A SCIENTIST'S GUIDE TO SOCIAL MEDIA

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EARTH

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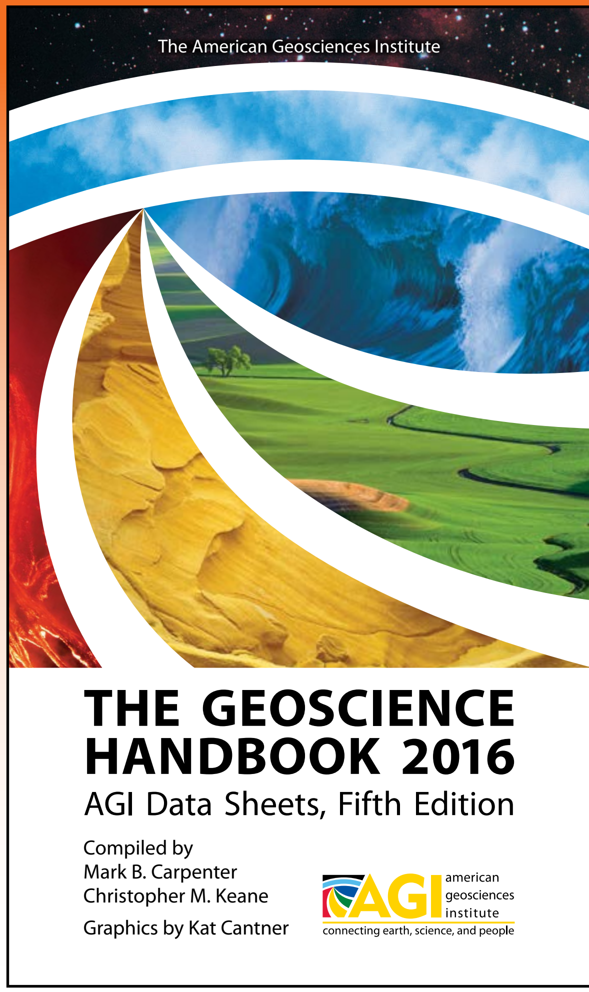
GEOSCIENCE HANDBOOK

AGI Data Sheets Fifth Edition

Mark B. Carpenter,
Christopher M. Keane

For more than 40 years, AGI's Data Sheets have been a critical tool for the geoscientist in the field, the lab, and the classroom. For decades its bright orange cover and three-ring binding were distinctive in the geoscience community. The book evolved into its current, full-color and spiral bound format with the 2005 debut of the fourth edition.

Now AGI has tapped some of the best minds in the geosciences to produce this fifth edition. Featuring the contributions of over 240 experts worldwide in their respective fields, this new, expanded edition is over 470 full-color pages. Three years of work went into the *Handbook* to broaden its scope across the disciplines. With more than 170 complete new data sheets, and full revisions of prior data sheets, over 85% of the content is either new or revised for the fifth edition. The *Geoscience Handbook* is the quick reference tool for key metrics and concepts, a guide to cornerstone papers and recent developments, as well as short tutorials on topics that may not be familiar to all geoscientists.



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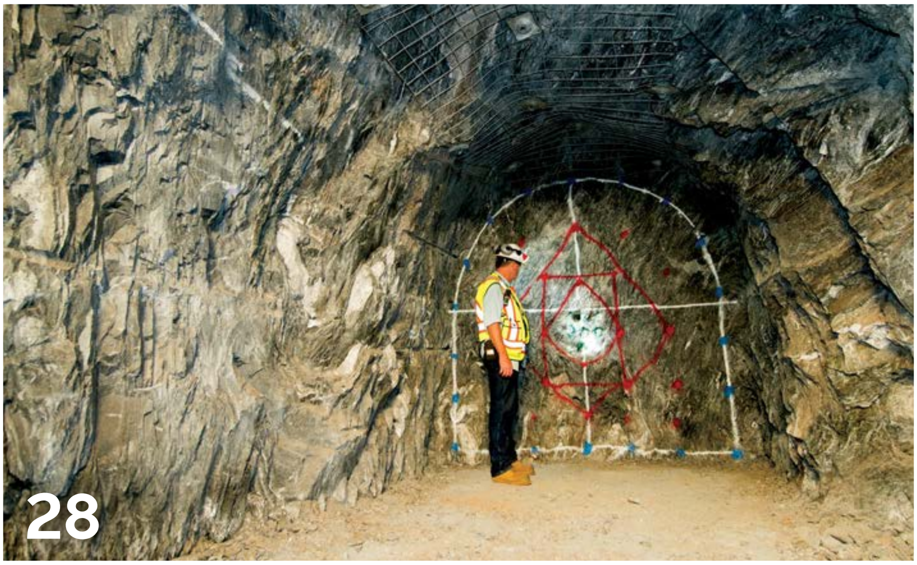
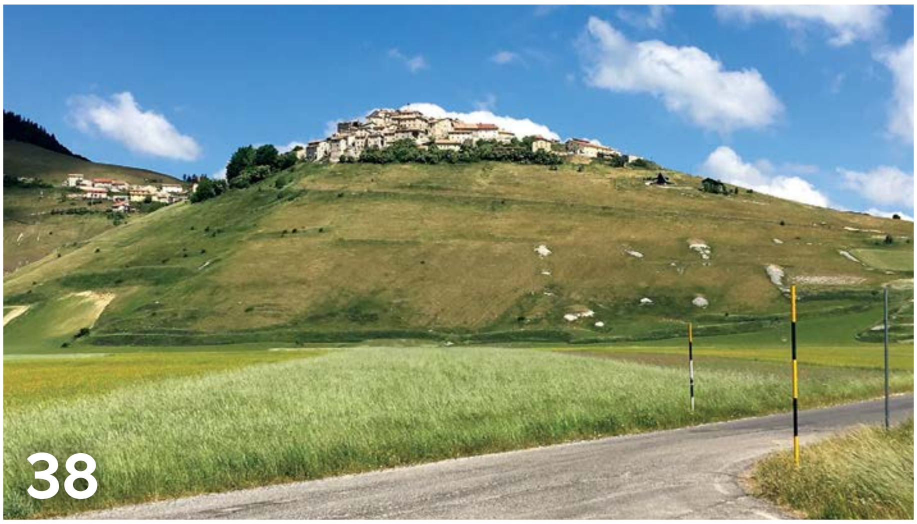
FEATURES

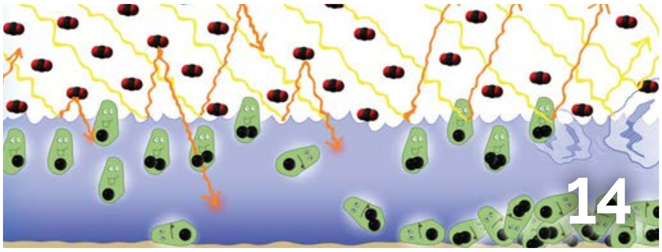


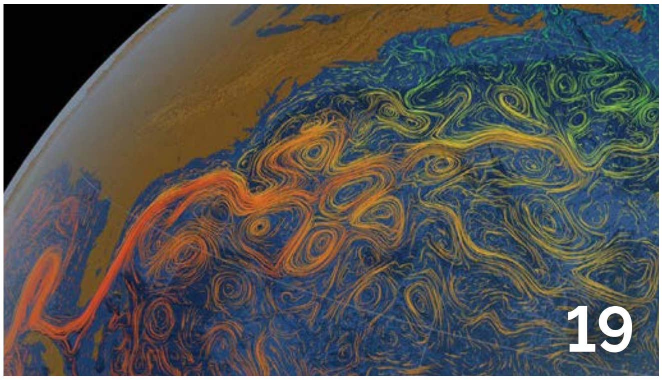


VOICES

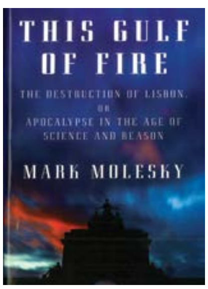
ON THE COVER: Around the world, old mines are being repurposed as research facilities. Credit: K. Cantner, AGI

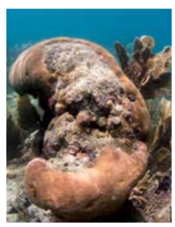
NEWS





DEPARTMENTS





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Seventy years ago, the National Academy of Sciences encouraged the major geology societies in the U.S. to form the American Geological Institute (AGI) to provide a federation to unify and serve the geological sciences. Like all things that thrive, AGI has evolved substantially since its founding in 1948. AGI now has 52 member societies — compared to 11 when the organization began — and represents the entire range of earth science. This wider scope led to AGI's renaming as the American Geosciences Institute in 2011, but the mission has remained the same: to serve the interests of the broader geoscience community. The ways in which that mission is fulfilled have changed, however, with commitments to education, public outreach, communications and policy growing stronger over the years. Of course, we still serve the needs of the geoscience profession through technical products and services.

AGI's longest-standing product has been its magazine, first published in 1956 as Geotimes, which has also evolved over the years from an industry newsletter to a popular magazine. In 2008, the magazine was rebranded as EARTH, and its coverage was broadened to serve anyone interested in earth sciences, as well as space science. For the public, EARTH offers an accessible way to learn about our planet; for professional geoscientists, it offers a great way to stay abreast of trends and hot topics in our science; and for AGI's member societies, the magazine offers exposure for research and initiatives in which the societies are involved. But this broad coverage would not be possible without the geoscience community itself, with individuals acting as contributing authors, researchers willing to discuss their findings, and sources and commenters offering expert opinions about the impact and opportunities that new findings provide.

To celebrate this collaborative effort with the community, and to make EARTH central to the same geoscientists who help make it possible, AGI will now provide complimentary subscriptions to the digital edition of EARTH to all members of its member societies as well as to the faculty, students and staff of geoscience-related programs in higher education around the world. And our digital readers are of course invited to subscribe to the bimonthly print edition, which has all the same content as the digital edition, but with an added measure of tactile enjoyment and analog portability.

EARTH is a celebration of geoscience and the community of people who help us learn more about the planet every day. We want you to share in this celebration.

Christopher M. Keane, Ph.D.
EARTH Executive Editor

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The American Geosciences Institute is a nonprofit federation of geoscientific and professional associations that represents more than 250,000 geologists, geophysicists, and other earth scientists. Founded in 1948, AGI provides information services to geoscientists, serves as a voice of shared interests in our profession, plays a major role in strengthening geoscience education, and strives to increase public awareness of the vital role the geosciences play in society's use of resources, resilience to natural hazards, and the health of the environment.

