FORECASTING ATMOSPHERIC RIVERS | **BIRDS EVOLVED** FROM THE GROUND UP | **GRAVITY ANOMALIES** PRECEDED TOHOKU

EARTH

The Ancient Wonders of Giza

September 2018
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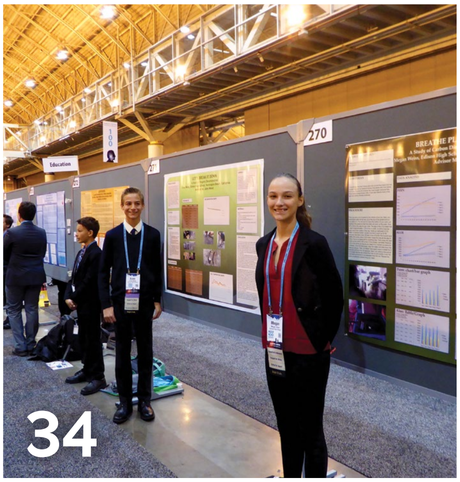
EARTH

FEATURES



VOICES

ON THE COVER: The Pyramids of Giza are arguably the most famous structures ever built. Credit: ©iStockphoto.com/pius99

NEWS

DEPARTMENTS

ON THE WEB AT www.earthmagazine.org

Credit: Megan Sever

On a recent vacation to Los Angeles, I convinced my family to join me at the La Brea Tar Pits. My husband skeptically asked, "What is there to see there exactly?" and my 3-year-old son was mad that there were no live animals or dinosaurs. Their minds were changed once there: Within about 10 minutes of seeing the pits and hearing about what had happened there, my son was off finding sticks and delightedly poking at the small tar pits that dot the park, as well as digging in the sand for fossils, he told me. That night — and every night for weeks afterward — he wanted his bedtime story to be about "mammoths getting stuck in armpits [tar pits in 3-year-old speak] and saber-toothed tigers." When we went to the San Diego Zoo a couple of days later, he was most fascinated by the tar pit display. His imagination had been piqued. And ever since the trip, he has been making up stories about animals getting stuck in tar pits.

I thought about this fascination when I read filmmaker John Copeland's Geologic Column about National Collect Rocks Day. John's interest in rocks was piqued at an early age and he's found ways to feed that interest all his life, for example, by working on earth science films and by making geology part of many family vacations.

Another article in this month's issue also explores sparking scientific interest early. In "Science as a Family Affair," contributing writer Harvey Leifert introduces us to Chad and Nicola Weiss and their five children, all of whom have presented posters on their scientific research at the annual meeting of the American Geophysical Union. Chad and Nicola have stoked their children's interests and helped them follow their scientific curiosity by building a backyard science lab where the kids turn their questions into real-life experiments. And, with the mentoring of their middle-school science teacher, the children have become inspired to not only study science but to work on solving some of the biggest problems facing our changing world. I hope this story, and others in this issue, will capture your imagination and provide inspiration.

Megan Sever
EARTH Editor

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NATIONAL GEOGRAPHIC ENDEAVOUR II

Out of Bounds: Rethinking U.S. Flood Risk Delineation

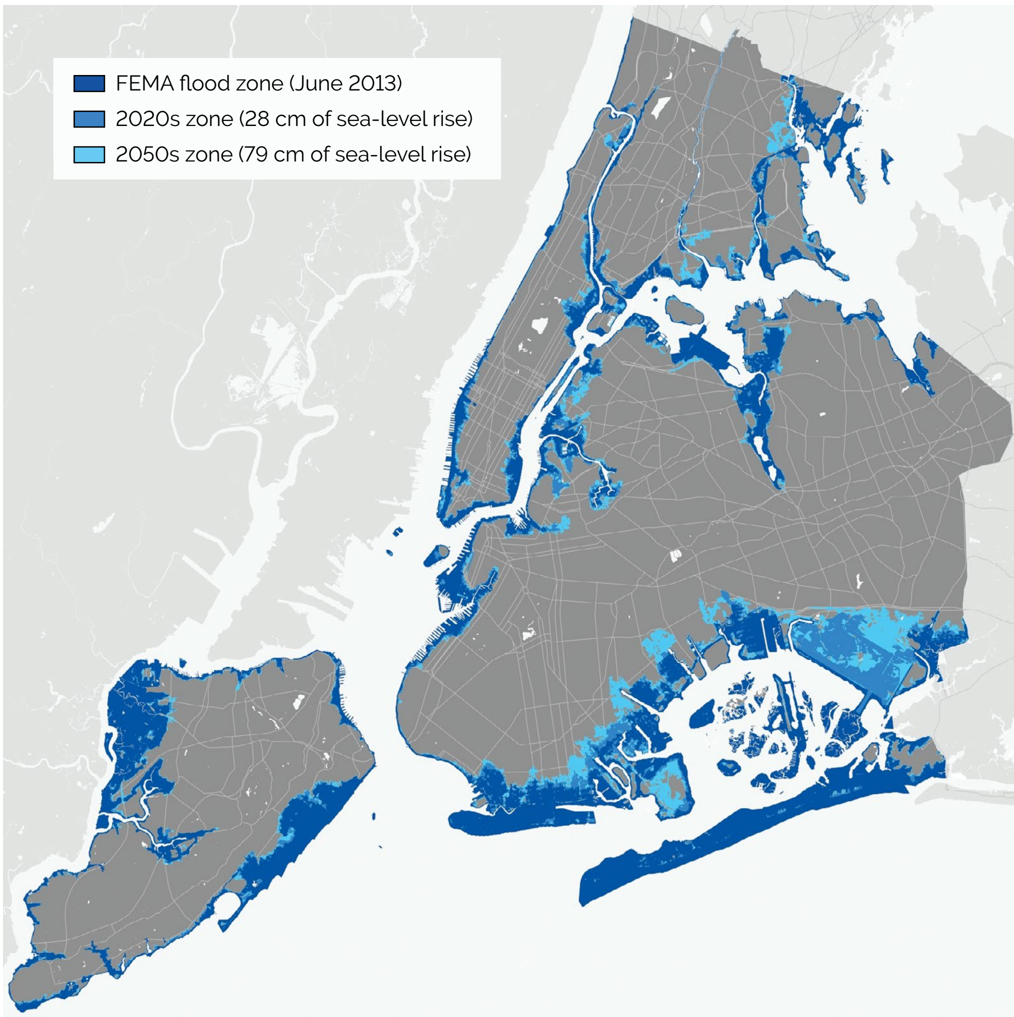
Russell Blessing and Antonia Sebastian

In 1968, the United States' National Flood Insurance Program (NFIP) designated the 100-year floodplain — the area of land projected to be covered by water during a flood event that has a one percent chance of occurring in any given year — as the primary mechanism for determining flood insurance premiums. Since then, it has not only become the de facto boundary used to convey flood risk, but it is also the key instrument used to inform household protective actions, development decisions and local flood mitigation policy. However, increasing evidence has illustrated that the 100-year floodplain is a poor predictor of actual flood losses, even for events smaller than a 100-year flood. Nationwide, about a quarter of all insured flood damage occurred outside the FEMA-delineated floodplain. This percentage is even larger in coastal communities where floodplains are more sensitive to changes in the landscape and climate. For example, in Harris County, Texas (where Houston is located), nearly half of all insured flood loss has occurred outside the floodplain. This "out of bounds" flooding, in part, helps explain the NFIP's current debt of more than $20 billion.

Recently, federal legislators have tried to compensate for this shortfall by increasing premiums and eliminating subsidies. However, this merely shifts the financial burden of flooding further onto homeowners, and skirts underlying issues, particularly inaccurate flood risk delineation. Addressing this issue requires an understanding of the sources of error, such as changing environmental conditions, a lack of long-term and high-resolution data, and problems with the models and methods used to assess flood risk. The last of these is perhaps the most critical.

Flood models often do not accurately capture how stormwater moves through the environment, which ultimately leads to inaccurate flood depth estimates. Additionally, current floodplain maps — which are often more than 15 years old — do not always account adequately for recent and rapid changes in land use, such as the spread of impervious surfaces and the loss of natural habitat, which can significantly increase the depth and extent of a 100-year floodplain. Infrequently updated maps undermine the ability of our flood risk assessments to keep pace with changing environmental conditions such as sea-level rise, subsidence, and changes in land use and land cover. These sources of error are all magnified in the areas most vulnerable to floods: low-lying, rapidly developing coastal watersheds.

The primary consequences of inaccurate floodplain delineation are twofold: delayed or inadequate flood risk adaptation and increasing debt burdens for the NFIP. Inaccurate floodplain delineation undermines the effectiveness of NFIP land-use controls and building codes intended to prevent loss of life and property and guide development away from the floodplain. For example, new construction within the



FEMA-projected flooding in New York City during a 100-year flood event. Dark blue is based on 2013 sea level, and lighter shades are expected flood areas for 2020 and 2050 sea levels respectively.

Credit: Climate.gov

100-year floodplain must be elevated at or above the anticipated height of the floodwater during a 100-year event. But in areas where the flood hazard is inaccurately delineated, there are homes that should be elevated but which are not, leaving them exposed to damaging flood events. Moreover, these same homeowners are not required to purchase federal flood insurance, and thus are more likely to be uninsured, placing the financial burden on them in the event of a flood. However, if they volunteer to purchase flood insurance, they will pay much less in premiums than those inside the floodplain despite being exposed to nearly the same amount of risk, meaning more of the cost burden of flood damage to their homes is shifted onto the NFIP and ultimately the taxpayer.

The 2017 hurricane season, directly followed by severe winter storms on the East Coast, pushed the nation's flood control policies to their breaking point and highlighted the need for a more comprehensive flood risk management program. Several successful initiatives within the NFIP are gaining momentum, including FEMA's Risk Mapping, Assessment, and Planning (Risk MAP) Program and the Community Rating System (CRS). Risk MAP represents a shift away from traditional flood mapping and toward an integrated process of identifying, assessing, communicating, planning for and mitigating flood-related risks. The CRS is designed to incentivize these behaviors by reducing flood insurance premiums for communities that exceed minimum NFIP standards primarily with nonstructural mitigation activities. For example, the CRS gives extra credit to communities that require homes to be constructed at higher elevations, or that preserve floodplain lands as open space, which has the combined effect of preventing development within flood-prone areas and increasing natural absorption of stormwater.

While these efforts undoubtedly increase flood resilience, it is uncertain how accurately updated flood risk maps will depict the true likelihood of being inundated by flood waters. While the

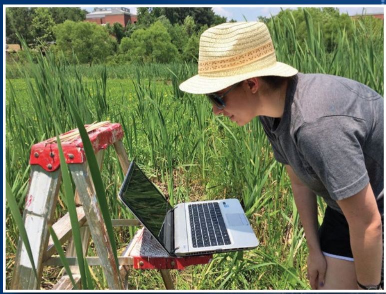
U.S. Marine Corps Reserve servicemen and members of the Texas Highway Patrol and Texas State Guard assist with rescue and relief efforts on a flooded street in Houston on Aug. 31, 2017, following Hurricane Harvey. In Harris County, most of the flood-damaged homes were outside FEMA's designated 100-year, and even 500-year, floodplain. Credit: U.S. Marine Corps photo by Lance Cpl. Niles Lee

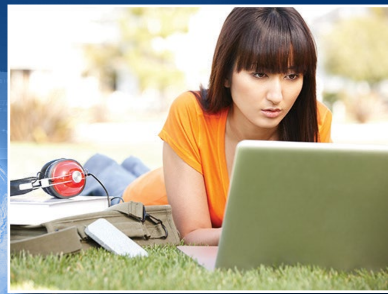
100-year floodplain may serve as a reasonable indicator of the areas at risk of flooding, it neglects areas where localized ponding occurs outside of the floodplain and fails to account for areas exposed to both storm surge- and rainfall-based flooding at the same time. In a recent study, we found that flooding often occurs well outside the floodplain and that this flooding is not captured using conventional models or methods used to assess flood risk. These flood-prone locations outside of the floodplain typify areas that are chronically flooded by small-scale flood events, leaving them with few opportunities for federal support.

Identifying and communicating about areas outside the regulatory floodplain that experience flood risk must be an integral part of comprehensive flood mitigation. One way to do this would be to allow public access to historical flood damage data so that potential homebuyers are more informed. One such online tool available in Texas, called Buyers Be-Where, allows prospective homebuyers to look up an address and see a graphical representation of flood risk for a specific property. Another option is to improve flood hazard estimates by using state-of-the-art, grid-based hydrologic and inundation models to rapidly account for the influence of small-scale land use and land cover on flooding. Such tools can be used by decision-makers to visualize and communicate the potential for property damage to local residents who may not have flood insurance or be aware of their risk because of their location outside the FEMA floodplain.

In short, people in the U.S. are unable to make informed decisions regarding flood risk management because we have become overly reliant on inaccurate 100-year floodplains. And although the 100-year floodplain will likely continue to serve as an indicator of high-risk areas, it is necessary to continue investing in improving models for flood hazard delineation, risk communication and nonstructural activities that exceed minimum NFIP standards.

Blessing is a postdoctoral researcher in the Department of Civil and Environmental Engineering at Texas A&M University, Galveston, and Sebastian is a postdoctoral researcher in the Department of Civil and Environmental Engineering at Rice University.





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Background: ©Shutterstock.com/Sergey Nivens. Insets, left: Megan Amanatides; center: Zsuzsanna Toth (both submitted to AGI's 2016 Life as a Geoscientist contest); right: ©iStock.com/Chris Gramly

An asteroid redirected bird evolution

When an asteroid hit Earth 66 million years ago, it helped wipe out all the dinosaur lineages save one: the birds. But birds didn't completely dodge the cataclysm the asteroid triggered. Recent research suggests that forests around the planet were devastated. With forests gone, bird species that called trees home went extinct alongside their nonavian dinosaur cousins. This means that the birds that we see living in trees today evolved from lineages that, in the aftermath of the impact, were ground-dwelling.

The asteroid impact triggered wildfires and sunlight-blocking dust clouds that spread around much of the planet, decimating forest communities. The arboreal havoc appears in the rock record in the form of a so-called "fern spike" following the impact boundary layer, explains Regan Dunn, a paleobotanist at the Field Museum of Natural History in Chicago and a co-author of a new study in Current Biology. The rapid rise in the proportion of ferns represented among fossil plant remains after the boundary suggests that as trees vanished from landscapes, ferns supplanted them and became pervasive.

A ground-dwelling bird tiptoes through burning forests in the aftermath of the asteroid impact about 66 million years ago at the Cretaceous-Paleogene boundary.

Credit: ©Phillip Krzeminski, Cornell Laboratory of Ornithology

The fern spike lasted about 1,000 years before forests began recovering, but these emerging forests didn't look the same as their predecessors had. Study co-author Antoine Bercovici, a palynologist at the Smithsonian Institution in Washington, D.C., examined pollen abundances in the aftermath of the impact, finding that the kinds of trees present were drastically different before and after the fern spike. "Many angiosperms — flowering plants — that were common in the Cretaceous disappeared," Bercovici says. Then, after the spike, once-rare trees like pines and palm trees became common, he says.

Researchers have known about the fern spike for years, but the new study connects the fate of forest ecosystems after the impact with the story of bird evolution. Bird fossils from before the extinction display traits — like toes adapted for perching on branches — that disappear in bird fossils immediately following the extinction, says Daniel Field, a paleontologist at the University of Bath in England and lead author of the study. "The groups of birds that exhibit feet like that failed to survive the mass extinction event," he says.

In 2015, Field and another team of researchers published a phylogenetic tree depicting the evolutionary history of all birds. The tree displays the timing of major branching events and reveals that "many of the deepest divergences within the living bird tree of life apparently sprung forth quite quickly after the impact 66 million years ago," right around the time of the fern spike, Field says. Then, a key pattern emerged: "All of those branches lead to groups that today are dominated by ground-dwelling birds," he says. This suggested to the team that the modern arboreal lineages that arose must have also emerged from groups that were ground-dwelling after the extinction.

So, the birds that flit around in trees today owe their existence to an asteroid impact and the ecological catastrophe that it wrought, Field says. But exactly how and when the terrestrial birds that survived the extinction evolved and moved into the trees that flourished after the fern spike is not clear, says Daniel Ksepka, a paleontologist at the Bruce Museum of Arts and Science in Greenwich, Conn., who was not involved in the new research. "It would be interesting to see how quickly the birds got to the trees," he says.

The thing to do next, Field says, is to hunt for fossils of tree-dwelling birds in rock layers just above the extinction boundary, which could help reveal the story of how modern arboreal birds came to be.

Lucas Joel

Great Barrier Reef has died and recovered before

It's hard to imagine Earth without the Great Barrier Reef, yet with the threats confronting it — including ocean warming and acidification — its demise is a possibility marine scientists are studying. A new study of how sea-level rise and sedimentation have impacted the reef over the last 30,000 years, however, shows it might be more resilient than previously thought.

Jody Webster, a marine geologist at the University of Sydney in Australia, and colleagues report in Nature Geoscience that the reef has rebounded multiple times in the wake of die-off events.

The team cored into fossil portions of the Great Barrier Reef and conducted sedimentological, biological and geochronological analyses to assess "the impacts of abrupt sea-level and associated environmental changes," the researchers wrote.

The cores were collected from 20 boreholes at 16 different sites off the coast of Mackay and Cairns in Queensland, Australia. In total, the team dated more than 580 samples of coral and coralline algae to produce the first continuous record of the Great Barrier Reef's evolution over its lifespan.

The oldest fossil reef sample, which was collected from a site called Noggin Pass near Cairns, indicates that the first iteration of the reef was exposed and died about 30,000 years ago as sea level began to drop heading into the last ice age.

A second iteration, constituting a "very narrow and ephemeral fringing reef system," existed from 27,000 to 22,000 years ago, but was killed by rapid sea-level fall and exposure as the ice reached its maximum extent in this part of the world. Vertical accretion, or growth, of this reef was slow — just 0.3 to 2.5 millimeters each year — possibly resulting from restricted available space or higher local sedimentation during its lifetime. The depth of the water in which the reef was growing plummeted to less than 10 meters before this portion of the reef perished, according to the team's analysis of coral-algae samples.

Between 21,000 and 17,000 years ago, sea-level rise resulting from early deglaciation spurred reef development with rapid yearly vertical accretion rates of 3.9 to 4.4 millimeters. About 16,000 years ago, however, "an increased flux of fine terrigenous sediments … may have reduced light availability and water quality," Webster and her team wrote. That, combined with rapidly rising sea levels, drowned the reef. The last reef die-off was due to similar causes and occurred about 10,200 years ago.

"This is a very interesting, detailed reconstruction of coral reef response — for example, growth rate and community structure — to Earth's last major period of climate disruption during the ice age and subsequent deglaciation," says Kenneth Rubin, a geochemist and volcanologist at the University of Hawaii at Manoa, who wasn't involved with the research. "It provides clues as to how coral reefs respond to environmental change."

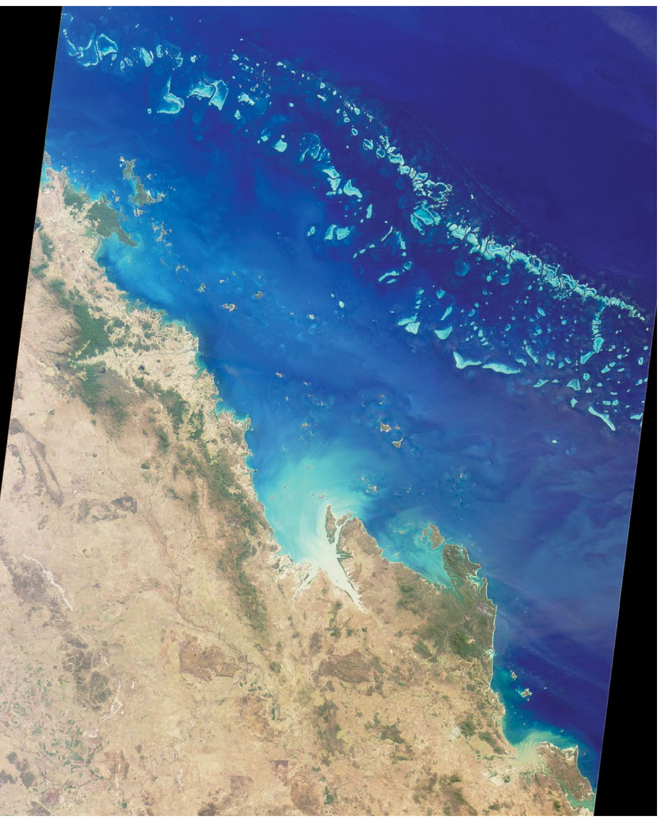
Today's Great Barrier Reef began growing about 9,000 years ago. While it faces sea-level rise and other threats from which previous incarnations of the reef bounced back, today's threats are occurring more widely, at the same time and at a faster pace, the authors note.

"The outlook is still likely bleak in the short term (10 to 50 years), if we continue to see year-on-year coral bleaching and other pressures," Webster says.

With additional pressures from sea-surface temperature increases of 0.7 degrees Celsius per century and "sharp declines in coral coverage … our new findings provide little evidence for resilience of the Great Barrier Reef over the next few decades," the researchers wrote.

Study co-author Donald Potts, a coral reef ecologist at the University of California, Santa Cruz, says the reef may disappear for a few human generations, but says it's likely the reef "will [eventually] re-establish and recover."

Rachel Crowell



The Great Barrier Reef has rebounded from die-off events many times; however, it has never faced the combination of threats that it does today.

Credit: NASA

Lunar meteorite indicates abundant water

Scientists analyzing a meteorite found in Africa determined it came from the moon and is composed primarily of a quartz-like mineral called moganite. Moganite requires water to form; thus, the researchers say it demonstrates the existence of water-ice at the moon's lower and midlatitudes.

Kayama et al., Science Advances, May 2018

Understanding how megathrust earthquakes like the 2011 magnitude-9.1 Tohoku event might rupture, including how long shaking might last, could help scientists prepare for future hazards.

Credit: U.S. Navy photo by Mass Communication Specialist 1st Class Matthew M. Bradley

New measurement shakes up earthquake estimates

As tectonic plates collide and sink in subduction zones, huge megathrust earthquakes can produce devastation above. Yet, there are many unknown factors that control how much energy is released in each earthquake. Now, a team of scientists has come up with a new model to help crack the complexity and nature of megathrust earthquakes using global historical records.

Earthquakes are currently measured on the moment magnitude scale, which describes the size of earthquakes based on the amount of energy they release: Large earthquakes are labeled with bigger numbers. But two earthquakes with the same moment magnitude can have very different styles of rupture. For example, the 2011 magnitude-9.1 Tohoku megathrust quake and the 2004 magnitude-9.2 Sumatran megathrust quake were similar in magnitude. However, during the Tohoku quake, the fault slipped primarily along one area for three minutes, whereas in the Sumatra quake, the fault ruptured in multiple areas at once and shook for eight long minutes.

