of each body, tidal forces, deviations in shape from perfect spheres, and so forth.

Ashby and Patla also performed the calculation for gravitationally stable positions in orbit between Earth and the Moon known as Lagrange points, which could be used for communications relay satellites.

Meanwhile, theoretical physicist Sergei Kopeikin of the University of Missouri and astronomer George Kaplan of the U.S. Naval Observatory independently calculated a 56-microsecond time shift between Earth and the Moon (bit.ly/lunar-time). They also calculated smaller, periodic fluctuations in clock rates due to tiny tidal force variations from the Sun and Jupiter, nanosecond-level effects that, nevertheless, need to be accounted for to obtain 10-meter-scale or better navigational precision.

"The [relativity] community has done us a great service by publishing all this work."

"The [relativity] community has done us a great service by publishing all this work," Gramling said. "Now we have something to bring to the whole international community of timing experts and say, 'Is this the model that we can standardize for the Moon?'"

It will be many years or decades before the Moon is populated with enough people and robots to need this level of timekeeping. However, scientists and engineers recognize how important it is to have a lunar standard time in place long before it's necessary. Now they have taken that difficult first step toward knowing what time it is on the Moon.

By **Matthew R. Francis,** Science Writer

Tourism and Distant Fires Affect Antarctica's Black Carbon Levels

Tourists visit the Antarctic Peninsula aboard the Star Princess *in 2008. Credit: Matt S./Flickr, CC BY-NC-ND 2.0 (bit .ly/ccbyncnd2-0)*

Antarctic tourism is increasing each year, with the vast majority of visitors arriving by ship. Though the tourist boom allows more people to appreciate the continent's stunning landscapes and unique ecosystems, a new study has revealed that it also contributes to seasonal increases in atmospheric black carbon (bit.ly/Antarctic-black-carbon.)

Refractory black carbon (rBC) comes from burning fossil fuels and biomass. It plays a significant role in climate change because it not only warms the atmosphere but also contributes to the melting of ice by darkening its surface albedo.

As study coauthor Joe McConnell, a climate scientist at the Desert Research Institute, explained, "Black carbon is a very good absorber of energy. Even a tiny bit of black carbon in the bright snow surface will reduce the albedo, cause the snowpack to warm, and eventually cause it to melt."

Recent studies of samples collected near research facilities and tourist sites have revealed rBC concentrations of 1–8 nanograms per gram of snow—much higher than the typical 0.1–0.2 nanogram per gram previously observed. Others have found seasonal patterns, with peaks during biomass-burning seasons. However, all of these studies have examined local and distant sources of rBC separately. According to the authors, their study is the first to look comprehensively at rBC sources in the northern Antarctic Peninsula.

Researchers measured rBC levels in a 20-meter ice core from the Detroit Plateau near the northern tip of the Antarctic Peninsula. They zeroed in on rBC data from 2003–2008. Rates of deforestation and fires were particularly high during this period, and the summer of 2007–2008 marked a tourism boom in Antarctica.

To assess the effects of both distant and local rBC emissions, the researchers also analyzed atmospheric rBC data from satellite measurements and models, such as the Moderate Resolution Imaging Spectroradiometer (MODIS) and the Modern-Era Retrospective analysis for Research and Applications, Version 2 (MERRA-2), as well as information on burned areas and tourism activities.

rBC Seasonality

Raul Cordero, a climate scientist at the University of Groningen in the Netherlands, was not involved in this study, but he coauthored a 2022 paper on how human presence in Antarctica affects black carbon levels (bit.ly/humans-Antarctic-carbon). "There's something this paper has that our paper doesn't," he said. "We focused on local sources of black carbon emissions, while they suggest—and we agree—that some pollution comes from distant fires."

Cordero's study reported annual rBC concentrations of 0.01–3.73 nanograms per gram. Concentrations were highest during spring and summer.

During Antarctic summer (December–February), tourist ships visited Antarctica, raising black carbon levels. Warmer temperatures and increased sunlight allowed the resulting black carbon to absorb more heat.

"Touristic activities occur when the snow and ice are most sensitive to black carbon," said Newton Magalhães, a geoprocessing analyst at Rio de Janeiro State University in Brazil and first author of the new study. Therefore, summer peak levels of rBC are largely attributed to tourism.

In the fall (March–May), the Southern Hemisphere saw the lowest burned area and minimal tourism, leading to the lowest rBC emissions. During winter (June–August), tourist activities and research operations decreased, but biomass burning peaked in southern Africa and South America, contributing significantly to rBC emissions.

In spring (September–November), when tourism was low (or not present at all in 2003–2005), rBC concentrations remained high, suggesting contributions from distant sources. For instance, during the 2007 Amazon fire season, rBC levels in the Detroit Plateau core reached 3.7 nanograms per gram.

Magalhães noted that though both local and long-range sources contribute to rBC, "quantifying their [relative] contributions is still a challenge." In winter, rBC peaks can typically be attributed to biomass burning, but pinpointing a source when tourism and burning co-occur is difficult. He suggested that carbon-14 could help to quantify their relative contributions: Fossil fuels contain little to no carbon-14 because of their age, whereas biomass fuels contain measurable carbon-14 levels.

Magalhães and McConnell suggested that tourist ships could reduce rBC emissions by using higher-quality fuel. "Black carbon is a result of incomplete combustion, so if you get complete combustion, you get very little or no black carbon. Higher-quality fuel means more efficient combustion," said McConnell.

By **Larissa G. Capella** (@CapellaLarissa), Science Writer

Earth May Survive the Sun's Demise

Earth's future is bleak. At best, our planet will become a burned-out cinder as the Sun expands at the end of its life. At worst, it will be engulfed by the Sun, leaving no trace that it ever existed.

Astronomers have found a clue as to which path Earth might follow in a star system about 4,300 light-years away. There, a rocky planet orbits the remains of a once Sun-like star at a distance similar to where Earth could park if it survives our own star's death throes. The system "may offer a glimpse into the possible survival of planet Earth in the distant future," according to a new study published in *Nature Astronomy* (bit.ly/Earth-survival).

The system, KMT-2020-BLG-0414L, was discovered in 2020 by the Korea Microlensing Telescope Network, a set of three automated 1.6-meter telescopes in the Southern Hemisphere.

The network looks for gravitational lensing events, those in which a star or planet passes between Earth and a background star. The gravity of the intervening object acts as a lens, making the background star appear much brighter. The length, intensity, and other details of the event, along with before-and-after observations, allow scientists to calculate the details of the lensing object.

Early analysis suggested that the system (abbreviated as KB200414) consists of a low-mass star, an Earth-mass planet, and a third object many times the mass of Jupiter.

An artist's concept depicts what the Earth-analogue planet might look like, with the white dwarf star in the background. Credit: W. M. Keck Observatory/Adam Makarenko

A Lucky Alignment

Astronomers tried to get a clearer look at the system with the 10-meter Keck II Telescope in Hawaii, but those observations did not detect the lensing system's host star.

"This system is part of a larger sample of microlensing planets," said Keming Zhang, an astrophysicist now at the University of California, San Diego and first author of the study. "This is the only one for which we don't detect the expected host brightness."

Zhang and his colleagues considered several scenarios that could explain that finding. They concluded that instead of being a bright main sequence star, the star must be a dimmer white dwarf about half as massive as the Sun. "There is some luck involved, because you would expect only around one in 10 microlensing planets to have white dwarf hosts," Zhang said.

The researchers' analysis also showed that the rocky planet orbiting that star is nearly double Earth's mass and more than twice Earth's distance from the Sun. It is the first possible Earth-like world discovered orbiting a white dwarf. Other studies have revealed white dwarfs that host gas giant planets, along with bands of rubble thought to be the remnants of rocky planets, but nothing comparable to Earth.

The third object in the system appears to be a brown dwarf—a "failed star" not massive enough to shine as a true star. It's about 27 times the mass of Jupiter and orbits the white dwarf at about 22 times the Earth–Sun distance, according to the researchers, which would put it beyond Uranus in a comparison with our solar system.

A Glimpse at Earth's Future?

During its time in the main sequence, a star fuses the hydrogen in its core to create helium. As that process ends, the star expands, becoming a red giant. The Sun, which is 4.6 billion years old, is expected to enter that phase in about 6–7 billion years, puffing up to dozens of times its current diameter. It will remain in this red giant phase for a billion years, after which it will expel its outer layers, leaving only its hot, dense, now-dead core: a white dwarf like the one at the center of KB200414.

When the Sun becomes a red giant, it will engulf Mercury and Venus. Mars and the outer planets almost certainly will survive.

Earth's fate is more difficult to foretell, however, because of the complicated nature of the Sun's final days.

> **"You would expect only around one in 10 microlensing planets to have white dwarf hosts."**

One possibility is that as the Sun loses mass and its gravitational grip on Earth weakens, our planet will migrate outward (though its oceans and atmosphere will have boiled away billions of years earlier). As it becomes a white dwarf, the Sun will lose half its mass, and Earth, if it survives, may expand its orbit to twice its current size, Zhang said. That's about as far as KB200414's rocky planet, suggesting that it met a similar fate.

The scenario will be further complicated by the motions of the other planets, especially Jupiter and Saturn, which can act as wrecking balls.

"Our solar system is relatively boring and stable today," said Carl Melis, also an astrophysicist at the University of California, San Diego, who was not involved in the study but has collaborated with some of its authors in the past. "But when the Sun begins to die, all bets are off," he added. "There are many studies of what will happen dynamically, and it's not pretty."

In the case of KB200414, the brown dwarf would have "wreaked absolute havoc" on other planets in the system as it moved away from the red giant, Melis said. "The brown dwarf would excite all kinds of weird things. I can't even imagine what it would do to the planet."

"Our solar system is relatively boring and stable today. But when the Sun begins to die, all bets are off. There are many studies of what will happen dynamically, and it's not pretty."

For that and other reasons, Melis doesn't consider the architecture of the system proposed by Zhang and his colleagues settled. "It is a possible solution—even a reasonable solution. But it's not 100% conclusive," he said. "My personal take is they need to keep cracking."

Extremely large ground-based telescopes, which are expected to come online early in the next decade, should reveal the white dwarf itself, allowing astronomers to confirm their scenario, Zhang said. And NASA's Nancy Grace Roman Space Telescope, due to launch in 2027, should find many additional white dwarf planetary systems, he said. Those discoveries could provide additional clues to the bleak fate of Earth.

By **Damond Benningfield,** Science Writer

Torrents of Sediment-Laden Water Worsened Disastrous Libyan Floods

Africa's deadliest flood in a century didn't happen in the continent's rain-soaked equatorial jungles or along the mighty Nile, Congo, and Niger rivers. It happened in Libya, along its dry northern coast.

"The deadliest flood happened in the driest country in all Africa, the only nation that has no rivers at all," said remote sensing scientist Essam Heggy of the University of Southern California and the NASA Jet Propulsion Laboratory.

When Storm Daniel slunk down from Greece to strike Libya's northern coast in September 2023, it unleashed flash floods that took thousands of lives and left some 45,000 people displaced.

Now, new research from Heggy and his colleagues shows that enhanced soil erosion in Libya loaded Storm Daniel's floodwaters with sediments, increasing their destructive power.