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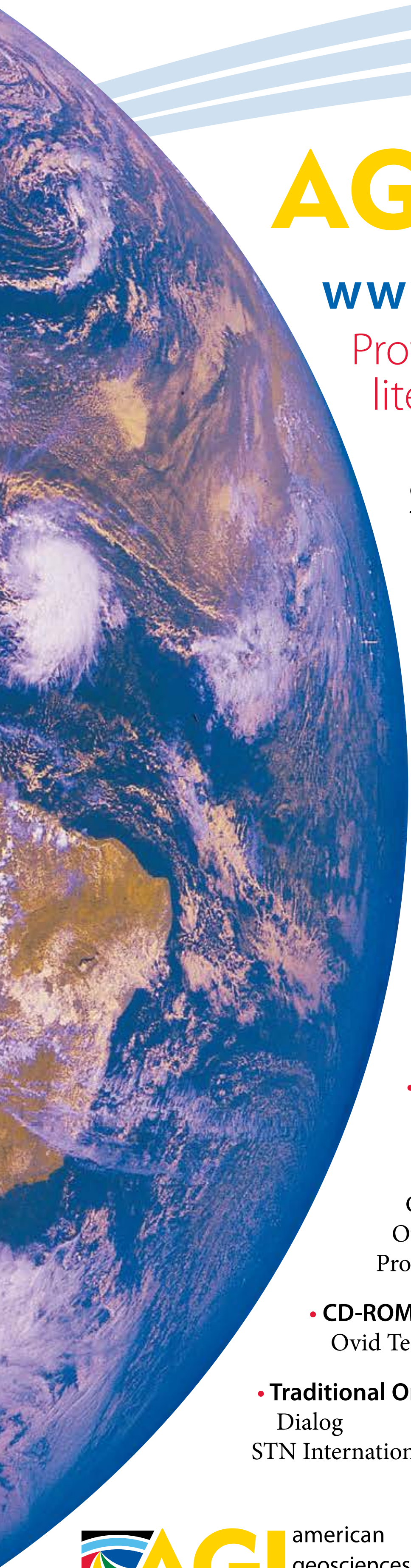

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For further information visit: www.americangeosciences.org/georef/groundwater-and-soil-contamination-database

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Comment

Making Social Media Work for Scientists

Amelie Meyer and Alexey Pavlov

Whether true or not, scientists are famous for not being great public communicators, yet communication is a key aspect of our work. Traditional science communication involves sharing findings with colleagues through published articles in peer-reviewed journals and presenting work at conferences. Scientists are encouraged to communicate using this well-defined framework and are rewarded for doing so; in fact, our career progress is often assessed using such publication records. Meanwhile, communication with wider audiences might entail visits with schoolchildren or perhaps talking to journalists for stories in a magazine like this one. But sharing findings with and promoting science to the public is a less-defined task, and often one with few incentives and little support. That communicating with wider audiences isn't encouraged is unfortunate considering many of us are funded by the public to research and answer questions relevant to society. We should clearly communicate our findings to the public, especially regarding complex topics such as climate change.

But we can take matters into our own hands: The internet, and social media platforms in particular, have opened simple and inexpensive avenues to communicate with the public. Science communication using social media not only has the potential to reach the public, but it also benefits scientists in many ways.

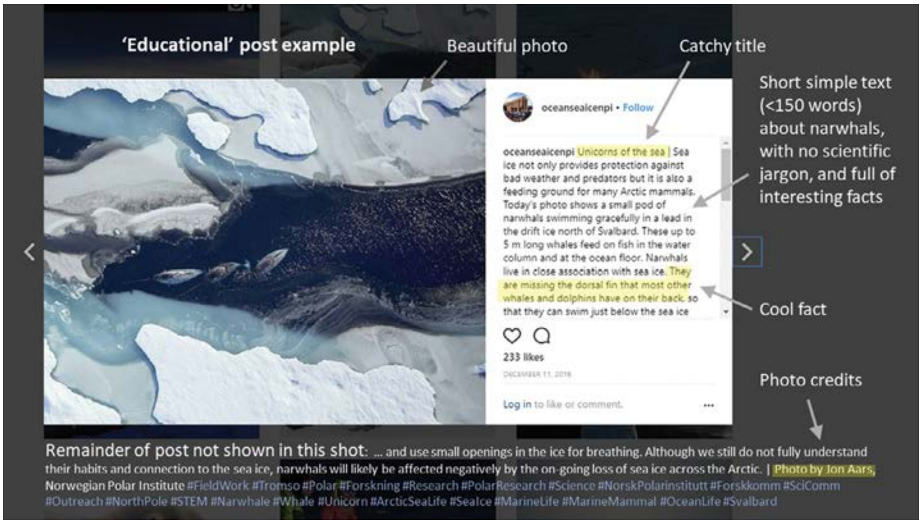
In early 2014, our team, the Oceans and Sea Ice research group at the Norwegian Polar Institute in Tromsø, Norway, created the @oceanseaicenpi handle on Instagram (www.instagram.com/oceanseaicenpi), Twitter (twitter.com/oceanseaicenpi) and Facebook (www.facebook.com/oceanseaicenpi) to communicate our science to the public and develop networks within the professional polar science community.

Scientists at the Norwegian Polar Institute (NPI) in Norway run a science outreach initiative using the handle @oceanseaicenpi. These photos were used in posts from their Instagram (www.instagram.com/oceanseaicenpi), Twitter (twitter.com/oceanseaicenpi) and Facebook (www.facebook.com/oceanseaicenpi) platforms.

Credit: clockwise from top left: Elina Nystedt (NPI), Paul A. Dodd (NPI), Jon Aars (NPI), Sebastian Gerland (NPI), Anja Rösel (NPI), CopernicusEU/Mikhail Itkin (NPI), Peter Leopold (NPI), Nick Cobbing (National Geographic), Amelie Meyer (NPI)

So far, our combined audience across these three platforms has grown to more than 7,000 followers in more than 100 countries. With each post, we reach many more people across a much broader area than we would by more conventional means. Our experience has been very positive: Using social media has increased our connection to the public, helped us become better communicators, grown our networks, and significantly increased the visibility of our research. Additionally, highlighting our peer-reviewed science papers through the @oceanseaicenpi channels has increased alternative metrics (altmetrics) scores that reflect the online impact of these papers, often beyond the scientific community. Highlighted papers also get more reads and more citations.

Our use of social media channels has also facilitated networking opportunities with other scientists, as well as with communities that are usually harder to connect with, such as artists, journalists and policymakers.



An example of an educational post from the @oceanseaicenpi Instagram account.

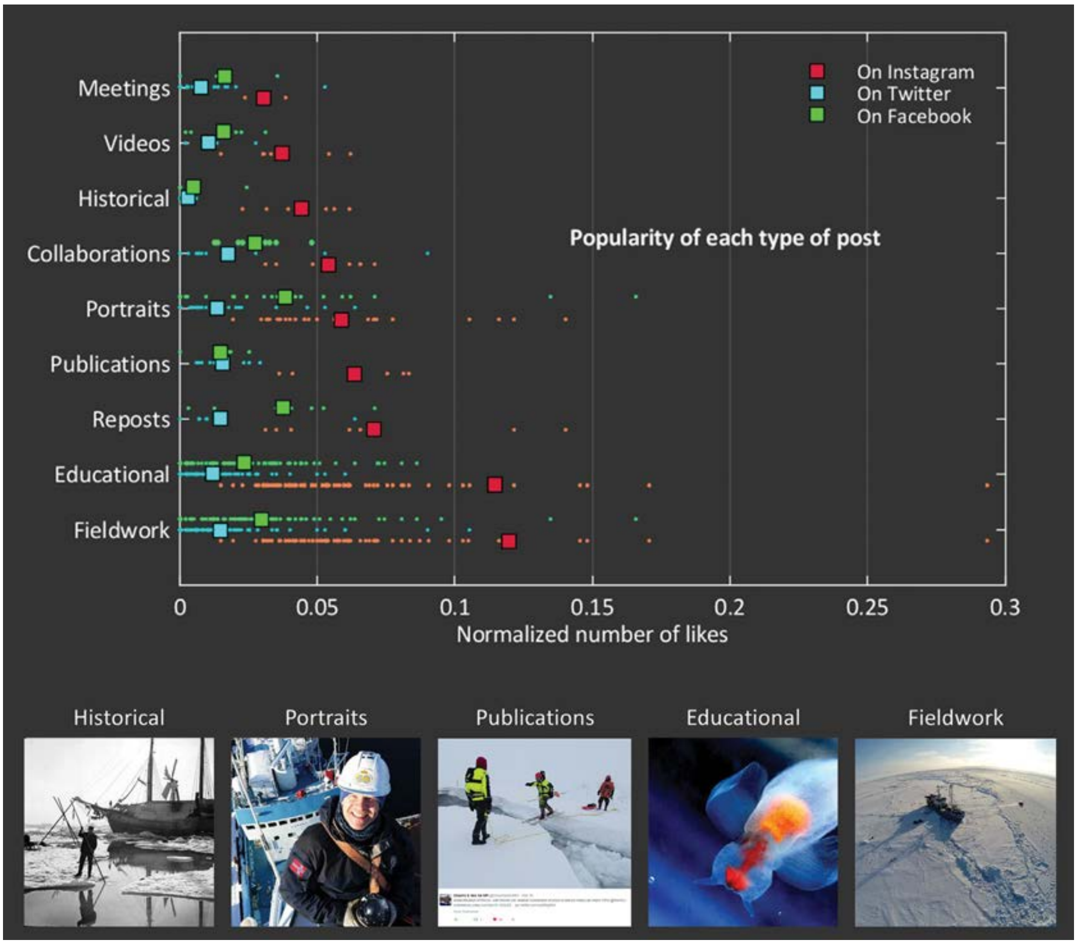
Credit: Meyer et al., Oceanography, June 2018

Creating and maintaining social media channels takes planning and effort, but the benefits of greater public outreach are worth it. To set up these channels, it's advisable to first get official approval and support from the leadership of your institution: Having a mission statement describing your goal and tools will help. Plan how tasks will be distributed within the team.

Next, decide what platforms (Twitter, Instagram, Facebook and/or others) you want to use and how you want to use them. Each platform attracts a different audience, and each allows a different type of communication. For brief announcements and posting links to papers, for example, you might use Twitter. For lengthier discussion posts, maybe use Facebook. For more visual posts, use Instagram.

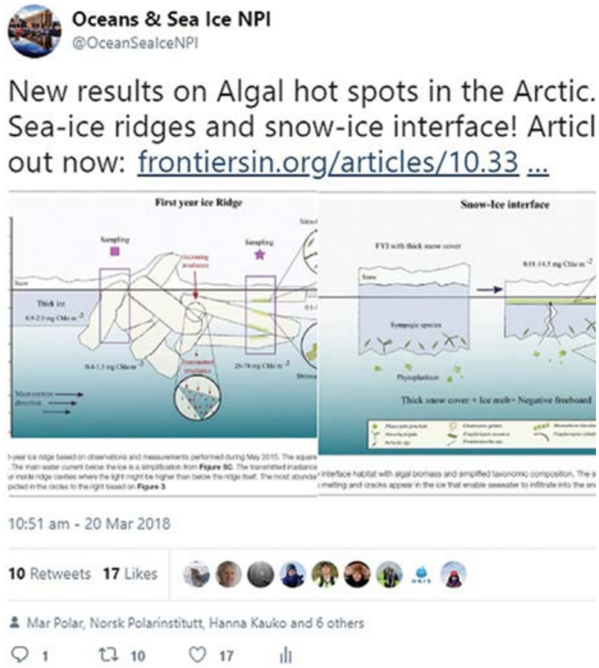
We at @oceanseaicenpi decided to classify our posts into seven categories — fieldwork, educational, project updates, historical, portraits of team members, publication highlights, and conference and meetings updates. Fieldwork posts talk about expeditions, instruments and field techniques; educational posts explain a scientific concept or introduce a topic such as ocean optics; project updates talk about ongoing projects and planned experiments; historical posts can be about famous scientists, historical expeditions or old maps, for example; team member portraits highlight individual scientists in our group; publication highlights present recently published papers by the team and collaborators; and finally, conference and meetings updates mention workshop attendance or advertise talks about to take place at a conference.