The way a megathrust ruptures — either continuously or sporadically, with stops and starts — can contribute to the release of different amounts of energy, says Lingling Ye, a seismologist at Sun Yat-sen University in China and lead author of the study in Science Advances. "However, we do not have a parameter, a number, to [distinguish] complexities [of rupture]," Ye says.

Now, she and her colleagues have developed a different way to measure energy release, called the Radiated Energy Enhancement Factor, or REEF, which can provide scientists with a more nuanced picture of variations among megathrust earthquakes.

REEF is the ratio of an earthquake's radiated energy (measured by seismic instruments) to the theoretical minimum possible energy that an event of equal seismic moment and duration of rupture could produce. The result gives researchers an idea of the complexity of a rupture. High REEF values mean high complexity — and high energy release. For example, the Sumatra earthquake had a REEF value of 2.0, meaning the energy released in the complex rupture was much bigger than the potential minimum amount of energy released in a magnitude-9.2 earthquake.

Ye uses an analogy to explain how earthquake energy varies: Consider driving a car from point A to point B. The efficient option is to gradually accelerate once and then decelerate once. The second option is to accelerate and decelerate many times throughout the journey. The second option will use more gas than the first because it is so irregular. Similarly, Ye says, earthquakes that have jerky, more complex ruptures will release more energy.

The team's analysis of 119 large historical quakes (ranging from magnitude 7 to greater than 9) from around the world, found a clear geographical pattern in the complexity of rupturing. For example, all earthquakes along the north and central parts of the South American plate boundary were complex, leading to high REEF values and a higher likelihood of triggering nearby faults to fail. Earthquakes off the coast of Central America had smoother, simpler rupture patterns that were less likely to trigger adjacent faults.

"We were a little surprised to see that," Ye says. Megathrust ruptures are controlled by geologic factors like frictional properties, fluids, sediments and the age of plates. "What exactly the factor is [for geographic grouping] is unclear — we are working on that."

"The complexity of the rupture is not necessarily captured in the current moment magnitude scale," and using REEF may help capture these differences, says Helen Janiszewski, a postdoctoral seismologist fellow at the Carnegie Institution for Science in Washington, D.C., who was not involved in the study.

"At least at some of the subduction zones around the globe, we seem to see characteristic behavior over multiple different types of earthquakes," Janiszewski says. She adds that this finding becomes important because it implies that structure, geometry and properties of a particular subduction zone can cause a certain type of rupture — which in turn produces a particular type of energy release. This discovery, Janiszewski says, may help researchers predict what kind of earthquakes might happen in certain areas.

Ye says REEF measurements can help future hazards estimates. "If an earthquake is more complex, it will generate more energy and create more damage," Ye says. For example, it is helpful to know if the first main megathrust slip is jerky and very energetic, as it can release enough energy to trigger slip on another nearby fault, like dominoes.

Janiszewski notes that the sample size in the study is small, especially considering that many of the quakes occurred before modern instrumentation and better coverage of seismic monitoring were available. It would help, she says, to broaden the dataset by looking at earthquakes of a smaller magnitude to see if the relationships observed in this study still stand.

Ye agrees and says that the team is looking to expand to smaller earthquakes as well as looking beyond megathrust earthquakes. She notes that REEF could also be used to quantify strike-slip earthquake hazards in places like California.

Sarah Derouin

Grazing gave elephant ancestors an edge

The poor dental hygiene of some ancient elephant-like beasts has proven a boon to future scientists. In a new study, researchers used grass fragments recovered from the teeth of two extinct species of Central Asian gomphotheriids to decode the animals' feeding habits during the middle Miocene.

Scientists led by Wu Yan of the Institute of Vertebrate Paleontology and Paleoanthropology (IVPP) in Beijing, China, examined bits of mineralized plant matter known as phytoliths scraped from the teeth of specimens of *Gomphotherium connexum* and *Gomphotherium steinheimense*, which both roamed Central Asia about 17 million years ago. By comparing the grazing habits of the two species, the team sought insights into how feeding preferences and changing vegetation patterns played a role in their survival.

They reported in Scientific Reports that *G. connexum* likely fed on mixed types of foliage, including leaves and grasses, whereas *G. steinheimense* showed a strong preference for grasses, a pattern also confirmed by examinations of tooth microwear patterns and structure in the two species. The team then analyzed fossil pollen records recovered from the sediments containing the teeth and found that the animals' shared habitat was changing from woodlands into semi-arid savanna. "By adopting a much more grass-based diet, *G. steinheimense* was apparently responding better to this habitat change than *G. connexum*," said co-author Zhang Hanwen, of the University of Bristol in England, in a statement.

A grass-based diet may have given *G. steinheimense* an advantage over *G. connexum*. *G. steinheimense* is thought to be ancestral to modern Asian elephants, according to the study's authors, whereas the lineages of *G. connexum* and several other species of gomphotheriids went extinct in Central Asia at the end of the middle Miocene. *G. Steinheimense's* "active adaption to the environment helped the species to survive by better exploiting newly abundant food sources in the form of grass," Wu told Xinhua.

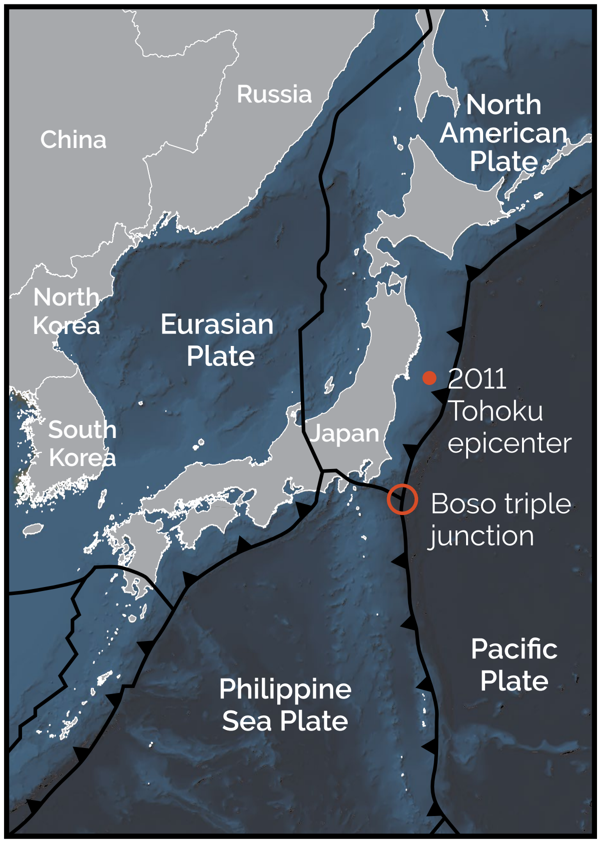
Replica of a reconstructed *Gomphotherium steinheimense* skeleton on display at the Basel Natural History Museum.
Credit: Zhang Hanwen, University of Bristol

Mary Caperton Morton

Gravity changes portended 2011 Tohoku earthquake

A new analysis of satellite data has revealed a distinct change in the gravity signal measured across the Japanese archipelago starting several months before the March 11, 2011, magnitude-9.1 Tohoku-Oki earthquake — one of the largest seismic events in recorded history. The gravity change reflects interactions among shifting tectonic plates in the region, and its timing shortly before the earthquake raises the tantalizing notion that such signals could portend impending seismicity elsewhere. But researchers say it's unclear if the signal seen in the new study is unique to the Tohoku quake or if it represents a phenomenon common to other large subduction zone quakes.

A team led by Isabelle Panet, a geophysicist at Paris Diderot University in France, studied regional deformation surrounding the subduction zone offshore Japan. They analyzed satellite data recorded by the twin satellites of the Gravity Recovery and Climate Experiment (GRACE), which launched in 2002 to track anomalies in Earth's gravity field. These anomalies reflect changes in the distribution of mass around the planet over time, particularly changes in water mass generated by rising sea levels, melting ice sheets, and seasonal filling and emptying of aquifers. Large earthquakes can also affect Earth's gravity field when large regions of the crust shift. Such changes have been detected previously after major earthquakes — including Tohoku — but the new study, published in Nature Geoscience, reports a change in the gravity field that occurred three months prior to the Tohoku event.



The tectonic setting of the 2011 Tohoku quake.

Credit: K. Cantner, AGI

"Our analysis revealed large-scale gravity and mass changes throughout three tectonic plates and connected slabs, starting three months before March 2011," Panet says. These changes began in late 2010 on both sides of the Boso triple junction, where the North American, Pacific and Philippine Sea plates meet to the east of Japan. And by March 2011, the gravity anomaly had spread along the subduction boundaries of the three tectonic plates.

In a subduction zone, as the subducting slab is forced deeper into the mantle, changing gravity signals are produced by the shifting of mass within and between the plates. This shifting creates stress in the system that propagates upward toward the surface, potentially triggering an earthquake, says Barbara Romanowicz, a planetary seismologist at the University of California, Berkeley, who was not involved in the new study. "The Panet study shows that gravity anomalies can be used to connect the motions that occur deep in the mantle over geological timescales to the surface expressions that occur on human timescales, such as earthquakes," Romanowicz says. "This technique is fascinating from a basic science point of view as it can help us understand the whole subduction zone system."

Since the gravity changes occurred months ahead of the earthquake, it's tempting to wonder if such signals could be used as part of an earthquake early warning system, but that idea is probably "far-fetched," Romanowicz says. "Right now, we don't know if this is a unique circumstance that occurred this one time only in this one place, or if there is a shift of masses months before every subduction zone earthquake," she says.

"There is also the question of timescale. The window [between signal detection and an earthquake] could be anywhere from days to months to millennia," Romanowicz says. The extreme size of

Grasslands not the only habitat early *Homo* called home

Most of what's known about the climate and environment in which early members of our genus, *Homo*, evolved is based on paleoenvironmental data gleaned from East Africa. These data indicate that that region was predominantly characterized by arid grasslands in the early Pleistocene about 2 million years ago. But a study of fossil herbivore teeth found in South Africa's Wonderwerk Cave dating to the same period suggests the interior of southern Africa was substantially wetter and hosted distinct vegetation compared to East Africa and eastern South Africa. The findings demonstrate that early *Homo* inhabited a variety of environments.

Ecker et al., Nature Ecology & Evolution, May 2018

Scientists find oldest giant dinosaur

Researchers in Argentina recently uncovered a new 10-ton sauropodomorph — which they named *Ingentia prima*, or "first giant" — that lived in the Late Triassic. Previously, the largest dinosaur found from that period weighed about 3 tons, and scientists had thought that giant dinosaurs didn't begin walking the planet for another 30 million years. The find also offers insight into how small, bipedal sauropodomorphs of the Triassic evolved into the behemoth quadrupedal sauropods of the Jurassic and Cretaceous.

Apaldetti et al., Nature Ecology & Evolution, July 2018

the Tohoku quake may also be a hard-to-meet prerequisite. "It may be possible that you need a magnitude-9 quake to be able to detect this kind of signal." It's more likely that a precursory gravity signal could be used to determine where to deploy more instruments and boost monitoring networks over a target region.

Panet agrees that "we cannot talk about prediction based on the analysis of only one event." She and her colleagues plan to investigate whether they can detect precursory gravity signals before other major subduction zone quakes, such as the 2004 Sumatran or the 2011 Chilean megathrust earthquakes. The GRACE satellites should offer data for most regions of the planet for earthquakes that occurred between March 2002 and October 2017, when the satellites were in operation. "GRACE satellite data have a nearly global coverage, so we expect that we can apply our technique to the GRACE gravity fields at other subduction zones as well," Panet says.

More modeling is needed to characterize the relationship between mass transfers and associated stress changes, and how these changes lead to earthquakes off Japan and elsewhere, Panet says. But, she notes, "this approach … has allowed us to put the local, extreme seismic event into the broader context of mass redistribution across the whole region."

Mary Caperton Morton

Bolts of insight on earthly gamma ray showers

A handful of times between 2014 and 2016, an array of ground detectors placed in Utah's western desert sensed something in thunderstorms that occasionally raged overhead: showers of gamma rays — the highest energy waves in the electromagnetic spectrum — occurring alongside lightning bolts. The observations, reported in a new study, mark the first time scientists spotted such gamma rays from the ground and reveal more about the relationship between lightning and gamma rays, potentially shedding light on some unanswered questions about lightning itself.

The gamma ray showers, also known as terrestrial gamma ray flashes (TGFs), were discovered serendipitously in 1994 by satellites instrumented to detect gamma rays produced by far-off astrophysical events like supernovae. Such showers had previously been observed only from satellites.

However, the immense size of the Telescope Array, which features more than 500 detectors spread over an area the size of New York City west of Delta, Utah, made it possible to spot the showers from Earth, says Rasha Abbasi, an astrophysicist at the University of Utah and lead author of the study in the Journal of Geophysical Research: Atmospheres. Because the bursts were detected from the ground, close to the storms, researchers could image them in greater detail than with satellite data. During the course of multiple storms, Abbasi and her team detected 10 downward-propagating TGF bursts, each of which only lasted a few microseconds.

Although the factors that cause such gamma ray showers are still unknown, the new work reveals that they happen in the first stage of a lightning strike. "The first stage is the step-leader stage," Abbasi says. When a bolt initiates and begins branching toward the ground, it takes "one step to the left, [then] one step to the right."

The gamma ray showers produced by the thunderclouds studied in the new research "are a byproduct of yet-unidentified acceleration mechanisms in our own atmosphere," says Hamid Rassoul, a space physicist at the Florida Institute of Technology who was not involved in the study. "It is surprising that thunderstorms and lightning can do this at all," he adds. "We don't usually think of the atmosphere as a powerful source of high-energy particles."

Surface detectors from the Telescope Array in Utah's western desert were used to detect gamma ray showers caused by lightning.

Credit: John Matthews, University of Utah

Now that it is clearer when gamma ray showers originate during lightning events, Abbasi says, researchers are "starting to zoom in on the mechanism of how the TGFs are produced." Understanding the mechanism behind TGFs may help reveal fundamental details of how lightning itself is initiated — still a topic of debate among scientists, Abbasi says.

Lucas Joel

New suspect emerges in theft of Earth's surface iron

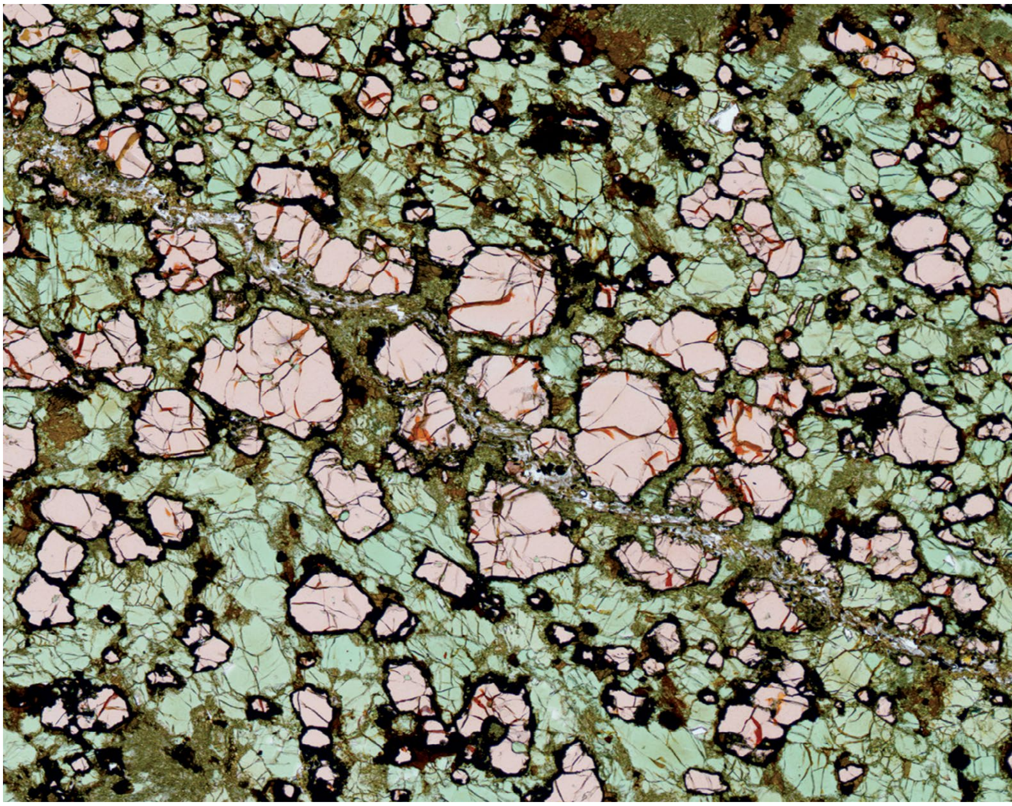
Iron is the fourth-most common element in Earth's crust, but why there isn't more found near the surface in continental crust has been a long-standing question among geologists. In a new study, scientists implicate an overlooked mineral culprit in the theft of iron from continental crust: garnet. But not everybody is ready to exonerate the long-implicated magnetite.

If iron were more concentrated in Earth's continental rock, our blue planet would look more like Mars, where highly oxidized, iron-rich rocks cause its trademark red color. But the missing iron isn't just a matter of color — it also has widespread implications for the chemistry of Earth's oceans and atmosphere: If more iron were found at the surface, our planet might not be habitable. So what do we have to thank for sequestering this iron in the planet's interior?

"The traditional view … is that iron is removed from continental crust by the mineral magnetite," says Ming Tang, a geochemist at Rice University in Houston, Texas, and lead author of the new study, published in Science Advances. This theory suggests that magnetite pulls iron out of crustal melt deep in subduction zones, before the melt rises to the surface to erupt. The trouble with the magnetite theory of iron depletion is that depletion is most pronounced beneath thick continental volcanic arcs, such as the Andes, while there's much less depletion beneath island arcs, where the crust is thinner. "The magnetite theory has been the dominant view for almost half a century, but it doesn't explain why iron-depleted magmas are preferentially found in thick arcs. The distribution of magnetite does not correlate with crustal thickness," Tang says.

However, what does correlate with crustal thickness is the distribution of garnet, particularly almandine, an iron-rich type of garnet that forms under high temperature and high pressure — the kinds of conditions found in deep regions of thick continental crust. "Garnet is a mineral that really likes high pressure. The more pressure, the more that crystallizes from magma and the more iron is depleted," Tang says. At continental arcs, where the crust can be 80 kilometers thick, the pressure is great enough to produce large quantities of almandine crystals, which are heavy and sink out of melt as it moves toward the surface. "The iron [the garnets] pull out is ferrous iron (Fe^{2+}), which is not highly oxidized. It goes back into the mantle, while the more oxidized iron (Fe^{3+}) remains in the melt that rises to the surface." This creates the highly oxidized, low-iron magmas commonly found at continental arcs.

Tang and his colleagues found new evidence for the role of garnet in iron depletion of continental crust in a collection of xenoliths — bits of deep rock



Abundant garnet crystals (pink) appear in this thin section from a garnet pyroxenite xenolith.

Credit: C. Lee/Rice University

East Antarctica seismically active after all

East Antarctica's seeming seismic quiescence — long attributed to exceptionally low tectonic stresses in the stable bedrock, as well as the compressive weight of the overlying glacial ice — was, it turns out, an artifact of data collection limitations across the vast and remote ice sheet. The first array of year-round seismometers was deployed in East Antarctica in the late 2000s. Now, researchers report that the instruments detected 27 earthquakes in 2009 alone, suggesting the region's seismic activity is on par with that of other stable cratons like the Canadian Shield.

Lough et al., Nature Geoscience, June 2018 brought to the surface by rising magma — found in Arizona. These fragments originated at depths of 60 to 80 kilometers and "offer a direct window into the deep roots of the continental arc," Tang says.

Geochemical study of the garnet-rich xenoliths offered some clues about where iron depletion is taking place in the crust, Tang says. If magnetite were the main culprit, the reaction would be taking place deep in subduction zones, which tend to be highly oxidized. But the xenoliths appear to have formed in less oxidized conditions. "When you bring garnet into the equation, everything falls into place," Tang says. The garnet theory holds that the oxidation occurs above subduction zones, as magma is rising to the surface.

The team tested their hypothesis on a global scale using the GEOROC database at the Max Planck Institute in Germany, a collection of published geochemical and isotopic analyses of volcanic rocks and mantle xenoliths collected all over the world. The researchers found a clear relationship between iron depletion and garnet fractionation, or crystallization, in continental arc volcanic rocks: "Magmas that fractionate more garnet are more depleted in iron," Tang says. "The evidence is something that wouldn't be obvious from looking at just one or two cases. It requires a global database, and those have only recently become available."

The study is "provocative," says Marc Hirschmann, an experimental petrologist at the University of Minnesota, who was not involved in the research. Senior author Cin-Ty Lee, also at Rice University, is "known for looking at data very differently and proposing unconventional viewpoints," Hirschmann says. The study doesn't eliminate the magnetite theory but rather offers an alternative pathway for iron depletion. It's possible that both the magnetite and garnet pathways play a role in iron depletion of continental crust, he says — one pathway does not eliminate the other. This isn't the first time the garnet pathway has been considered — the new paper cites a 1968 study that initially proposed the idea — "but this team is definitely advancing it with new data, new analyses and new arguments."

Hirschmann expects that this study will stimulate other research teams. "People are going to be resistant to accepting this garnet idea right away," he says. "I think we're going to see teams looking for igneous garnet in the field and continuing [to use] modeling and thermodynamic studies to find out if garnet is as major a player in iron depletion."

Mary Caperton Morton

Sunstones useful as Viking-era GPS

The Vikings ruled the North Atlantic for hundreds of years without the benefits of magnetic compasses on the rough, often stormy waters. Legends have told of Vikings using sun compasses during clear weather and "sunstones" in cloudy conditions to navigate their weeks-long journeys between ports. A new study finds that sunstones made of calcite, cordierite or tourmaline may have indeed been accurate navigational tools.

A piece of Iceland spar, a type of calcite that may have been used by Vikings to navigate in cloudy conditions.

Credit: ArniEin, CC BY-SA 3.0

The technique, called sky-polarimetric navigation, is cumbersome, requiring a navigator to estimate the direction of skylight polarization using a sunstone and then plot the location along two celestial great circles relative to scratches made on the sunstone — all to determine the direction of north.