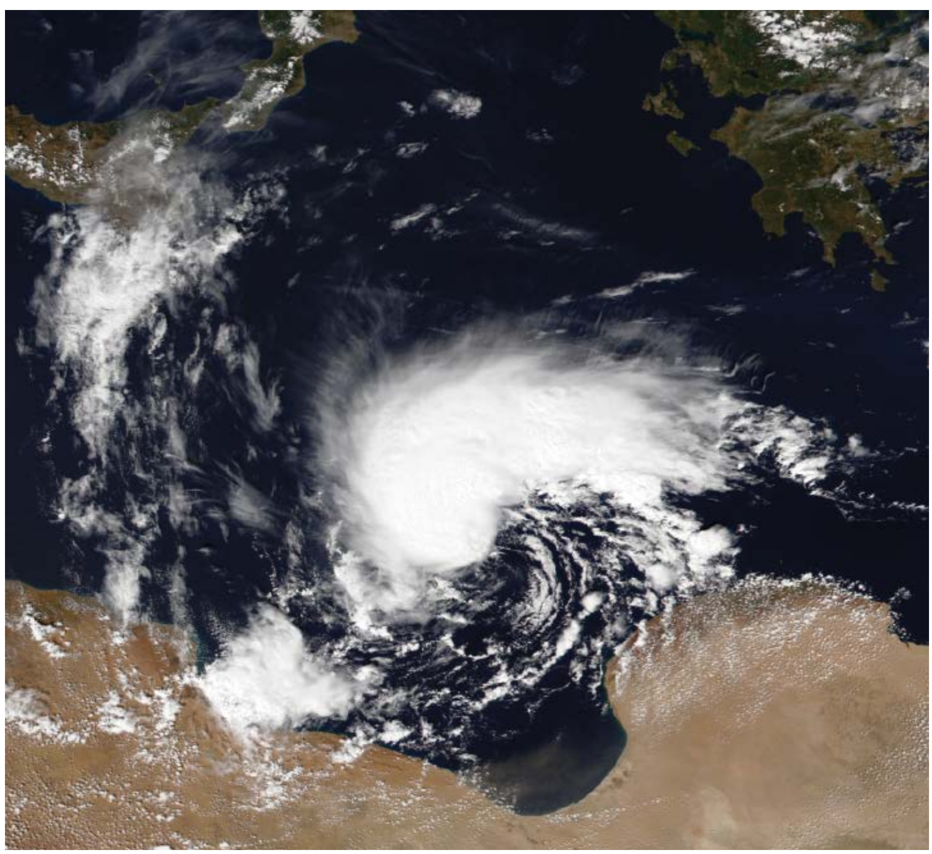
By analyzing satellite radar images, the researchers mapped storm damage and tracked sediments washed out by the storm. The data show that 66% and 48% of the cities of Derna and Susah, respectively, were moderately or severely damaged.

The results, published in *Nature Communications,* point to a looming threat in the Mediterranean: increasingly catastrophic floods in arid regions driven by intensifying cycles of drought and deluge (bit.ly/Libya-floods).

Drought and Deluge

Storm Daniel spun up over the Ionian Sea in early September 2023, fueled by lingering high sea temperatures after a sweltering summer in southern Europe. Storms like Daniel, sometimes called medicanes, are expected to get more intense as the Mediterranean warms.

Rain fell in torrents over southeastern Europe and Türkiye, flooding towns and tak-



Storm Daniel struck Libya in September 2023. Credit: VIIRS imagery from the NOAA-20 satellite

Pictured here is Derna, Libya, before (left) and after Storm Daniel in 2023, which left the city covered in sediment. Credit: Lauren Dauphin/NASA Earth Observatory

ing dozens of lives, before the storm moved south into Libya. There, disaster struck after two dams collapsed upstream of Derna. Water rushed down Wadi Derna, a dry riverbed, directly into the city.

"The deadliest flood happened in the driest country in all Africa, the only nation that has no rivers at all."

Heggy and his colleague, graduate student Jonathan Normand, wanted to understand how soil erosion might have contributed to the damage wrought by Daniel's catastrophic floods. The researchers compared radar images taken by satellites before and after the flood to assess soil erosion and damage to structures that would have been invisible to optical satellites.

They studied the broader watershed rather than just urban areas at its outlet, allowing them to identify where the storm eroded soils and track how floodwaters transported sediments.

The radar analysis revealed that flood erosion occurred in 22%–26% of rangelands, 11% of bare soils, and 11% of urban areas within the studied area of Wadi Derna's watershed. Material washed into wadis, or dry riverbeds, forming streams of sediment-laden water. Loaded with soil and rocky material, these streams wrought more destruction than they would have otherwise, Heggy said. Sediment-laden streams contributed to the collapse of dams upstream of Derna, according to the researchers.

The result highlights the perhaps unintuitive connection between drought and flooding. Throughout 2021, 2022, and 2023, serious droughts and heat waves plagued the Mediterranean. Dry soils are less cohesive than wet ones. Plant roots hold soils together, but parched plants die off in drought. So when the rains finally come after a long dry spell, soils are more easily sloughed off the surface and entrained in floodwaters. The combined effect of drought and deluge can be deadly.

Drowning in the Desert

"What Storm Daniel told us is that the Mediterranean area is fragile and is not ready [for storms like this]. Because Storm Daniel didn't impact only Libya," said physical geographer Paolo Tarolli of the Università Degli Studi di Padova in Italy who was not involved in the study. The new research highlights the importance of studying flood hazards in the Mediterranean beyond just Europe, which has historically received most of researchers' attention, he added.

Intensifying waves of drought and extreme rain are causing problems across the region. Northeastern Italy suffered its most severe drought in 200 years in 2022, followed by two record-breaking floods within just 15 days in May 2023. In Greece, where Storm Daniel first made landfall, the storm did substantial damage to agricultural lands, Tarolli said. He added that although cities are often the focus of flood adaptation efforts, severe floods in the countryside are serious too, especially because they can threaten food security.

"What Storm Daniel told us is that the Mediterranean area is fragile."

The study is an alarm bell, Heggy said. He hopes it will draw attention to the need for climate adaptation in arid regions across the Mediterranean and beyond. "We need to act at the Mediterranean scale," Tarolli said. "We need to include North African countries at the table of discussion."

Adapting to the Mediterranean's new normal could take many forms. Heggy pointed to the importance of better monitoring and analysis of storms and flooding across the region. Existing flood management infrastructure, including dams like the one that collapsed in Derna, needs to be assessed and maintained, he added. Tarolli and his colleagues have suggested establishing a pan-Mediterranean disaster risk management fund.

"We could have avoided it," Heggy said of the destruction in Libya. Without monitoring and mitigation systems, floods and droughts in deserts will be more and more deadly, he added.

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

Weather Extremes Influence Human Migration Between Mexico and the United States

Community-scale rainfall extremes influence undocumented migration patterns between Mexico and the United States, according to research published in the *Proceedings of the National Academy of Sciences of the United States of America* (bit.ly/weather-migration). The findings confirm previous studies that showed a link between extreme weather and migration to the United States and show that extreme weather affects migration back to Mexico, too.

"We see a lot of fluctuations in migration from Mexico, and the climate story is a part of that," said Filiz Garip, a sociologist at Princeton University and a coauthor of the new study.

Garip and her colleagues used estimates of daily rainfall and precipitation on a 1-square-kilometer scale throughout Mexico to determine which years had normal and anomalous weather. They combined these data with annual surveys of households in agricultural communities in Mexico, which detailed information about when and where individuals migrated each year between 1992 and 2018. Those data came from the Mexican Migration Project (MMP).

The researchers used the data to estimate two things: the link between extreme weather in Mexican communities and migration to the United States and the link between extreme weather in a person's origin community and return migration to Mexico.

They analyzed weather patterns only during the local corn growing season (May–August) because the impacts weather can have on crop growth can cause economic stress that spurs migration.

The study also focused on only undocumented migrants, who experience the greatest danger from border crossings, Garip said. "It's really important to study this group, and our data is unique in capturing this group," she said.

Seasonal rainfall extremes—defined as seasonal rainfall more or less than twice the average deviation from the 1980–1990 mean—affected movement both out of Mexico and back. Extremely dry conditions in an individual's home community increased the likelihood they would migrate from Mexico to the United States, whereas extremely wet and extremely dry seasons significantly lowered an individual's likelihood of returning to Mexico in their second year of residing in the United States. Wet seasons, between 1 and 2 times the average rainfall deviation, also lowered the likelihood of return migration.

Temperature extremes did not play a significant role in migration patterns. That may be because the researchers' calculations had a very stringent definition of "extreme heat," Garip said. These events are very rare, so there were not enough instances for the researchers to capture their effects. Another possibility is that extreme heat does not affect crops, and therefore the economic health of a community, as starkly as rainfall extremes do.

Return Migration

Return migration is an "important but under-studied aspect" of climate migration research, Alex de Sherbinin, a geographer at Columbia University who was not involved in the new study, wrote in an email.

One key question in migration studies is how changes in migration patterns can become permanent, said David Wrathall, a geographer at Oregon State University who was not involved in the new study. The new study's results on return migration indicate that weather deviations drive changes to the permanence of migration between Mexico and the United States, he said—extreme drought causes people to stay in the United States rather than returning.

"We see a lot of fluctuations in migration from Mexico, and the climate story is a part of that."

Weather extremes may influence people's decisions to make dangerous crossings between the United States and Mexico, according to new research. Credit: Anthony Albright, CC BY-SA 2.0 (bit.ly/ccbysa2-0)

"They're helping us see this migration permanence question a little bit more clearly," he said.

The results confirmed previous findings that weather stress in agricultural areas can lead to increased migration from those areas, according to Hélène Benveniste, an environmental and social scientist at Stanford University. Benveniste was not involved in the new research but is currently working on another project with Garip using the same dataset.

The weather impacts were concentrated in communities without irrigation systems, which are less resilient when drought hits. For example, in one such community in Mexico, the share of the population that migrated was less than 2% each year until 2002, when extremely dry conditions occurred. In 2003, 14% of those living in the community decided to migrate.

Garip said the findings regarding irrigation show that there are things communities can do to prepare and give people options when extreme weather occurs. Making home communities more economically secure might help people avoid dangerous border crossings, she explained.

"We came to learn that the scale you use really, really matters."

"We're going to have to help people stabilize their livelihoods in drought-affected areas," Wrathall said.

Data Decisions

Though previous studies have linked weather extremes to migration patterns between the two countries, the new research uses more spatially granular migration data, which the researchers were able to couple with highly local weather data, Benveniste said (bit.ly/climate-MX-migration, bit.ly/disaster-MX-migration). "The MMP data is highly valuable in that regard," she wrote.

The results also show how useful small-scale weather data can be in understanding migration, Garip said. "We came to learn that the scale you use really, really matters."

Garip added that some of the weather data are interpolated because weather stations do not evenly cover communities in Mexico. Even more granular data, as well as a better understanding of conditions that affect crops, such as measurements of soil moisture and weather variability within a season, could give an even more accurate picture of how migration decisions are made, she said.

Such collaboration between geoscientists and social scientists may be especially useful as the climate warms because climate-induced weather changes may continue to spur migration through dangerous crossings, the authors wrote in the study. "We should, across the sciences, become more knowledgeable about how to measure the changes that we're experiencing," Garip said.

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

South America Is Drying Up

In August and September 2024, huge portions of South America were shrouded in intense smoke from wildfires raging in the Amazon and other parts of Brazil and Bolivia. The Brazilian Pantanal—the world's largest tropical wetland—had an almost eightfold increase in wildfires last year compared with 2023. From Manaus to São Paulo and Buenos Aires, the smoke, visible from space, blurred sunlight for weeks and threatened the health of millions.

The occurrence raised alarms, but some experts warned that in the future, it might not be such an extraordinary episode. Nor was it an isolated incident over the past few years.

South America, according to a new study published in *Communications Earth and Environment,* is becoming drier, warmer, and more flammable (bit.ly/dry-South-America). These conditions favor not only natural wildfires but also the uncontrolled spread of human-caused fire.

Even though general warming trends extend across the continent, some zones are enduring a steeper temperature rise than others. And this rise comes with a greater risk of droughts and fire.

To better understand the problem, a team of researchers working in Chile, Japan, the Netherlands, and the United States delved into the ERA5 dataset (European Centre for Medium-Range Weather Forecasts Reanalysis version 5).

The team looked for warm, dry, high-fire-risk days in South America between 1971 and 2022. The simultaneous occurrence of these three factors results in conditions called "dry compounds" by the researchers.

Many studies explore the conditions of dry compounds separately, explained coauthor Raúl Cordero, a meteorologist at Universidad de Santiago de Chile. "We believe this is the first [study] to search for when these conditions happen at the same time. What we found matches with the conditions reported in these previous, separate studies," he said.

South America, the authors wrote, is a hot spot for compound extremes but is still understudied.