In terms of what we post to which platform, we have realized that certain types of



Popularity of each type of post based on likes on Instagram (red), retweets on Twitter (blue), and likes on Facebook (green), where the number of likes or retweets has been normalized by the number of followers at the time of the post. Small dots represent individual posts, while large squares are the mean for each type of post. Note that the x-axis has been truncated for clarity and that some posts reached values close to 1.

Credit: from left to right: Henrik Blessing, Tor Ivan Karlsen, Tor Ivan Karlsen, Amelie Meyer, and Sebastian Sikora (NPI), from Pavlov et al., BAMS, June 2018



Example of a publication highlight post on the @oceanseaicenpi Twitter channel.

Credit: Fernandez-Mendez et al., Frontiers in Marine Science, March 2018

posts are more popular than others and that followers on different social media channels have different preferences. We figured this out by keeping track of the number of likes and shares of each type of post. For our channels, fieldwork and educational posts are most popular on Instagram, publication highlights on Twitter, and team portraits on Facebook.

Finally, start posting! Each post should have one key message, ideally explained in less than 150 words and, vitally, accompanied by an engaging photograph or illustration. Be accurate and check your facts. And use tags and hashtags — like #SciComm or #polarfox, matching the theme of the post — to increase your reach.

Get to know your audience and post when your followers are most responsive. You can work this out using the built-in analytics for each platform, which provide basic statistics: information such as who and where your followers are, when they are online, how much they clicked or shared a post, and what their interests are. Analytics can also help you assess the impact of your social media outreach.

More and more individual researchers are using social media platforms (especially Twitter) for professional networking and science communication. But the numbers of scientists and research groups on social media are still low.

Running social media channels can be time-consuming, especially if you're doing it on your own, and it requires adept coordination if it's a team effort. It might seem easier to work on overdue manuscripts than to invest time in new outreach tools. Nonetheless, scientists should be taking advantage of these tools to better communicate our science.

Example of an @oceanseaicenpi post on Instagram showing a researcher standing in a melt pond atop Arctic sea ice, which is about 1 meter thick.

Credit: Alexey Pavlov (NPI)

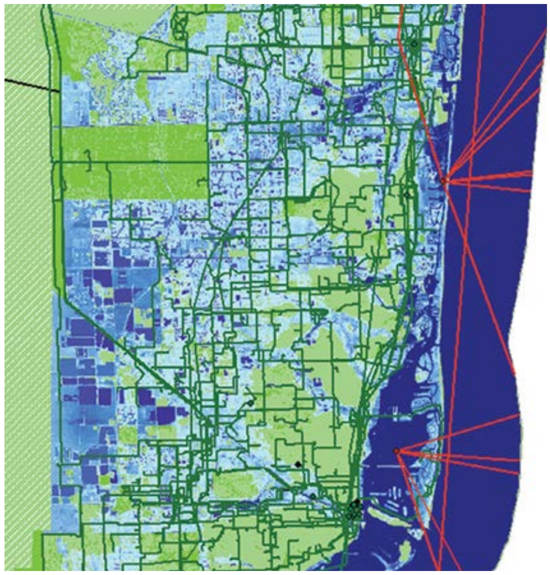
Meyer, formerly at NPI, is now a research associate at the ARC Center of Excellence for Climate Extremes at IMAS at the University of Tasmania in Hobart, Australia. She specializes in polar oceanography and advocates for science communication and outreach.

Credit: Allison Bailey (NPI)

Pavlov (@mvpgeo), also formerly at NPI, is an interdisciplinary Arctic researcher and science communicator who currently works for Akvaplan-niva and the Institute of Oceanology of the Polish Academy of Sciences. They've presented about the potential of social media for science communication at several conferences as well as in recent papers in the Bulletin of the American Meteorological Society (Pavlov et al., June 2018) and Oceanography (Meyer et al., June 2018). They can be reached through their social media accounts at: twitter.com/OceanSeaIceNPI, www.facebook.com/oceanseaicenpi and www.instagram.com/oceanseaicenpi/. The views expressed are their own.

Credit: Anna Raczkowska, Institute of Oceanology of the Polish Academy of Sciences

Underwater WiFi? Rising sea levels threaten physical internet



On this map of Miami, blue areas are projected to be underwater by 2118, according to NOAA. Undersea, long-haul and local metro fiber cables are shown, respectively, in red, green and black.
Credit: Paul Barford, UW-Madison

It seems like you can find wireless internet almost anywhere now, but the backbone of the internet is wired: Infrastructure such as fiber optic cables, data centers, traffic exchanges and hubs keeps us connected. In many coastal cities, however, these critical communication pieces are facing increasing risk from rising seas. A new study shows that thousands of kilometers of cables and hundreds of internet traffic hubs will be inundated by rising sea levels in the next 15 years, putting coastal cities like New York, Miami and Seattle at risk for widespread disruptions.

Much of the cable that makes up the physical internet is buried, following existing rights of way such as highways and railroads built along coastlines. "When these networks were first installed around 25 years ago, little thought was given to the impact that climate change and rising sea levels might have on these components," says Paul Barford, a computer scientist at the University of Wisconsin-Madison and senior author of the new study, which was presented in July at the annual Applied Networking Research Workshop in Montreal.

For the past seven years, Barford and his colleagues have been mapping the physical components of the internet installed and owned by more than 1,500 service providers for a project known as the Internet Atlas. "We now have the largest repository of maps of physical internet infrastructure in the world, which gives us a unique perspective and a unique capacity to study different aspects of the internet's vulnerabilities," Barford says. By overlapping their Internet Atlas with sea-level rise projections from NOAA, the team identified 6,545 kilometers of fiber optic conduit and 1,101 nodes that will be underwater in the next 100 years. "The most surprising finding in our analysis is that most of the infrastructure at risk will be underwater in the next 15 years," Barford says. "The expectation was that we'd have 50 years to plan for this, but we don't have 50 years."

Some parts of the physical internet are designed to function underwater, specifically the transoceanic cables that run along the seafloor to connect continents. "Submarine cables are superbly engineered for the marine environment," Barford says. "They're also incredibly expensive to make, deploy and maintain." In contrast, the fiber optic cables that carry communication signals over land typically run through PVC pipes that are merely weather resistant. "Rainwater and groundwater typically don't penetrate the pipes unless there's a breach," he says. But "they aren't designed to function fully submerged in water."

The points of the physical internet at greatest risk to seawater inundation are landing points where marine cables connect to standard fiber optic cables, Barford says. "Most landing points are very close to coastlines. Given the projections of seawater inundation, those landing points are likely to be surrounded by [water] or underwater in the very near future," he says.

Coastal flooding and storm surges associated with hurricanes, like Katrina, Sandy and Harvey, offer glimpses of how rising sea levels may impact internet connectivity, Barford says. "Katrina and Sandy were disasters of epic proportions. It took years to restore service to some of those areas."

The internet was designed to be resilient, with many redundancies built into the system, says Duane Verner, an urban planner with the Decision and Infrastructure Sciences Division at Argonne National Laboratory in Illinois, who was not involved in the new research. "But there are key hubs, links and nodes in the system that can cause widespread disruptions, perhaps even globally, if they are compromised. This study is an important first step in identifying the most vulnerable components," he says. It also highlights the rapid onset of the problem. "Sea levels are rising and becoming an issue much faster than anybody thought."

The next step will be to model the dynamic flow of data through the physical internet to identify which of the vulnerable regions are most crucial for maintaining connectivity. "The clusters of risk that this team has identified should be the starting points for further modeling," Verner says. "It's important to identify which ones are truly key and focus mitigation efforts at those connections."

Mitigating the effects of sea-level rise will take unprecedented cooperation from government agencies, internet providers, and major cities and municipalities. "The internet is a unique animal. It's not run by any one entity, and no one entity is responsible for maintaining it in the face of climate change," Barford says. The best strategies for coping with rising seas have yet to be identified, but Barford predicts that solutions will combine various means of infrastructure hardening, such as building sea walls, waterproofing hub buildings, fortifying cables and relocating some networks farther inland, with efforts to streamline existing networks. "The Internet Atlas shows that there's a huge amount of cable infrastructure in the U.S. One of the things we can do is use existing infrastructure in other areas to reroute the communication traffic," he says.

"We hope that this study will serve as a call to action on this issue," he says. "As we see it, we only have about 15 years to make these changes."

Mary Caperton Morton

STEVE not an aurora after all

Earlier this year, scientists published a paper identifying some auroral spectra that had previously been called "Steve" by amateur auroral enthusiasts as a particular type of auroral event known as a Strong Thermal Emission Velocity Enhancement, or STEVE. However, using a network of ground-based imagers combined with energetic particle detectors aboard NOAA's Polar Orbiting Environmental Satellites, scientists have now determined that STEVE is, in fact, not an aurora. They are unsure, though, what causes the sky glow, and suspect it may be caused by an as yet unknown mechanism.

Gallardo-Lacourt et al., Geophysical Research Letters, August 2018

Globe-trotting kelp set new world record

When marine biologist Erasmo Macaya, from University of Concepción in Chile, found a piece of kelp washed up on a beach in Antarctica, he suspected the scrap of seaweed had come a long way.

"Kelp does not grow in Antarctica, but we know it can float and can act as a raft, carrying many other intertidal plants and animals with it across oceans," he said in a statement released with a new study in Nature Climate Change. DNA testing revealed the kelp had traveled more than 20,000 kilometers, in the longest-known marine rafting event ever recorded.

Previously, scientists had thought that Antarctica's flora and fauna were effectively isolated from the rest of the world due to its remote location, but the new study suggests that influxes of new biota are limited more by the icy continent's environmental extremes than by geographic isolation.

"This is an unequivocal demonstration that marine species from the north can reach Antarctica," said lead author Ceridwen Fraser of the Australian National University in Canberra. Modeling by Fraser and colleagues demonstrated how the kelp could have reached Antarctica from the Kerguelen Islands in the southern Indian Ocean. Another scrap of kelp was traced to South Georgia Island in the South Atlantic.

"Our findings also indicate that plants and animals living on Antarctica could be more vulnerable to climate change than we had suspected," Fraser said, as living conditions become milder, allowing more invasive species to gain a foothold on the extreme landscape.

Mary Caperton Morton

Saharan dust a storm killer

Each year between 900 million and 4 billion metric tons of dust from the Sahara Desert in Africa is swept into the atmosphere and blown around the world. In places like Texas, the dust often leads to poor air quality. A new study suggests that desert dust may also suppress the formation of severe storms and hurricanes in the southern United States.

NASA satellite imagery shows Saharan dust crossing the Atlantic Ocean into the Gulf of Mexico, where the dust may suppress developing storm systems.

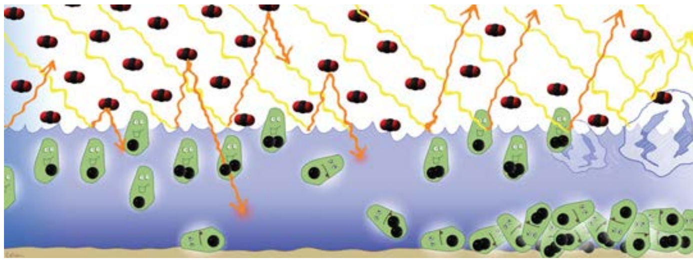
Credit: NASA/Texas A&M University

Bowen Pan, a graduate student at Texas A&M University, and colleagues used atmospheric computer models to study how Saharan dust moving across the Gulf of Mexico into southern Texas might affect storms generated in the Gulf. They reported in the Journal of Climate that dust-laden air creates temperature inversions that tend to prevent cloud and storm formation while also reducing the amount of sunlight reaching Earth's surface.