To study the effectiveness of sunstone navigation, Dénes Száz and Gábor Horváth of Eötvös Loránd University in Hungary ran computer simulations of 1,000 three-week-long voyages between Norway and Greenland under varying degrees of cloud cover. The simulated voyages started from the Viking-era community of Hernam (now Bergen, Norway) and followed along 60 degrees 21 minutes 55 seconds North latitude, the main route to the settlement at Hvarf in south Greenland. Sky-polarimetric navigation using different types of light-polarizing crystals has been tested in previous studies in laboratories and planetariums. But "to date, this is the most detailed and precise rating of sky-polarimetric navigation that is achievable without testing this method directly on the high seas," the team wrote in the journal Royal Society Open Science.

The researchers found the sunstone technique to be surprisingly successful regardless of the type of crystal used for sky polarization, with voyages reaching Greenland between 92.2 and 100 percent of the time, assuming a navigator used the crystal every one, two or three hours. "We conclude that the sky-polarimetric Viking navigation [method] is surprisingly successful at spring equinox and summer solstice even in cloudy weather," the team wrote.

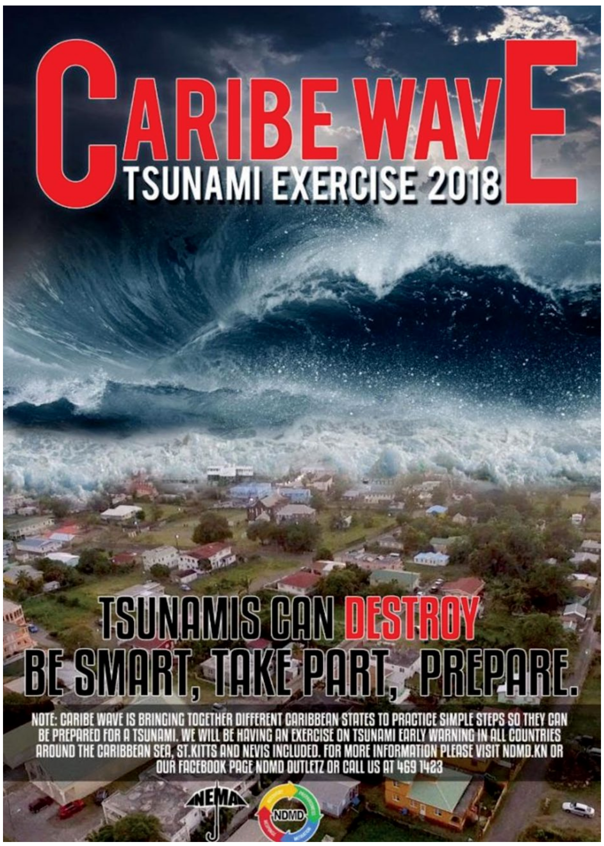
Mary Caperton Morton

Readying the Caribbean for the next big wave

The Caribbean is famous for clear blue waters and serene white sand beaches, and infamous for destructive hurricanes — but another type of natural disaster can also strike: tsunamis. On Aug. 4, 1946, a magnitude-8.1 earthquake shook the Dominican Republic and set off a tsunami across the Caribbean that killed as many as 1,800 people and registered on tide gages as far away as Atlantic City, N.J. At the village of Julia Molina on the northern coast, the waves reached 5 meters. In the decades since, smaller waves have caused flooding and injuries. Now, geoscientists are helping the region prepare by modeling worst-case scenarios for the annual CARIBE WAVE tsunami drill.

Today, more than 40 million people live in the Caribbean, with tourism driving population numbers far higher. Enough time has passed since the last big tsunami in the Caribbean "that many people have forgotten all about the threat," says Christa von Hillebrandt-Andrade, manager of NOAA's Caribbean Tsunami Warning Program, based in Puerto Rico. "During that time, the populations living along the coasts have increased dramatically, so if a wave were to strike, the impact could be unprecedented."

The Caribbean region is made up of more than 700 islands, many of which sit atop or alongside the Caribbean Plate. The northern and southern edges of the plate form transform fault boundaries with the North American and South American plates. To the east, at the Puerto Rico Trench — home to the greatest depth in the Atlantic Ocean at 8,648 meters — the boundary dives deep into the Lesser Antilles Subduction Zone, which produced large earthquakes in 1839, 1843 and 1918. Several active submarine volcanoes also dot the seafloor of the eastern Caribbean, with the potential to trigger tsunamis through underwater eruptions or large-scale marine landslides.



March is tsunami awareness month in the Caribbean.

Credit: Nevis Disaster Management Department

In May, von Hillebrandt-Andrade gave a presentation at the Seismological Society of America annual meeting in Miami entitled "Megathrusts and tsunamis in the Caribbean." We used to think a roughly "magnitude-8 earthquake was the largest we might see in the Caribbean, based on the history of earthquakes there and the length and motion of the faults," she says. "But now some scientists think that several faults in the region could be capable of producing earthquakes of magnitude 8.6, and the catastrophe planning by our emergency management community is now considering 8.5 and 9 earthquakes as the worst-case scenarios."

To remind people about the dangers of tsunamis and help them prepare for potentially deadly events, von Hillebrandt-Andrade and colleagues spearhead the CARIBE WAVE tsunami exercise, an annual event held in March that offers different wave scenarios, generated by different ruptures, and encourages emergency response agencies, communities and individuals across the Caribbean to update and practice evacuation drills. In 2018, more than 680,000 people participated in the drill, with 46 out of 48 countries and territories involved.

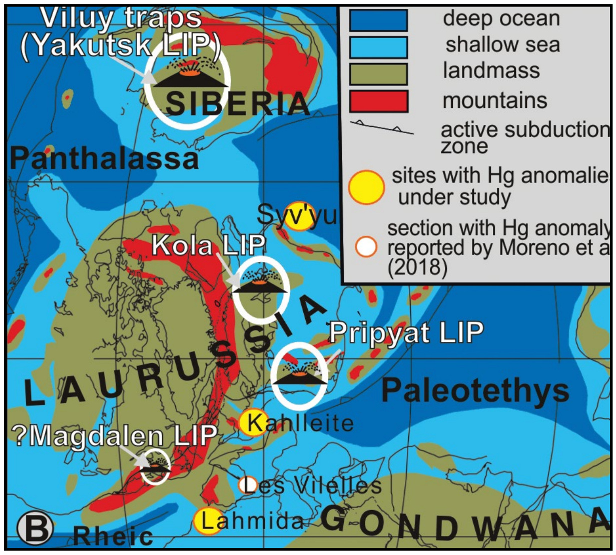
This year's CARIBE WAVE recreated the 1918 Puerto Rico Trench earthquake and subsequent tsunami. The magnitude-7.1 quake triggered a 6-meter-high wave that destroyed villages on the west side of Puerto Rico. "It can be very motivating for people to respond to a historical event that they have heard stories about," Hillebrandt-Andrade says. "We want people to do an actual evacuation, so if a tsunami strikes, they've already practiced their evacuation route to higher ground."

In 2019, the CARIBE WAVE exercise will feature a new scenario not based on a specific past event: a flank collapse at the Kick 'em Jenny Volcano, an active submarine volcano 8 kilometers north of the island of Grenada, which could displace enough water to trigger a tsunami.

Practicing such drills is important because the emergency response to a tsunami differs from the more commonly deployed response to a hurricane due to the different lead-times involved, says Ronald Jackson, executive director of the Caribbean Disaster Emergency Management Agency. "When dealing with storms you often have days to prepare, but in the event of a tsunami we're always going to be racing against time. We have to get the word out and get everybody moving to higher ground in a matter of minutes. It's a very daunting task and one that needs to be practiced."

Mary Caperton Morton

Mercury links Big Five extinction events



The locations of sites studied for mercury abundances are shown in yellow on this plate reconstruction from the time of the Frasnian-Famennian extinction.

Credit: Racki et al., Geology, April 2018

Mercury concentration spikes in the geologic record have been linked to massive volcanism in the form of large igneous provinces (LIP) such as the Deccan Traps, a kilometers-thick heap of basalt layers that formed in what is now India beginning late in the Cretaceous, and the Siberian Traps, an even larger mass of lava that erupted in Siberia at the end of the Permian. It's thought that vast gas emissions associated with LIP eruptions could have significantly changed climate patterns and affected conditions such as ocean acidity. And four out of five of the most devastating extinction events of the last 550 million years have previously been linked, at least partly, to the formation of LIPs. A new study looking at mercury in rocks dating to the Late Devonian has now linked the fifth to volcanism as well.

In the new work, published in Geology, researchers found evidence for a mercury anomaly in rocks from Germany, Morocco and Russia that coincides with the Frasnian-Famennian, or Late Devonian, extinction, which took place between about 376 million and 360 million years ago. This mercury spike is thought to be linked to rapid climatic perturbations brought on by cataclysmic volcanism at the Viluy LIP in Siberia.

"Our study provides the first worldwide evidence of a major phase of volcanogenic [mercury] injection into the atmosphere during the F-F mass extinction boundary, thus lending support to the postulated relationship between LIP volcanism and global crises for all of the 'Big Five' crises," the team, led by Grzegorz Racki of the University of Silesia in Poland, wrote.

Mary Caperton Morton

Ancient DNA reveals diversity of Southeast Asia

Workers excavate ancient human remains at Man Bac, Vietnam, in 2007. DNA from skeletons at this site was included in the current study.

Credit: Lorna Tilley/Australian National University

Southeast Asia is one of the most genetically and linguistically diverse regions on Earth. New sequencing of ancient human DNA is helping scientists piece together the puzzle of how repeated influxes of hunter-gatherers and farmers to the area over the last 50,000 years created the high level of diversity seen today.

In one of the first efforts to study the genetic history of the region, David Reich, of Harvard Medical School, and colleagues extracted DNA from the remains of 18 people who lived between 4,100 and 1,700 years ago in what are now Cambodia, Myanmar, Thailand and Vietnam. As reported in Science, the team found evidence of at least three major migrations into the region, starting with hunter-gatherers roughly 45,000 years ago.

Then about 4,500 years ago, a wave of Neolithic farmers from China brought new agricultural practices and Austroasiatic-based languages to the region. More recently, during the Bronze Age, influxes from China arrived in Myanmar about 3,000 years ago, then Vietnam about 2,000 years ago, and lastly in Thailand about 1,000 years ago. These later migrations likely brought the dominant languages spoken in the region today.

"The major population turnover that came with the arrival of farmers is unsurprising, but the magnitudes of replacement during the Bronze Age are much higher than many people would have guessed," Reich said in a statement. "This study reveals a complex interplay between archaeology, genetics and language, which is critical for understanding the history of Southeast Asian populations," added co-author Ron Pinhasi of the University of Vienna in Austria.

Mary Caperton Morton

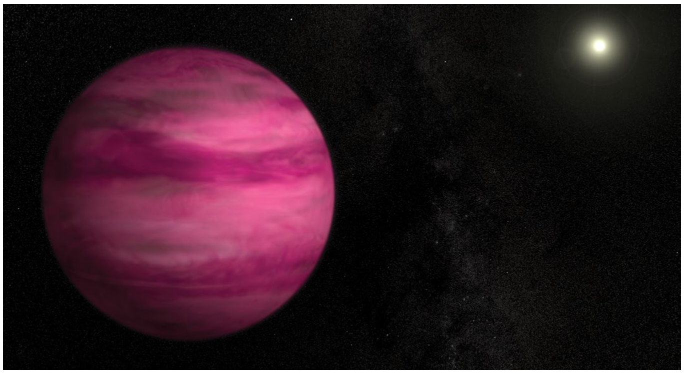
Obliquity and eccentricity determine exoplanet habitability

Finding habitable Earth-like planets may be even more challenging than previously thought, suggests a recent Astronomical Journal study looking at how the planetary obliquity, or tilt relative to an orbital axis, and orbital eccentricity affect the habitability of planets orbiting G-dwarf stars — which are similar to the sun.

Scientists led by Russell Deitrick, an astrophysicist at the University of Bern in Switzerland, modeled how orbitally induced climate variations on exoplanets influence the planets' climates. The researchers found that these cycles can induce rapid and cataclysmic "snowball" states, causing oceans to freeze, which greatly reduces the possibility of life on these planetary surfaces.

The team "found that planets in the habitable zone could abruptly enter snowball states if the eccentricity or the semi-major axis variations — changes in the distance between a planet and star over an orbit — were large or if the planet's obliquity increased beyond 35 degrees," Deitrick said in a statement.

Although some previous studies have found that increases in eccentricity can rescue a planet from a snowball state, or that obliquity variations or high obliquity can even warm planets, these prior studies lacked a "complete synthesis of orbital evolution, obliquity evolution, and climate, including the effects of ice sheets on oceans," the researchers wrote.



Obliquity and eccentricity affect the habitability of exoplanets like GJ 504b, the lowest-mass planet ever directly imaged around a star like the sun.

Credit: NASA/Goddard/S. Wiessinger

This study demonstrates the crucial role that orbital dynamics plays in planetary habitability, the authors say. The results can be used to narrow future searches for habitable planets, to focus on ones with obliquities and eccentricities that are conducive to life. "If we have a planet that looks like it might be Earth-like, for example, but modeling shows that its orbit and obliquity oscillate like crazy, another planet might be better for follow-up," Deitrick said.

Rachel Crowell

European mammals will struggle under climate change

As temperatures on Earth rise, many animals have already begun migrating to more amenable climates, shifting their ranges. But not all animals will be able to relocate, according to a new study in the journal Diversity and Distributions.

Researchers analyzed how 62 European mammal species would respond to future climate change and found that, under a worst-case scenario climate model, about half of the animals would likely struggle because of their individual characteristics and because of the loss of available habitat. This includes species already at risk, such as wolverines, and others currently not considered at risk, such as the Eurasian elk.

Lisbeth Morrison, an ecologist at the University of Reading in England, and colleagues calculated how much land would be lost or gained under current climate models, and how far each animal would have to move to reach new habitat. Then, they ranked the animals' abilities to persist based on two key characteristics: whether they are dietary generalists or specialists, and their reproductive strategy. For instance, if an animal bears many young, or can eat a variety of foods, the species can better colonize a new area, Morrison says. Unfortunately, for animals with limited diets and which don't bear many offspring, the picture appears bleak. "For the wolverine, the situation is only going to get worse," she says.

When it comes to looking at how animals will respond to climate change, she says, "we can't only consider climate models, it's important to look at species individually." Ultimately, this can help with management and conservation, she says.

Bethany Augliere

Roughly half of European mammals, including wolverines, could struggle to find new habitat amid changing climates.

Credit: CC BY-SA 4.0, Jonathan Othén

A research camp on Pine Island Glacier, a major ice outlet for the West Antarctic Ice Sheet, which, a new study shows, lost 2.72 trillion metric tons of ice (plus or minus 1.3 trillion metric tons) between 1992 and 2017.

Credit: U.S. Antarctic Program/photo by August Allen, NSF

Ice (Re)Cap

From Antarctica to the Arctic; from polar caps, permafrost and glaciers to ocean-rafted sea ice; and from burly bears to cold-loving microbes, fascinating science is found in every nook and crevasse of Earth's cryosphere, and new findings are announced often. Here are a few of the latest updates.

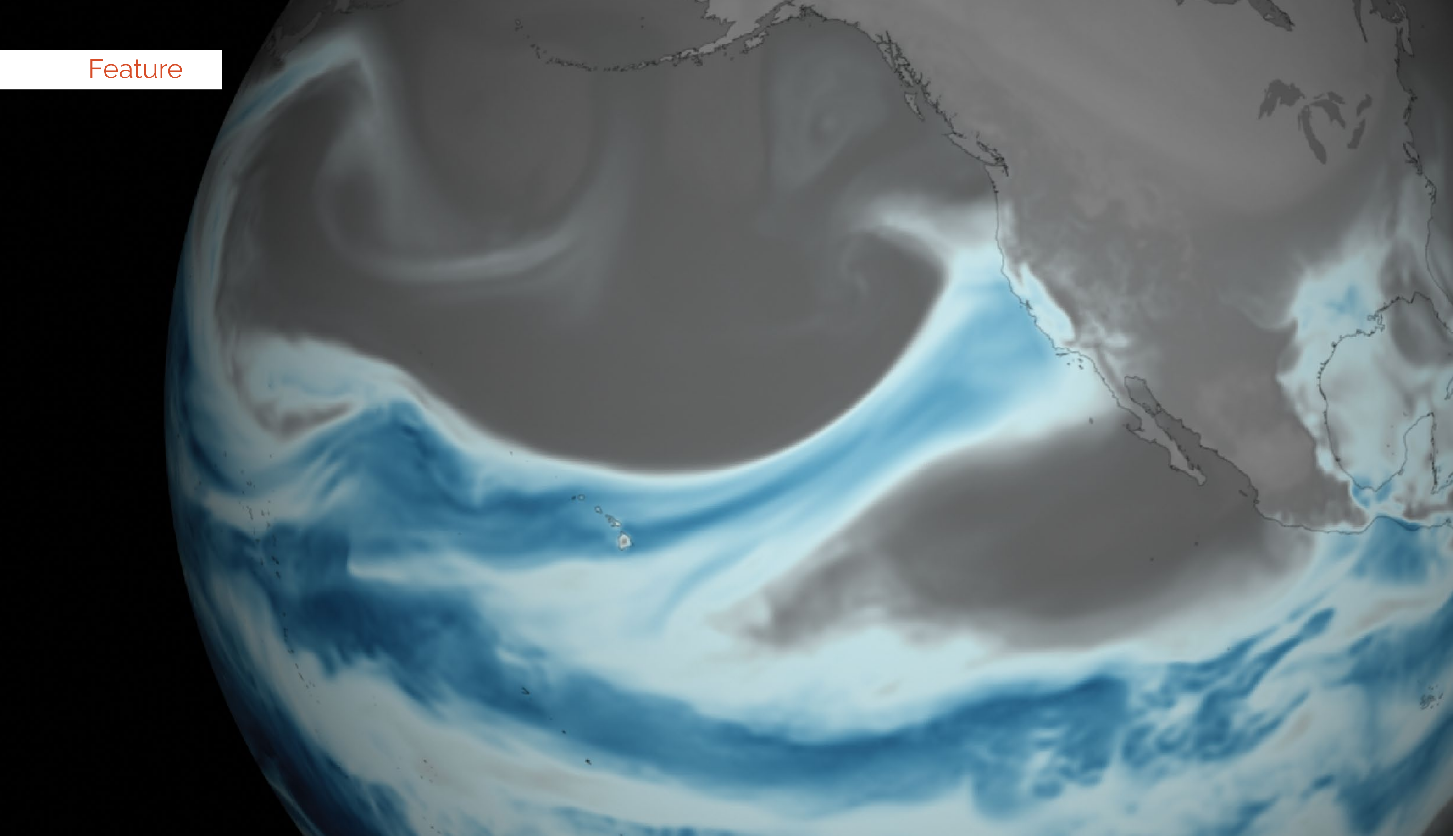
- Previous studies of lead pollution throughout human history involved sparse data and limited age controls. Now, scientists have collected a subannual archive from a 423-meter-long Greenland ice core and are using this continuous record to estimate lead levels from lead-silver mining and smelting in Europe between 1100 B.C. and A.D. 800. When paired with atmospheric modeling, the ice-core data, published in a new study in Proceedings of the National Academy of Sciences, show lead pollution signatures from various European historical events, including imperial expansion and wars, which produced spikes in lead production, and major plagues, which caused declines in mining and smelting.

- Thick sea ice around Antarctica can make winter sampling of Antarctic waters difficult. A group of scientists has discovered a novel way of measuring deep waters in the Amundsen Sea: seals. Partnering with the Sea Mammal Research Unit at the University of St. Andrews in Scotland, the team tagged seven southern elephant seals and seven Weddell seals with instruments that measure temperature and salinity. For nine months, as the animals dove for food, the devices monitored the water column and transmitted data via satellite. "We were able to collect much more information from the seals than all the previous ship-based surveys in the area combined," said Helen Mallett of the University of East Anglia, lead author of a new study, in a statement. The team found large seasonal differences, including a thicker, saltier Circumpolar Deep Water layer in the winter, suggesting that more melting occurs in winter than summer — an example of "reverse seasonality," the team wrote in Geophysical Research Letters.

- The Pine Island Glacier is a major ice outlet for the West Antarctic Ice Sheet (WAIS). Warm water from the Antarctic Circumpolar Current has been melting the ice sheet from below, thinning the floating mass by about 5.3 meters a year for the past 25 years. Despite the melt, the Pine Island Glacier has barely retreated over the past several decades, with the position of the calving front remaining almost constant — until 2015, when a calving event caused the glacier to retreat 20 kilometers closer to shore, opening up previously uncharted waters. Now, researchers taking advantage of the ice-free waters have mapped the ocean floor and discovered the mystery of the stationary ice front: underwater mountains and ridges that acted as pinning points. The ice grounded on these underwater ridges, slowing its retreat, according to a new study published in Cryosphere. Researchers found that these pinning points can also push the overlying ice up, creating a ripple in the glacier's surface. Sometimes, these ripples can rift the ice, instigating an ice calving event like the one in 2015. The new bathymetry mapping will contribute to future WAIS modeling.

- New WAIS surface mass-balance models based on satellite observations reveal that, between 1992 and 2017, the ice sheet lost 2.72 trillion metric tons of ice (plus or minus 1.3 trillion metric tons), which corresponds to an average sea-level rise of 7.6 millimeters (plus or minus 3.9 millimeters). In a study in Nature, researchers noted that annual WAIS melting increased by more than 100 billion metric tons (from about 53 billion to 159 billion metric tons) over the period studied, driven by warmer ocean waters circulating below the floating ice shelves that buttress the ice sheet.

Sarah Derouin



Atmospheric rivers are long, narrow weather systems that carry large amounts of moisture from the tropics into the midlatitudes. This NOAA illustration of a system stretching from the tropics around Hawaii to the U.S. West Coast, with darker blue shades representing greater amounts of precipitable water, depicts an atmospheric river that drenched Northern California in April 2018.

Credit: NOAA National Environmental Satellite, Data, and Information Service

RIVERS IN THE SKY

Improving Predictions of Atmospheric Rivers to Reduce Risk

Steve Murray

In early February 2017, authorities in Northern California ordered more than 180,000 residents around the Oroville Dam to evacuate over concerns that heavy rains might cause the dam's spillway to fail. The rains were brought by an atmospheric river (AR) — a long, narrow system of moist, tropical air that can deposit enormous amounts of water — adding to an already wet season for the U.S. West Coast. ARs occur around the planet, but certain regions — including western North America, where moisture from the tropics near Hawaii is repeatedly delivered by recurring "Pineapple Express" events — are especially prone.

Between October 2016 and March 2017, 45 ARs made landfall in California, according to researchers at the Scripps Institution of Oceanography (SIO) in San Diego. Of these, 12 were considered "strong" and another three were considered "extreme." And in October 2017, an AR dubbed the "Big Dark" arrived in the Pacific Northwest, stayed more than a week, and dropped more than 25 centimeters of rain and snow. While timely and accurate predictions of these storms are vital for both public planning and emergency response, knowledge and data gaps exist in the weather science needed to provide them. New tools and theories, however, are now beginning to close them.