Rapid Change Across the Region

The Maracaibo basin in northern Venezuela, the northern Brazilian Amazon, and the Gran Chaco basin of Bolivia and Brazil are the regions with the largest land use changes and precipitation losses in South America. Scientists focused their research on these three immense areas, as well as on central Chile, which also experienced severe wildfires in 2024.

"Unfortunately, we're not talking about a small zone in South America," Cordero said, "but of ample zones…affected by this immense rise in risk of catastrophic fire."

Between 1971 and 2000, the Maracaibo, northern Amazon, and Gran Chaco basins had fewer than 20 days per year with highly warm, dry, and flammable conditions. Between 2001 and 2022, the number escalated to almost 70 days per year.

South America is a hot spot for compound extremes but is still understudied.

Most of the dry compounds in the three regions took place in the past 2 decades, pointing to brisk change. Between 2001 and 2022, yearly precipitation in the Gran Chaco dropped by about 100 millimeters in comparison with 1971–2000 levels, according to the study. In the Maracaibo region, it dropped by about 200 millimeters in the same interval. In the past decade alone, days with flammable conditions tripled in the northern Amazon and Maracaibo regions, going from 40 days per year between 1971 and 2000 to the current 120.

The study also found that dry compounds were influenced by fluctuations of the El Niño–Southern Oscillation (ENSO). The warming of eastern tropical Pacific waters during the El Niño phase of ENSO has a substantial influence on northern Amazon weather, increasing its dryness and fire risk. The cooling of Pacific waters during the La Niña phase, on the other hand, has greater influence on the Gran Chaco region, which includes the southern portion of Brazil's Pantanal. From 2020 to 2023, the world had three consecutive years of La Niña—and 2020, 2021, and 2023 were the driest years in the Pantanal since 1985, according to land cover mapping project MapBiomas.

One of the biggest problems with more frequent and intense fire seasons, said forest engineer Camila Silva, is that most burned

A firefighter from the Brazilian Institute of Environment and Renewable Natural Resources fights one of the Pantanal fires in the municipality of Corumbá, Mato Grosso, in June 2024. Credit: Marcelo Camargo/Agência Brasil, CC BY-NC-SA 2.0 (bit.ly/ccbyncsa2-0)

areas do not have the time to recover. This is true "even in Pantanal," she explained, "which, unlike the Amazon, partially evolved in the presence of fire."

"The increase in frequency of extreme events and wildfires is depleting these biomes' recovery capacity," she added. Silva, a researcher at the Amazon Environmental Research Institute who did not take part in the study, said the research is "important because it spells with all letters what is happening and reinforces the message of previous studies."

According to Silva, however, the study misses a few details despite its robust analysis and clear message. "The paper did not uncover the weight of climate change and land use change when it comes to wildfires. Up to what point can we attribute the findings to El Niño or to land use? It would be interesting to have a bit more detail of how anthropogenic factors influence what they found."

"We might be losing a biome we know little about."

Regardless, more action and research are urgently needed to mitigate further wildfire damage throughout South America, Silva said. "Compared to the Amazon, there's a huge gap in what we know about the Pantanal [and other regions]. We might be losing a biome we know little about," she said.

Cordero hopes the new research contributes to greater fire preparedness and biomass management. Such actions may help communities avoid the worst effects of wildfires, which are not limited to the environment. "We cannot forget that fires also kill people directly and indirectly," he said.

By **Meghie Rodrigues** (@meghier), Science Writer

Martian Meteorite Points to Ancient Hydrothermal Activity

In 2011, a striking black rock about the size of an apple was discovered in the Sahara desert. Its unusual appearance tipped off its finder, and it soon passed into the hands of a meteorite dealer in Morocco. An American collector ended up buying the stone, and pieces of it have since been parceled out to various scientists. And that meteorite, which has come to be known as NWA 7034, or "Black Beauty," is different from most other meteorites: It's a chunk of Mars.

Despite many orbiters and landers visiting Mars, none has returned a piece of the Red Planet to Earth. Scientists turn to meteorites such as Black Beauty to better understand the conditions on Mars just a few tens of millions of years after it formed.

Tiny grains of zircon from NWA 7034 have now revealed that hydrothermal activity likely persisted in Mars's crust 4.45 billion years ago. That's the earliest indirect evidence of water on the Red Planet.

"If you want to reach back to some of the oldest history of Mars, there's not too many ways to go about doing that."

Not Just Any Old Meteorite

The vast majority of the roughly 60,000 meteorites that have been collected to date are pieces of asteroids. But about 200 belong to a rarefied group of Martian meteorites. These rocks were dislodged from Mars's surface by asteroid impacts and imbued with sufficient kinetic energy to escape the planet's gravitational field. They then went on to intersect Earth's orbit and plunge through the atmosphere before ultimately being picked up by a person.

A Martian meteorite is something special, said Jack Gillespie, a geochemist at the University of Lausanne in Switzerland. "It represents something from the Martian surface that we have access to on Earth."

Gillespie and his colleagues recently analyzed a single grain of zircon from Black Beauty measuring about 20 × 30 micrometers. Roughly three such grains could be stacked widthwise across a human hair.

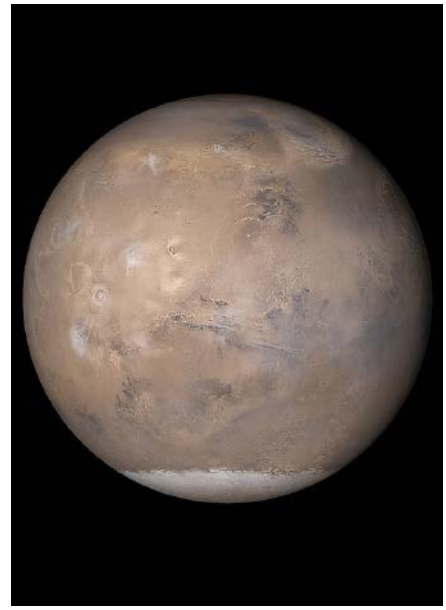
Zircon is a mineral that's extremely tough and can be readily dated, which makes it an ideal tracer of the distant past. "If you want to reach back to some of the oldest history of Mars, there's not too many ways to go about doing that," said Aaron Cavosie, a planetary scientist at the Space Science and Technology Centre at Curtin University in Perth, Australia, and a member of the research team.

In 2022, Cavosie and his colleagues published an analysis of 66 zircon grains from Black Beauty and two other Martian meteorites. The team showed that the crystal structure of one of the grains in Black Beauty had been distinctly rearranged, a feature that suggested the passage of an intense shock wave. Similar features have been noted in rocks unearthed from the site of the cataclysmic Chicxulub impact in the Yucatán Peninsula that spelled the demise of nonavian dinosaurs, the researchers reported.

Unexpected Elements

Gillespie, Cavosie, and their colleagues revisited that same zircon grain, which was previously shown to have an age of 4.45 billion years. The team used a variety of techniques, including one particularly powerful method known as time-of-flight secondary ion mass spectrometry, to probe the chemistry of the grain. They found trace amounts of iron, aluminum, and sodium.

Finding those elements in a zircon grain was a big surprise, said Carl Agee, director of the Institute of Meteoritics at the University of New Mexico who was not involved in the research. "They aren't normally there." And when they are, the mineral typically also exhibits signs of radiation damage. "Grains that have this level of trace elements are normally damaged goods," Cavosie said. (Radiation damage is far more destructive, structurally speaking, than shock wave–imparted changes.) A grain exposed to radiation damage would lose its structural integrity and be prone to incorporating such "nonformula elements" after it formed, said Cavosie. But the grain from Black Beauty showed no sign of this damage—its atoms were all neatly arranged. "They're like little oranges lined up at the grocery story," Cavosie said.



An amalgam of hot rock and water-based fluids likely persisted on ancient Mars. Credit: NASA/JPL/Malin Space Science Systems

Gillespie and his collaborators showed that atoms of iron, aluminum, and sodium persisted within growth zones of the zircon grain. That finding suggests that these unexpected elements were deposited as the grain crystallized rather than incorporated at a later date. One well-known way for delivering such elements is a hydrothermal event, in which a zircon crystallizes in an underground amalgam of hot rock and water-based fluids.

It's likely that this zircon grain was therefore bathed in hydrous fluids during its birth 4.45 billion years ago on Mars, the researchers concluded. That's the earliest evidence of water on the Red Planet, the team noted. These results were published in *Science Advances* (bit.ly/hydrothermal-Mars).

These findings make a lot of sense, Agee said. Mars was likely more geologically active in the past, and many of its features suggest that water coursed over its surface long ago. "It seems very plausible that there would be hydrothermal activity on Mars," he said.

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

Bacteria Battled for Iron in Earth's Early Oceans

Banded iron formations such as this one in Dales Gorge, Australia, formed in Earth's early, oxygen-poor oceans. Credit: Graeme Churchard/Flickr, CC BY 2.0 (bit.ly/ccby2-0)

Banded iron formations (BIFs) are striking, red-hued sedimentary rocks that contain alternating layers of iron and chert. They are relics of Earth's early history, thought to have formed when microbes oxidized iron in ancient oceans, causing it to precipitate as iron ore.

A new study published in *Nature Geoscience* shows that different strains of bacteria may have competed for the iron, with some strains using toxic gases to get the better of their competitors (bit.ly/iron-inhibition).

"The study shows how microbial community dynamics may have affected BIF precipitation in ways that are previously unrecognized," said Leslie Robbins, a geobiologist at the University of Regina in Canada who was not involved in the research.

Most BIFs are more than 1.8 billion years old. They appeared in the greatest abundance near the end of the Archean eon, 2.5 billion years ago. At that time, conditions on Earth were drastically different from today.

"The main difference is oxygen," explained Casey Bryce, a geobiologist at the University of Bristol and a coauthor of the study. In the Archean, the oceans and atmosphere contained almost no oxygen. That's what makes BIFs so intriguing.

Today, iron that is in contact with air or water oxidizes rapidly to rust. But scientists need another explanation for oxidized iron in the oxygen-poor Archean.

According to current understanding, a group of microbes called photoferrotrophs played a major role in BIF deposition. Photoferrotrophs floated in the shallow waters of Archean oceans, where they oxidized iron with the help of sunlight. The iron then sank to the seafloor, over time building layers of oxidized iron up to 900 meters (3,000 feet) thick.

But researchers aren't certain whether other kinds of bacteria were involved in BIF formation and how they interacted with photoferrotrophs. "Most of the time in laboratory studies, a single microbial strain or a small group are studied. In reality, though, we know that microbial communities are much more complex," Robbins said.

The new study's authors aimed to explore this complexity. "We designed a study to look at competition between two different types of anaerobic iron-oxidizing bacteria that should be in direct competition for iron," Bryce said. Their experiments pitted photoferrotrophs against nitrate-reducing bacteria, which react iron with nitrate.

To test which strains were most successful at snatching up iron, the scientists cultivated these two types of bacteria both together and in separate vials. They found that photoferrotrophs failed to grow when they were cultivated with nitrate-reducing bacteria, suggesting that nitrate reducers were outcompeting photoferrotrophs for the available iron.

But the photoferrotrophs in the mixed culture not only lost the struggle for iron—they also died more rapidly than expected. The researchers traced the die-off to a microbial chemical weapon: The nitrate-reducing bacteria in the culture were producing nitric oxide, which poisoned the photoferrotrophs.

"We expected one to be faster but not that one of them would poison the other," Bryce said. "We had worked with the 'winning' bacteria for many years and had no idea it produced this toxin."

A Supporting Role for Nitrate Reducers

The study raises the possibility that nitrate-reducing bacteria played a supporting role in BIF formation. Photoferrotrophs may have driven iron oxidation in the shallow ocean for much of the Archean but struggled as the ocean's chemistry changed.

Photosynthetic cyanobacteria started to colonize shallow coastal waters, exhaling oxygen and possibly pushing oxygen-shy photoferrotrophs offshore. In the open ocean, photoferrotrophs had limited access to nutrients flushed into the ocean by rivers. This lack of nutrients likely inhibited their ability to oxidize iron.