"If we have more frequent and severe dust storms, it's likely that we will have cooler sea-surface temperatures and land-surface temperatures," Pan said in a statement. The colder surface temperatures in turn provide less kinetic energy to fuel the storm systems, dampening their severity.

Mary Caperton Morton

Algae ate themselves to death and caused a global extinction



A new study suggests that enhanced burial of carbon from eukaryotic algae drew down atmospheric carbon dioxide levels during the Ordovician, resulting in a diminished greenhouse effect that triggered an ice age and a mass extinction.

Credit: Callan Bentley, 2018

Errant asteroids and toxic emissions from volcanic eruptions are the usual suspects in mass extinctions. But during the Ordovician, it was a million-year stretch of cooling ushered in by proliferating algae that triggered a worldwide glaciation and extinction event, according to a new study.

The Hirnantian mass extinction occurred during the Late Ordovician about 445 million years ago and was the first major extinction event of the Phanerozoic. The extinction hit shallow-water marine creatures especially hard, with 26 percent of families and 49 percent of genera disappearing.

Previous research has suggested that changes in atmospheric carbon dioxide levels — brought on by changes in the carbon cycle, increased volcanic activity or increased weathering of land as terrestrial plants developed — triggered the Hirnantian extinction and an ensuing ice age. These processes would have driven more nutrients into the sea, increasing the productivity of marine algae, says Ann Pearson, a biogeochemist at Harvard and co-author of the new study in Nature Geoscience. But these scenarios don't fully explain the global changes that occurred at the time, she adds. The challenge, she says, was connecting the algae to carbon storage, especially over a million years or more.

Previous studies looked at lipid biomarkers in, and the inorganic chemistry of, Ordovician rocks. Pearson and her colleagues used similar approaches but also found residues of both bulk organic matter and molecules called porphyrins — leftover chemical products of photosynthesis — preserved in rock from the Ordovician Vinini Creek section in Nevada. Together with carbon and nitrogen isotopic data also gleaned from the rock, the porphyrins the researchers detected allowed them to estimate how both algae and marine cyanobacteria were faring just before the Hirnantian extinction.

The team found that algae living just before the Hirnantian were plentiful — and big. "Our new data specifically point to an expansion of eukaryotic algal cells relative to cyanobacterial cells," Pearson says. Eukaryotes are larger than cyanobacteria, and they sink faster through the water column — consistent with the idea that biomass and carbon burial would have increased as populations of eukaryotic algae grew. "The faster an algal cell reaches the sediment, the higher the percentage of its carbon that will ultimately be buried rather than quickly recycled back to [the atmosphere as] carbon dioxide," Pearson says.

As more carbon was sequestered from the atmosphere and buried, the planet cooled. And the porphyrins preserved in Vinini Creek rocks are the proof of this process.

It's "quite exciting" to see a study detailing porphyrins found in ancient rocks, says Amber Jarrett, a geochemist with Geoscience Australia who was not involved with the study. Porphyrins are big molecules that easily break down over geologic time into smaller molecules called lipids. When looking at rocks from deep time, she says, "it's rare to find such well-preserved molecules."

Explosive growth of ancient algae, like that documented by Pearson and her co-authors, is not unheard of. Jarrett points out that after the near-global glaciations of the Proterozoic called "Snowball Earth" events, there was so much phosphorus (from glacial erosion of continents) and food in the water column that algae gorged themselves, leading to large-scale burials of carbon. But the Ordovician is different. "In this case, it's like [algae] had this huge party and then caused their own glaciation," she says. "Basically, they ate themselves to their own demise."

The work highlights the important interactions between biological activity and physical processes like changes in sea level and sedimentation, Pearson says. "Changing biology on its own was insufficient to trigger this climate event," Pearson says. "But similarly, the geological processes by themselves cannot create enough of a perturbation in the carbon cycle." Instead, it took a combination of factors to send the planet into a glaciation.

The team's approach is a great example of how multiple proxies can be used together to recreate past environments, Jarrett says. "They've taken the inorganic chemistry, the isotopes, the porphyrins, and used the biomarker work that's been done [before] — all of these things stack up and tell the same story" of a drawdown of atmospheric carbon — and consequently a cool down — during the Late Ordovician.

Jarrett says studies like this can help scientists understand future as well as past climate change, and that there are also industrial applications of reconstructing past algal blooms, which degrade over time to produce petroleum deposits. In this case, a massive algal bloom was followed by a global glaciation. "These glacial units [like those found in the Hirnantian glaciation] are really thick and really identifiable," Jarrett says, explaining that finding glacial markers may allow identification of potential basins for future petroleum exploration.

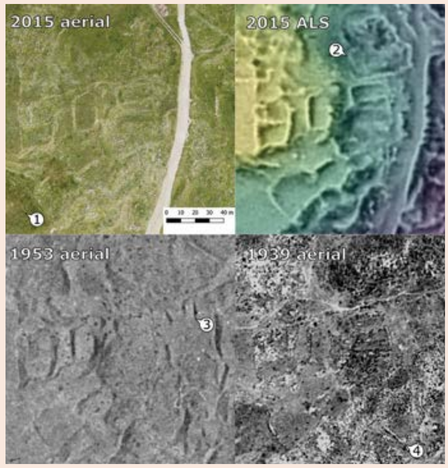
Sarah Derouin

Turning modern "eyes" on ancient sites

People have inhabited Jerash, Jordan, since the Neolithic. But much of its history has been buried by subsequent occupation, including over the last two centuries. Archaeologists have excavated Jerash with trowels and screens to uncover its long history, but now, with the help of lidar and old photographs, a team of researchers is discovering more about Jerash's past by gazing down on the city from the sky.

Previous studies focused on monuments rather than sites associated with everyday life, so "we know nothing about what went on in the part of the city where people actually lived," says Rubina Raja, a classical archaeologist at Aarhus University in Denmark and a co-author of the new study in Proceedings of the National Academy of Sciences. The team wanted to study the unknown areas using approaches less intrusive than excavation, says lead author David Stott, also an archaeologist at Aarhus.

The team collected a series of 10 historical aerial photographs over Jerash from 1917 to 1953 from various sources, and a 2015 lidar image of the city from the Royal Jordanian Geographic Center. The photographs were processed to remove geographical distortions typical in old aerial photographs taken from various angles, Stott says, so the team could confidently compare the same locations at different times. After comparing the historical images, the team used GIS software to analyze the lidar image, revealing subtle topographic changes that potentially indicated archaeological remains, he says.



Researchers used different datasets to uncover Jerash's past, because each dataset showed something different. 1) High-resolution photography revealed a stone wall not visible in other datasets. 2) Lidar clearly revealed another wall that was poorly defined in aerial photography. 3) Clearing up distortions in this 1953 photo revealed a possible structure defined by highlight and shadow that was obscured by a modern road in 2015 and by vegetation in 1939. 4) This wall from the 1939 aerial photo was not visible in other datasets.

Credit: Danish-German North-West Quarter Project

The ancient city of Jerash is juxtaposed with the modern one.

Credit: Danish-German North-West Quarter Project

The researchers then created maps showing possible locations of former roads, walls and other infrastructure, including those that had disappeared at some point. These maps provided a means to observe the city's changing landscape over the past century, particularly where archaeological remains had been lost to recent development.

"In a place like Jerash, if we only use modern data, there's a lot of stuff we don't see," Stott says. It's important to see features in their original context, especially large features like aqueducts and roads, he says. "We still have bits of [these large features] left in the present. But without being able to see the whole [urban] system, they don't mean very much, and that's really what the archival imagery and the deep-time perspective add to this work."

Combining remote-sensing data with old aerial photos is a key contribution of this work, says John Weishampel, an environmental scientist at the University of Central Florida who specializes in remote sensing but was not involved in the study. "Those older datasets allow you to have a more complete picture of the entire city area" and the activities occurring in and around the urban center, Weishampel says.

Some features identified in the work, like cisterns and channels, were known, but the researchers also documented previously undiscovered elements of the city's ancient water management system, such as a potential aqueduct and potential reservoirs. "Water management, in antiquity, and even today, in these semi-arid areas … means everything for survival," Raja says. "If we can get to the heart of how water was managed over centuries or millennia, we might actually crack the code to the resilience threshold for urban societies over time."

This has modern implications, Raja notes. "When are you overexploiting your resources, and when does the balance tip so that urban societies disappear? Looking at that in a historical perspective might give us some new thoughts on what we can do for modern situations."

Next, the team plans to investigate the area around Jerash and keep probing the city's ancient water management, Stott says. Many previous excavation reports remain unpublished, so the researchers want to explore excavated areas they identified on their maps. Indeed, the need for careful documentation and sharing of archaeological data is another important lesson of this study, Raja says.

The research may also prove useful for identifying where archaeological remains in other areas are threatened by modern development or conflict, Weishampel says.

Lauren Milideo

Japanese diaries show sun's cycle sparks lightning on Earth

The effects of solar cycles on Earth's climate over timeframes of thousands of years are well documented, but the shorter-term effects on weather are less understood. A new study using ancient Japanese diaries to track storms in the 18th and 19th centuries suggests that one of the sun's shortest cycles — the 27-day rotational period — may play a role in stimulating lightning on Earth.

Every 27 Earth days, the sun completes a full rotation about its axis. As the sun turns, sunspots, solar flares and coronal mass ejections can come into alignment with Earth, sometimes subjecting our planet to spikes in ultraviolet radiation and solar winds that can lead to increased storm activity on Earth. "The exact mechanisms that cause these changes [in Earth's atmosphere] remain unknown, but we propose that the electrical properties of the air are somehow altered as the incoming charged particles collide with the atmosphere," says Hiroko Miyahara, a physicist at Musashino Art University in Tokyo and lead author of the new study, published in Annales Geophysicae.

Miyahara and his colleagues turned to two diaries kept in Japan for a period spanning more than 200 years. A farming family in Hachioji, in what is now in the western part of Tokyo, kept the "Diary of the Ishikawa Family," recording agricultural milestones such as plantings and harvests, natural disasters like fires and floods, and daily weather reports. The second diary, "Diary of Hirosaki Clan Government Office," was kept by civil servants in Edo, in what is now central Tokyo.

"The advantage of using these diaries is that we can study the characteristics of meteorological phenomena for a more than 200-year period," Miyahara says, "including periods when solar activity was much [stronger] or weaker than today." The team looked for references to thunder and lightning between the months of May and September and found peaks in activity every 24 to 31 days — the window for increased sunspot exposure during the solar rotation.

"It's pretty amazing that even using somewhat crude records such as centuries-old diaries, they can still see this 27-day signal," says Chris Scott, an ionospheric physicist at the University of Reading in England, who was not involved in the new study. The study complements other published studies that have detected the 27-day solar rotational cycle in modern lightning records. Those records typically span less than a decade, however, while the new study is the first to offer a long-term look at these cycles, Scott says. "The more cycles you have, the better, statistically speaking," for documenting such phenomena, he says.

The next step should be to use the Japanese diaries to assess whether they document weather patterns influenced by the sun's 11-year sunspot cycle, Scott says. And, he notes, "we know from looking at ice-core and tree-ring data that the sun has even longer cycles that occur over hundreds of years. Anything we can use to tease out those relationships is really helpful."