Capricious Gifts

The term "atmospheric river" came into use in the early 1990s to characterize the shapes of these meteorological systems, which are typically several hundred kilometers wide, but can extend more than 1,600 kilometers. The "Big Dark," for example, stretched for roughly 8,000 kilometers.

Warm tropical oceans feed moisture to the atmosphere through evaporation and increase its moisture-carrying capacity, which enables the air to move large amounts of water. Although ARs cover only about 10 percent of the planet at any given latitude, they are responsible for as much as 90 percent of the north-south water transport in the midlatitude atmosphere.

Rainfall from ARs accounts for 22 percent of runoff globally, a figure that rises to 50 percent in some regions like Southeast Asia, New Zealand, and the coasts of North America. "If you condense the total water vapor in an atmospheric river down to liquid, from the surface to space, it's only about a centimeter or two deep," says Marty Ralph, director of the Center for Western Weather and Water Extremes (CW3E) at SIO. Nevertheless, Ralph says that an average AR transports water at a rate of about 25 times that of the Mississippi River, and "there are about three or four ARs at any given time in the Northern Hemisphere." While the U.S. West Coast sees a lot of atmospheric rivers, these systems can impact almost anywhere across the country. "ARs sometimes hit the East Coast and feed blizzards in the winter," Ralph says, "and storms in the Great Plains and the Southeast can have ARs behind them."

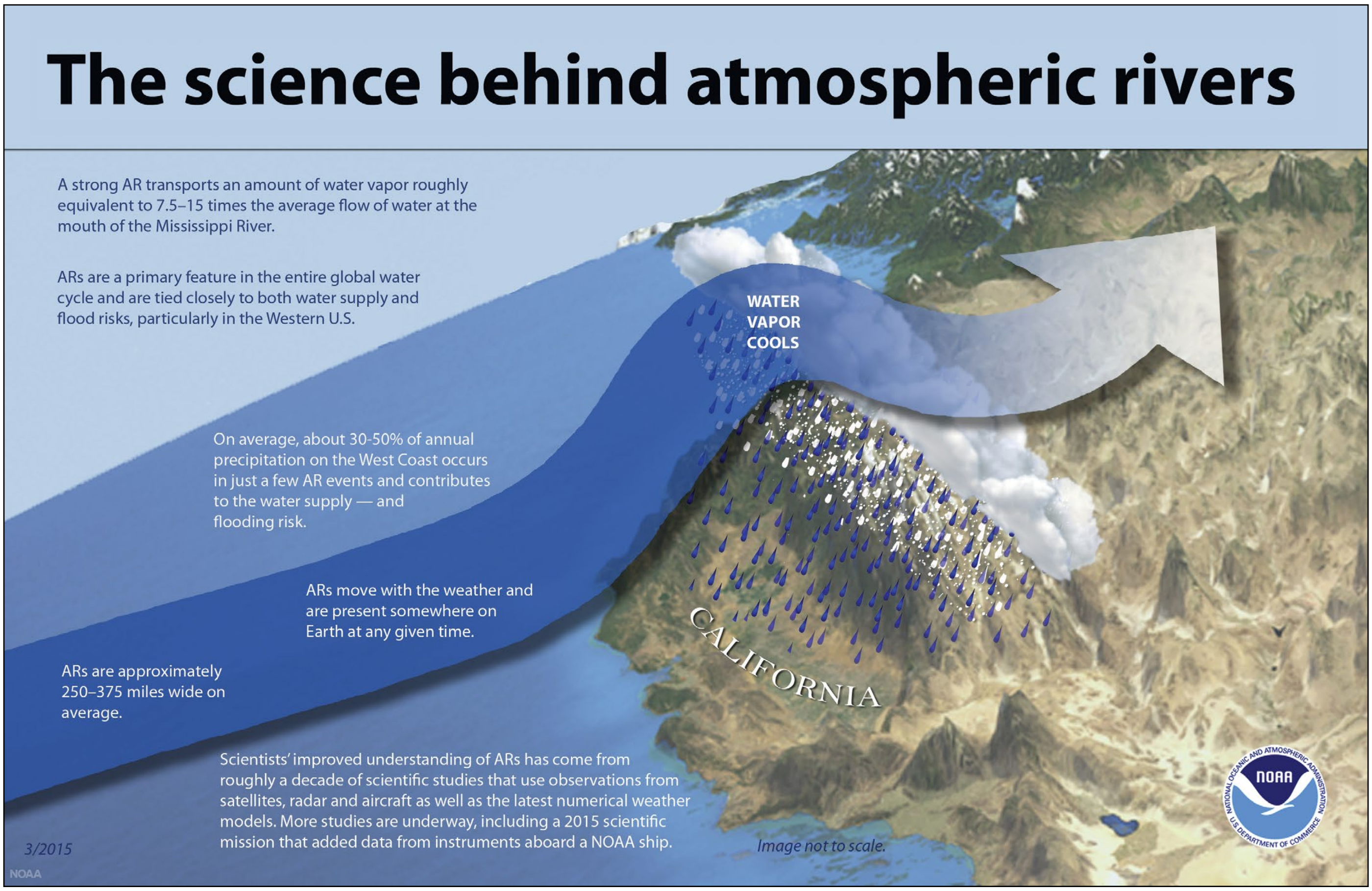
A 2013 review of European weather data collected between 1979 and 2011 found that up to 8 of the 10 largest daily rainfall events across parts of western Europe were due to ARs, and that these systems reach as far east as Germany and Poland. ARs have been linked to many of the largest winter floods in the U.K. in recent decades, and AR-driven storms in 2012 contributed to an estimated $1.6 billion in flood-related damages in the U.K.

ARs even reach Earth's polar regions. In 2009, snowfall in East Antarctica broke records that stood for 60 years. When researchers examined satellite data covering the same period, they found the first evidence of an AR winding from Madagascar to the coast of East Antarctica, along with two other AR patterns that could account for heavy snowfalls in other regions of Antarctica.

Atmospheric rivers play an important role in Earth's water cycle and can relieve periods of serious drought. Between 1950 and 2010, AR storms ended 40 percent of persistent droughts in California and 74 of persistent droughts in the Pacific Northwest.

A massive gully is carved by water pouring from the damaged main spillway of Northern California's Oroville Dam on Feb. 11, 2017, after an atmospheric river brought persistent heavy rains to the region.

Credit: William Croyle, California Department of Water Resources



Atmospheric rivers (AR) are responsible for dropping substantial amounts of rain and snow on the western United States. When ARs move ashore and encounter mountains, the water vapor is pushed up higher into the atmosphere, where it cools and condenses to form precipitation. Although AR weather systems are often weak, strong ones lead to heavy rain and snowfall that induce damaging flooding and mudslides.
Credit: NOAA

Balance, however, isn't a strong characteristic of these weather systems. The same restorative rains that might end a dry spell can, in the same stroke, overload reservoirs and rivers and stress regional infrastructure.

California has an especially conflicted relationship with ARs. Soon after the moist air makes landfall, the state's mountainous terrain pushes it upward — a process known as orographic lifting. As the rising air cools, it releases entrained moisture. As a result of AR-derived precipitation, California suffers an average of $300 million a year in flood damages. "Atmospheric rivers keep up both the water supply and the flood risk," says Mike Anderson, California's state climatologist. "Don't think of it as flood or drought; think of it as flood and drought — all tied to this AR process."

Weighing Risks Against Resources

Most western states in the U.S. maintain agencies responsible for managing reservoirs, agriculture, transportation and emergency response activities — all of which are impacted by extreme weather. Policymakers administer plans, for example, regarding when to drain reservoirs in advance of heavy storms or when to hold onto water as a reserve against possible future drought. The challenge is to weigh the risk of flood damage against the waste of a vital resource. Although advance weather forecasts might offer timely guides for such decisions, they rarely offer the precision and accuracy needed for definitive action. California law, for example, requires managers to maintain a certain amount of free reservoir storage space during the winter rainy season in case of unexpected storms, regardless of the weather outlook, which at times forces needless releases of water.

"Most of the reservoir agencies in the West require water to be on the ground before a decision can be made to change the reservoir releases," Ralph says. The relevant policies were enacted, however, "back when forecasts were uncertain enough that you didn't know what the next day or two would bring.

Atmospheric rivers can relieve periods of serious drought, but can, in the same stroke, overload reservoirs and rivers and stress infrastructure. Above: The water level at New Hogan Lake, a reservoir near Stockton, Calif., was low in winter 2014 amid a severe multiyear drought. Right: Three years later, in winter 2017, heavy rains brought by atmospheric rivers refilled reservoirs in the state and sent water pouring down the South Yuba and other rivers.

Credit: above: U.S. Army Corps of Engineers; right: Kelly M. Grow, California Department of Water Resources

Our forecasts are getting better, so in the future, reservoir operators may be able to safely keep a little extra water in case a storm doesn't materialize," he says. "If a big storm is actually predicted, reservoirs could potentially release extra water that would normally be kept for the summer, knowing that the storm would replenish their supplies." Ralph notes, for example, that an analysis he co-led with Jay Jasperse of the Sonoma County Water Agency determined, for example, that more accurate forecasting could save up to 25 million cubic meters of water biennially in Northern California's Lake Mendocino Reservoir — enough to supply about 50,000 homes for a year.

Emergency response plans, which consider worst-case scenarios, are also often invoked without the best weather information. In March, an AR was tracking toward regions of Southern California that had suffered major damage the previous year from wildfires, including the Thomas Fire, the largest in the state's history. Heavy rains would risk the kind of flash floods and mudslides on fire-ravaged lands that Santa Barbara County experienced in January, which killed 21 people and injured more than 160. In March, up to 30,000 people in three counties were ordered to evacuate. "What ended up happening," Ralph says, "is that the heavy precipitation hit farther north, in Big Sur. The heaviest part of the storm missed Santa Barbara by maybe 200 to 250 kilometers." While safety concerns understandably prevailed, better forecasting might have minimized public disruption in communities already experiencing evacuation fatigue.

Crunching the Numbers

Weather forecasting models integrate many interconnected factors across scales. Sea-surface temperatures, for example, affect how much moisture is delivered to the atmosphere and how much water it can carry. Large-scale climatological patterns, such as the El Niño-Southern Oscillation (ENSO), which impacts equatorial Pacific Ocean temperatures, also influence ARs over periods of several months to years. ENSO's warm phase, called El Niño, raises sea-surface temperatures in the eastern Pacific while its cool phase, La Niña, has the opposite effect. The pattern can, in turn, modulate how strong, high-altitude winds known as Rossby waves interact with atmospheric pressure gradients, the Coriolis force and the jet stream. All of these interactions eventually influence where ARs make landfall.

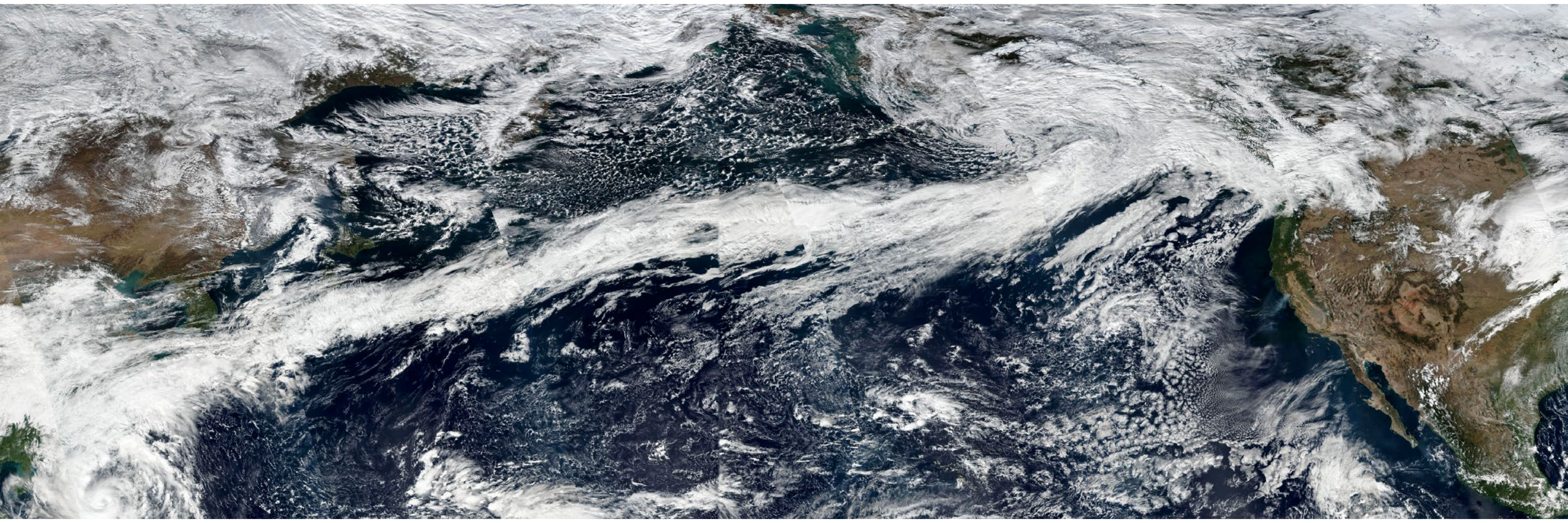
California law requires that a certain amount of free storage space be maintained in reservoirs, like Folsom Lake, during the winter rainy season in case of unexpected storms, regardless of the weather outlook, which could force needless releases of water. Improved forecasts could allow reservoir operators to decrease such releases, keeping more water in reservoirs when storms don't materialize.

Credit: United States Army Corps of Engineers, Michael Nevins

The amount of precipitation an AR drops also depends on factors such as how much moisture it carries, the topography of the land it travels over, local temperatures and winds, and the duration of its passage. Not surprisingly, models that process all these factors are complex.

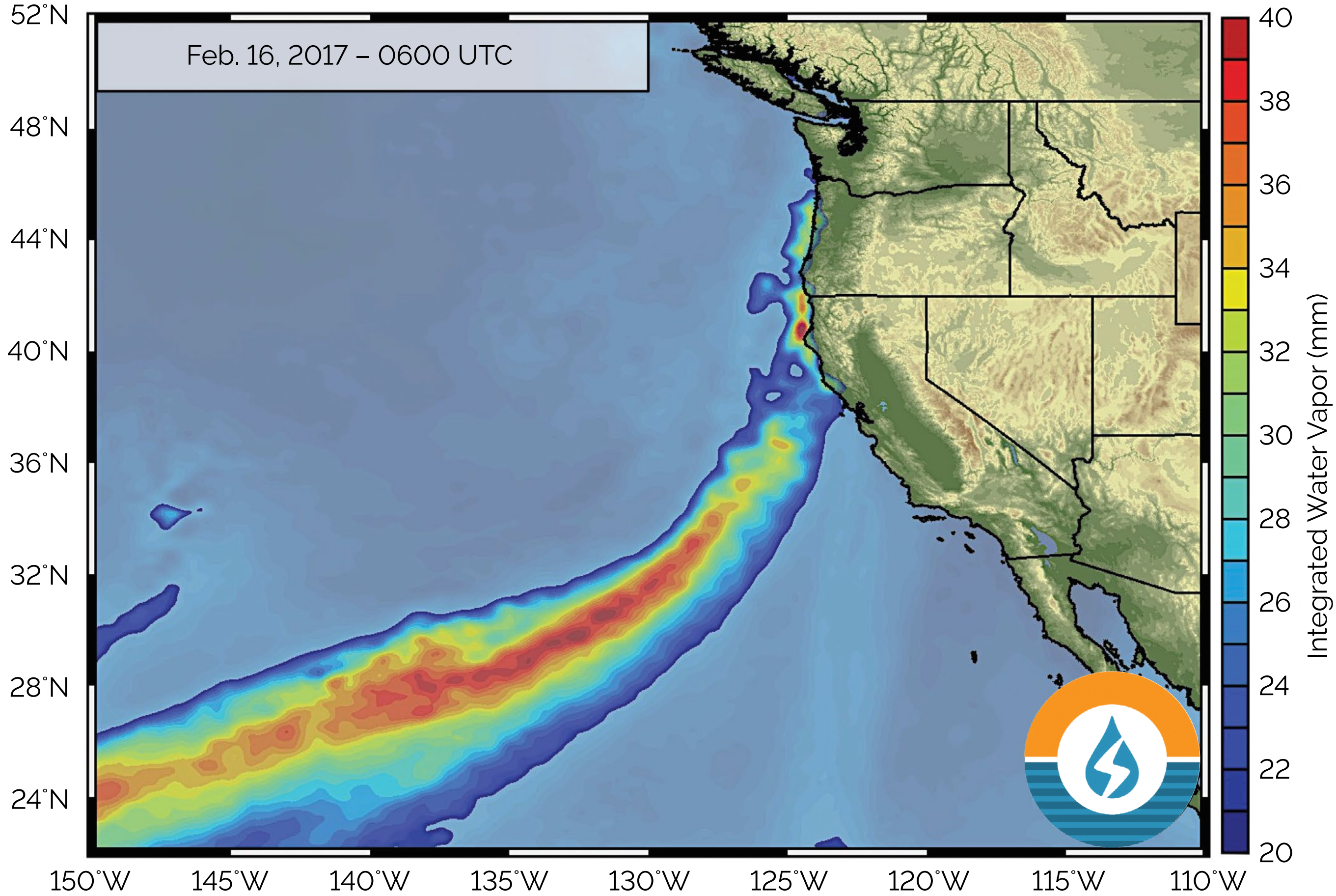
Most forecasting models are developed and improved by running simulations using historical weather data as input conditions, and then comparing the model results to what actually happened. Operational weather forecasters use what are called ensemble predictions, says Christine Shields, an atmospheric scientist and paleoclimatologist at the National Center for Atmospheric Research in Boulder, Colo. This method creates probabilities for weather predictions based on multiple modeled outcomes rather than just a single model outcome. "That can give us a better basis for forecasting," Shields explains. "You run a model several different times and tweak the way you initialize each one to add a bit of randomness. The result is an ensemble of solutions. Then you take a look at … where most of their predictions point and that's your best forecast."

Weather models that perform better than random forecasts are said to have "skill," and skill is a function of how far into the future a forecast reaches. Currently, operational weather models demonstrate good skill out to two weeks, with better performance in the first week. "For weather forecasts, we use numerical models that derive their skill from accurate knowledge of the current state of the atmosphere," says Cory Baggett, an atmospheric scientist at Colorado State University. "We only have skill in predicting ARs at lead times out to 14 days," he says. Meanwhile, "for seasonal forecasts, we use large-scale climate features such as sea-surface temperature or the ENSO. Seasonal



A roughly 8,000-kilometer-long atmospheric river extending from Asia to the Pacific Northwest was imaged by the Suomi NPP satellite on Oct. 14, 2017. Many interconnected factors influence where atmospheric rivers make landfall and how much precipitation they deliver.

Credit: NASA Earth Observatory image by Joshua Stevens



Integrated water vapor transport, which is the total amount of water vapor carried by an AR at all altitudes, is the best measure of AR strength at present. This diagram shows integrated water vapor measurements during a February 2017 atmospheric river hitting California and Oregon.

Credit: Center for Western Weather and Water Extremes

forecasts run from about two months to 12 months or beyond and have only fair skill."

Between these short- and long-term forecasts is the seasonal-to-subseasonal (S2S) window, typically defined as two weeks to two months (although some definitions vary). "Skill is harder to come by" for S2S forecasts, Baggett says, as they combine data about atmospheric conditions that lie beyond the timeframe of operational weather forecasts with long-term data about climatic conditions. These midrange forecasts may be particularly useful in making informed decisions about reservoir storage and water management.

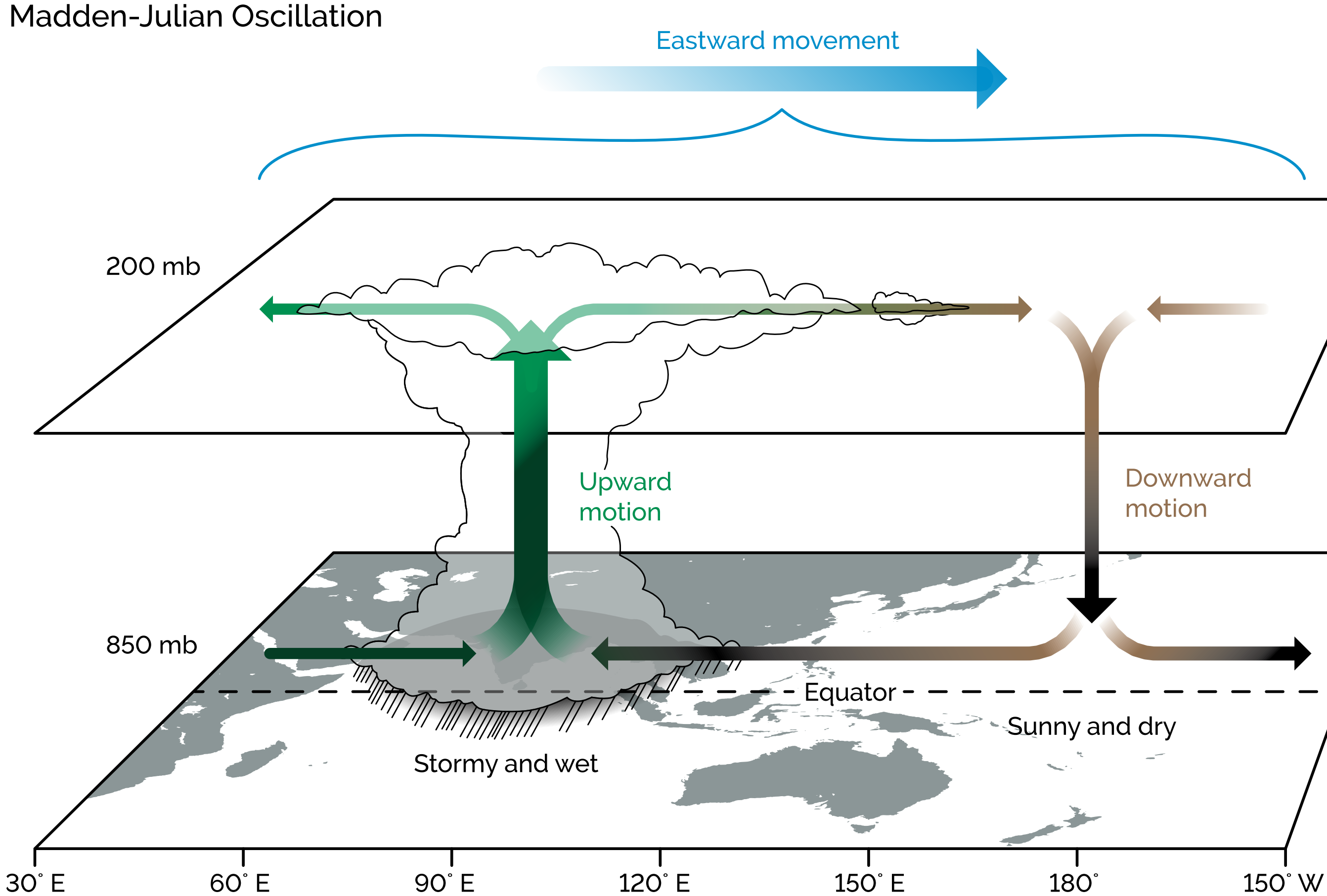
Applying the Science

In May, the Western States Water Council (WSWC), an organization of water agencies for 12 states, met in San Diego to focus on better precipitation forecasting in the S2S timeframe. It's a sobering problem. "The current state of forecasting capabilities at S2S timescales is not really useful for making water management decisions," says Jeanine Jones, vice-chair of the WSWC. "The skill just isn't there."