Nitrate-reducing bacteria may have increased the pressure on photoferrotrophs by producing toxic nitric oxide. As photoferrotrophs were increasingly stifled, nitrate reducers could have flourished and continued forming BIFs.

"We expected one to be faster but not that one of them would poison the other."

Robbins pointed out that further research is needed to show how complicated bacterial communities affected iron oxidation in the Archean. "There is a lot to still be learned," he said. "Studies like this one may yield further insights into how BIFs formed."

By **Caroline Hasler** (@carbonbasedcary), Science Writer

Cultivating Trust in AI for Disaster Management

Floodwaters inundate Bad Neuenahr-Ahrweiler, a town along the Ahr River in Germany. Artificial intelligence, used skillfully and transparently, could aid disaster management efforts to mitigate the impacts of such events. Credit: Christian/Adobe Stock

When a wildfire spreads, an earthquake strikes, or a storm makes landfall, the public depends on timely, precise, and accurate information from authoritative sources so it can effectively respond and recover. People also expect vital infrastructure and services (telecommunications, evacuation routes, and first-response measures, to name a few) to be in place to reduce the impacts when disaster hits.

In communities and countries around the world, humans—aided by traditional technologies such as physical-based flood models and numerical-based weather forecasts—meet these disaster management expectations as best they can. Studies increasingly show that artificial intelligence (AI) can build on and supplement these traditional technologies [*Sun et al.*, 2020]. However, AI-based disaster management tools, like their non-AI counterparts, can fail. Furthermore, the complexity of some AI algorithms makes it difficult to pinpoint causes of failure.

Transparency with respect to the data, training, evaluation, and limitations of AI for disaster management is therefore critical to ensuring the safety and robustness of these tools. Transparency also cultivates trust among end users, including disaster management agencies, first responders, and individuals, enabling them to make informed decisions with confidence.

Here we highlight examples of how AI is already contributing to disaster management and identify steps to foster transparency.

AI and the Four Phases of Disaster Management

Disaster management refers to strategies intended to offset the impacts of hazards. Traditionally, these strategies consider four phases of intervention: mitigation, preparedness, response, and recovery [*Sun et al.*, 2020] (Figure 1).

Mitigation includes actions taken well in advance of a disaster, such as purchasing insurance to minimize potential financial burdens and constructing barriers to hold back future flooding. Preparedness refers to actions taken as a disaster becomes imminent, including forecasting and monitoring its progress, preparing shelters, and stockpiling disaster supplies. The response phase covers actions taken during a disaster, such as providing humanitarian assistance and sending out search and rescue missions. Finally, the recovery phase refers to actions taken after most of the damage has occurred, including impact assessment, debris removal, and reconstruction.

AI technologies, including machine learning (ML) algorithms trained to recognize patterns in datasets, are showing great promise for beneficial use in all four phases, even outperforming some traditional tools in terms of accuracy and efficiency.

For mitigation, AI is being used to identify vulnerabilities in critical infrastructure and to inform urban planning. For example, the resilience technology company One Concern is combining AI with virtual representations (known as digital twins) of natural and built environments in Japan to visualize possible impacts of disasters on critical infrastructure, including power grids, roads, and airports. In Europe, the DestinE project is building digital twins of Earth systems and funding extensive ML development to better understand the effects of climate and extreme weather events.

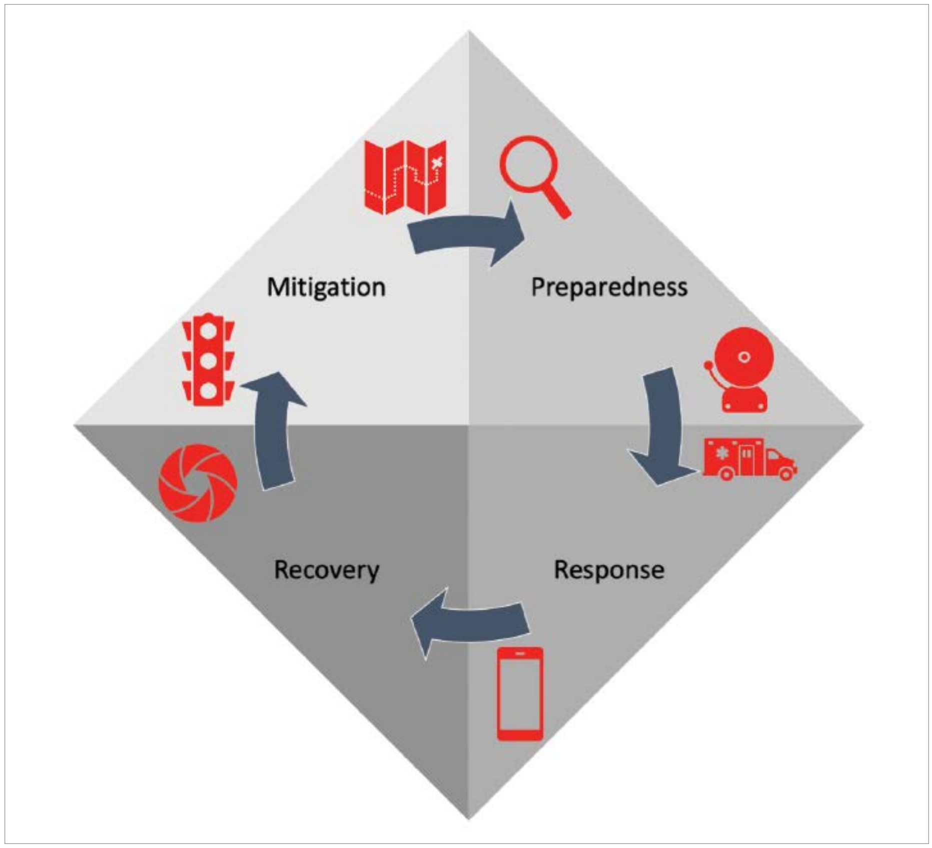


Fig. 1. AI can contribute at each phase of disaster management, from mitigation (e.g., optimizing the location of traffic sensors and providing susceptibility maps) to preparedness (e.g., forecasting or monitoring conditions and triggering alerts) to response (e.g., providing situational awareness and decision support) to recovery (e.g., damage assessment).

Low computational costs and high accuracy are benefits of these algorithms. General disadvantages include the black box nature of AI-generated forecasts.

Using a different approach, *Gazzea et al.* [2023] applied AI to understand traffic during hurricanes (Figure 2), which can help urban planners strategically position sensors to capture traffic flow and enhance situational awareness during disasters. Researchers are also using AI to produce maps of landscape susceptibility (e.g., to landslides) to guide infrastructure development [e.g., *Azarafza et al.*, 2021].

AI can support preparedness by contributing to forecasts. To predict wildfires, for example, AltaML is training AI with data on historical fires, regional weather, and forest conditions. In addition, the European Centre for Medium-Range Weather Forecasts, enabled by additional funding from member states, runs and publishes publicly available weather forecasts using AI models from Google DeepMind (GraphCast), NVIDIA (FourCastNet), and Huawei (Pangu-Weather) and its own Artificial Intelligence Forecasting System.

Low computational costs and high accuracy with respect to global metrics and certain extreme weather events are benefits of these algorithms. General disadvantages include the black box nature of AI-generated forecasts: As AI models grow in complexity, it can become increasingly difficult to understand how they reach their decisions. Other uncertainties relate to how climate change will affect future weather regimes. More specific challenges that Pangu-Weather, for example, has faced include overly smooth forecasts, bias with greater lead time, and issues predicting tropical cyclone intensity [*Ben Bouallègue et al.*, 2024]. However, the growing involvement of domain experts in developing data-driven forecasting models can help address shortcomings and expand forecasting capabilities.

AI's ability to detect and monitor hazards can also enhance preparedness. For example, ALERTCalifornia and CAL FIRE are using AI to recognize smoke and other fire indicators in the footage from 1,050 cameras distributed across California and to alert local fire departments, applications that are especially useful for monitoring remote regions. During its first 2 months of operation, the agencies' system correctly identified 77 fires before they were reported via 911.

Pano AI similarly applies AI to data from rotating ultrahigh-definition cameras, satellites, field sensors, and other sources to detect smoke rapidly. Detections verified by human analysts are then communicated to first responders, cutting response times to fires.

During the response phase, AI can provide situational awareness and decision support for disaster management efforts. For example, research has demonstrated the ability of AI to sift through geolocated social media posts and find clusters of emergency messages, which could help identify where response efforts may need to be prioritized [*Powers et al.*, 2023]. In the Real-time Artificial Intelligence for Decision Support via RPAS Data Analytics (AIDERS) project, data

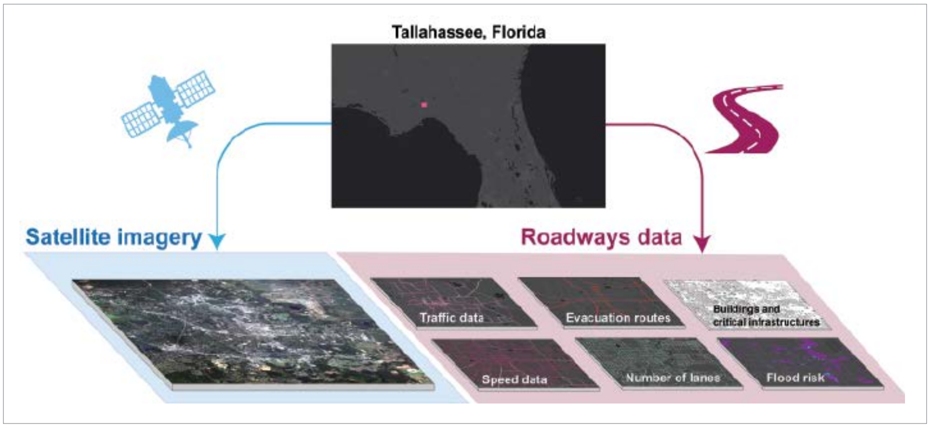


Fig. 2. Using a combination of satellite imagery and data on roadways, AI can be trained to optimize the placement of traffic sensors to best capture traffic flows and enhance situational awareness during disasters. Credit: Adapted from Gazzea et al. *[2023], CC BY 4.0 (bit.ly/ccby4-0)*

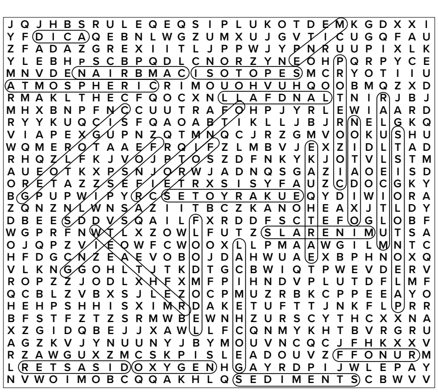
collected by sensors on board remotely piloted aircraft systems (RPAS) are being analyzed using AI to support actionable decisions for first responders in emergency situations.

Following a disaster, AI can be used to detect differences in aerial or satellite imagery from before and after the disaster to ascertain the extent of damages [e.g., *Kaur et al.*, 2023].

The Importance of Transparency

Despite many positive examples, applying AI in disaster management also presents substantial challenges. One is understanding how models arrive at their results and thus whether they are reliable. Humans must be able to evaluate the quality of AI-generated information before using it to make important decisions. Often, however, end users are not provided information about how an AI model is trained and evaluated.

Consider Google's Android Earthquake Alerts System, which for some parts of the world pools anonymized accelerometer data



Humans must be able to evaluate the quality of AI-generated information before using it to make important decisions.

from individual Android phones on Google servers, applies AI algorithms to detect seismic events, and triggers alerts if a seismic event meets or exceeds a magnitude of 4.5. Reception of the alerts was reportedly patchy during the 2023 Kahramanmaraş earthquake sequence along the Türkiye-Syria border, however, despite circumstances that should have enhanced its reliability: The largest earthquakes exceeded the 4.5 magnitude threshold; density of Android users in the region was high; and at least early in the sequence, many of these phones were likely stationary during the shaking, as it occurred at night.