Improving our understanding of the mechanisms behind the sun's influence on Earth's weather is important, Scott says. "Solar winds don't directly create lightning, they just enhance it. You still need the right storm conditions, such as convective instability and ice particles rubbing against one another, to generate lightning."

The research may prove useful for weather forecasting, Miyahara says. "Solar wind streams rotate with the sun, sweeping past Earth at regular intervals, [sometimes enhancing the atmospheric conditions needed to generate lightning storms]. As these streams can be tracked by spacecraft, this offers the potential for predicting the severity of hazardous weather events many weeks in advance."

Mary Caperton Morton

New research links lightning to the 27-day solar rotational cycle.

Credit: ©iStockphoto.com/mdesigner125

Marine animals have been migrating for millions of years

Scientists have suspected that ancient animals migrated in response to changing global temperatures, but until now, there was no documentation of this across extensive time periods. In a new study, researchers found that, for millions of years, marine organisms like corals, sponges and snails, have shifted their ranges in response to climate change.

"Life always tracks its preferred temperature as climate changes," says Carl Reddin, a paleobiologist at the University of Erlangen-Nürnberg in Germany and lead author of the new study, published in the journal Global Ecology and Biogeography. By analyzing North American and European fossils, Reddin and his colleagues uncovered migration patterns of ancient marine organisms over the last half billion years. The team used a global paleobiological database to analyze the occurrence of hundreds of thousands of fossils. Based on age estimates, fossils were grouped into one of 94 geological ages, which averaged 6.12 million years.

Then, the team filtered the data. For instance, one requirement for their data collection was that the organisms did not go extinct during the time period the study was investigating. Additionally, they identified and grouped animals at the genus level, rather than as individual species. "The main reason we use genera instead of species is because that's the level of confidence most fossils can be identified to," Reddin says. Overall, the scientists analyzed 458,000 fossils in 76,000 fossil collections.

Reddin and his team also had to correct for sampling biases. They wanted to analyze where the organisms lived, not where they were found. "Most fossils are found where paleontologists [spend the most time searching], and that has historically meant North America and Europe," says Matthew Powell, a geologist at Juniata College in Pennsylvania, who was not involved in the study.

To correct for that bias, the scientists averaged the latitude at which fossils were found for all specimens of a given genus, as well as the average of all fossils found. The difference in those two numbers is the latitude the scientists used to analyze migration over time. They tracked only genera that survived across time steps, only from well-fossilized groups such as clams, only at geographic grid cells that were sampled across time steps, and focused on the best sampled hemisphere.

Once the scientists had the corrected latitude coordinates for the fossils, they could find the change in a genus' location over time. Then they modeled how plate tectonics impacted the animals' movements and compared the results to the locations of the animals' current habitats.

Reddin and his team found that organisms had shifted their ranges in response to climate change over the post-Cambrian Phanerozoic Eon. The genera studied moved an average of about 30 centimeters per decade.

Climate change explained 31.4 percent of the migration. This number is higher than what's been observed in recent studies of marine life range shifts, Reddin says. Other explanations for shifting ranges could involve changes in habitat availability, he adds.

The researchers found that the shifts were stronger among tropical organisms, and weaker among high-latitude organisms, which was surprising because they thought polar organisms would move toward the equator seeking more suitable habitat during cooling episodes. "In some ways we were expecting high-latitude organisms to show this pattern a bit more strongly," Reddin says.

Looking at the past can help scientists understand the future. Current studies show that marine organisms today are already shifting their ranges based on changing temperatures. What that means for future ecosystems and the potential risks to humans is unknown, Reddin says. "That was the overall motivation for looking at this question, given the climate warming we are experiencing at the moment," he says.

Marine organisms like corals, sponges and snails have been migrating for millions of years, mostly driven by temperature changes.

Credit: Carl Reddin

"I'm excited by this paper," Powell says. "This study enables us to use the fossil record to start answering some questions about how organisms have responded to climate change in the past." Powell says he hopes more studies like this will follow. In the fossil record, "we have not really been able to explore changes in geographic ranges of taxa," he says. "It's really only been treated at the global scale."

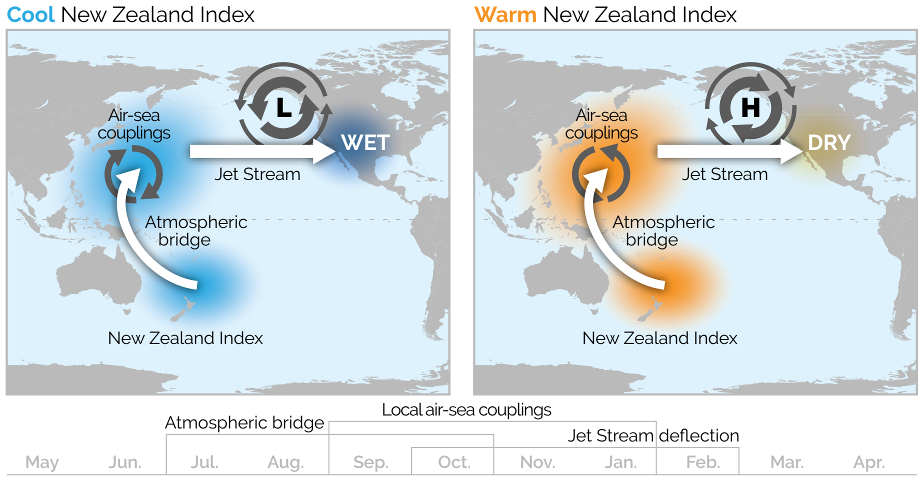
Bethany Augliere

Record Atlantic hurricane season unlikely to be topped

The 2005 Atlantic hurricane season set a historical record with 15 hurricanes — Katrina, Rita and Wilma among them — plus 13 other named tropical storms. New research based on millennia-long climate simulations suggests that, under existing climate conditions, the odds of another season producing as many or more named tropical storms are between about 1 and 9 percent. Even when the number of storms in a simulated year surpassed 28, it was not by much. Thus, researchers wrote, the 2005 season can serve as a "risk management benchmark for the maximum possible number of tropical cyclones in the Atlantic."

Lavender et al., Science Advances, August 2018

Winter precipitation in southwestern U.S. tied to Kiwi Coast



New research suggests a strong negative correlation between fall sea-surface temperatures off the north coast of New Zealand and winter precipitation in the southwestern U.S. If, for example, there are lower-than-normal sea-surface temperatures north of New Zealand, there is a much higher chance for a wet winter in Southern California and the southwestern U.S.

Credit: K. Cantner, AGI, after Mamalakis et al., Nature Communications, June 2018

Water supplies in the southwestern United States largely depend on winter precipitation. Predicting seasonal rain and snowfall is becoming more difficult, however, as climate change causes precipitation patterns to vary. A new study provides evidence of a strong correlation between late-summer to fall sea-surface temperatures off the coast of New Zealand and winter precipitation in the southwestern U.S. — a correlation that could help provide earlier and more reliable forecasts for the southwestern U.S., and improve water resource and ecosystem management in the region.

The predictability of the effects of the El Niño-Southern Oscillation (ENSO) — and other established teleconnections such as the Pacific Decadal Oscillation (PDO), the Interdecadal Pacific Oscillation, the Atlantic Multidecadal Oscillation, and atmospheric high-pressure ridges over the Gulf of Alaska — on seasonal precipitation in the southwestern U.S. is limited. "In much of the southwestern U.S., there are major important variations in precipitation which have previously been loosely associated with El Niño events," says Kevin Trenberth, a senior scientist at the National Center for Atmospheric Research in Boulder, Colo., who was not involved in the study. "Previous studies have indeed found that this New Zealand region is unique and plays a very strong role in the evolution of ENSO and the PDO," he says, but "this [study] is important in highlighting some long-distance teleconnections that have not been well explored previously."

In the new research, published in Nature Communications, Antonios Mamalakis, a doctoral candidate at the University of California, Irvine, and colleagues explored whether undiscovered teleconnections could influence southwestern U.S. precipitation. "We did not restrict ourselves [to] looking only [at] tropical Pacific sea-surface temperatures; our diagnostic analysis was global," Mamalakis says. The team evaluated relationships from 1950 to 2015 between winter (November – March) precipitation amounts in Arizona, California, Nevada and Utah and both global monthly sea-surface temperature data and geopotential height (GPH) reanalysis data for late summer (July – September) and fall (September – November). "GPH represents the height from Earth's surface to reach a specific value, or level, of atmospheric pressure," Mamalakis says. They looked at GPH data because "sea-surface temperature correlates positively with GPH ... GPH is lower over colder water, and higher over warmer water," he says.

The team found a strong negative correlation between fall sea-surface temperatures off the north coast of New Zealand and winter precipitation in the southwestern U.S. — a correlation that was shown to be strongest over the past 40 years. "This means that in years we had lower-than-normal sea-surface temperatures in New Zealand, we had a much higher chance to have wet winters in Southern California and the southwestern U.S.," while warmer-than-normal sea-surface temperatures off New Zealand correlated with higher odds of dry winters in the southwestern U.S., Mamalakis says. That is "the same strong correlation we found using GPH, which provided confidence in our findings," he adds. Mamalakis and colleagues refer to this teleconnection as the New Zealand Index (NZI).

The team suggests that above, or below, average sea-surface temperatures near New Zealand can weaken, or strengthen, the Hadley cell (a large-scale atmospheric circulation pattern that circulates air from the tropics to mid-latitudes). This introduces anomalous temperatures in the northern and central Pacific, which can then reposition storm tracks controlling the amount of precipitation received in the southwestern U.S.

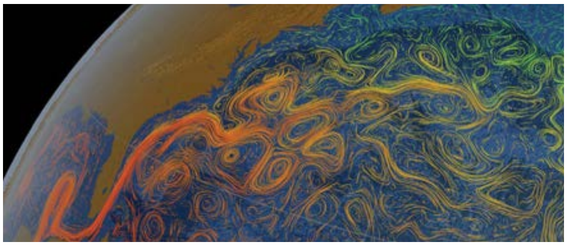
However, Trenberth says, the GPH reanalysis data used in the study are questionable because the reanalysis was constructed only from surface data — it doesn't include information about winds, or upper atmospheric conditions from radiosonde data, balloon sounding data, or satellite data. "There are much more detailed and more credible reconstructions of what has happened in the atmosphere ... but it's difficult to go back before about

1979." So he says he understands why the researchers used these data. "But in terms of reconstructing important ingredients that go into this [atmospheric record], they might be missing a little bit," he adds.

"This [study] sort of demands a follow-up to explore how and why this [teleconnection] is happening," Trenberth says, "and how this relationship might be exploited to give better guidance as to what's happening in California and a little farther to the east. That information could be very valuable to a lot of people."

Jennifer Georgek

Gulf Stream eddies transport iron to North Atlantic subtropical gyre



New research shows that counterclockwise-rotating cold eddies are transporting iron from the Gulf Stream into the North Atlantic subtropical gyre.

Credit: NASA Goddard Space Flight Center Scientific Visualization Studio

Dust from the Sahara Desert is a major supplier of iron to the North Atlantic subtropical gyre — the huge circular ocean current stretching between North America and the west coasts of Africa and Europe — where cyanobacteria use the scarce nutrient to fuel nitrogen fixation, which then fertilizes other organisms at the base of the marine food chain. Now, researchers have discovered that eddies spinning off the Gulf Stream also transport iron to the northwestern edge of the gyre.