Water resource managers monitor physical infrastructure like reservoirs, dams and spillways to ensure the effective allocation of water in their states. A lot of that infrastructure is aging, such as dams built before World War II (or even earlier), posing risks to downstream populations.

Virtually all of these states must also deal with drought. State laws typically give priority to human and livestock needs when water is scarce, but that can be of little comfort to other agricultural and economic interests. Managing the Colorado River Basin is especially complicated, as its water must meet the needs of seven western states. Most policies are based on the status of current water levels, and while networks of field sensors provide public managers with data for this purpose, reliable predictions of future water could simplify a lot of management challenges.

Madden-Julian Oscillation



The structure of the Madden-Julian Oscillation (MJO), an eastward-moving equatorial atmospheric pattern characterized by adjacent regions of enhanced thunderstorms — caused by convection of moist air — and dry, sunny conditions. The MJO pattern takes about one to three months to circle the planet, and it may influence the frequency with which atmospheric rivers occur.

Credit: Climate.gov drawing by Fiona Martin

The May WSWC meeting allowed scientists to present new ideas and tools that might improve the situation. "What's special about S2S forecasting right now," says Anderson, "is that it's coming into prominence because you have a meeting of the operational need with the technical capability." If researchers continue developing that capability, he says, "we can actually get some usable results."

Baggett is one researcher attempting to stretch the window of skillful AR forecasting past two weeks by including information about additional macroscale features of the atmosphere. Currently, the best measure of AR strength is an indicator called vertically integrated water vapor transport (IVT), which is the total amount of water vapor carried by an AR at all altitudes. Baggett is investigating the Madden-Julian Oscillation (MJO) and the Quasi-Biennial Oscillation (QBO) — two equatorial atmospheric patterns that appear to modulate the frequency at which ARs occur — to see whether knowledge of these phenomena could improve the IVT measure.

The MJO begins with tropical thunderstorms that lift enormous quantities of moist air via convection. When the rising air hits the tropopause, about 11 kilometers up, it encounters the jet stream, which then carries the moisture over the North Pacific to North America over a period of seven to 10 days (although it takes about 30 to 90 days for the oscillation to travel completely around the equator). The QBO is a consistent back-and-forth oscillation over the equator, about 50 kilometers up in the stratosphere. QBO winds alternate from east-blowing to west-blowing about every two to three years.

In the past few years, scientists have identified a statistical relationship between the phase of the QBO and the magnitude of the MJO. When the QBO is westerly, MJO convection is suppressed; when the QBO is easterly, MJO convection is

Researchers at Scripps Institution of Oceanography in San Diego involved in a project to collect direct measurements of atmospheric rivers from aircraft attend a meeting on Jan. 25, 2018, to discuss flight plans.

Credit: Center for Western Weather and Water Extremes

enhanced. "So the MJO produces a wave train that sets up over the northern Pacific, which can enhance the number of ARs over the West Coast," Baggett says. "Or it can block ARs and deflect them up toward Alaska. Just knowing the current state of the MJO can give us an idea of what ARs are going to do seven to 10 days from now."

Baggett has been testing his ideas with historical AR data from 1979 to 2015 and comparing MJO activity during both easterly and westerly QBOs. The results have been encouraging out to three weeks, Baggett says. "In some cases, the skill extends out pretty well to four or five weeks."

At CW3E, Ralph and his colleagues are also developing better AR forecasting by taking direct measurements of these systems while they're still moving east over the ocean. For the past three years, CW3E and several collaborating agencies have sampled ARs over the Pacific one to three days before they make landfall. Two U.S. Air Force C-130 "hurricane hunters" and a NOAA Gulfstream IV fly over selected ocean tracks to release dropsondes — expendable sensor packages that measure temperature, pressure, wind speed and moisture as they descend. The group's data have shown that the vertical and horizontal distribution of water vapor in ARs appears to be the largest single source of modeling errors — information that can be used to enhance future forecasts. Another round of flights is proposed for winter 2019.

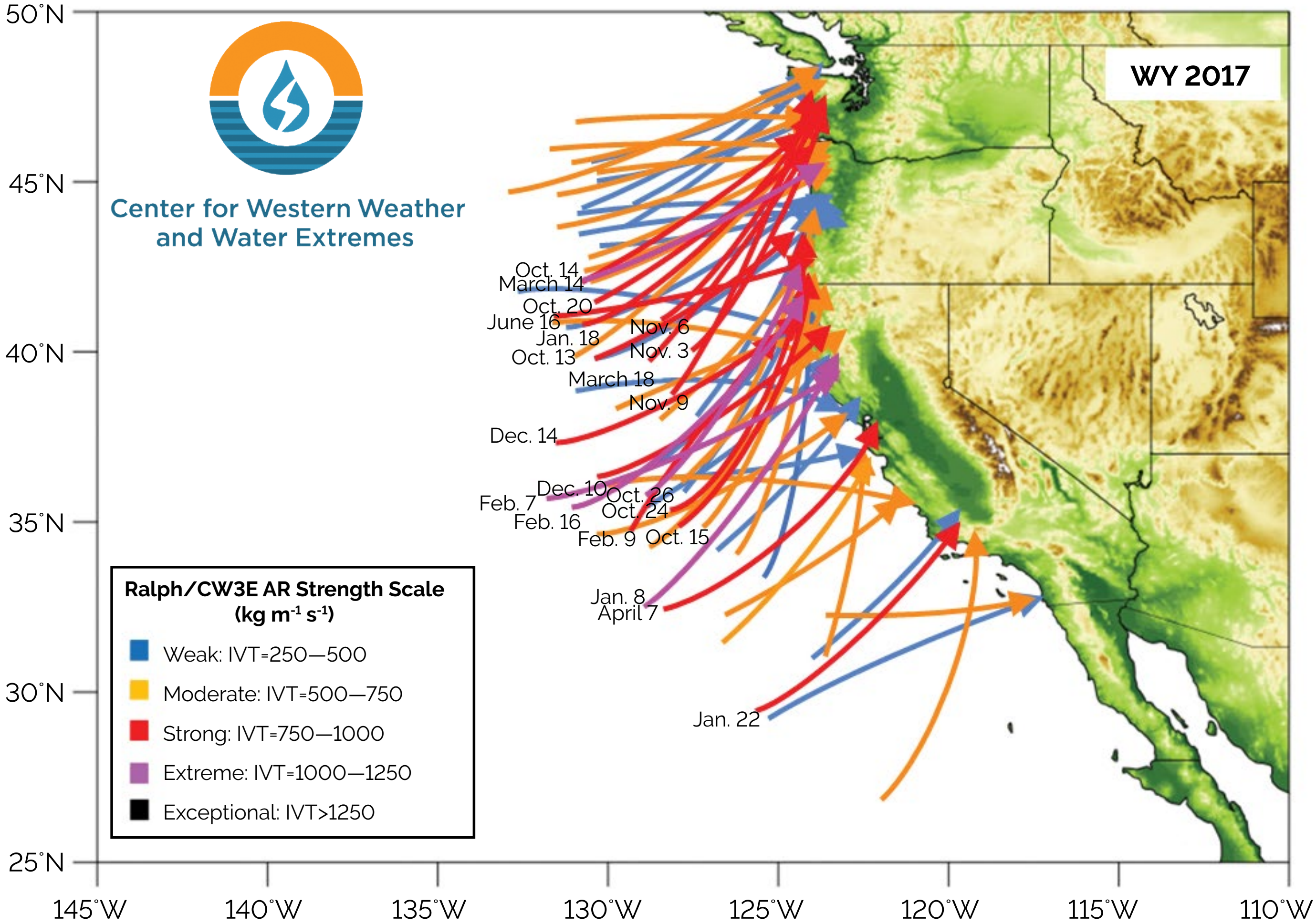
Changing Climate, Changing Rules

Even as scientists gather and integrate new insights about weather dynamics into better forecasting models, a changing climate may be altering the rules of the game. While AR intensity has been linked to ocean-surface temperatures, those temperatures have increased worldwide by an average of about 0.6 degrees Celsius since the late 1940s. Because the atmosphere can hold about 7 percent more moisture for every 1-degree Celsius rise in its temperature, increased AR water vapor transport will almost certainly be part of future weather patterns. In fact, water vapor transport over land, including the water carried by ARs, has been increasing over the past 70 years, in keeping with warming of ocean surfaces.

The ARs of 2017, for example, brought more moisture to California than the state had seen in any winter since at least 1948 — and that could be just an early salvo. "The 2016–2017 season that California went through was remarkable," Baggett says. "I think most locations received more than 200 percent of their normal precipitation that winter. If you look at some of the records, however, there is concern that there are bigger events out there and bigger years waiting in the wings."

Wet seasons may grow more volatile, as well as more intense. Two 2017 studies led by SIO scientists showed that California is experiencing increasingly dramatic swings in precipitation and projected that this variability will likely grow more extreme. In addition to making water management and flood protection more challenging, the state may also have to contend with longer dry periods between storms. Similar results have been predicted for northern Europe, as well.

At least one study of historical weather data since the 1980s shows a pattern of more winters with wet conditions in Northern Europe owing to more frequent ARs, but fewer wet winters in Southern



Numerous atmospheric rivers made landfall on the U.S. West Coast between October 2016 and September 2017. The direction and intensity (color) of each are seen here. Arrows show where integrated water vapor transport was strongest.

Credit: map by C. Hecht and F.M. Ralph of the Center for Western Weather and Water Extremes, with funding from the California Department of Water Resources

Europe owing to changes in moisture transport. Increased AR water vapor transport may also lead to larger winter floods in Britain. Duane Waliser and his team at NASA's Jet Propulsion Laboratory at Caltech in Pasadena, Calif., recently published work that systematically characterizes such global effects. The team created an atmospheric river database from over 20 years of global weather data and applied the database to a set of 21 models to evaluate how ARs responded in a future climate. The results suggested that the number of distinct AR events will decrease by 10 percent, but those that do occur will be 25 percent longer and 25 percent wider on average, and extreme events will carry more water. This means that locations will "experience AR conditions 40 to 50 percent more often. Even though there are fewer [events, they] get bigger, so taken together AR conditions occur more often," he says. The results also indicated that the frequency of the most intense AR storms may nearly double. "This is the first study like this that's been done globally," Waliser says.

Weather prediction models have been improving with new data and methods. "We've figured out the mathematical equations for our numerical models pretty well," Baggett says. But prediction is a tricky science, and "our equations rely on an accurate picture of what … the atmosphere looks like," he says. "Until we are able to observe every cubic meter of it and model everything perfectly, there will always be limits to weather predictability."

Murray (www.stevemurrayink.com) is a freelance writer based in San Diego. A former engineer and professor, he's interested in anything connected with astronomy, space science, archaeology and travel (not always in that order).

The Weiss family at the fall meeting of the American Geophysical Union (AGU) in December 2017 in New Orleans. From left to right: father Chad, Cameron, 15, Sean, 16, Ian, 13, Megan, 15, Evan, 15, and mother Nicola.
Credit: Harvey Leifert

Science as a Family Affair

Harvey Leifert

Ian Weiss had already taken off his shoes and socks when he realized he'd left his lacrosse stick in the car one day in May 2015. He went to retrieve it, stepping barefoot onto the asphalt street outside his family's Southern California home. "While opening the trunk I had to do the hot-feet dance on the pavement," he recalls. It was a pivotal moment in more ways than one for Ian, then a sixth-grade student at Samuel E. Talbert Middle School in Huntington Beach, Calif.

"That gave me the idea that heat is energy," he says, and the miles and miles of roads in Southern California means "a lot of heat, [which] equals a lot of energy." Ian did not simply file the insight away; instead, he began researching the urban heat-island effect and related phenomena, encouraged and assisted by his science teacher, John Wood, and his parents, Chad and Nicola Weiss, neither of whom are scientists.

Ian's investigation was not completely theoretical. After Wood put him in touch with some engineers for information and advice, Ian constructed a device to simulate a section of asphalt roadway, with subsurface pipes carrying solar-heated water to a homemade thermoelectric generator. Placed outside at noon each day, the "roadway" generated a small electric potential of about 5 volts, when the air temperature reached 27 degrees Celsius — enough to recharge a smartphone. Ian was 11 at the time.

Last December, as I was looking for ideas for unusual stories among the 13,000 posters on display at the American Geophysical Union's (AGU) fall meeting in New Orleans, a voice called to me, "Would you like to hear about my research?" It was Ian speaking up.

His poster was titled, "Our Roads: A Large Thermoelectric Power Generator." Following his "hot-feet" incident, he explained, he investigated the idea that solar heat absorbed by asphalt roadways could be captured and converted to electricity. As he put it: "So much energy is being put into our streets and wasted and not being used at all."

The project — and Ian's presentation of it — was impressive. And the surprises continued: I learned that, although he was just 13 years old, this was not his first AGU meeting. He'd previously presented his work at the 2016 conference, and this time showed an updated model roadway and new data. He has presented his work at state and county fairs as well. I also learned that he conducted his experiments not at school, but in the home laboratory his parents had created in their backyard, originally for his older siblings. And those siblings — all four of them — were at AGU as well, each presenting his or her own poster.

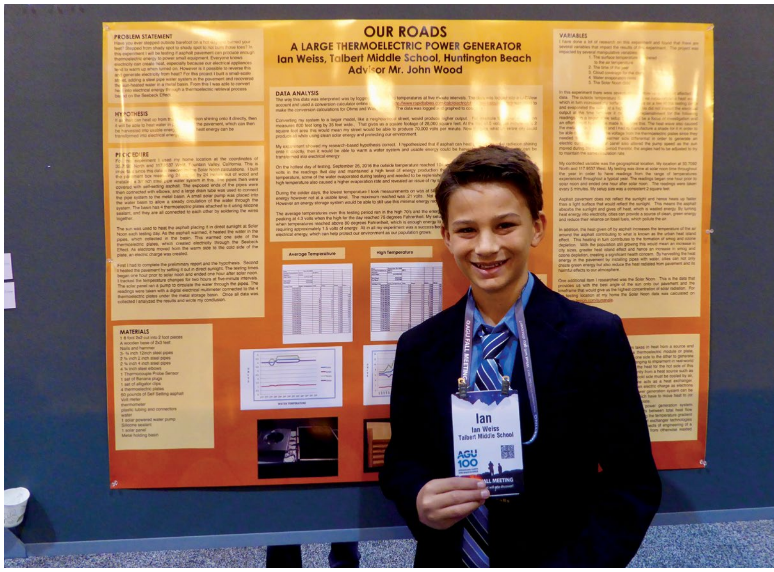
Sean, the oldest at 16, and 15-year-old triplets Megan, Cameron and Evan, were all happy to describe their projects. I asked them and their parents: How did this one-family science fair come about?

Chad said his kids were inspired in sixth grade by their science teacher, John Wood. As each of the younger children entered middle school, "they all seemed to have that same spark," he said. "We tried to foster it by giving them space and opportunities to continue [exploring] at home — by building a backyard science lab and things like that, so they could have places to experiment and keep learning."

Air, Land and Sea

Sean's 2017 AGU poster was titled, "The Phenomenon of Ocean Acidification." His interest in the topic began during a family vacation in Belize, he told me, where he saw firsthand the damage done to coral reefs by increasingly acidic seawater. Sean, who attends Edison High School in Huntington Beach, decided to investigate the effects of ocean acidification closer to home. In consultation with Wood, he built a 45-centimeter-long, underwater remotely operated vehicle (ROV). Over the next year, he collected weekly samples of ocean water up to 30 meters out from a local pier.

The ROV sampled both near the surface and at the bottom, providing data about the water's pH that he compared with air temperature observations collected by NOAA from a site several kilometers offshore of San Pedro. After studying the data, Sean found that increased acidity — in the form of carbonic acid — in the water offshore of Huntington Beach resulted after stretches of warmer temperatures, while decreased acidity was associated with cooler temperatures.



Ian Weiss, 13, at AGU's 2017 fall meeting presenting his research on capturing solar heat absorbed by asphalt roadways and converting it to electricity.

Credit: Harvey Leifert

While Sean studied the sea, Evan investigated the land. His poster, "Let's Break It Down: A Study of Organic Decomposition," reported on his investigation of how soil temperature affected decay of organic matter buried in three places around his home. He hypothesized that cooler temperatures would maintain higher soil moisture contents and thus increase the rate of decomposition in the clay soil, understanding that other factors, such as soil pH and precipitation, also played a role. After 15 days, during which he monitored soil temperature and moisture, he found that the organic matter in the cooler areas did undergo more decomposition, "but the greatest rate of decomposition was not at the coldest site." He says he'd like to repeat the experiment over a longer period and at more sites to collect additional data.

Meanwhile, Megan investigated the rate at which some common house plants convert carbon dioxide into oxygen. She compared pothos, fern, aloe and panda plants, hypothesizing that the pothos plants' many thick leaves would win out. The experiment involved planting specimens in separate sealed environments and using a carbon dioxide meter to determine how much of the gas was converted to oxygen in a given amount of time. Pothos, she reported in a poster titled "Breathe Plant, Breathe," was indeed the most efficient.

Cameron's poster, titled "H_2O SOS: Help Heal the Ocean," was inspired by a program he attended in Newport Beach, Calif., about threats to the ocean such as marine debris, stormwater runoff, invasive species, overfishing and acidification. On his poster, he noted the effects of each threat on the ocean and provided suggestions for mitigating its impact.

AGU's Bright Students Training as Research Scientists (Bright STaRS) program provides the opportunity for elementary, middle and high school students to present research and participate in the organization's annual fall meeting at no charge. At the 2016 meeting, Alexia Bravo of Illahee Elementary School in Camas, Wash., presented her research on ocean acidification to Michael Hubenthal, senior education specialist at the IRIS Consortium.

Credit: AGU

The Power of Mentoring

Wood has clearly been central in the creative inspiration of all five Weiss youth. He was credited as advisor on four of the posters the kids presented last December. And in 2015 and 2016, he attended AGU's fall meeting to support his pupils.

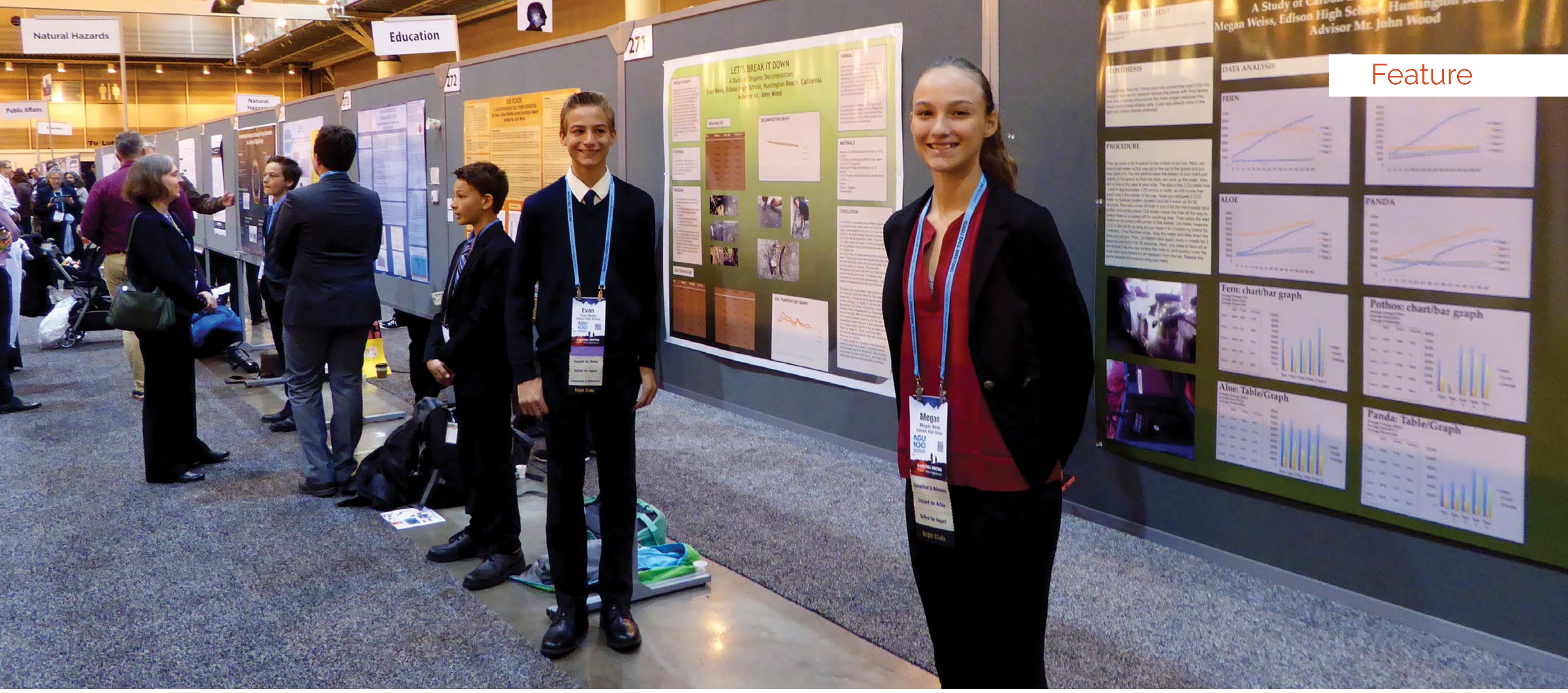
Wood, who has been a middle-school science teacher for 29 years, created and coordinates Talbert's science fairs and teaches elective STEAM (Science, Technology, Engineering, Arts and Mathematics) classes for seventh and eighth graders. He has maintained an active interest in all five Weiss children, from the time they entered his sixth-grade classroom on, even as the four older kids have moved on to high school.