A seeming lack of transparency from the company about how the system operates, how well it works, and how users responded to surveys about its functionality following the event has raised concerns about the system's reliability, about whether and where it failed (i.e., during the training of the AI model, the detection of the seismic event, or the triggering of the alert). By contrast, the inner workings of other early-warning systems, such as the U.S. Geological Survey's ShakeAlert system, which relies on data from a network of seismometers and issues alerts from a publicly accountable entity, are far more transparent.

Sometimes AI algorithms might not perform as expected because of deficiencies in the data used for training or as operational input. For example, biases in training data—related to, say, the selection of data collection sites [*McGovern et al.*, 2024]—can distort model outputs. Or if sensors are not sufficiently sensitive—to detect wildfires in remote or otherwise inaccessible regions, for example—an AI algorithm might miss signals, resulting in failures to warn residents.

Another avenue by which AI is being applied in disaster management is in chatbots. AI can provide guidance and decision support during disasters by generating text (see, e.g., the Strengthening Disasters Prevention approaches in Eastern Africa chatbot from the United Nations Educational, Scientific and Cultural Organization). However, AI chatbots can raise additional challenges if they hallucinate—that is, if they generate convincing but unreliable answers that could be misleading and even dangerous.

Because of the complexity of many AI systems, identifying points of failure is difficult, and potential risks may be hard to spot in advance, especially for underinformed users. Thus, it is important for the developers of these tools to be transparent about the quality, suitability, accessibility, and comprehensiveness of data used in an AI model; about how the model, its components, and its training algorithm function; and about limitations in capability and applicability [*Mittelstadt et al.*, 2019].

Furthermore, this transparency must also be meaningful. In other words, the information provided to stakeholders should be complete and understandable to enable informed decisionmaking. AI developers should implement fail-safes (e.g., involving human oversight), consider the AI literacy of human end users (which affects their ability to interpret output information), and combat cognitive biases such as users' tendency to rely too heavily on algorithms.

Together these approaches can ensure the safety and robustness of AI tools for disaster management, enhance trust in them, enable the replication of methods, and contribute to more efficient transfer of knowledge and capacity sharing among current and potential users of the technology.

Steps to Success

Two deliberate steps that academic researchers, companies, and others developing AI-based tools for operational disaster management can take to foster transparency include sharing comprehensive documentation and undergoing regular independent audits.

Documentation such as open-access metadata, data sheets, and other publications should disclose the origins and characteristics of AI training data according to the FAIR (findable, accessible, interoperable, and reusable) principles and should detail how these data have been processed. Considerations of data quality (including information about missing values or biases) and privacy, as well as ethical considerations such as whether the data are equitably shared, should also be documented. These approaches safeguard sensitive information and build public confidence in the resulting AI application.

During training and evaluation of an AI model, it is important to follow best practices to ensure the reproducibility and validity of the model. Modeling methods, decisions, limitations, and ethical considerations should be disclosed and documented in a short file called a model card [*Mitchell et al.*, 2019], which can be disseminated in publicly available materials on platforms such as GitHub and GitLab or in open-access journals.

We advise using white box algorithms (e.g., causal trees) that are inherently interpretable or, if a higher level of complexity is necessary, combining black box models (e.g., deep neural networks) with explainability methods. Explainability methods help justify the recommendations, decisions, or actions of an AI model. Some of these methods provide a local explanation for why a decision was made for a single prediction, whereas others provide global insights into general model behavior [e.g., *Mamalakis et al.*, 2022]. For example, if a user wants to understand why an AI system detected a specific earthquake, a local explanation would suffice. If, however, the user wants to understand why an earthquake detection system repeatedly fails, a global explanation would have greater value.

When an AI model is operationally deployed, it is important to convey its uncertainties and thresholds clearly to users. For instance, what level of uncertainty in the model output is tolerable, and what threshold must be crossed for an early warning of an earthquake or flash flood to be triggered? Also, what technical requirements (e.g., Internet connectivity) must be met for such a warning to be received?

Finally, it is imperative for developers to conduct regular audits of and report publicly on the AI systems they are designing and implementing. Independent evaluations using relevant performance metrics and benchmarks—supported by, for example, the U.S. Government Accountability Office and the U.S. Department of the Interior—should assess the effectiveness and fairness (the absence of bias in data and algorithms [see *Gevaert et al.*, 2021]) of AI applications. Public reporting of findings promotes transparency and encourages continuous improvement.

In addition to sharing comprehensive documentation and undergoing regular auditing, we emphasize the importance of integrating stakeholders and end users in the development of AI-based systems. Such multiparty and interdisciplinary collaboration is vital for disaster management, in which various groups must work harmoniously in critical situations [*Kuglitsch et al.*, 2022].

When an AI model is operationally deployed, it is important to convey its uncertainties and thresholds clearly to users.

Through partnerships among AI researchers, natural hazards and disaster management experts, policymakers, and members of affected communities, AI development becomes more inclusive and responsive to diverse needs and more transparent to all levels of stakeholders. Within these partnerships, adoption of harmonized terminologies around disaster risk and AI—such as those produced by the International Strategy for Disaster Reduction, the United Nations Office for Disaster Risk Reduction, and the Focus Group on AI for Natural Disaster Management (FG-AI4NDM, which has transitioned into the U.N. Global Initiative on Resilience to Natural Hazards through AI Solutions)—can lead to clearer communication across disciplines. Furthermore, adopting policies at the national level (e.g., U.S. federal Executive Order 13960 on promoting trustworthy AI in the government) and regional level (e.g., the European Union's AI Act), as well as standards at the global level (e.g., the technical reports produced by FG-AI4NDM), can help foster transparency.

These steps toward collaboration and transparency—especially in the documentation, implementation, and public presentation of AI systems—are critical to the success of AI for helping at-risk communities worldwide through disaster mitigation, preparedness, response, and recovery.

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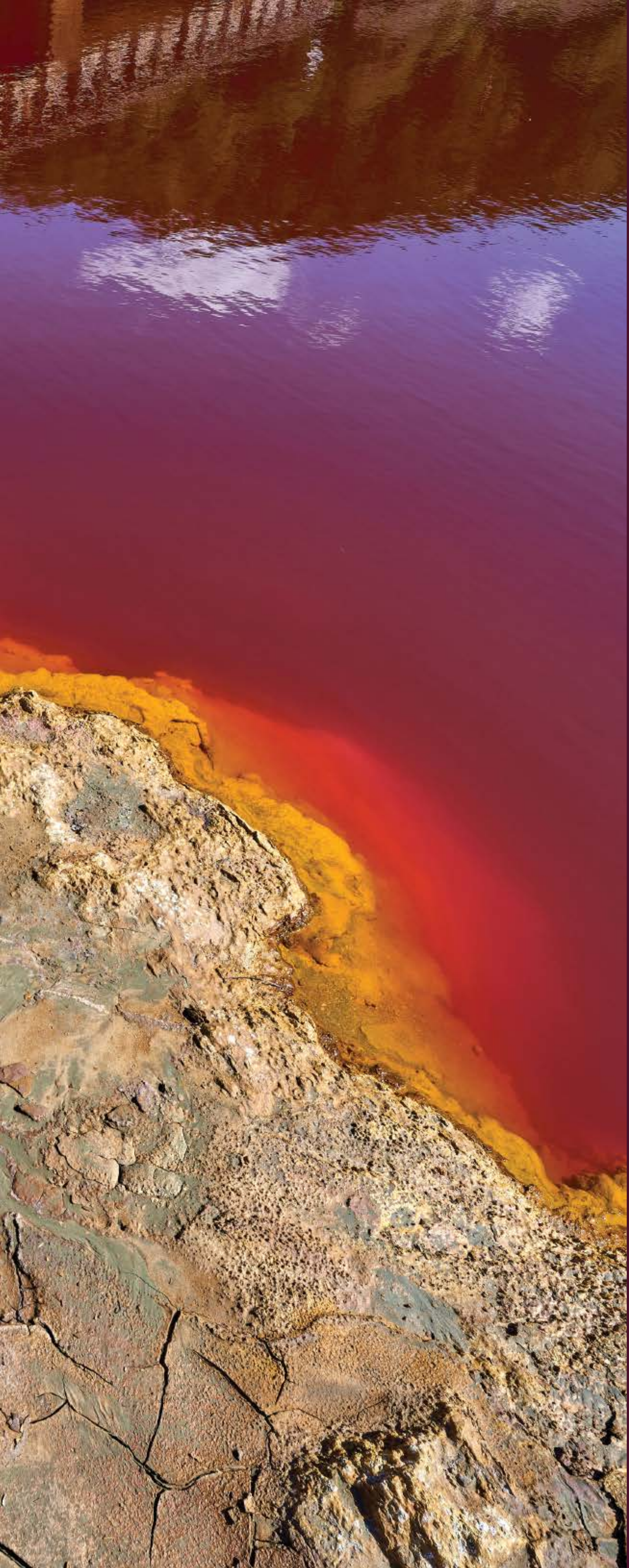

HOW GREAT WAS the Great Oxidation Event?

BY AUBREY ZERKLE

Geochemical sleuthing amid acid mine runoff suggests that scientists should rethink an isotope signal long taken to indicate low levels of atmospheric oxygen in Earth's deep past.

The waters of the Rio Tinto in Spain's Huelva Province are acidic and metal-rich as a result of mine drainage. Credit: Uwe – stock.adobe.com

When the single-celled ancestors of plants learned to combine carbon dioxide and water, these early innovators spat out a waste product formerly absent from their environment: free molecular oxygen.

If water is the key to life, then oxygen is the key to animal life. All animals breathe oxygen. Despite decades of research, however, scientists still don't know when Earth's atmosphere first held enough free oxygen to support the planet's early animals. Most geologists agree that oxygen first accumulated in the atmosphere around 2.4 billion years ago. But they don't agree on how much there was at that time or whether it was enough for animals to thrive.

My colleagues and I recently found new clues to help answer these questions. These clues come from an unlikely source: the acidic, metal-rich waters of Rio Tinto in southern Spain. The composition of these waters is considered extreme today, yet the sort of acid rock drainage that causes these conditions was widespread long ago, when newly available atmospheric oxygen first began interacting with sulfur minerals on land.

In our work, we showed that the chemistry occurring in these acidic waters can reconcile seemingly contradictory estimates of past levels of breathable oxygen determined from ancient sediments. Our data support growing evidence that enough oxygen was present for animals to have evolved nearly 2 billion years before they burst onto the scene.

The distinctive red waters of the Rio Tinto at Berrocal in southern Spain are seen here in April 2019. Credit: Aubrey Zerkle

Earth's First "Great Oxidation"

A critical transition in our planet's history occurred when the single-celled ancestors of plants learned to combine carbon dioxide and water—two chemicals found everywhere on Earth—to make their cells and produce energy. These early innovators spat out a waste product formerly absent from their environment: free molecular oxygen (O_2). This highly reactive gas began to run rampant on Earth's surface, leaving telltale signs of its activity in minerals and sediments.

It's been more than 5 decades since scientists began deciphering these signs in the geologic record. Over that time, most scientists have come to agree that O_2 first reached appreciable concentrations in Earth's atmosphere roughly 2.4 billion years ago, during the Great Oxidation Event (GOE) [*Farquhar et al.*, 2014].

Geologists who first described the GOE estimated that oxygen levels rose from near zero to about 10%–40% of what they are today (oxygen currently makes up 21% of the air we breathe). They also proposed that atmospheric O_2 remained at these levels until it started climbing to modern levels more than 1.5 billion years later. This extended interval roughly coincided with the third and longest of the four geologic eons of Earth's history, the Proterozoic.

Other researchers have since challenged those original estimates of Proterozoic O_2. They have suggested that oxygen concentrations rose to less than 0.1% of today's level during the GOE and remained there, with only occasional short-term increases, through the ensuing eon. This substantial distinction—10% or more versus less than 0.1%—bears critically on the role of oxygen in animal evolution. Various forms of animal life require different minimum oxygen levels for survival, but even primitive animals like sponges require at least 0.25% of today's atmospheric oxygen levels to metabolize [*Cole et al.*, 2020].