Iron content can be challenging to measure because samples are easily contaminated with metal from instrumentation and other sources, says Jaime Palter, a physical oceanographer at the University of Rhode Island and co-author of a new study in Nature Geoscience. With few experts available who are trained in clean iron sampling techniques, "every measurement [of oceanic iron content] is considered very valuable," she notes.

Scientists already knew that eddies swirling off the Gulf Stream transport phosphorus to the subtropical gyre. The discovery that such eddies also transport iron happened serendipitously when researchers examined previously published dissolved iron concentration data collected during a November 2011 oceanic research expedition from North America to Bermuda.

"The data was collected as part of a U.S. National Science Foundation-funded GEOTRACES expedition — an international program involving 35 countries, which is mapping the oceans for trace elements," notes Timothy Conway, a chemical oceanographer at the University of South Florida and lead author of the study.

The team found evidence of a "cold core ring" — a type of "mesoscale" eddy that typically is less than 100 kilometers in diameter and rotates counterclockwise, forming a low-pressure system in the atmosphere above it that's sustained over the several-year life cycle of the eddy. Within the otherwise iron-poor subtropical gyre, this ring contained iron-rich water originating from above the North American continental slope.

The team analyzed satellite altimetry data from 1993 to 2014. "Altimetry gives a measure of sea-surface height — and deformations of the sea surface are a very clear indicator of the presence of eddies," Palter says. Their analysis revealed that approximately seven to eight cold core rings potentially capable of delivering iron to the subtropical gyre broke off the Gulf Stream each year. The finding, the team wrote, suggested that such rings could represent a significant source of iron to the North American subtropical gyre.

From there, the team looked at how the amount of iron transported to the subtropical gyre by cold core rings compares to that delivered via iron-rich dust from the Sahara, which was thought to be the leading source of iron for this area, Palter says.

The team estimated that the rings deliver about 15 percent as much iron to the area as atmospheric Saharan dust does, but the actual amount of iron delivered by the rings "could be much higher (or as low as a few percent)," Palter notes. To calculate the amount of iron delivered by the rings, the team first estimated the total iron flux to the gyre, based on the average number of rings, their average surface area and other considerations. "Then we accounted for rings that get re-absorbed by the Gulf Stream before sharing the iron with the gyre. Finally, we compared the result of this calculation against a compilation of atmospheric fluxes," Palter says.

Although it appears for now that the eddies deliver less iron than dust does, she notes that there are still unanswered questions about the dust-delivered iron, such as how much of it dissolves in seawater and becomes bioavailable for phytoplankton to use. Eddy-delivered iron, meanwhile, is readily bioaccessible. Further study, she says, may reveal whether these eddies contribute an almost equal share, just a small fraction of the usable iron, or some amount in between.

Ocean eddies can carry iron and other materials over long distances and are known to be "leaky," but the extent of this leakiness through an eddy's lifetime is unknown, says Ivy Frenger, a biogeochemist at GEOMAR Helmholtz Center for Ocean Research Kiel in Germany, who wasn't involved in the new study. Follow-up work is needed to determine if standard biogeochemical models of ocean mixing can adequately represent these transport processes or if updated models are needed, Frenger says.

"This is a very interesting study that highlights very well the importance of mesoscale ocean circulation — more specifically [cold core] rings — on primary productivity in the ocean," says Carolina Dufour, a physical oceanographer at McGill University in Montreal who was not involved with this study. "Because iron is key to primary productivity, better understanding of the sources of iron to the ocean" could help researchers better predict the impacts of oceanic processes on Earth's climate, Dufour says.

Rachel Crowell

Amazon River is capturing the Orinoco

In Venezuela, thousands of kilometers from its mouth, the Rio Orinoco bifurcates, sending about 25 percent of its water into the Rio Casiquiare, which leads to the Rio Negro, a tributary of the Amazon. While the connection has existed for centuries and has previously been suggested to be an instance of river capture — a widely inferred, but rarely observed phenomenon in which a river starts draining down a nearby riverbed instead of its own — new sedimentary analysis confirms the steeper Rio Casiquiare is actively capturing 40,000 square kilometers of the Upper Orinoco drainage basin. The finding shows how the Amazon may have grown to become the largest river basin in the world. "The Rio Casiquiare appears to be the most recent in a series of similar captures by the Amazon River that have substantially influenced the landscape of South America," the researchers wrote.

Stokes et al., Geophysical Research Letters, May 2018

Scientists discover granite crystallizes at lower temperatures

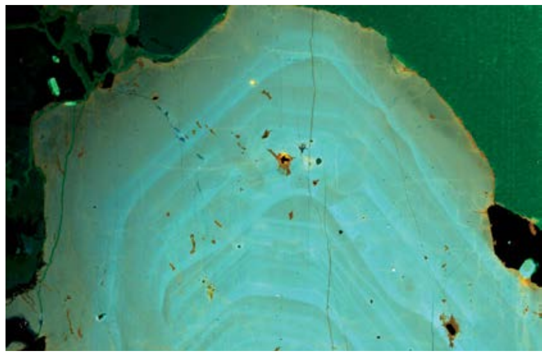
Investigating the properties of granite has given researchers insight into how gold and other economically important ores are produced, the thermal properties of Earth's crust, the state of magma in active volcanic regions, and how Earth's continents formed. "The temperature of granite crystallization underpins our thinking about many of these phenomena," researchers note in a new study in Nature. "But evidence is emerging that this temperature may not be well constrained," added the study authors, who found that certain granites crystallize at temperatures as much as 200 degrees Celsius lower than previously thought.

The conventionally accepted wet solidus for granite — "the temperature below which a water-saturated granitic melt completely solidifies" — is between 650 and 700 degrees Celsius and was established based on roughly 60-year-old laboratory experiments, says Michael Ackerson, a petrologist at Rensselaer Polytechnic Institute in New York, and lead author of the study. In those experiments, researchers heated granite powders until they melted, and these melting temperatures were then used to determine the granite solidus, Ackerson notes. Although these early results have been repeated, they may not accurately represent the temperatures at which granite solidifies in nature, he says.

His team combined two independent techniques — titanium-in-quartz thermobarometry and diffusion modeling of titanium in quartz — to evaluate the crystallization temperatures of rocks from the Tuolumne Intrusive Suite (TIS), a collection of granites found in the Sierra Nevada of Yosemite National Park. They chose to study quartz because it's "one of the most abundant minerals in granitic rocks, which means our approach could potentially be applied to granites across the globe," Ackerson says.

The TIS, which includes the Cathedral Peak granite and the Half Dome granodiorite, is the youngest intrusive formation among the seven found in Yosemite. It is also the most extensive bedrock formation in Yosemite, covering about one-third of the park's area. Samples from the TIS were chosen because they are easy to access, relatively fresh and pristine, Ackerson says.

He and his colleagues found that their quartz samples crystallized at temperatures ranging from 474 to 561 degrees Celsius.



Under an electron microprobe, areas in this quartz crystal that are bluer indicate higher concentrations of titanium and higher crystallization temperatures.

Credit: Michael Ackerson

For the thermobarometry technique, the researchers used an electron microscope to quantify the amount of titanium in each sample, which depends on the temperature and pressure at which they crystallized, Ackerson says. Higher titanium concentrations indicate higher temperatures or pressures at the time of crystallization.

After assuming that the rims of these quartz crystals "represent late-stage, near-solidus crystallization," the researchers linked the granodiorite wet solidus with a model for titanium concentration in quartz. That model describes the titanium concentration in quartz as a function that varies with different values for temperature, pressure, and titanium concentration relative to saturation of

Matterhorn Peak in the Cathedral Peak Granodiorite is part of the Tuolumne Intrusive Suite, a collection of granites from the Sierra Nevada. Researchers studied quartz in this granite to determine granite crystallization temperatures.

Credit: Dug Ross, CC BY-N.C 2.0

rutile — the most common natural mineral composed primarily of titanium dioxide — in the melt.

The researchers found that if crystallization occurred at pressures between 1.6 x 10^8 pascals and 2.4 x 10^8 pascals — the range found roughly 6 kilometers below Earth's surface — the crystals' rims would have titanium contents ranging from 132 to 219 parts per million (ppm), Ackerson notes. Those pressures are required for the quartz to crystallize at the wet solidus of granite. However, the researchers observed titanium concentrations of 20 ppm to 40 ppm, suggesting that the quartz crystallized at lower pressures. Thus, "the main volume of quartz within these granitic rocks crystallized below the expected wet solidus temperatures," Ackerson and the other researchers wrote.

"The arguments in this paper are very sound," says Craig Lundstrom, a petrologist and geochemist at the University of Illinois at Urbana-Champaign who was not involved with the study but has extensively studied granite formation. "There is controversy surrounding the use of the titanium-in-quartz thermometer, and some might question the conclusions based on that alone," he adds, but "what makes the work powerful is that the authors use a second method involving modeling of diffusion profiles that gives the same low-temperature requirement that the thermometer does."

To model titanium diffusion, the team used an electron microprobe to map titanium concentrations across cross sections of quartz crystals from the TIS, and then compared those maps to computer models of how titanium concentrations evolve in growing crystals. The microprobe images look something like cross sections of trees with numerous growth rings, Ackerson says. "We should see a lot more blurring of these growth rings" if the quartz was exposed to higher temperatures for long periods of time, as would have happened if this granite crystallized at 650 to 700 degrees Celsius, he says. Instead, there are regions with sharp distinctions between adjacent rings, which show "where there was an abrupt change in how that quartz was crystallizing." This pattern "can only happen if [granite] crystallizes at really low temperatures," he adds.

Lundstrom co-authored a 2009 study describing laboratory experiments that showed that "a granite could form at 400 degrees [Celsius] when intermediate-composition hydrous magma was placed into a temperature gradient for two months," Lundstrom notes. "A 2-centimeter-long capsule with andesite and 4 percent water was placed into a temperature gradient that spanned 950 degrees Celsius down to 350 degrees Celsius. Over the two months, there was a continuous reaction and diffusive transport that resulted in a gabbro forming at a higher temperature and granite at a lower temperature," he says.

The work of Ackerson's team "perhaps provides evidence that processes like those in the laboratory may actually occur in making granitic intrusions — and thus even in making continental crust," Lundstrom says.

The results of the study have diverse implications, Ackerson says. For instance, while "certain deposits that form gold, copper and molybdenum occur directly above granites — hence their location is already known — there is some debate about how these types of important ore deposits form," he says. "Part of the conundrum," he adds, is "in understanding the compositions and temperatures of the fluids that generate the ore deposits. For example, are the fluids that crystallize these ore deposits derived from the granites, or do the granites merely supply heat to the overlying rock to form the ore deposits?" And "if granites crystallize at lower temperatures, does this also mean that these ore deposits can form at lower temperatures as well?"

Moreover, lower granite crystallization temperatures may impact researchers' understanding of how Earth's continents, formed primarily of granite, took shape, Ackerson notes. "If we didn't have granites, we wouldn't have continents like we know them today."

Rachel Crowell

Biologic origin of Archean microfossils supported

Tiny bits of organic matter found in 3.4-billion-year-old cherts from the Strelley Pool Formation in Western Australia are indeed the remains of ancient microorganisms, now among the oldest-known life on the planet, according to new research. Although scientists have speculated that the Strelley Pool specimens — and others in even older rocks — came from early microorganisms, there's been little unequivocal evidence to date. Now, elemental and molecular analyses of the microfossils have revealed compounds whose molecular precursors are similar to molecules present in younger microfossils and in modern bacteria.