"It is quite amazing to see how the students grow more mature and develop their projects from sixth through eighth grade," Wood says. Sean, for example, showed "such a huge change. When I first met him as a sixth grader, he was full of imagination and curiosity, but he lacked the depth of understanding on how to go about designing an experiment." But by eighth grade, he'd developed this knowledge and had begun "to focus on his own interests and find areas to study that he related to," Wood says.

Wood credits support from other science teachers and the Weiss parents for Sean's blossoming. By the time he left Talbert, Sean had presented a credible research project at both the International Teacher-Scientist Partnership (ITSP) Conference and at AGU. His was also judged one of the top 300 projects nationwide at the Broadcom MASTERS National Competition, as was Ian's road-power project.

Broadcom MASTERS (Math, Applied Science, Technology and Engineering for Rising Stars) is a national competition among middle school students. Its goal is to encourage and inspire students to participate in science fairs, take science courses in high school and, eventually, pursue STEM (Science, Technology, Engineering and Mathematics)-related careers.

In part to encourage Talbert students to enter the Broadcom competition, in 2016, Wood started a chapter of GLOBE (Global Learning and Observations to Benefit the Environment) at the school. Now an international program, GLOBE was created by the U.S. government in 1995 and is sponsored by NASA, with participation from several other agencies. The program has further encouraged the Weiss family: Cameron's interest in ocean health



The Weiss siblings, with Evan and Megan in the foreground, stand by their research posters in the poster hall at AGU's 2017 fall meeting.

Credit: Harvey Leifert

emerged from a project he participated in through Talbert's GLOBE chapter, and Ian is currently the club president.

Wood is passionate about the importance of environmental education. In 2017, he won the Presidential Innovation Award for Environmental Educators, which is administered by the White House Council on Environmental Quality and the U.S. Environmental Protection Agency (EPA). In an interview with EPA in August 2017 upon receiving the award, he said that "we try to make [the students] aware of the issues in our community, as well as beyond our community, and then get them into action to help the community find solutions and then project those solutions out into the larger world. We emphasize every day the fact that kids can get out and make a difference."

Bright Stars

With all five kids pursuing scientific interests, not just in school but at home too, science occupies much of the family's time. But how did their abiding interest lead to the entire family participating in AGU's fall meeting, the world's largest meeting of earth and space scientists?

AGU, it turns out, sponsors a program called Bright STaRS (Bright Students Training as Research Scientists), which provides chances for middle and high school students to present research and participate in the organization's annual fall meeting, at no charge. Opportunities like this are few and far between for pre-college students, says Janet Warburton, who manages educational projects for the Arctic Research Consortium of the United States and was the lead convener of the 2017 Bright STaRS session in which the Weisses participated. The session "is a great opportunity for students to share their research and meet with world-class researchers face to face," she says. "The scientists that take the time to interact with the students seem to be very pleased with the experience. It's a win-win situation."

Pranoti Asher, AGU's manager of higher education, agrees. "I spend my entire Thursday morning [at the fall meeting] walking the poster hall, watching the students put up their posters and practice their elevator speeches with their parent or teacher or coordinator," Asher says. "When a scientist walks down the hall and stops at a youth's poster, one can see the sheer delight in the eyes and face of the youth. The youth go from being nervous to gaining confidence as the morning progresses."

Sixty-two posters were included in the 2017 Bright STaRS session, among the roughly 13,000 research posters total at AGU. "The abstracts were scrutinized by the co-conveners in the same way as one would for any session," Asher says, meaning each was vetted to ensure it fit within earth and space science. "No special criteria were used for judging the posters."

With regard to the Weiss family, both Asher and Warburton say they know of no other family of five siblings that has presented posters at a single AGU

Middle-school science teacher John Wood (above left and far right), who mentored the Weiss children's science explorations, with Sean (above, right) in front of the poster he presented at the 2015 AGU fall meeting in San Francisco, and with Ian (near right) at the Orange County Science and Engineering Fair in March 2018. Credit: above: Nicola Weiss; right: Chad Weiss

meeting. In fact, "I don't believe we have had an entire family engaged in this manner in the Bright STaRS session," Asher adds. They both credit Wood, as well as Chad and Nicola Weiss, for stoking the kids' interest and motivating them to share their work.

Nicola and Chad provide essential support to the ambitions and achievements of their kids, Wood emphasizes. The backyard lab testifies to their commitment to nourishing the scientific curiosity of their children, despite neither of them having a professional scientific background.

Nicola says she recognizes that the opportunities afforded her children are not as easily available to others. Having spent several years developing project-based STEAM/STEM learning programs at her children's schools — to help kids move beyond textbook learning and become problem solvers and innovators, she says — she realized it was necessary to help other schools and districts do the same, so more children could have the same opportunities. "I work closely with those who want help in creating these programs at other schools, as a volunteer," she says, adding that "STEM will be in all our kids' futures. Every job will have STEM aspects, and we need to give our students the opportunities to learn the tools, and [gain] the capabilities to know how to problem-solve, innovate and think outside the box." Book smarts are not enough, she says. We must raise students "with the abilities to implement their knowledge in real-world situations."

On to the Future

What lies ahead for the Weiss kids specifically? Sean, who will begin his final year of high school this fall, says he is still studying ocean acidification, but he has other interests in STEM. He adds that he "started developing a social media app for the local children's hospital and started looking into developing a heart valve for children." It would be developed from stem-cell technology, he says, "so that the valve would grow with them and not require surgery after surgery."

Evan, Cameron and Megan will begin their junior year at Edison this fall; each is already looking ahead to college and career. Evan says that presenting posters at multiple AGU meetings has given him the ability "to communicate and share research that I have done" and to understand "opinions or findings on topics that are similar to mine." Currently, he says he is deciding between two career paths: engineering or sports broadcasting.

Cameron says participating in AGU meetings has helped him develop "presentation skills that I didn't learn from presenting in a classroom. It taught me how to present to formal audiences and helped [raise] my confidence in what I do." Looking forward, he says he'd perhaps like to study architecture or graphic design and that he'd like to attend college in Southern California.

Megan presented at AGU for the second time in 2017. "This year was better than the last," she says, "because I have more experience with presenting and I know the general type of questions that I will be asked." As for college, she says she'd like to stay in California as well, and "as my project pertains to the health of people, that may be where my career plans are headed."

Ian, who recently finished eighth grade at Talbert, is already a veteran of several professional science meetings. Although he will start high school in the fall, he is looking beyond his secondary education to eventual engineering and business degrees. He says he wants to be an engineer, to "keep coming up with solutions to real-world problems." Why the business degree as well? "I need to know how to run my own company one of these days," he says.

The 2018 AGU fall meeting is taking place in December in Washington, D.C., and it will again feature a Bright STaRS session. If you attend the conference, stop by to meet the motivated youth presenting their research in the poster hall, and learn about their work. Among them, you might even meet a member — or five — of the Weiss family.

Leifert is based in Bethesda, Md. From 1998 to 2007, he was public information manager at AGU. Since 2008, he has attended scientific meetings as a freelance writer.

Sean (left) and Megan (far right) work in the science lab that their parents, Chad (right) and Nicola, built in the backyard of their Southern California home to give their five kids room to conduct science experiments.
Credit: below: Nicola Weiss; right: Ian Weiss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Feature

TRAVELS IN GEOLOGY

The Pyramids of Giza: Wonders of An Ancient World

The Pyramids of Giza, near Cairo, Egypt, are perhaps the most famous structures ever built.
Credit: Terri Cook and Lon Abbott

Terri Cook and Lon Abbott

Few sights on our planet are as recognizable as Egypt's Pyramids of Giza, the towering trio of monuments built to house the remains of three Old Kingdom pharaohs for all eternity. The pyramids are arguably the most famous human-made structures ever built, and their colossal scale, perfect symmetry and lofty perch on a plateau above the fertile Nile River Valley reflect the divine role that Ancient Egypt's leaders held in both their lives and afterlives. For years we wanted to see these 4,500-year-old architectural and archaeological monuments but were reluctant to travel to Egypt during the social and political upheaval of the Arab Spring and its chaotic aftermath. Now with tourism there on the rise and hints of increasing stability, we decided it was finally time to view these ancient wonders for ourselves.

The Pyramid Builders

Located in the city of Giza on Cairo's southwest fringe, the pyramids stand in stark contrast to the bustling city and the surrounding desert. Despite the first, tantalizing glimpse of their pointed peaks

Located in the city of Giza on Cairo's southwest fringe, the pyramids stand in stark contrast to the bustling city and the surrounding Western Desert.

Credit: K. Cantner, AGI

that we caught through the smog en route to Giza, we were stunned by their scale and grandeur when we saw them up close the next morning from our hotel balcony.

Built atop the Giza Plateau, whose parched, stony surface rises above the west bank of the lush, palm tree-studded Nile Valley, the three pyramids are the best-known monuments in a necropolis built during the reigns of several generations of pharaohs in the Old Kingdom's Fourth Dynasty (circa 2575 to 2465 B.C.). This was a time of peace and plenty during which the pharaohs could marshal enough resources and labor — including farmers working in the off-season — to build these immense structures. Their purpose was to house the ka, the portion of the spirit that ancient Egyptians believed remained with the mummified body, along with all the practical necessities — such as furniture, food and means of transportation — considered necessary for the rulers' afterlives.

The Great Pyramid, the oldest and largest of the three monuments, dominates the skyline with sides that rise an impressive 147 meters above the plateau. Erected by order of Pharaoh Khufu, the second of the Fourth Dynasty's eight rulers, the Great Pyramid was classified by ancient writers as one of the Seven Wonders of the Ancient World — and it is the only Wonder to survive to modern times. Completed in about 2560 B.C., the Great Pyramid remained the world's tallest human-built structure for more than 4,000 years.

Located a few hundred meters to the southwest, the central pyramid was built by Khufu's son Khafre, who ruled from about 2520 to 2494 B.C. The smallest pyramid, which Khufu's grandson Menkaure built, rounds out the trio. Each pyramid is part of a large mortuary complex that included funerary temples, mini-pyramids for each pharaoh's queens, and a causeway that led to the top of the plateau from a "valley temple" built along the edge of the Nile.

From the hotel balcony, we had amazing views not only of all three pyramids, but also the mythical Great Sphinx of Giza, whose lion's body and human head, which sports a pharaoh's headdress, was looking directly at us.

The Great Pyramid

The Giza Plateau, whose flat surface rises more than 100 meters above sea level, is an extension of the country's vast Western Desert. The bulk of the plateau

One of the Seven Wonders of the Ancient World, the Great Pyramid was assembled from 2.3 million blocks of limestone, most of which were quarried from the Giza Plateau.

Credit: Terri Cook and Lon Abbott

The Giza pyramids were constructed by several generations of pharaohs during the Old Kingdom's Fourth Dynasty to house their mummies along with practical necessities for the afterlife.

Credit: Terri Cook and Lon Abbott

Many of the blocks in the Great Pyramid host the calcified remains of *Nummulites*, large single-celled marine organisms that flourished in the Tethys Sea about 50 million years ago.

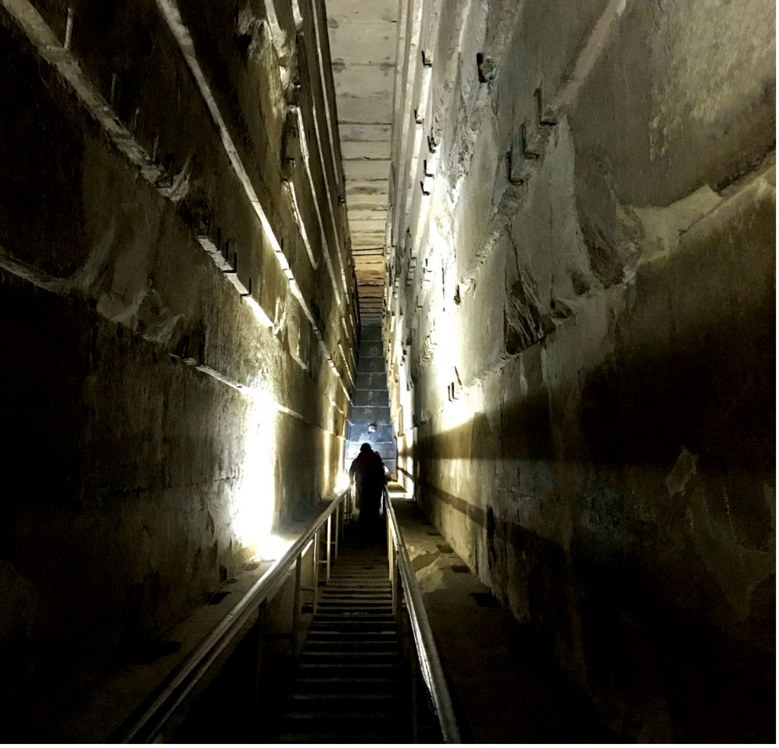
Credit: Terri Cook and Lon Abbott

is composed of stacked carbonate layers deposited from the Late Cretaceous through the Eocene on the floor of the Tethys Sea. This long and narrow ocean separated Africa from Asia following the breakup of the supercontinent Pangea, which began about 200 million years ago. The remnants of this ancient ocean make up the modern Mediterranean Sea.

Khufu and his successors had their pyramids built atop the Mokattam Formation, a series of relatively hard middle-Eocene limestone and dolomite layers that form the surface of this part of the plateau. Many of the blocks that compose the Great Pyramid appear to have come from the same formation, excavated in a quarry a short distance south of the structure. The Mokattam breaks cleanly along bedding layers and is riddled with many vertical joints, so the rock was ideal for dividing into blocks, even with the simple hand tools available to Ancient Egyptian masons.

The scale of the construction is mind-boggling; the Great Pyramid alone consists of an estimated 2.3 million blocks averaging 2.5 tons apiece. The majority of these consist of nummulitic limestone, which contains numerous fossil shells from especially large single-celled marine foraminifera of the genus *Nummulites*. As you walk around the Great Pyramid's base, you can clearly see in many of the blocks the round and oblong shells from these creatures, which thrived in the Tethys Sea some 50 million years ago.

The limestone blocks, after being removed from the quarry, were probably dragged overland using ropes and sleds, possibly aided by wet sand to reduce friction. Once at the pyramid's base, the blocks were likely raised into position using a series of ramps, although this theory remains controversial due to a lack of archaeological evidence. In fact, the near perfection of these ancient monuments, including their alignment with the cardinal directions, has inspired many debates. The designers were clearly master builders; they even figured out an elegant way to use the landscape to their advantage by building both Khufu's and Khafre's pyramids around natural



A highlight of any trip to Egypt is the climb through the Great Pyramid's Grand Gallery to visit Pharaoh Khufu's burial chamber.

Credit: Terri Cook and Lon Abbott

hills, which accounted for 23 and 12 percent of their respective volumes, according to a study by French and Egyptian researchers.

After snapping dozens of photos of the Great Pyramid's exterior and searching for nummulites in its lowermost blocks, we ducked through the small doorway that now marks its tourist entrance. After giving our eyes a chance to adjust to the dark interior, we began ascending a sloping wooden ramp that lines the floor of a narrow tunnel. This soon opened into the Grand Gallery, a soaring passageway about 2 meters wide, 9 meters high and 50 meters long that is lined with smooth, white limestone.

Near the top of the ramp, the Grand Gallery connects to a small passageway that leads into what is believed to be Khufu's burial chamber. It hosts a lidless, four-ton granite sarcophagus that archaeologists believe was placed there first, with the pyramid later erected around it. Unlike the rest of the monument, where limestone is so prevalent, this rectangular room is completely lined with smooth blocks of medium-gray syenite, a relative of granite that contains less silica. This darker rock, along with the dim light and sarcophagus, creates an appropriately somber mood.

The syenite blocks, which weigh up to 50 tons apiece, were shipped down the Nile from Aswan, more than 800 kilometers to the south. This stone, which is about 600 million years old, is part of the Arabian-Nubian Shield, a group of Precambrian rocks sutured together during the final assembly of Gondwana, the southern supercontinent that joined with its northern counterpart to form Pangea.

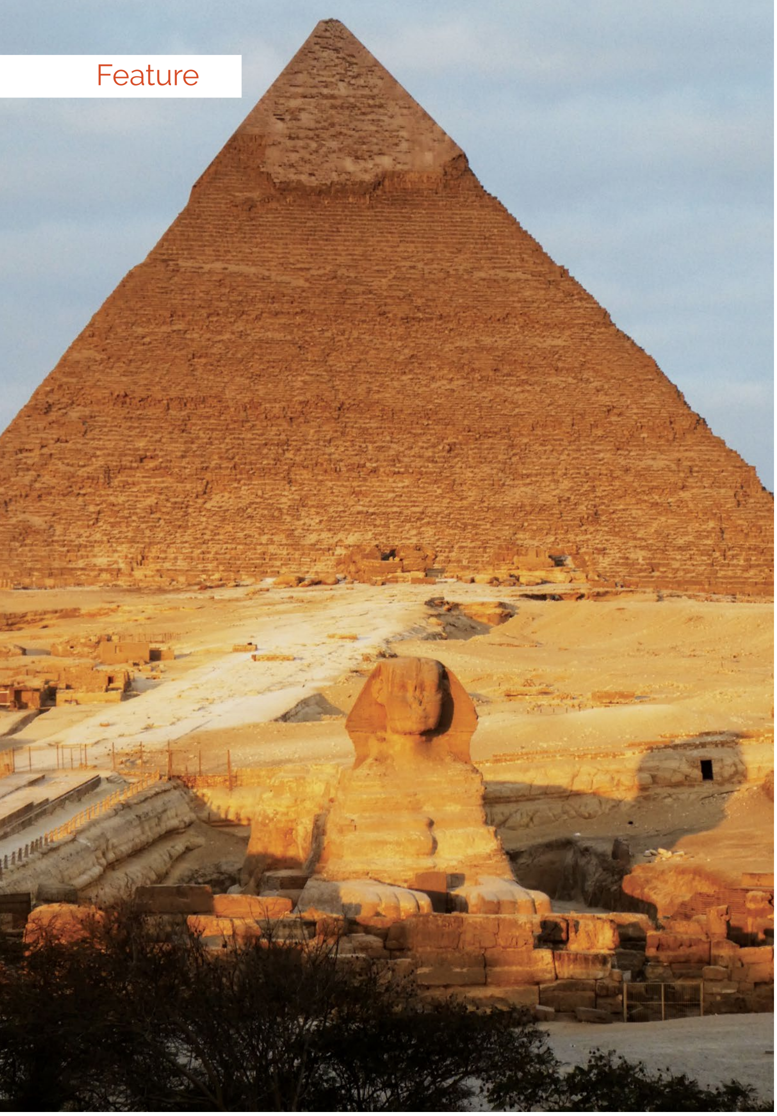
After viewing the King's Chamber, we slowly descended the steep passageway to emerge back into the bright sunshine. Before continuing our tour, we stopped just below the tourist entrance to see a casing layer of glistening limestone, one of the few remaining scraps of the higher-quality, snow-white Tura Limestone that once covered the lower-quality blocks quarried nearby. Although much of this smooth casing was later removed to incorporate into other construction projects, the pieces that remain, including a large, gleaming patch at the top of Khafre's pyramid, offer a tantalizing hint of what the three pyramids looked like following their completion four and a half millennia ago.

Secrets of the Sphinx

In contrast to the pyramids, the Sphinx was carved directly out of the Giza Plateau's limestone bedrock. And because the layers here tilt about 10 degrees to the southeast, the famous statue was, despite its lower perch on the plateau's eastern edge, sculpted out of

Now housed in its own museum, this fabulous 44-meter-long "solar barque," a ritual or funerary vessel meant to carry the deceased to the sun god, was buried adjacent to the Great Pyramid. Despite its antiquity, 95 percent of its wood is original.

Credit: Terri Cook and Lon Abbott



The Sphinx, which has guarded Pharaoh Khafre's Valley Temple for about 4,500 years, is now threatened by rising groundwater levels that are weakening its foundations and causing flaking on its surface due to evaporation.

Credit: Terri Cook and Lon Abbott

the same Mokattam Formation of which the pyramids were constructed. The Sphinx stands guard over Khafre's Valley Temple, which was originally located alongside a now-vanished canal that connected the complex to the Nile and through which pyramid construction equipment and materials were transported.

The Sphinx was carved from three subunits of the Mokattam, and each subunit offers a glimpse of how variable the conditions were at the bottom of the Eocene Tethys Sea. The paws are part of the lowermost, and hence oldest, subunit, which consists of brittle material from an ancient, petrified reef. Most of the body was sculpted from a stack of alternating soft and hard layers that reflect small changes in water depth, grain size and depositional energy in an ancient lagoon environment. The Sphinx's head and neck were carved from a harder limestone unit, which is why the face is so much better preserved than the body. Despite the general durability of limestone in arid climates, the Sphinx has frequently required repairs (beginning, according to New Kingdom records, at least as early as 1400 B.C.) The statue has continued to deteriorate from various causes, including vandalism, the misuse of grout, and a recent rise in groundwater levels caused by irrigation and leaking sewage. This rise is believed to have weakened the statue's foundations and caused wicking of moisture up through the Sphinx to its surface, where evaporation causes material to flake off, grain by grain.

For all we know about it, the Sphinx still harbors several secrets, including when it was carved and whose countenance is mounted on the lion's body. Some scholars have speculated that it represents Khafre, builder of the central pyramid. Yet despite his having left behind such an impressive monument, only one known depiction of his face has been found (on a small statue that you can see in the fabulous Egyptian Museum, which also has an extensive exhibit of King Tutankhamun artifacts), so the likeness is difficult to judge.

Sakkara, Dashur and the Citadel

Although the Pyramids of Giza are by far the most famous ancient Egyptian tombs, their construction would have been impossible had several earlier pharaohs not conducted some innovative architectural experiments at nearby sites, including Sakkara and Dashur, two other Ancient Egyptian royal burial grounds that are easily reached.

Early in the civilization's history, royal tombs (called mastabas) consisted of subterranean burial chambers covered with rectangular, flat-roofed stone structures. During the Third Dynasty, under the reign of Pharaoh Djoser, an architect named Imhotep designed a new type of tomb that mimicked a

During the Third Dynasty, Pharaoh Djoser built Egypt's first true pyramid at Sakkara, a necropolis that visitors can tour in addition to viewing the ancient Egyptian capital of Memphis.

Credit: Terri Cook and Lon Abbott


The tombs at Sakkara, which include many elaborate carvings, span most of Egypt's dynastic period.
Credit: both: Terri Cook and Lon Abbott

series of six stacked mastabas. Completed in about 2630 B.C., the so-called Step Pyramid, which historians generally consider Egypt's first, dominates the necropolis at Sakkara, an important archaeological site about 23 kilometers south of Cairo. Located near the ancient capital of Memphis, which was strategically situated near the mouth of the Nile River Delta, this royal burial ground came into use during the First Dynasty around 3100 B.C. In addition to the Step Pyramid, the site hosts thousands of burial tombs spanning most of Egypt's dynastic period.