In the fossil record, paleontologists have found the oldest undisputed fossil eukaryotes, the single-celled precursors to animals, in marine sediments that accumulated about 1.7 billion years ago [*Knoll and Nowak*, 2017]. Despite the antiquity of eukaryotes, fossils of large multicellular life-forms representing putative animals don't appear until more than a billion years later in the 0.57-billion-year-old Ediacaran biota, and undisputed animals don't appear until the Cambrian period, about 0.54 billion years ago.

Some of the earliest putative animals found in the fossil record are represented in this depiction of life from the Ediacaran period (635–541 million years ago) at the Smithsonian National Museum of Natural History in Washington, D.C. Credit: Ryan Schwark/Wikimedia Commons, CC0 1.0 Universal (bit.ly/cc01-0)

Paleontologists have also described a pronounced expansion of fossil eukaryotes around 0.8 billion years ago, coinciding with when atmospheric O_2 began rising toward near-modern levels. Some researchers have hypothesized that this rise in O_2 allowed these early eukaryotes to diversify and eventually evolve into multicellular animals. But this simple cause and effect scenario relies heavily on debated claims that oxygen remained too low to sustain animal life for roughly 1.6 billion years prior.

Controversial Clues from Chromium

One problem with attempts to resolve the history of Earth's breathable oxygen is that the data researchers use to estimate past levels have provided conflicting results. The atmosphere doesn't directly fossilize, so geochemists rely on indirect traces, or proxies, to tease out the gases it contained at different times.

One proxy that researchers have widely used to estimate atmospheric O_2 levels in the Proterozoic involves the heavy metal chromium [*Wei et al.*, 2020]. Like many elements, not all chromium atoms are created equal. Although all have 24 protons in their nuclei, they can have different numbers of neutrons; in other words, different isotopes of chromium exist.

These different chromium isotopes react at different rates, leading to fractionation, or a change in their ratios, when they undergo chemical reactions in the environment. For example, chromium isotopes are fractionated when they react with manganese oxide minerals. This reaction preferentially releases heavier isotopes of chromium into natural waters, which become more concentrated in sediments as a result.

Manganese oxide minerals such as birnessite and todorokite are very common in modern environments, for example, in soils and fluvial settings and on the seafloor. Researchers have estimated that reactions with these minerals fractionate chromium isotopes when free O_2 is present at concentrations greater than 0.1% of modern atmospheric levels [*Planavsky et al.*, 2014]. So some scientists have argued that chromium isotope fractionation in ancient rocks provides an "oxygen signal," indicating when O_2 exceeded 0.1% of current levels. They have also claimed the corollary that a lack of chromium isotope fractionation in rocks indicates that oxygen levels were below

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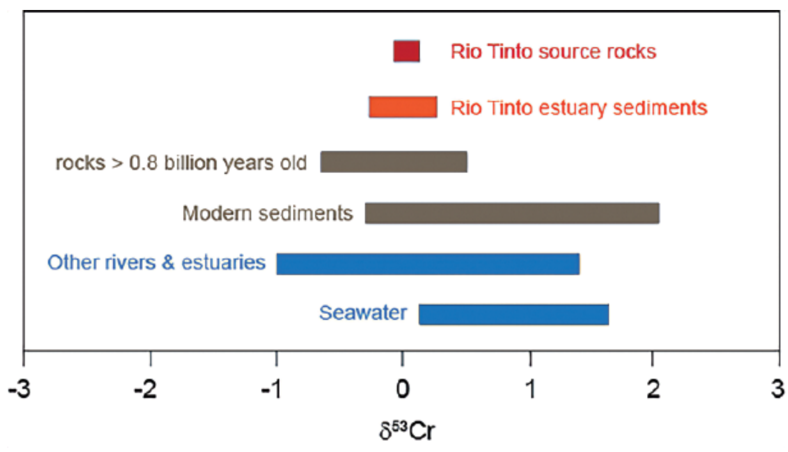

Fig. 1. Most sediments and waters today show a wide spread in chromium isotope ratios because the chromium they contain has been fractionated through reactions with manganese oxides. In contrast, because manganese oxides do not form in acidic waters, sediments from the Rio Tinto estuary show a very small spread in chromium isotope ratios that centers around a δ^{53}Cr of 0 parts per thousand (‰), similar to the range measured in rocks supplying chromium to the river. The range of chromium isotope ratios measured in rocks older than 0.8 billion years is also relatively narrow and centers around a δ^{53}Cr of 0‰, indicating that little chromium isotope fractionation is evident in these rocks. δ^{53}Cr (in parts per thousand, ‰) represents depletion (negative values) or enrichment (positive values) of chromium-53 relative to chromium-52 in a sample compared to a standard reference material; $\delta^{53}Cr = 1{,}000 \times \{[(^{53}Cr/^{52}Cr_{sample})/(^{53}Cr/^{52}Cr_{standard})] - 1\}$.

that threshold at the time the rocks formed.

Geochemists who first measured chromium isotopes in Proterozoic rocks found that large chromium isotope fractionations didn't appear until 0.8 billion years ago, suggesting that O_2 levels were too low to support animals until late in the Proterozoic [*Planavsky et al.*, 2014]. However, researchers recently found large fractionations in chromium isotopes preserved in ancient soils and marine rocks as far back as 1.9 billion years ago. These researchers contended that Proterozoic O_2 levels were at least intermittently high enough for animals to evolve well before their first occurrence in the fossil record [*Canfield et al.*, 2018]. Scientists want to resolve these disparate scenarios to understand oxygen's role in animal evolution on Earth and potentially on other planets too.

Scientists want to resolve these disparate scenarios to understand oxygen's role in animal evolution on Earth and potentially on other planets too.

Going to the Extreme

The Rio Tinto flows roughly 100 kilometers (62 miles) through southwestern Spain, stained blood red from its headwaters in the Sierra Morena to the Ría de Huelva estuary, where it spills into the Atlantic Ocean.

Mining activities over millennia in the Iberian Pyrite Belt, one of the largest hydrothermal ore deposits in the world, have exposed large piles of the iron sulfide mineral pyrite in the headwaters of the river to attack by atmospheric O_2 at Earth's surface. When pyrite reacts with O_2, it produces sulfuric acid, which is responsible for the river's very low pH of 2 (similar to the pH of lemon juice).

The reaction and resulting acidity also release iron, which gives rise to the river's characteristic red tint, and other heavy metals—including chromium—from surrounding rocks.

Today, Rio Tinto's waters are an extreme environment. But such conditions were once far more common. Scientists have proposed that as a result of the GOE, newly liberated O_2 in the atmosphere attacked extensive pyrite deposits on the land surface. Like today's rock weathering in southern Spain, this chemical attack released heavy metals and sulfuric acid, producing widespread acid rock drainage [*Konhauser et al.*, 2011]. In the aftermath of the GOE, rivers like Rio Tinto were likely the norm rather than the exception.

Despite the preponderance of acid rock drainage after the GOE, geochemists had not looked into how chromium isotopes fractionate in acidic natural waters. After nearly a decade of teaching geochemistry at Rio Tinto, I knew that manganese oxides rarely form in similarly acidic waters. And I figured that if manganese oxides are necessary for imparting the chromium isotopic oxygen signal into rocks, then a lack of these minerals might prevent the formation of the signal, even in today's high-O_2 atmosphere.

To investigate this hypothesis, I teamed up with my longtime friend and colleague Kate Scheiderich, who was then at the U.S. Geological Survey and had set up a lab to measure chromium isotopes. Returning to Rio Tinto, I collected samples of river water, rocks, and sediment from different locations along the bank of the river. Then I shipped them to Kate's lab for her and another colleague to analyze.

We found that the acidic headwaters of the Rio Tinto were, indeed, leaching chromium from the surrounding rocks, then carrying it downstream to the Atlantic, where it accumulated in sediments around the estuary. However, the river was simply too acidic for manganese oxide minerals to form, despite flowing in an atmosphere with 21% oxygen. The analytical results in our study confirmed that without any manganese oxides to react with, chromium isotopes in the estuary sediments remained unfractionated and the chromium isotope values were identical to those in the source rocks they came from upstream (Figure 1).

Millions of years from now, after these estuarine sediments have lithified into marine rocks, future geochemists analyzing the rocks with the same techniques and understanding of the chromium isotope oxygen signal scientists have used until now might thus mistakenly infer that our current air was unbreathable. Are scientists today similarly misinterpreting the lack of chromium isotope fractionation in rocks older than 0.8 billion years?

We proposed that the prevalence of acid rock drainage on Proterozoic continents could have hindered development of the chromium isotope oxygen signal until 0.8 billion years ago (when, perhaps, most acid rock drainage had been consumed). This idea reconciles seemingly contradictory chromium isotope data and suggests that O_2 in the atmosphere could have been elevated above 0.1% of modern levels far earlier in the Proterozoic [*Scheiderich et al.*, 2023].

Why Did Animals Wait?

As scientists increasingly focus on oxygen in the Proterozoic, more geochemical estimates [e.g., *Mänd et al.*, 2020] and atmospheric models [e.g., *Gregory et al.*, 2021] are suggesting that atmospheric O_2 concentrations were high enough for animals to have thrived more than 2 billion years before the early Cambrian. So why did it take so long for them to appear?

One explanation could be that oxygen concentrations in the Proterozoic ocean fluctuated too much. Most scientists agree that shallow marine habitats, likely hotbeds for evolution, had oxygen levels high enough to support eukaryotes throughout the Proterozoic. But oxygen-free waters from the deep ocean routinely circulated upward, possibly diluting the oxygen oases at the surface. The instability of back-and-forth swings in oxygen in the surface ocean could have posed a big challenge to the evolution of early animals.

Some scientists suggest that famine could also have held early animals back. The same protoplants that produced oxygen in the Proterozoic also formed the base of the food chain, so researchers have inferred that low oxygen and a low food supply went hand in hand. Animals could also have been starved for nutrients essential to life, such as nitrogen, which is found in nearly all biomolecules, including DNA, RNA, and proteins. Many geochemists have suggested that nitrogen was scarce in the Proterozoic, when denitrifying microbes first started converting oxidized nitrogen (e.g., nitrate) into forms that animals can't use (e.g., nitrogen gas).

Other researchers have proposed developmental hypotheses for the lag in animal evolution. They have pointed out that it could have taken billions of years for the core set of genes found in all multicellular life to evolve in eukaryotes and that only after those genes emerged could animal life diversify greatly. Or perhaps environmental and biological hurdles together slowed animal evolution.

For now, more answers to why animals debuted only at the end of the Proterozoic will have to wait. Whatever the explanations, recent research seems to make clear that it wasn't for want of oxygen.

Are scientists today misinterpreting the lack of chromium isotope fractionation in rocks older than 0.8 billion years?