Alleon et al., Geochemical Perspectives Letters, August 2018; Goldschmidt Conference Press Release, August 2018

"Easy bake" fossils resemble real deal

Most fossils are millions of years in the making, but a new technique is allowing scientists to simulate the process of fossilization in about 24 hours. The laboratory-based method, described in a study published in the journal Palaeontology, sheds light on how exceptionally preserved fossils form generally over geologic time and may provide custom samples for research projects investigating specific conditions under which certain fossils formed.

Fossil simulation is "not making or replicating fossils. [It is] experimentally degrading modern tissues," says Maria McNamara, a paleobiologist at the University College Cork in Ireland, who was not involved in the new study but has separately investigated how to simulate fossilization. "But in terms of their morphological and chemical features, simulated fossils are very similar to actual fossils."

Scientists have been attempting to simulate fossilization in lab settings for the last 30 years, usually by subjecting samples to high temperature and pressure in a process known as maturation. Results have been mixed, however. Maturation experiments are typically conducted by placing a sample inside a small sealed container, which traps biomolecules that would normally be lost in the fossilization process. "When you open the capsules used in traditional maturation, this really stinky goo spills out, which is essentially broken down, degraded proteins," says Evan Saitta, a paleontologist at the Field Museum of Natural History in Chicago and lead author of the new study. "Since we don't see gooey fossils [in nature], that's a sign that those simulations are not getting it quite right."

During true fossilization, most specimens are encased in sediment that holds the fossil in place, while pore spaces allow mobilized fluids and gases to leach away from the sample. "Fossilization often occurs in a fairly open system, where materials can come and go throughout

A new method to simulate fossilization can be used on much larger samples than previous methods, including whole lizard heads and feet (foot shown below) as well as feathers (right).

Credit: both: The Field Museum

the process," Saitta says. To more closely mimic these conditions, Saitta and colleagues first packed samples of lizard heads and feet, bird feathers, leaves, and arthropod cuticles into clay tablets using a hydraulic press. They then heated the tablets inside sealed metal tubes to 210 degrees Celsius at a pressure of about 24 megapascals (roughly 240 times atmospheric pressure at sea level). The sealed chambers were equipped with air lines, which the researchers used to change the pressure.

"When we cracked open the tablets, we were absolutely thrilled," Saitta says. The specimens "looked very much like real fossils at the macroscopic level, consisting of darkened, browned bones surrounded by a dark halo left by the degraded soft tissues. The feathers we tested closely resembled exceptionally preserved fossil feathers found in China." The true-to-form appearance of the feathers also held up under a scanning electron microscope, which clearly showed melanosomes — the organelles responsible for pigmentation of feathers that are used in paleo-color reconstructions — resting on the surface of the sediment. "The melanosomes appear very much the same as we see in fossil feathers," Saitta says, suggesting the new method offers "a fairly true simulation."

"This is an interesting study, and the [researchers'] method has potential in the realm of experimental paleontology," McNamara says. One advance it represents is in the size of the samples being used, she says. "Their samples are up to 19 millimeters across, whereas most maturation techniques are applied to samples around 5 millimeters. By using bigger chunks of tissue, it may be easier to conduct some kinds of experiments [on the simulated fossils]."

The fossils are also "easily manipulated and very stable. You can treat and store them in the same way that you treat and store [real] fossils," Saitta says. The method is not yet perfect, however, he notes. The team is currently tinkering with improvements, such as adding unidirectional compaction during the pressure-cooking phase to more closely mimic true fossilization conditions in which pressure is mainly applied from above by overlying rock and sediments. "We'd also like to incorporate flowing water to the process at some point. Water flows through sediments underground, which can lead to a loss of unstable biomolecules and greater cementation of sediments."

Real fossils will always be the bread and butter of paleontology, but simulated fossils have their place, Saitta says. "Paleontology cannot divorce itself from actual fossils — they are the true recordkeepers of evolution — but if we find a fossil in the future with a unique form of preservation, then we can go to our experimental platform and begin to play around with it to see if we can mimic those conditions," he says. "There's a lot of potential with these samples. It'll be interesting to see all the ways that [other researchers] can devise to experiment with them."

Mary Caperton Morton

Spiky new American ankylosaurid originated in Asia

A new genus and species of ankylosaurid discovered in Grand Staircase-Escalante National Monument in southern Utah reveal new information about the spread of armored dinosaurs into North America. Most North American ankylosaurids are known for their smooth skulls, but the new specimen more closely resembles spiky-skulled Asian ankylosaurids.

The new specimen, dubbed *Akainacephalus johnsoni*, was named for the Greek words "akaina," meaning "thorn" or "spike," and "cephalus," meaning "head," as well as for dedicated museum volunteer Randy Johnson, who helped prepare the dinosaur for display at the Natural History Museum of Utah in Salt Lake City. The formidable arrangement of cone- and pyramid-shaped bony armor on *Akainacephalus*' snout and head point to a close relationship with the similarly prickly New Mexican ankylosaurid *Nodocephalosaurus kirtlandensis*.

An artist's vision of the newly discovered *Akainacephalus johnsoni*. The unusually spiky armored head points to an Asian origin for this new genus and species.

Credit: ©Andrey Atuchin/DMNS

In a new study published in PeerJ, researchers assert that *Akainacephalus* and *Nodocephalosaurus* are more closely related to Asian ankylosaurid genera, such as *Saichania* and *Tarchia,* than to other Late Cretaceous North American ankylosaurids, including *Ankylosaurus* and *Euoplocephalus*, which sport flattened skull armor. The new specimen of *Akainacephalus*, which dates to 76 million years ago, is also one of the most complete North American ankylosaurids found to date, including an intact skull, most of the vertebral column, the tail club, parts of the fore and hind limbs, and some body armor, including distinctively spiked armor plates.

Study authors Jelle Wiersma, now at James Cook University in Queensland, Australia, and Randall Irmis, at the Natural History Museum of Utah in Salt Lake City, suggest that the spiky skulled ankylosaurids may have crossed over the Beringian land bridge between Asia and North America, resulting in two distinct populations. Ankylosaurids are thought to have originated in Asia between 125 million and 100 million years ago, and appear in the North American fossil record about 77 million years ago, 11 million years before the end of the Cretaceous.

Mary Caperton Morton

Mercury on the roof of the world

Traditional Tibetan Medicines (TTM) are dispensed in pill form by pharmacists who mix minerals and herbs together in centuries-old recipes. But some of the ingredients may be doing more harm than good. Previous studies have found that mercury and methylmercury, both highly toxic to humans, are sometimes intentionally used in the medications. In a new study, published in Environmental Science & Technology, researchers analyzed total mercury and methylmercury concentrations in seven common TTM remedies and found concentrations as high as 12,000 micrograms per gram and averaging 5,600 micrograms per gram. They found that daily mercury intake by Tibetans who practice traditional medicine was as much as 3,000 times higher than exposure rates in the general populations in Japan, Norway and the U.S.

Contact with even small amounts of mercury can lead to a host of neurological problems and organ system failures, and exposure to methylmercury — an even more potent form of the heavy metal — can lead to paralysis, coma and death. What's more: Mercury doesn't stay in the body; it is readily excreted into the environment. Lead author Maodian Liu, of the University of Connecticut and Peking University in Beijing, and colleagues also tested municipal sewage plants in Tibet for mercury content. They estimated that in one year, 3,600 kilograms of mercury — nearly the weight of an adult elephant — were deposited into sewage treatment plants and the environment as a result of TTM use, making it "a major contributor of [environmental] mercury in Tibet," the team wrote.

Mary Caperton Morton

New galaxy found

In 2017, Chris Carr, an undergraduate astronomy major at Case Western Reserve University in Cleveland, was reviewing images from the university's telescope at Kitt Peak National Observatory in Arizona when he found a tiny yet distinctive smudge. Upon further analysis, the smudge turned out to be a new galaxy 37 million light-years from Earth in the Leo I galaxy group. The object is the "lowest surface brightness object ever detected via integrated light," the researchers wrote in a study describing the finding.

Mihos et al., The Astrophysical Journal Letters, August 2018

News

Congress, states look to address impacts of ocean acidification

Global ocean chemistry is changing at a historically unprecedented rate, with rising ocean acidity threatening populations of shellfish and other marine species worldwide. Recent observed changes in ocean chemistry off U.S. coasts, particularly along the shores of Alaska, California, Oregon and Washington, where fisheries are already being affected, have scientists studying the potential impacts, fishermen worrying about their livelihoods, and politicians pushing for action.

Ocean acidification occurs when carbon dioxide dissolves in ocean water, producing carbonic acid and lowering the pH of the water. Approximately 25 to 30 percent of the carbon dioxide absorbed by oceans comes from the atmosphere; the rest comes from other sources, including runoff, hydrothermal vents, submarine volcanism and the decay of organic material. Since the beginning of the industrial revolution, the rise in carbon dioxide levels in the atmosphere — from 280 parts per million (ppm) to more than 400 ppm currently — has led to an increase in carbon dioxide absorbed by the ocean, and a 30 percent increase in ocean acidity: The average pH over the global oceans during that period has dropped from 8.16 to 8.07. And it is projected to drop to 7.67 by 2100 if carbon dioxide emissions continue at the same pace.

Decreased pH causes carbonate, an essential building block in the shells and skeletons of calcifying marine species like oysters, clams and corals, to become relatively less abundant in ocean water, thus posing a serious threat to the health and survival of such animals.

The Pacific Northwest is particularly susceptible to negative impacts of ocean acidification because seasonal upwelling events occur along the coast, forming the basis of many fisheries. Upwelling events occur naturally, involving cool, carbon dioxide-rich water ascending to the ocean surface, driving down the pH. This compounded input of carbon dioxide through upwelling events and increased absorption from the atmosphere has already impacted shellfish farms on the coasts of Oregon and Washington, where in the past decade, there have been some near-total failures of hatcheries. Since 2007, the Whiskey Creek Shellfish Hatchery in Netarts Bay, Ore., for example, has undergone mass mortalities of oyster larvae each year. In an area where shellfish is a $111 million industry and supplies thousands of jobs, business owners are growing more concerned. In response, federal and state politicians have sought to address this issue by pushing for legislation to better understand the problem.

In 2009, the Federal Ocean Acidification Research and Monitoring (FOARAM) Act was signed into law, establishing the NOAA Ocean Acidification Program, which established an intricate network of monitoring buoys and wave gliders that report ocean chemistry data in real time, allowing scientists to study short- and long-term trends. The program also provides financial support for research studying the impacts of ocean acidification on economically and ecologically important species, like shellfish and plankton; and there's a strong education and outreach component to communicate with the public about scientific findings and the potential impacts of ocean acidification on society.

The FOARAM Act was written to be a living document, changing as our scientific capabilities change. Recently, members of Congress introduced legislation to update the act to accommodate new scientific innovations. Building off of previous legislation championed by former U.S. Rep. Sam Farr, D-Calif., on June 28, 2018, Rep. Suzanne Bonamici, D-Ore., introduced the Coastal and Ocean Acidification Stressors and Threats Research Act, or COAST Research Act,

Shellfish such as oysters are a big business in the Pacific Northwest, but some places have seen mass mortalities of larvae in recent years due to acidic oceans.
Credit: Rick Obst, CC BY 2.0

which was co-sponsored by Reps. Don Young, R-Alaska, and Bill Posey, R-Fla. The COAST Research Act would amend the FOARAM Act to add an ocean acidification advisory board, composed of members from the seafood industry, academia, and regional ocean and coastal acidification networks. These participants would provide advice regarding federal activities related to ocean acidification and recommend the best paths for research and monitoring in the future. In addition, the COAST Research Act would establish an ocean acidification data archive and provide grants for education and outreach activities. The bill now awaits consideration by the House Committee on Science, Space and Technology.