It's easy to combine a trip to Sakkara with an excursion to Dashur, where you can see the Red Pyramid built by Khufu's father, Snefru. Named for the reddish limestone blocks used for its core, this structure was the first smooth-sided pyramid and is one of three this pharaoh built. Another, the nearby Bent Pyramid, developed cracks as it was being constructed, forcing ancient engineers to reduce the slope of the sides midway through construction and creating its characteristic "bend."

Like Khufu's and Khafre's pyramids, the Red Pyramid was also originally cased with gleaming Tura Limestone. This was quarried on the east side of the Nile near the center of modern-day Cairo. You can catch a glimpse of the quarry while visiting the beautiful Citadel of Salah El Din, a medieval fortification completed in 1183 A.D. While there, you can tour the impressive Ottoman-style mosque built between 1830 and 1848 by Pasha Muhammad Ali, who is considered the father of modern Egypt.

Given the political tumult currently enveloping parts of the Middle East, we almost decided to forgo a trip to Egypt. We were finally swayed by our kids' organized lobbying campaign, including their comprehensive list of pros and cons. As we stood at the Citadel and peered through the smog of modern Cairo at the Pyramids of Giza in the distance, we were glad that we'd chosen to come. We didn't experience any problems, every Egyptian we met welcomed us warmly, and now we've seen the world's grandest monuments from human antiquity.

Cook (www.down2earthscience.com) is a science and travel writer based in Colorado and an EARTH roving correspondent. Abbott is a geology professor at the University of Colorado, Boulder.

Getting There & Getting Around

Egypt's main gateway is Cairo International Airport (CAI), which has nonstop flights to most major Middle Eastern and European cities. EgyptAir offers direct flights to Cairo from New York City and Toronto. From other North American locations, it's usually most convenient to fly through Dubai, Abu Dhabi or a European hub. British Airways, Emirates, Etihad, Lufthansa and Turkish Airlines are among the carriers offering connecting service.

After landing at the airport, U.S. passport holders must obtain a 30-day tourist visa, which costs $25 per person and is payable only in cash in U.S. dollars. According to the Embassy of Egypt website, Americans should also bring extra passport photos and copies of the completed visa application and passport information pages, although we were not asked for this additional documentation.

If you're heading directly to Giza, most accommodations will arrange transport from the airport northeast of Cairo to the pyramids, which are located southwest of the city. Depending on traffic, it can take more than an hour to travel between the two. Suntransfers.com also offers door-to-door transfer service. For other transportation in Cairo, we don't recommend driving yourself as the city's traffic can be chaotic. Instead, consider hiring a driver. This service should also be included in any private tour.

During winter it's advisable to book accommodations ahead of time, especially if you want to stay close to the pyramids. Egyptian hotels range widely in price, services and quality but are generally a better value than in the U.S. Located near the entrance to the pyramid complex, the plush Marriott Mena House offers luxurious accommodations with up-close views of the Great Pyramid. If, like us, you're willing to forgo luxury for a basic, clean room, the Pyramids View Inn boasts one of the very best views of all three pyramids and the Sphinx from its balcony. From there you can also watch the sun rise and set, eat breakfast, and enjoy the colorful (though hokey) sound and light show that illuminates the pyramids nightly — all for free.

An Egyptian woman bakes bread outside a Cairo restaurant.
Credit: Terri Cook and Lon Abbott

To enter the Great Pyramid, you must have two tickets: one to visit the necropolis and a second to see the inside of the pyramid. The latter are timed for either the morning or afternoon and best booked in advance through a tour guide or your accommodation. Egypt's currency, the Egyptian pound, is available from ATMs throughout the city, and U.S. dollars are also widely accepted. Although most accommodations accept credit cards, it's a good idea to have some small bills handy for tipping.

The weather is typically sunny but chilly during winter, while the heat is scorching in summer, so the best time to visit is from October through March. Before you head to Egypt, it's a good idea to check with the U.S. Department of State for current travel advisories and sign up for the Smart Traveler Enrollment Program to receive alerts.

TC & LA

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Credit: K. Cantner

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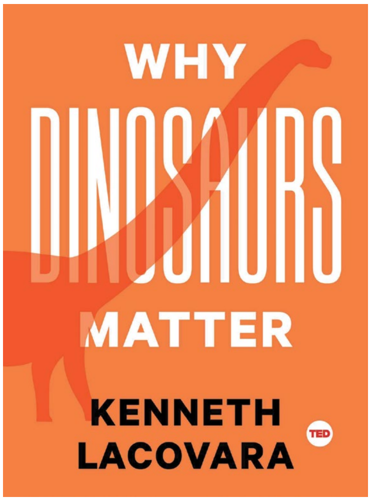
Books: Informative and Inspiring: "Why Dinosaurs Matter"

Ali Nabavizadeh

"Why should we care about dinosaurs? They're all dead!" It's a question paleontologists get all the time. There are many people who don't see the point of studying dinosaurs (or any other prehistoric animal) and would much rather see scientists researching topics that "actually matter to humans."

In his new book, "Why Dinosaurs Matter," vertebrate paleontologist Kenneth Lacovara aims to explain why, in fact, studying ancient life does matter. Lacovara has spent his career excavating and publishing on dinosaurs and paleoenvironments, as well as communicating the wonders of paleontology. To share this passion, Lacovara founded Edelman Fossil Park at Rowan University in New Jersey, a publicly accessible quarry containing vertebrate and invertebrate fossils from the Cretaceous-Paleogene boundary, roughly 66 million years ago.

Lacovara believes it is important to understand these animals and their times to understand our own place in our own time, and in the book, he includes a chapter on how we can protect Earth amid the ongoing consequences of human-made climate change. Other chapters cover the major components of paleontology, with, of course, a strong emphasis on dinosaurs. Topics range from detailed accounts of historical figures in paleontology and effective explanations of the geologic timescale, to dinosaur biology, origins and extinctions. No good dinosaur book would be complete without explaining the incredible fact that today's birds are, indeed, descendants of extinct theropod dinosaurs, and Lacovara addresses this eloquently. In addition, he pays special attention to a few titanic creatures, including the infamous carnivorous theropod *Tyrannosaurus* ("the king") as well as his own discovery: a gargantuan titanosaurian sauropod he named *Dreadnoughtus*, which translates to "fears nothing." *Dreadnoughtus*, an herbivore with an extremely long neck and tail and enormous column-like limbs, was one of the largest animals to have ever walked the earth.



"Why Dinosaurs Matter" by Kenneth Lacovara, Simon & Schuster, 2017, ISBN 1501120107

Lacovara covers other herbivorous dinosaur groups as well, such as the broad-billed hadrosaurs and the armored, tank-like ankylosaurs, both ornithischian groups, although not in quite as much detail as he covers the theropods and sauropods. His treatment of other popular herbivorous dinosaur groups, meanwhile, is unusually lacking: the horned ceratopsians (e.g. *Triceratops*), the dome-headed pachycephalosaurs (e.g. *Pachycephalosaurus*), and the plated and spiked stegosaurs (e.g. *Stegosaurus*) receive less attention. As a result, the breadth of dinosaur diversity is not fully represented. But otherwise, Lacovara does a nice job conveying the excitement and importance of dinosaur biology through his commentary on dinosaur paleoecology (their interactions with the environment and each other) through time.

Throughout the book, there are nice illustrations, each with a little vignette describing important themes posed throughout the book. The images are drawn with simple yet bright color schemes that help the reader understand concepts of dinosaur biology, paleoecology and extinction, among others. In particular, one illustration displays multiple depictions of Earth, each representing another time period in our planet's history. This image effectively drives home the point that fossils come from many time periods, and each carries crucial information about deep time. Another image captures Lacovara's team working to dig up the skeleton of *Dreadnoughtus*, with a life reconstruction of the animal majestically looking on from the opposite page. These illustrations are informative and attention-grabbing, and several concepts and prehistoric animals throughout the book could have benefitted from more illustration.

Lacovara's passion for scientific communication and talent for storytelling are visible throughout "Why Dinosaurs Matter." His prose is engaging and filled with detail that, at times, almost reads like poetry — a difficult feat to accomplish when writing about science. With many references to historic figures in paleontology and geology, he weaves a charming narrative of both the geological and biological significance of dinosaurs and other prehistoric life. Overall, the book offers meaningful context to why we should care about all species — living and extinct.

If you are looking for an inspiring book on dinosaurs, and life on Earth as a whole, look no further than "Why Dinosaurs Matter."

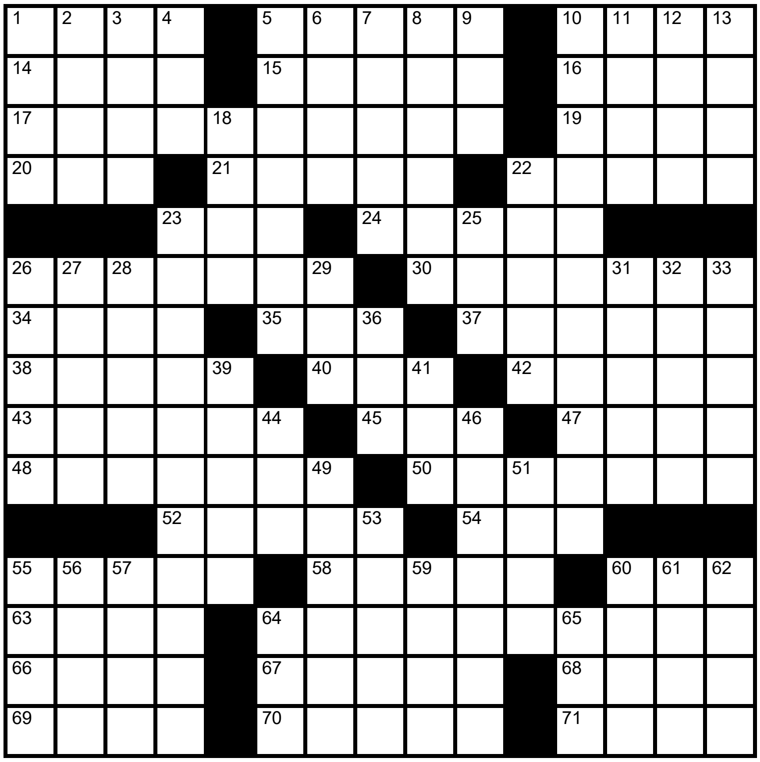
Nabavizadeh is an assistant professor of anatomy in the Department of Biomedical Sciences at Cooper Medical School of Rowan University, which also hosts the Edelman Fossil Park. His research investigates comparative anatomy and evolution of craniofacial musculature and feeding function in herbivorous dinosaurs, as well as in many other large herbivorous vertebrates, ranging from dicynodonts to elephants.

Across

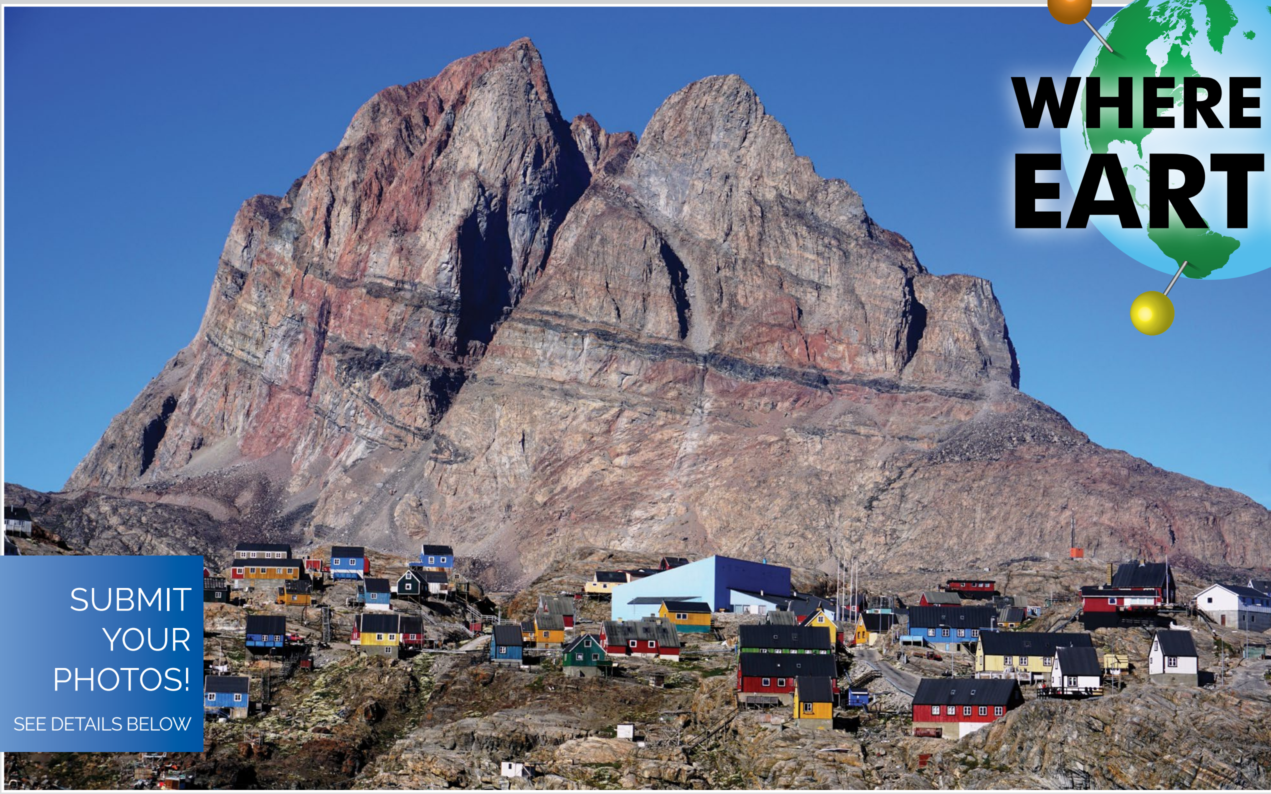
1. Icelandic epic
5. Snake, e.g.
10. Andean land
14. Look sullen
15. Liquid waste
16. Hubbubs
17. Pale feline
19. Theda Bara, e.g.
20. Armageddon
21. Indian state
22. Bad gaits
23. Air hero
24. Gum
26. Fatal
30. Of the tongue
34. Egg
35. Drink from a dish
37. Planet-scale wave
38. Japan fighters
40. Airline's home base
42. Runs through
43. Desk item
45. Family dog, for short
47. Arch type
48. Hit the brake
50. Equine tool
52. Shack
54. Deception
55. Nunnery
58. Fertile soil
60. Bird ___
63. Brand, in a way
64. Tough
66. "Frasier" actress Gilpin
67. Anti-old prejudice
68. Container weight
69. Particular, for short
70. River to the Rio Grande
71. Coaster

Down

1. "... or ___!"
2. "Whatcha ___?"
3. Couple
4. Branch
5. Athletic brand
6. Burns up
7. Parish priest
8. Crown covering
9. Abbr. after a name
10. Slate use
11. ___ cheese
12. Cakewalk
13. Mailer
18. A head
22. Flooring
23. Rain-making river type
25. "Dear" one
26. Drops off
27. Flip
28. Surrounding glows
29. Cry of disgust
31. Grammar topic
32. Nancy abbots
33. Causes cell death
36. Afghani cent
39. ___ Rebellion of 1857-59
41. "___, humbug!"
44. Gun, as an engine
46. Fragrant resins
49. AR surge
51. "Simpler" computing
53. Reasoned decision
55. Dangerous biters
56. Page
57. In need of resupply, maybe
59. Pacific warmer
60. Farm youngster
61. Artificial bait
62. Brought into play
64. Drivel
65. "___ alive!"



Puzzle solution appears in the Classifieds section.



WHERE ON EARTH?

CLUES

- This island is located within a fjord and showcases the prominent granite and gneiss mountain seen here, which rises 1,170 meters above sea level. The mountain's two summits, of roughly equal elevation, give rise to the island's name, which means "heart-shaped."
- In 1972, eight mummies of Inuit women and children thought to date from about A.D. 1475 were found nearby on the shores of the fjord.
- The only town on the 12-square-kilometer island, which serves as a research base for scientists studying the nearby ice sheet, is at the southern end and covers about 10 percent of the land mass.

June 2018 Answer:

These mud volcanoes southeast of the Salton Sea in Southern California formed when carbon dioxide bubbled up through the Davis-Schrimpf Seep Field, which is heated by a magma chamber more than a kilometer below the surface. Photos by Albert L. Lamarre.

June 2018 Winners:

Gerhard Kunze (Akron, Ohio)
Gary L. McGavin (Redlands, Calif.)
Chris Robinson (Vancouver, Wash.)
J. Brad Stephenson (Oak Ridge, Tenn.)
William Underwood (Bethany, Okla.)

HOW TO PLAY

NAME THE ISLAND & ITS HOST COUNTRY.

Where on Earth was this picture taken? Use these clues to guess and send your answer via Web, mail or email by the last day of the month (September 30). Subscribers can also view contest photos and clues in EARTH's monthly digital editions. From those who answer correctly, EARTH staff will randomly draw the names of five people who will win a prize from AGI. Enter the contest at www.earthmagazine.org/whereonearth.

You can also submit entries to Where on Earth? EARTH, 4220 King Street, Alexandria, VA 22302 (postmarked dates on letters will be used). EARTH also welcomes your photos to consider for the contest. Find out more about submitting your photos at www.earthmagazine.org/whereonearth/submit, and send them to earth@earthmagazine.org. If we print your photo in EARTH, you'll receive a free one-year subscription or renewal.

With Volcanologist Scott Rowland

Catherine Hudson

Hawaii seems like an ideal place to nurture a budding volcanologist. Kilauea, on the Big Island, is one of the world's most active volcanoes. And the terms used to describe the main types of basaltic lava flows — aa and pahoehoe — are Hawaiian words.

Yet when Scott Rowland returned to his home on Oahu after earning a bachelor's degree in geology at Oregon State University, intent on heading to graduate school, he was torn between studying volcanoes or groundwater. Ultimately, he chose to study Hawaii's basalt lavas as a graduate student at the University of Hawaii at Manoa.

Rowland is now a faculty member in the same department in which he earned his doctorate. He spends most of his time teaching and pursuing three main research projects: modeling how channelized lava flows advance, mapping thick lava flows on the island of Molokai, and, slightly farther afield, assigning operational directions to the Mars Curiosity rover a few times a month.

But since Kilauea's long-running eruption changed its character right at the end of April, his daily activities have become livelier and more varied. Active Hawaiian volcanoes are officially monitored by the U.S. Geological Survey (USGS) and faculty at the University of Hawaii's Hilo campus, but Rowland has taken an active role in communicating the latest events, speaking with news media and research colleagues.

Rowland talked with EARTH about the recent volcanic activity on the Big Island, the evolution of the eruption, and the challenges involved in communicating to the public during an ongoing natural hazard event.

***Editor's Note:** This interview took place June 19, after which additional eruptive events occurred. On Aug. 2, however, both the eruptive activity in Leilani Estates and the collapse activity at Kilauea's summit stopped. At the time this issue went to press, neither had resumed.

Volcanologist Scott Rowland, who studies Hawaiian lava flows and also works as a volcanologist on the Mars Curiosity Rover team, with the testbed rover at the Jet Propulsion Laboratory in Pasadena, Calif.

Credit: Megan Kennedy-Wu

CH: What is your role related to the recent volcanic activity on the Big Island?

SR: All the activity is officially monitored by USGS and University of Hawaii at Hilo faculty. I've only been on site briefly. But I have done a lot of interviews for news media and I try to keep my colleagues up to date with what's happening.

CH: Can you describe the evolution of the recent eruptions of Kilauea?

SR: Pu'u O'o is a scoria and spatter cone located on the East Rift Zone of

The constant volcanic activity on Kilauea allows volcanologists to easily collect fresh lava samples and study their composition, gas content and viscosity.
Credit: Ruth Weatherwax

Kilauea volcano that has been erupting since 1983. Typically, the lava from Pu'u O'o vent has spilled over the top of the cone or entered lava tubes leading downslope, and the average effusion rate has been 3 to 5 cubic meters per second. This slow flow has been going for decades more or less continuously and usually empties into the ocean.

Beginning in late March, magma accumulated in the Pu'u O'o vent. The lava lakes at Pu'u O'o and up at Halemaumau Crater at the summit of Kilauea were both rising (we know there is a connection between them). It seems there was some type of blockage at the outlet of Pu'u O'o causing magma to back up to the summit. Rather than flowing out the flank of Pu'u O'o cone as it has in the past, the magma flowed out the bottom of the cone into the East Rift Zone and traveled underground. It drained very rapidly from Pu'u O'o and migrated down the rift zone. This was tracked by localized earthquakes, which eventually centered around Leilani Estates (a residential subdivision). The earthquakes were so shallow that residents could hear them as well as feel them. Cracks began to form in the area, indicating that magma was working its way toward the surface.

May 3 was when the first small eruption took place in Leilani Estates, and the cracks and vents spread both downslope and upslope along the rift from that eruption. For the first week or so, a little lava would come out of a vent and then stop. The chemistry of that lava indicated that it was not magma that had drained from Pu'u O'o, but rather magma that had been sitting in the rift zone for some time and was now being pushed out by the Pu'u O'o magma.

By May 18 and 19, the vents had propagated outside of Leilani Estates and the composition was more similar to that of Pu'u O'o magma. The lava advanced rapidly to the south and entered the ocean for about a week. Then that activity wound down, but one vent (Vent 8) back in Leilani Estates reactivated around May 25 or 26. The lava fountain [at Vent 8] reached 60 meters high and fed a channelized lava flow that reached and flowed right through the community of Kapoho, destroying about 500 homes, which was devastating.

CH: While eruptions were taking place downslope along the East Rift Zone, what has been happening back up on the summit?

SR: The walls of the lava lake at Halemaumau became unsupported when the lava lake drained, which triggered collapse. The surrounding ground has started to subside due to the draining of both the lava lake and the larger underground magma chamber. The subsidence is concentrated at Halemaumau and decreases farther away, but it has caused cracks in the nearby highway and in the floor of the Hawaiian Volcano Observatory's building [at the summit].

While the lava lake was still exposed, rubble from the crater walls dropped into it, causing explosions that released both gas and volcanic ash. There also may be some groundwater providing steam for the explosions, but it seems more likely that it is gas in the magma.

CH: How does this eruption compare to other eruptions in Hawaii?

SR: Compared to other Hawaiian eruptions, it's been remarkable how persistent this relatively high effusion rate — 100 cubic meters per second is the estimate USGS has published — has lasted. Mauna Loa and Kilauea have both erupted at rates higher than that before, but never for this long, at least that we know of. This rate has persisted for a month now, and that is very puzzling. That's the most amazing aspect, the duration at a high eruption rate.