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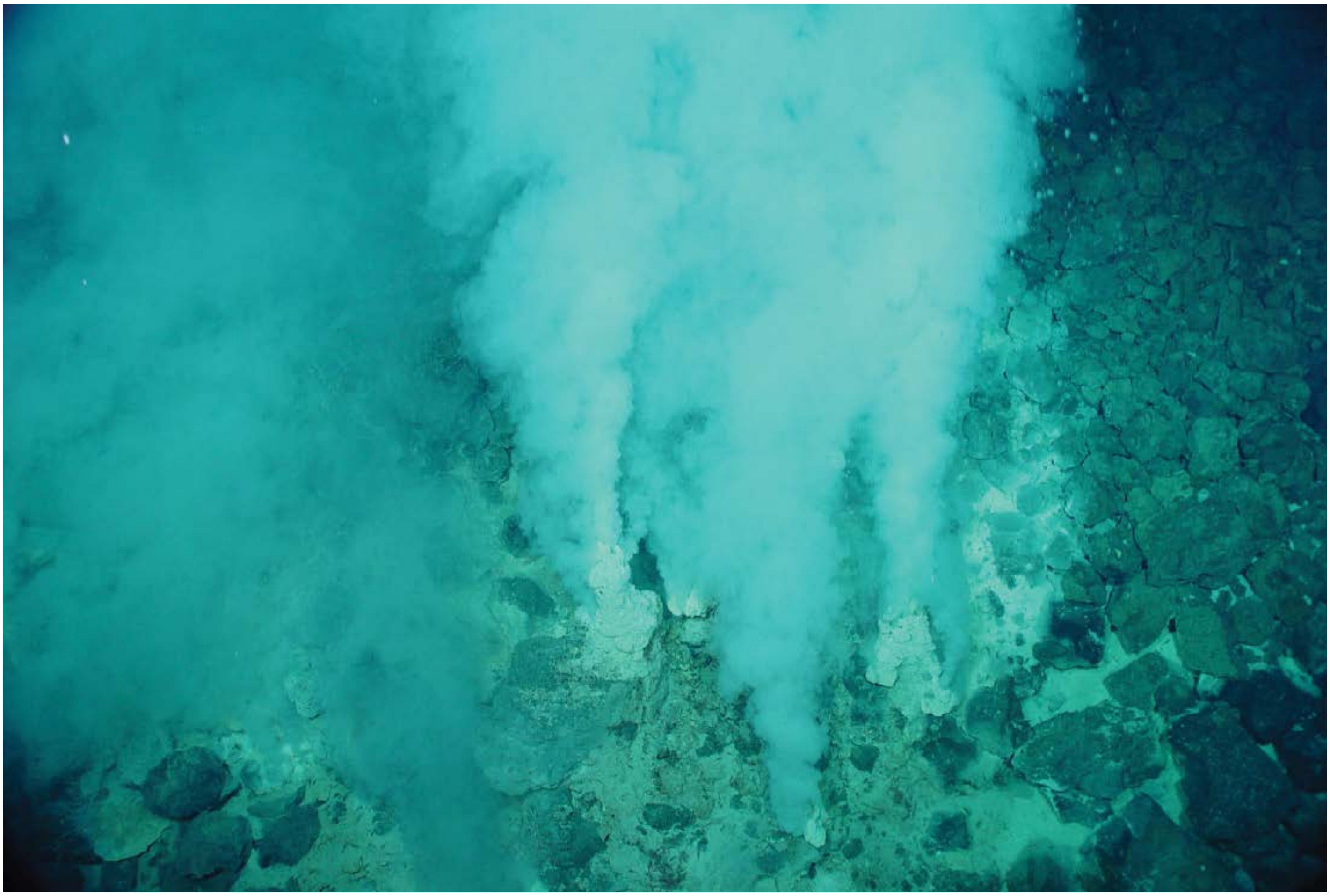
A New View of Deep Earth's Carbon Emissions



Gases escape from the deep-sea Champagne Vents in the northern Marianas region of the Pacific, where tectonic plates are colliding. Credit: Submarine Ring of Fire 2014–Ironman, NOAA/PMEL, NSF

From time to time, when Earth's tectonic plates shift, the planet emits a long, slow belch of carbon dioxide. In a new modeling study, *Müller et al.* show how this gas released from deep Earth may have affected climate over the past billion years.

Volcanoes, undersea vents, and mid-ocean ridges are all found where Earth's plates collide or separate. Each of these structures gives carbon dioxide a route to escape from the depths of the planet and enter the atmosphere. Although their near-term influence on the climate is minor compared with anthropogenic emissions, gases released from deep Earth are thought to have a substantial impact on the composition of Earth's atmosphere over geologic timescales.

Scientists have often estimated the volume of such carbon emissions solely on the basis of the gas released by plate tectonics. But plate tectonics can also *capture* carbon by incorporating it into new crust formed at mid-ocean ridges. In the new work, the researchers drew on two recent studies about the past billion years of plate movement to model more precisely how much carbon dioxide this process has generated.

The model's findings are consistent with how Earth's climate is thought to have changed over time. For example, the periods during which the model suggests that more carbon was being released line up with warmer periods of Earth's history, such as the start of the Ediacaran period, about 653 million years ago. Periods during which the model suggests lower levels of carbon outgassing coincide with colder periods of Earth's history, such as the "snowball Earth" period from 700 million to 600 million years ago.

The research also suggests that Pangaea's breakup allowed large amounts of carbon dioxide to be released as the planet's plates moved apart, which is consistent with the warming thought to have occurred during that time.

Tectonic activity is a major determinant of Earth's atmospheric composition over geologic time, the researchers conclude. Despite recent advances, however much remains to be learned about how plate movement affects the planet's carbon cycle. (*Geochemistry, Geophysics, Geosystems*, https://doi.org/10.1029/2024GC011713, 2024) **—Saima May Sidik,** *Science Writer*

Helping the Most Vulnerable Stay Cool in Extreme Heat

A saguaro cactus stands in the desert near Phoenix, where summer temperatures frequently exceed 100°F (38°C), leaving many susceptible to heat-related illnesses and even death. Credit: Ray Redstone/Wikimedia Commons, CC BY-SA 4.0 (bit.ly/ccbysa4-0)

The health effects of heat waves hit some communities harder than others. People with preexisting health conditions, as well as those who have low incomes or are physically or socially isolated, very old or very young, from racial or ethnic minority groups, or experiencing homelessness, are more at risk for hospitalization and mortality when faced with extreme heat.

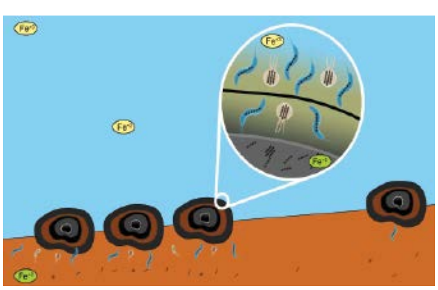
In metropolitan areas, public officials have enacted heat mitigation efforts, including providing air-conditioned cooling centers in public places such as government buildings. *Watkins et al.* developed a tool to identify optimal sites for these cooling centers, helping to ensure access for those who need it most.

The team collaborated with groups such as the Arizona Cooling Center Working Group and focused on Phoenix and Tucson, Ariz., metropolitan areas where temperatures frequently top 100°F (38°C). Nearly 3,000 emergency room visits stemming from heat-related illnesses occur in the state each year. The researchers chose those two cities to demonstrate that their tool—developed with commercially available software and publicly available data—could be tailored to cities with different sizes, needs, and data availability.

The team used the U.S. Centers for Disease Control and Prevention's (CDC) Building Resilience Against Climate Effects framework, which was designed to help health officials prepare for the effects of climate change. They also referred to the CDC's Social Vulnerability Index to identify census tracts with high-risk populations and considered barriers that may prevent people from using cooling centers, including a lack of awareness that such centers exist.

The researchers identified candidate facilities that could serve as potential cooling center locations, including churches, health care centers, hotels, schools, shelters, and government facilities. The new workflow is designed to be reproducible in other locations by governments and partners with varying resources. The researchers say the work could ultimately improve heat resilience for community members affected by extreme heat. (*Community Science*, https://doi.org/10.1029/2023CSJ000038, 2024) **—Sarah Derouin**, *Science Writer*

The Unexpected Role of Magnetic Microbes in Deep-Sea Mining



The growth of polymetallic nodules provides a low-oxygen, organic-rich microenvironment suitable for magnetotactic bacteria. Credit: Yan Liu

Polymetallic nodules are potato-sized formations on the ocean floor that are rich in minerals such as nickel, cobalt, and manganese. Their concentration of rare, economically important minerals has made the nodules the focus of controversial deep-sea mining enterprises.

Various hypotheses exist as to how the nodules grow, but most agree that they form as metallic components in seawater slowly precipitate onto the seafloor. Several studies suggest that microorganisms play a role in nodule growth as well. The nodules tend to contain biogenic magnetite—the fossil remains of magnetotactic bacteria, which have magnetic organelles that act like tiny compass needles.

Liu et al. examined the relationship between bacteria abundance and polymetallic nodule distribution in the Clarion-Clipperton Fracture Zone (CCFZ), an environmental management area south of Hawaii managed by the International Seabed Authority. The CCFZ could be an economically vital region for the burgeoning deep-sea mining exploration industry.

A submersible vessel explores a nodule field on the floor of the Pacific Ocean. Credit: Philweb/Wikimedia Commons, CC BY-SA 3.0 (bit.ly/ccbysa3-0)

The authors analyzed seafloor sediments collected during a research cruise in 2013. They used a vibrating sample magnetometer to determine magnetic properties, electron microscopes to identify minerals based on electron diffraction, and spectroscopy techniques (which test how materials absorb and emit light and other radiation) to test for rare earth elements.

The results revealed three distinct origins for magnetic minerals in the samples: wind-borne dust, volcanoes, and bacteria. Wind-borne sediments were likely transported into the region by midlatitude westerlies and northeasterly trade winds, as indicated by decreasing magnetite concentrations from north to south and from east to west in the CCFZ. Volcanic magnetite occurs as a result of erosion of the Line Islands and the Hawaiian Islands chain by ocean bottom waters.

The highest abundance of magnetite associated with bacteria coincided with the highest densities of polymetallic nodules in the CCFZ. The findings led the authors to hypothesize that the nodules produce carbon-rich, low-oxygen microenvironments that both support bacteria and encourage the biomineralization of magnetite nanocrystals. In turn, the bacteria help to foster the growth of the nodules.

The results offer new insights into the formation of polymetallic nodules and the ecological distribution of magnetotactic bacteria, with implications for potential deep-sea exploration. (*Journal of Geophysical Research: Solid Earth*, https://doi.org/10.1029/2024JB029062, 2024) **—Aaron Sidder,** *Science Writer*

Down in the Slumps: Tracing Erosion Cycles in Arctic Permafrost

Mega retrogressive thaw slumps, such as this one on Herschel Island, Canada, in the Beaufort Sea, transport millions of cubic meters of sediment and water over their lifetimes. This slump is among the 10 largest on Earth. The yellow tent at right provides a sense of scale. Credit: Michael Krautblatter

In the Arctic, landslide-like features known as mega retrogressive thaw slumps threaten infrastructure, alter regional biogeochemistry, and emit carbon.

Sometimes eroding more than 1 million cubic meters (about the volume of 400 Olympic-sized swimming pools) of sediment and ice during their lifetime, these slumps occur when permafrost thaws. They are common on hillsides and along shorelines.

The basic mechanics of slumps are well described scientifically. Less understood is what causes them to form, especially in the same locations where others occurred previously—a phenomenon known as polycyclicity.

Krautblatter et al. used electrical resistivity tomography (ERT) and ground-penetrating radar (GPR) to study how slumps form and then reactivate after going dormant. The research took place on Herschel Island in Yukon, Canada, a global hot spot for slumps. As many as 90% of active slumps in the Canadian Arctic are polycyclic. GPR and ERT are common geophysical reconnaissance tools, but this study is one of the first to use them to reveal polycyclic slumps' internal structure.

The surveys uncovered several mechanisms driving slump evolution. The ERT survey showed that intruding seawater at the farthest-reaching edge of a slump floor (also known as the toe) can destabilize permafrost and initiate a new slump. As slumps retreat, the ground surface cover changes and the underlying permafrost warms. This warming then extends tens of meters into the ground, where it can persist for up to 300 years, priming the ground material to develop into yet another slump in the future.

In addition, once slumps are reactivated, mudslides develop and narrow ravines can form, removing organic layers and transporting large quantities of sediment and organic matter to the shoreline. This warms underlying permafrost and continues the cycle.

Using the survey data, the authors developed a classification scheme to characterize the stages of polycyclicity, charting the evolution from undisturbed tundra to slumps retreating beyond their historic limits. Not all slumps follow this precise progression, but the framework offers a common language for comparing those of similar size or behavior. The insights offer an improved understanding of temporal and spatial patterns of this unique Arctic form of erosion. (*Journal of Geophysical Research: Earth Surface*, https://doi.org/10.1029/2023JF007556, 2024) **—Aaron Sidder,** *Science Writer*

Blasts from the Past: New Insights from Old Space Storms

This large solar prominence was imaged in August 2012 by NASA's Solar Dynamics Observatory. Powerful bursts of energy and particles from the Sun can trigger space storms on Earth. Credit: NASA/SDO/AIA/Goddard Space Flight Center

On 4 August 1972, a burst of solar plasma rocked Earth's magnetic field after hurtling through space for about 14.6 hours—the fastest Sun-to-Earth plasma journey ever recorded. The resulting space storm, one of several that occurred from 2 to 11 August, triggered widespread disturbances to electrical and communication grids and likely caused accidental detonations of U.S. undersea naval mines in North Vietnam.

Nearly 2 decades later, from 6 to 19 March 1989, another series of space storms took place. The largest, on 13 March, damaged North American electrical grids and caused a 9-hour blackout across Quebec, Canada.

In a new review, *Tsurutani et al.* take a closer look at the 1972 and 1989 events, comparing them with each other and with other historical space storms. Their study underscores the potential for modern space storms to rival or even surpass the power of the most extreme geomagnetic disturbance in recorded history, the Carrington event of 1859.

Like most space storms, the 1972 and 1989 events involved coronal mass ejections (CMEs)—strong bursts of highly energetic plasma particles and magnetic field structures ejected from the Sun as part of a solar flare.

However, each storm had distinct qualities. The 1989 storm featured two CMEs, both of which moved more slowly than the one in the record-breaking 1972 storm, taking about 54.5 and 31.5 hours to reach Earth. The solar flares behind the 1989 event were also at least 10 times less intense than the flares in the 1972 storm. However, at more than 23 hours, the main phase of the 13 March storm in the 1989 event was the longest in recorded history. Typical magnetic storms studied by scientists last an average of about 12 hours.

Having revisited data from both events, the researchers propose that under slightly different, but realistically possible, conditions, the 1972 CME could have produced a storm even bigger than the destructive Carrington event. They also suggest that the largest 1989 storm actually did surpass the Carrington event by one measure: the amount of energy carried by particles in the ring current, a stream of charged particles that surrounds Earth, whose current intensifies during a space storm.

The 1859 Carrington event triggered aurorae that reached the tropics and destroyed telegraph equipment. Should a similar storm occur today, its destructive effects could cost trillions of dollars and leave millions of people without electricity for 2 years.

By looking at these historical storms, the researchers gained new insights into the complex mechanisms that drive extreme space weather. Their findings could help guide future space weather research and prediction, the authors say. (*Journal of Geophysical Research: Space Physics*, https://doi.org/10.1029/2024JA032622, 2024) **—Sarah Stanley,** *Science Writer*

Mapping Landslide Risk in the United States

Living in a landslide-prone region means facing the dangers and damage that may occur when a slope fails. Communities that understand their risk for such events can be better prepared to save both infrastructure and lives.

Susceptibility maps help with this preparation by showing where terrain and environmental conditions may make landslides more likely. However, current U.S. susceptibility maps focus mostly on steep, high-risk areas, offering little detail on or underestimating risk for gently sloping regions. Such regions—including parts of North Carolina that were devastated by Hurricane Helene in September 2024—can still experience landslides and are more likely than steeper areas to host infrastructure and other development.

Using a U.S. Geological Survey (USGS) database of 613,724 landslide events, *Mirus et al.* developed a high-resolution (10-meter grid size) map to detail the landslide hazard risk throughout all 50 U.S. states and Puerto Rico. (Other U.S. territories didn't have sufficient topographic data or landslide inventories to be included.)

By combining this national dataset with high-resolution topographic data, the researchers developed four threshold models—a type of model that can help determine which combinations of factors lead to a particular outcome. In this case, the models used the relationship between slope (or steepness) and relief, or the difference in elevation between an area's highest and lowest points, to determine landslide potential. They then reduced the resolution to a 90-meter grid size to account for uncertainty at larger scales and tested how well each model could differentiate susceptibility in different landslide-prone areas.

The best-performing model captured 99% of recorded landslides. The researchers then ran the model using landslide datasets from specific states, based on an additional 172,367 events. The model performed well with these datasets too, but it showed more variability by region. Using these outcomes, the researchers created a more accurate national-scale map that highlights areas at greater risk of landslides in the future.

The new map could become a valuable tool to boost hazard mitigations, particularly in regions where stakeholders are not yet aware of their landslide risk. Already, in the wake of Hurricane Helene, USGS has combined the hazard map with rainfall data from the National Weather Service to aid ongoing search and rescue operations. (*AGU Advances*, https://doi.org/10.1029/2024AV001214, 2024) **—Rebecca Owen,** *Science Writer*

Fifteen Years Later, Scientists Locate a Lunar Impact Site

In 2009, NASA intentionally crashed a spacecraft into the Moon and used a small trailing spacecraft to observe the results: The Lunar Crater Observation and Sensing Satellite (LCROSS) was designed to search for frozen water and other volatiles, materials that readily vaporize, in the lunar regolith by knocking them off the Moon.

The LCROSS impact kicked up a cloud of regolith containing plenty of water (5.6% by mass), along with small amounts of carbon dioxide, sulfur dioxide, methane, and ammonia. But it did so in a permanently shadowed area of the Moon, leaving scientists unable to directly observe the crater after its formation.

Now, researchers have located the crater the LCROSS mission left behind, allowing scientists to better contextualize the mission's results and informing future efforts to locate and use resources on the Moon.

To locate the crater, *Fassett et al.* used two data sources. The Miniature Radio Frequency instrument on the Lunar Reconnaissance Orbiter (LRO) observes the Moon at radar wavelengths to search for subsurface water ice. The ShadowCam on the Korea Pathfinder Lunar Orbiter is a hypersensitive camera that launched in 2022, built specifically for seeing inside eternally dark areas of the Moon. Its capabilities allowed the researchers to see the LCROSS crater directly and confirm that changes to radar-based reflectivity seen by LRO after the impact corresponded to a new crater.

The LCROSS impact crater is about 22 meters across, the researchers report, slightly smaller than the LCROSS team originally estimated. To determine the age of the volatiles ejected by LCROSS, the research team incorporated into a model knowledge about the Moon's inclination throughout history and information about how impacts disturb the lunar crust.

They found that the regolith ejected from the crater was likely disturbed between 100 million and 500 million years ago and that the LCROSS impact location entered permanent shadow only about 900 million years ago, making it relatively young. This finding supports earlier evidence suggesting that the ejected volatiles themselves are young and originated outside the Moon—perhaps from comets, asteroids, or the solar wind—rather than from volcanic eruptions early in the Moon's history.

These results have given researchers further context on the origins and distribution of water on the Moon, which could be complemented by future missions. (*Geophysical Research Letters*, https://doi.org/10.1029/2024GL110355, 2024) **—Nathaniel Scharping,** *Science Writer*

In the LCROSS mission, NASA crashed a spent rocket booster into the Moon to search for frozen lunar water. Now, new research has located the crater the mission left behind. Credit: NASA

THE UNIVERSITY OF CHICAGO

Senior Instructional Professor

The University of Chicago's Institute for Climate and Sustainable Growth invites applications for Senior Instructional Professor (open rank) to manage the new suite of undergraduate and master's degree programs based on the Institute's Chicago Curriculum on Climate and Sustainable Growth. Appointment will be made in an appropriate primary department or school. The selected candidate will be appointed as Assistant Senior Instructional Professor, Associate Senior Instructional Professor, or Senior Instructional Professor, with rank determined by qualifications. Depending on the rank, the appointment will be for a term of up to five years, renewable with the possibility for promotion. This is a career-track position with competitive salary and benefits. The appointment has an expected start date on or around July 1, 2025.

The primary responsibility of this position involves the management of a pioneering new suite of undergraduate and master's degree programs overseen by the Institute's Chicago Curriculum on Climate and Sustainable Growth. This position will provide broad oversight over the Curriculum's evolution and refinement and course design; update the content of the courses, having periodic discussions with other departments about their needs; supervise other instructors who teach in the program; and recruit and supervise professional staff, such as student and career advisors. Additional duties include ensuring courses fit together through collaboration with, and oversight of, instructors teaching service courses; teaching in the curriculum; supervising course instruction, and assisting with course placement. Review of applications will begin on January 2, 2025. Screening of applications will continue until the position is filled or the search is closed.

Minimum Qualifications
- Completion of a PhD, by the appointment start date, in Economics, Climate Science, Environmental Science, Public Policy, or a closely related field
- Experience in management of academic programs, personnel, and budgets

Preferred Qualifications
- At least two years of teaching experience as the instructor of record in a range of undergraduate courses in fields in energy, climate change, public policy, political science, or related fields.
- Experience or academic background in energy and climate change issues.

Application Instructions
Applicants must apply online at the University of Chicago's Academic Recruitment website at apply.interfolio.com/159577.
A complete application consists of:
- Cover letter
- An up-to-date curriculum vitae;
- Sample syllabus for a class the applicant has taught before, or would be interested in teaching;
- Evidence of successful management of programs or evidence of potential to do so;
- Evidence of teaching effectiveness (such as, but not limited to, course evaluations or other relevant assessments)
- A teaching statement, including a summary of teaching activities, a detailed explanation of teaching philosophy and goals, and a list of courses previously taught, if applicable;
- Three letters of recommendation.

Submit all materials in PDF.

Word Search: The Great Oxidation Event

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J Q J H B S R U L E Q E Q S I P L U K O T D E M K G D X X I
Y F D I C A Q E B N L W G Z U M X U J G V T I C U G Q F A U
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Y L E B H P S C B P Q D L C N O R Z Y N E O H P Q R P Y C E
M N V D E N A I R B M A C I S O T O P E S M C R Y O T I I U
A T M O S P H E R I C R I M O U O H V U H Q O O B M Q Z X D
R M A K L T H E C F Q O C X N L L A F D N A L T N I R J B J
M H X B N P F N C C U U T R A F O H P J Y R L E W I A A R D
R Y Y K U Q C I S F Q A O A B T I K L L J B J R N E L G K Q
V I A P E X G U P N Z Q T M N Q C J R Z G M V O O K U S H U
W Q M E R O T A A E F R Q I F Z L M B V J E X Z I D L T A D
R H Q Z L F K J V O J P T O S Z D F N K Y K J O T V L S T M
A U E O T K X P S N J O R W J A D N Q S G A Z I A O E I S D
O R E T A Z Z S E F I E T R X S I S Y F A U Z C D O C G K Y
B G P U P W I P Y R C S E T O Y R A K U E Q Y D I W I O R A
Z Q N Z N L W N S A Z I I T B C Z K A N O H E A X J T L D Y
D B E E S D D V S Q A I L F X R D D F S C T E F O G L O B F
W G P R F N W T L X Z O W L F U T Z S L A R E N I M U T S A
O J Q P Z V I E O W F C W O O X L L P M A A W G I L M N T C
H F D G C N Z E A E V O B O J D A H W U A E X B P H N O X Q
V L K N G G O H L T J T K D T G C B W I Q T P W E V D E R V
R O P Z Z J O D L X H F X M F P I H N D V P L U T D F L M F
Q C B L Z V B X S J L E Z O C P M U Z R B K C P P E E A Y O
H E H P S H H I S X I M R D A K E T U F T T J N K F L P R R
B F S T F Z T Z S R M W B E W N H Z U R S C Y T H C X X N A
X Z G I D Q B E J J X A W L L F C Q N M Y K H T B V R G R U
A G Z K V J Y N U U N Y J B Y M O U V N C Q C J F H K X X V
R Z A W G U X Z M C S K P I S L E A D O U V Z F F O N U R M
L R E T S A S I D O X Y G E N H G A Y R D P I J W L E P A Y
N V W O I M O B C Q Q A K H L Q S E D I M E N T S C B W V V
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Search up, down, forward, backward, and on the diagonal in the grid above to locate the words listed below.

- acid
- atmospheric
- Cambrian
- disaster
- earthquake
- eukaryotes
- flood model
- forecasting
- fossils
- geochemical
- geologic
- isotopes
- landfall
- mine
- minerals
- multicellular
- oxidation
- oxygen
- paleontologists
- Proterozoic
- Rio Tinto
- runoff
- sediments
- weather

See p. 16 for the answer key.