CH: How might this eruption influence our views of past eruptions?

SR: [During an eruption] in 1924, the violent explosions were thought to be purely generated by the interaction of the groundwater with hot rock, with maybe a little magma involved. That doesn't seem to be the case with the current eruption. USGS believes the explosions occurring now are at least partially driven by magmatic gases. This hypothesis is based on the chemistry of the gases being collected and on the morphology and type of particles coming

Rowland teaches at the University of Hawaii at Manoa, where volcano-focused field trips abound. On this field trip to Mauna Loa, Rowland explains how lava flowed around a small outcrop of older lava, then inflated upward, leaving the old lava well below the level of the new lava.

Credit: Andy Ryan

out. Now, USGS is starting to question the interpretation of the 1924 eruption, trying to determine if it was perhaps more magma-driven than originally thought. After the current eruption has settled down, USGS may take another look at the 1924 eruption.

CH: How has news about the eruption been communicated to the public?

SR: It's mostly been via local TV news, print news and a lot of social media. There are a number of folks who live in the vicinity of the eruption who post videos and try to keep friends and neighbors updated. Of course, there's a large amount of information USGS posts on websites, including maps, photographs, real-time seismic data, tilt data, webcams and even a live YouTube video of the caldera. USGS has been my main source of information. They established a Facebook page, which allows rapid interactions with the public. USGS has done a really good job of responding to people's questions, and most of the time the questions the public asks show their natural wonder and curiosity for the topic.

The National Guard, County Civil Defense, USGS, and local police and fire departments have radios and helicopters, and the lines of communication appear very effective. There are community centers where people can gather for information and drop off donations — the community has pulled together very well.

CH: What questions about the eruption remain?

SR: The current ash eruptions and summit earthquakes are occurring in a relatively regular pattern. Pressure is not being released until a sufficient amount builds up and causes an explosion, but the exact cause of the eruptions remains unknown.

And why did the vents form within Leilani Estates as opposed to a different location along the rift? The reason the magma was pushed out and erupted at that specific location is unknown.

The other major questions are: What caused the magma to break out the bottom of Pu‘u O‘o? Pu‘u O‘o has erupted lava from its side before, but why did the lava lake suddenly drain and exit at the bottom of the cone into the rift zone? Was there a big pulse of magma that came into the volcano and set all of this in motion?

CH: What are your personal predictions for the future of this eruption?

SR: I made a bet with a colleague that it would end tomorrow (June 20), but I'm guessing I'll lose that bet, so don't listen to me! In all seriousness, we must consider previously erupted volumes and the volume of the magma chamber at Kilauea, which has not been emptied yet. So, it seems possible this eruption may last longer.

Hudson recently earned her master's degree in geology and geophysics from the University of Hawaii at Manoa and currently lives in Portland, Ore.

September 6, 1869: Pennsylvania's Avondale Coal Mine Fire Kills 110, Igniting Reform

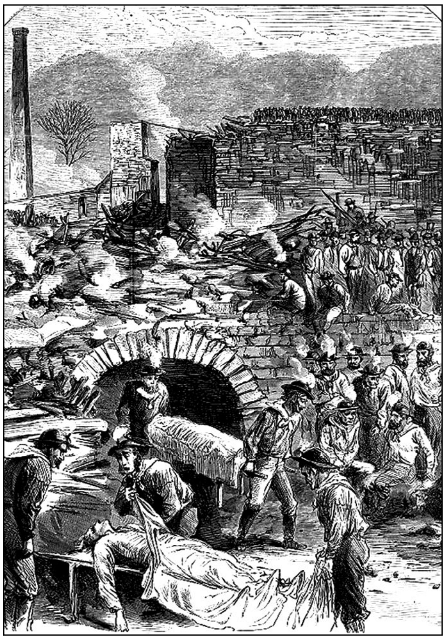
Rachel Crowell

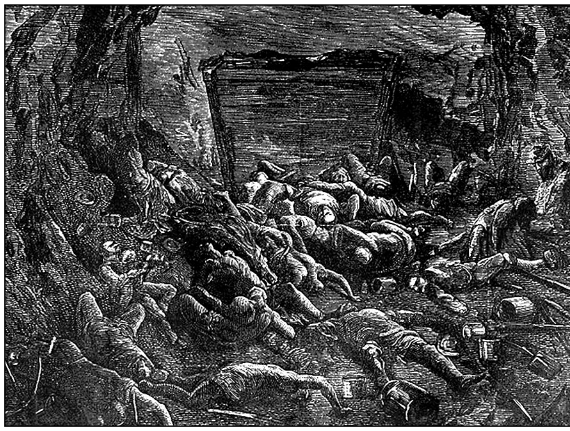
In the mid-19th century, American industry was fueled by coal, which was provided largely by the anthracite coal mines of eastern Pennsylvania. The work drew tens of thousands of immigrants, including experienced English and Welsh miners, and many fleeing the Irish Potato Famine. But the work was dangerous, and each year thousands of workers died in the mines and many thousands more were seriously injured. In one of the worst disasters of this era, a fire at the Avondale Colliery in Plymouth, Pa., trapped and killed 108 miners, including five boys, as well as two men who attempted to rescue the workers.

While it was neither the first nor the last mining fire of its time, Avondale had a significant effect on the history of labor unions and mining safety regulations. One year later, Pennsylvania created the first mining inspection law for anthracite (hard coal) mines. Eight years after that, the law was extended to include bituminous (soft coal) mines, setting a precedent that other states soon followed.

Additionally, after the disaster, thousands of miners flocked to join the Workingmen's Benevolent Association (WBA), the first industrywide labor union for anthracite miners, according to an article published in the journal Labor History. Increased unionization drew attention to the Molly Maguires, an alleged secret Irish society that advocated for workers' rights, sometimes resorting to violence.

Some of the details of this transformative disaster are muddled by the nearly century and a half that has elapsed since it occurred, and because of "how far some of the numerous historical references to the Avondale disaster have strayed from the truth," according to a historical report about the fire. For example, reports in 1916 and 1946 by the U.S. Department of the Interior's Bureau of Mines erroneously tallied 179 deaths from the fire. Yet certain details from the tragedy are undisputed and were key in the eventual adoption of mine safety protections.





Harper's Weekly illustrations of the Sept. 6, 1869, fire at the Avondale Colliery that killed 110, including five children and two rescuers. When the coal breaker caught fire and blocked the only exit, the miners attempted to seal themselves off, but were asphyxiated.

Credit: both: public domain

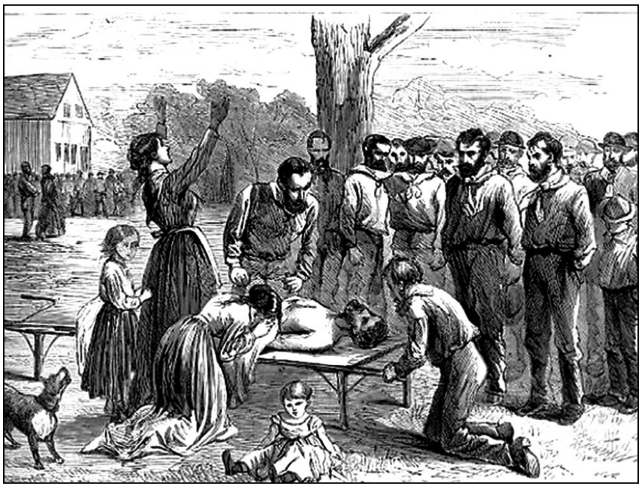
Early Reforms in Pennsylvania

Pennsylvania's first mine safety law was passed by the state legislature in April 1869, but that law, created just months prior to the mine fire in Plymouth, didn't prevent the conditions that contributed to the fire's deadliness, notes the website Explore PA History.

The 1869 law was partly a result of lobbying efforts organized by the WBA's Committee on Political Action, according to a Mine Safety and Health Administration (MSHA) account of the history of Irish workers in American mining. John Siney, the Irish immigrant founder of the WBA, became a miner after immigrating in 1863 to St. Clair, Pa., in Schuylkill County. There, he helped lead a six-week-long strike in 1868 that succeeded in preventing miners' wages from being slashed for the second time in half a decade. He also led strikes to enforce state-legislated eight-hour work days.

The narrowly drafted 1869 law called "for the better regulation and ventilation of mines and for the protection of the miners" — but only in Schuylkill County. It outlined many requirements, including that mines possess ventilation in the form of furnaces or suction fans, that each mine employ a boss who would perform a safety inspection each morning before workers entered, and that systems be installed to enable communication between the mine and the surface. Under penalty of fine, it also prohibited mines from having workers ride to the surface in loaded cars and stipulated that the law would be enforced by newly designated inspectors authorized to enter and inspect the mines and machinery at "reasonable" times.

However, the law did not apply in neighboring Luzerne County, where the Avondale Colliery was located, and none of the new regulations accounted for that mine's deadliest shortcoming: It was equipped with just one exit.

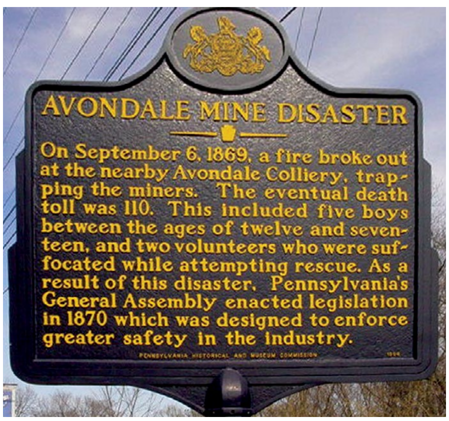


Harper's Weekly illustration of the aftermath of the Avondale Colliery disaster, which devastated the population of the small town of Plymouth, Pa.

Credit: public domain

No Way Out

Catastrophe engulfed the Avondale Colliery at approximately 10 a.m. on Sept. 6, 1869 — the miners' first day back at work following a seven-day strike. The fire took hold in the coal breaker, which proved perilous. At Avondale, the breaker — where coal was sorted from rock and broken into various sizes — was built directly above the shaft that served as the sole opening to the mine. England had, by this time, banned mines from installing coal breakers above shafts, but the practice was still being implemented in the northeastern U.S. According to Explore PA History, it was the practice of the company that ran the Avondale mine — as well as other coal mining companies — to keep small fires "burning at the bottom of shafts to create drafts that promoted better air circulation for the working miners."



The 1869 Avondale fire, the deadliest anthracite coal mine disaster in U.S. history, occurred in Luzerne County, Pa. — the county and state, respectively, with the most mine disasters.

Credit: Johnny Johnsson and Mike Kaas, Mining History Association

According to the historical report on the fire, Alexander Weir, an engineer at the Avondale mine who was working aboveground that day, was the first to notice the flames shooting up the mine shaft. Sparks from the ventilating furnace had ignited the wooden breaker. The flames rushed "up the shaft with great fury and with a sound not unlike an explosion," leaving Weir with just enough time to blow his whistle, alerting workers more than 60 meters below to "arrange matters to prevent a boiler explosion." As the rapidly progressing blaze turned the shaft into "a roaring inferno which no man could approach," Weir jumped out of the way. The burning breaker consumed the oxygen from the mine below and flooded it with carbon monoxide.

Soon, the area around the mine was engulfed by a line of fire that extended more than 90 meters from the mine's head house, the structure enclosing the mine entrance, to the nearby railroad tracks. The historical report describes "a plane of fire" running toward the hill above, then shooting up "in one immense column into the air, while dense clouds of smoke envelop[ed] all surrounding objects."

Recovering the Victims

As word of the fire spread, the families of the trapped miners rushed to the mine. A bucket brigade was organized to transport water from a tanker until fire engines arrived, first from neighboring Kingston and then from Scranton. By the middle of the afternoon — several hours after the blaze was first noticed — streams of water from the two engines had "subdued the fire in a great measure," according to the report. But it would still be some time before the blaze and deadly fumes were controlled enough that the mine could be safely entered.

With the fire extinguished from above, men at the surface cleared debris — largely the remains of the breaker, which had collapsed into the shaft amid the fire — from the mouth of the shaft and installed a hoisting device powered by horses that could be used to descend into the mine. To ascertain the safety of the area below, they sent down a small dog and a lighted lantern. At 6 p.m., the canine and the lantern were hoisted back up. The dog survived but the lantern's flame was snuffed out.

Confusion ensued. After calling down the shaft into the mine, some thought they heard miners below answer that they were alright. "Immediately, cheer after cheer went up from the assembled multitude, but the most experienced miners were not of the same mind. They could hear no answer," the report notes.

Charles Vartue, 85, volunteered to descend into the mine's shaft to investigate. He emerged unscathed but reported that more than one man would be needed to dig through the debris in the shaft to get into the mine. Next, two men — Charles Jones and Stephen Evans — went down together, discovering two dead mules and a closed door. After pounding on it and receiving no answer, they ascended.

Next, Thomas W. Williams and David Jones volunteered to enter the mine but died from lack of oxygen. "It took two days of clearing debris and poisonous gases from the mine before rescuers reached the first victims," who had been asphyxiated and discovered in various states. "Some men had fallen while running, another was kneeling, and a father was found with his arm around his son," Explore PA History notes.

This reproduction of a 19th-century coal breaker in Eckley, Pa., was constructed for the filming of the 1970 movie "The Molly Maguires," starring Sean Connery as Jack Kehoe and Richard Harris as James McParland. After the film, the town of Eckley, which was chosen as a film location because it had barely changed since the 1870s, was preserved as the historic Eckley Miners' Village.

Credit: Mike Kaas, Mining History Association

The Molly Maguires

In the wake of the Avondale Colliery catastrophe, Siney implored miners: "You can do nothing to win these dead back to life, but you can help me to win fair treatment and justice for living men who risk life and health in their daily toil," he said. The General Council of the WBA sent a committee of miners — formed by representatives from each county union — to the capital. Their lobbying resulted in the Mine Safety Act of 1870, which stipulated, among other things, that each mine had to have more than one exit.

Despite this modicum of progress, the mining industry remained rife with dangers and abuses, which the Molly Maguires worked to settle on their own terms. The group, which led riots in Ireland in the 1840s against exploitive English landowners, was purportedly brought to the U.S. by Irish coal miners who had immigrated to Pennsylvania.

Disputes between coal operators and their employees stemmed from many issues. Besides the dangerous working conditions, there were also child labor issues — with boys as young as 6 employed as "breaker boys" — as well as overcrowded and unsanitary company housing, exploitive company stores, and little or no money offered to the families of workers who were injured or killed on the job.

The Molly Maguires were accused of delivering "coffin notices" threatening to kill mining supervisors and strikebreakers. However, it is unknown whether they murdered anyone, or indeed if any such secret society existed in the U.S. In the 1860s and '70s, Schuylkill County recorded a dozen or more murders per year. In the 1870s, 24 victims were English and Welsh mine bosses. The arrest, conviction and hanging of alleged Molly Maguires for some of the murders was based on the questionable testimony of James McParland, a Pinkerton agent who infiltrated the group at the behest of Franklin B. Gowen, president of the Philadelphia and Reading Railroad.

Gowen, who was known for starving striking workers into submission and other ruthless behavior, was attempting to break the WBA and establish a monopoly on the Pennsylvania anthracite mines. He was also a former district attorney for Schuylkill County, who then served as the special prosecutor in the trials of the 20 accused Molly Maguires, none of whom were permitted to testify on their own behalf and all of whom were found guilty.

On June 21, 1877, 10 of the convicted men were executed by hanging. On Dec. 18, 1878, the alleged leader, John "Jack" Kehoe, a local tavern owner and labor activist who had stymied Gowen's political career, was executed for the murder of F.W. Langdon, a mine boss who had died 15 years earlier, three days after being involved in a bar fight. Langdon had never mentioned Kehoe as one of his attackers.

In 1979, the governor of Pennsylvania, Milton J. Shapp, posthumously pardoned Kehoe, officially recognizing Gowen's subversion of the criminal justice system. "The Molly Maguire trials were a surrender of state sovereignty. A private corporation initiated the investigation through a private detective agency. A private police force arrested the alleged defenders, and private attorneys for the coal companies prosecuted them. The state provided only the courtroom and the gallows," wrote Carbon County Judge John P. Lavelle in his 1994 book, "The Hard Coal Docket."

The Legacy of Avondale

The first federal mine safety statute wasn't passed by Congress until 1891, 22 years after the Avondale Colliery fire. It only applied to coal mines. (Noncoal mines weren't regulated by such statutes until the passage of the Federal Metal and Nonmetallic Mine Safety Act of 1966.) The Federal Coal Mine Health and Safety Act — a more comprehensive law that covered both surface and underground mines, required inspections, increased enforcement power, set penalties for safety violations (including criminal penalties for willful violations), established health and safety standards, and provided compensation to miners who contracted black lung disease — was passed in 1969, a century after Avondale.

Crowell is a former AAAS Mass Media Fellow and a freelance math and science writer based in the Midwest who can be found on Twitter at @writesRCrowell.

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Information about the Department can be found at www.lsa.umich.edu/earth.

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The application deadline is August 20, 2018 for full consideration, but applications will continue to be reviewed until the position is filled. Women and minorities are encouraged to apply. The University is supportive of the needs of dual career couples and is an equal opportunity/affirmative action employer.

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If you are selected as an EARTH extern, the position is essentially an as-you're-available writing opportunity. In any given week or month when you have time to write, you'll email us and say, "Hey, I have time to write." Then, either we can assign you a story or you can pitch stories to us — it's up to you. If you've got a great idea for a story and would like practice pitching your idea to an editor, you're encouraged to do so. On the other hand, if you'd prefer that we provide you with an assignment — as is the case with many first-time externs, for example — that's fine too.

Our extern-written stories typically cover a recent, peer-reviewed scientific study or report, and include quotes about the study from multiple expert sources — obtained via first-person interviews — just as a professional news story would. Before your first assignment, we'll provide guidance about the general style, tone and structure of the news stories we publish in EARTH to help get you started. And then we'll work with you through the writing and editorial process. You're encouraged to ask questions, and you're welcome write as frequently or infrequently as works for you and the magazine's editorial staff.

The externship is a remote position; you can work from any location and at your leisure. Once a story is assigned, you'll generally have one to two weeks to research, report and write it before turning it in. (We do ask that you stick closely to deadlines, so please keep that in mind

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when determining your availability to write.) Once edited and finalized, extern-written stories are posted on EARTH's website as soon as possible. Select extern-written pieces may also appear in a print issue of the magazine. Publication, either online and/or in print, is subject to the discretion of the editorial staff and is not guaranteed. The externship is unpaid.

If you're interested in the experience, email a cover letter discussing your interest in the geosciences and why you'd make a great extern at EARTH, your resume or CV, and at least one writing sample to earth@earthmagazine.org to apply.

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Solution to the September 2018 puzzle

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“Collect Rocks Day” Offers Opportunity for Inspiration

John Copeland

I have been intrigued by rocks since I was a kid. In fact, as I write these lines I am surrounded by rocks I have collected over the years. On my window sill is a piece of shale containing several preserved ammonites, obsidian from Iceland, dolerite from Tasmania, and a sedimentary rock bearing fossilized sand ripples attesting to former currents along the western edge of the Western Interior Seaway, which stretched from the Gulf of Mexico to the Arctic during the late Mesozoic.

Sept. 16 is National Collect Rocks Day, which has only been commemorated since 2015. I have not found any reference to who first observed this day or why, but that does not really matter. It offers a good excuse to celebrate Earth and science, to indulge your inner geologist, and to learn fascinating things about the material that makes up Earth’s surface.

Rocks seem to have always drawn the interest of humans and have been a valuable resource throughout human history. Starting hundreds of thousands of years ago, ubiquitous rocks served as tools for our hominin ancestors. Some of the earliest weapons and musical instruments were made from rocks, as were building materials and jewelry. The first geologists were prospectors looking for valuable minerals and gemstones, and mining rock has made it possible for humans to use metals and other materials in developing technology.

Today, while an interest in rocks draws some people to geology as a profession, it brings many more to the field as a hobby, mainly for the beauty of rocks and minerals. My grandparents were avid rock hounds who made treks to the California desert in search of geodes. They collected beautiful specimens and spurred their grandchildren’s interest in rocks. We all had rock collections growing up — and some of us still do. (Who says you have to give up your rock collection when you become an adult?)

Rock collecting is a great endeavor, for kids and adults alike, for many reasons. Anyone can participate, anywhere. And it’s highly individualistic. Although there are of course rock and mineral guides, there are no books telling you specifically what rocks you should collect or listing values for each and every rock specimen. When it comes to rock collecting, beauty is indeed in the eye of the beholder. This brings me back to Collect Rocks Day — and inspiring young minds.

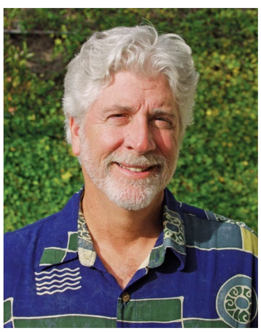
This Sept. 16, take a young person out to collect rocks. You never know where their curiosity and wonder will lead them on life’s journey.

Many of the earth scientists I know and have worked with on natural science documentaries over the years became interested in rocks, fossils and minerals when they were young, and their interest stayed with them into adulthood. I still remember the first time I held a piece of shale with the fossil of a trilobite embedded in it. For a moment, I felt transported into the deep past of our planet and marveled at what this strange creature’s life would have been like. An experience such as this can be life-altering for a curious mind. Collect Rocks Day is an ideal opportunity to help spark the interest of a young person in what may become a lifelong pursuit. There are endless possibilities for celebrating Collect Rocks Day: Take a trip to a fossil-filled beach in search of rocky treasures, or to a rock and mineral shop, or even just to a nearby roadside outcrop to scout for interesting specimens and structures.

Many of today’s pressing issues involve the geosciences, from climate change to managing natural resources. That is why it is so important to encourage children’s interest in science and the natural world. There is a myth that we have to convince children that science is fun. For young learners, science is just an extension of their everyday world. We don’t have to teach young children how to wonder and ask questions, or how to discover and explore through play, because they do it naturally.

Although I did not pursue a career in earth science, I have had an interest in it since childhood. And I have been very lucky to be able to combine filmmaking with science, meeting a whole host of earth scientists and continuing to learn about the planet’s interconnected systems in the process.

This Sept. 16, take a young person out to collect rocks. You never know where their curiosity and wonder will lead them on life’s journey.



Credit: Fran LoCascio

Copeland is a filmmaker in California who has produced television programs ranging from “Babylon 5” to “Faces of Earth” (produced with the American Geosciences Institute). Copeland also works with MIT’s Experimental Study Group to instruct undergraduate science and engineering students in the art of visual communication and storytelling. The views expressed are his own.