In January 2018, the Senate passed a bill introduced by Sen. Roger Wicker, R-Miss., called the Coordinated Ocean Monitoring and Research Act, that also addresses an array of NOAA ocean monitoring and research initiatives. Among other things, the Senate bill would require an interagency committee, originally created by the FOARAM Act for oversight and development of federal ocean acidification research, to produce an economic vulnerability assessment to identify gaps in ocean acidification research and monitoring and improve our understanding of how acidification is impacting economically important species. That bill also currently awaits action from the House.

While these bills would update federal research initiatives, state and local governments have been developing their own programs as well.

In February 2012, for example, then-Washington Gov. Christine Gregoire created the Washington State Blue Ribbon Panel on Ocean Acidification to maintain public and private partnerships to expand Washington's monitoring network and research the local impacts of acidification. It also seeks to remediate the impacts of acidification through the development of new water treatment methods and aquaculture designs. Similar efforts are being pursued in Alaska by the Alaska Ocean Acidification Network established in 2016.

Chris Micucci

Titan's dunes form the same way as Earth's

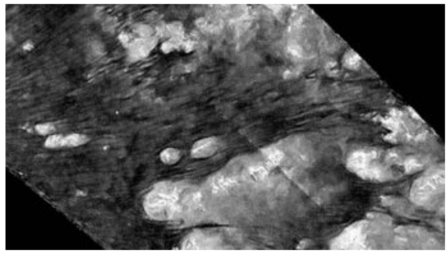
The mountains of East Xanadu rise high above the wind-swept plains and dunes of Shangri-La. This fantastical landscape isn't found in a scene from a Hollywood movie, or even a desert on Earth, but on Titan, Saturn's largest moon. New research looking at the surface topography of Titan — more than a billion kilometers from Earth — reveals it has a lot in common with our planet. The work, published in the Journal of Geophysical Research: Planets, shows that the dunes likely formed in a process that's analogous to how dunes form on Earth — through weathering, erosion and deposition.

From 2004 to 2017, NASA's Cassini spacecraft studied Saturn and its satellites, sending back countless images of Titan taken with visible, infrared and radar cameras. Jeremy Brossier, a doctoral student at the German Aerospace Center, and his colleagues used this imagery to map Titan's equatorial regions, finding that the moon's dunes are formidable and range across millions of kilometers more than previously thought. They also studied transition regions on the surface where dunes border mountains or craters, using radar to infer and distinguish different landscape features — mountains, craters, dunes and ice beds, for example. Additionally, infrared imagery helped the scientists determine grain sizes and compositions of particles at each location, essential for teasing out the geologic processes that formed them.

The researchers found that the dune-forming process begins high above Titan's surface in its dense atmosphere of gaseous methane and nitrogen. When methane rains fall, they bring with them a fine coat of tholins — complex organic molecules formed by irradiation of cosmically abundant gases or ices. (Tholins were discovered and named in 1979 by Carl Sagan and Bishun Khare, who suggested the sticky solids could also aptly be named "star-tar.") As the liquid hydrocarbon rain erodes mountaintops and craters, forming canyons and channels, the runoff carries pieces of ice and tholins. Over time, winds sweep away the smaller grains, which eventually form the dunes that cover 18.6 percent of Titan's surface. This process is similar to how dunes are created on Earth, with the exception that the particles on Titan are initially formed in the atmosphere rather than on the ground. "The tholins composing the dunes … are themselves formed through photochemical reactions involving hydrocarbon gases and dinitrogen," Brossier says. "By knowing how the dunes are formed, we understand part of [the hydrocarbon] cycle on Titan, at least the interactions between the atmosphere and surface of the moon."

Titan's nitrogen-rich atmosphere might be hospitable to life, so understanding the moon's geological processes may help scientists in their search for extraterrestrial life. The researchers also suggested their results offer evidence of water ice in some areas, an observation that has been largely speculative based on previous work.

However, "this is not the first time a plausible sign of water ice has been seen in [the Visual and Infrared Mapping Spectrometer, or VIMS] data," says Juan Lora, a planetary climatologist at UCLA who was not involved in the study. "The combination of VIMS' low resolution and Titan's obscuring atmosphere means that definitive spectral detections of the surface are just not possible with these data."



New research reveals that Titan has dunes that form much like those on Earth.

Credit: NASA/JPL-Caltech/ASI/Université Paris-Diderot

The dry, desert-like dune landscapes studied in this work are in Titan's equatorial region. Eventually, Brossier says, future studies using similar techniques could help scientists understand Titan's polar regions, where most of the moon's methane rainfall occurs, providing a fuller picture of the planet's hydrocarbon cycle.

Mara Johnson-Groh

Ship exhaust increases Arctic melt

The type of ships that currently operate in the Arctic, and will do so more as marine traffic increases in the region, often burn heavy oil. Burning heavy oil emits significantly more particulates, especially light-absorbing organic molecules called brown carbon, than lighter oils, according to new research quantifying the radiative forcing of fuels on snow in the Arctic. Such emissions need to be included in climate models, the researchers noted.

Corbin et al., Journal of Geophysical Research: Atmospheres, May 2018

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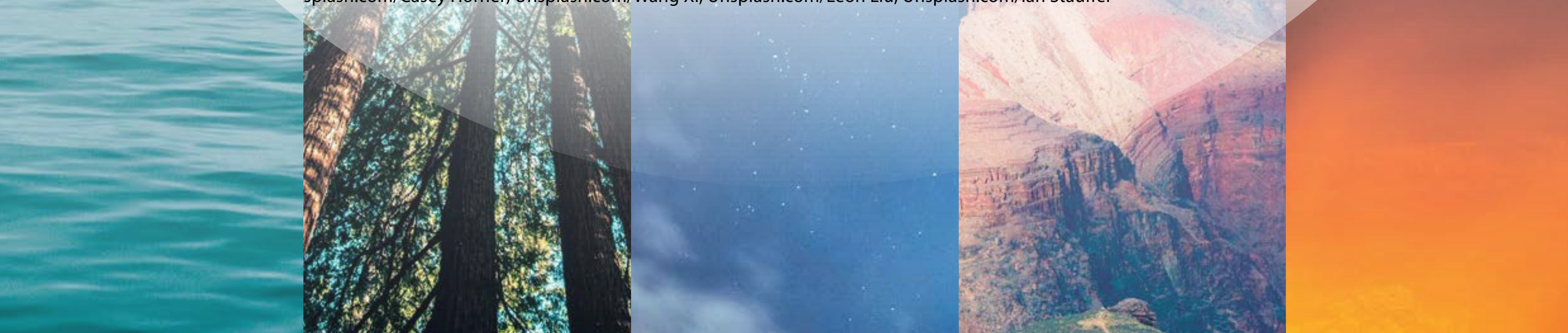

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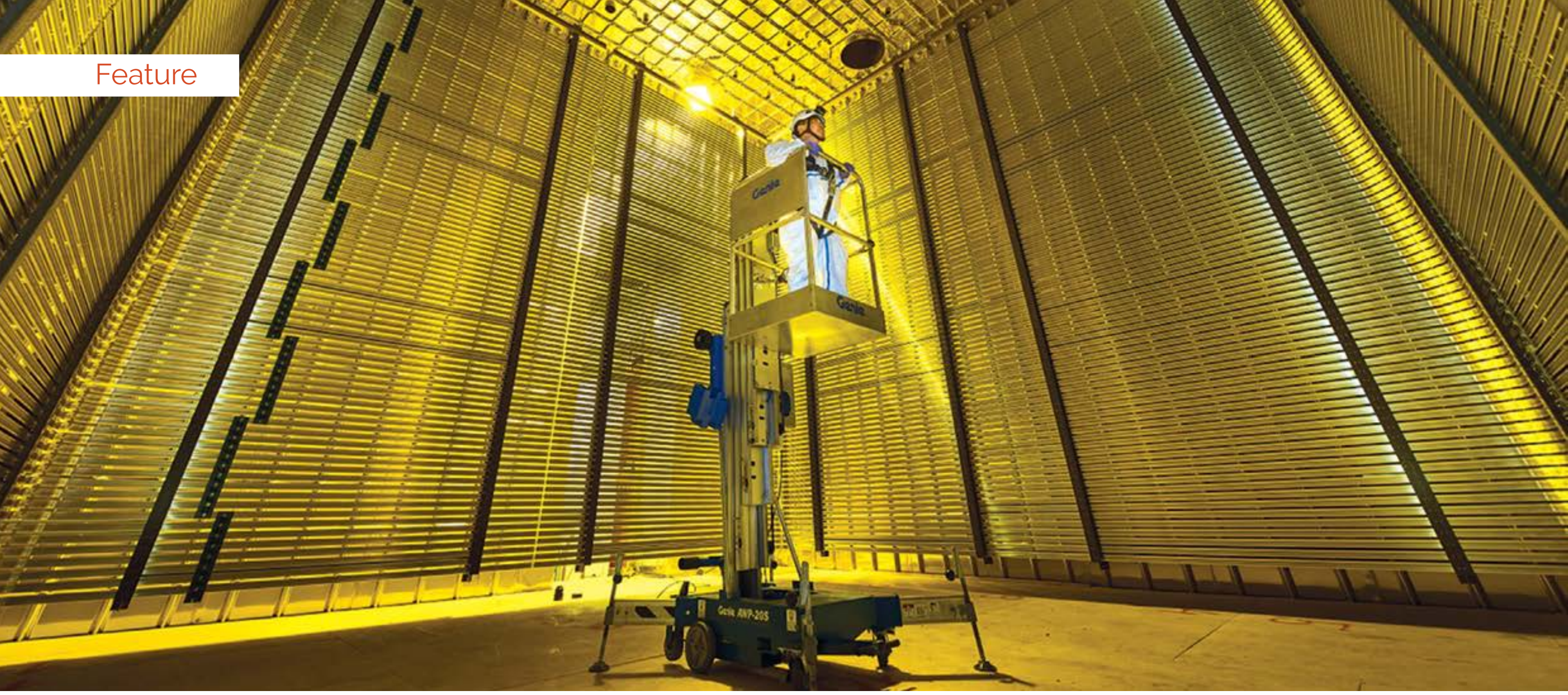


A technician works inside a roughly 500-cubic-meter neutrino detector during its construction in April — one of two liquid argon detectors being built at the European Organization for Nuclear Research's (CERN) facility near Geneva, Switzerland. Known together as ProtoDUNE, the detectors at CERN are prototypes of four larger versions to be built at the Sanford Underground Research Facility (SURF) — housed in the former Homestake Gold Mine near Lead, S.D. — as part of the Deep Underground Neutrino Experiment (DUNE).
Credit: CERN

GOING SUBTERRANEAN

Repurposed Mines Become Innovative Labs

Josh Knackert

At about 5 a.m. on a frigid, icy February day in northern Minnesota — the kind of day when it feels like your eyeballs might freeze — a group of about 10 undergraduates in a geobiology course at the University of Minnesota-Duluth jumped onto a bus, headed for a destination far more temperate and out of the elements — or, rather, deep below the elements. Joined by their professors, microbiologist Cody Sheik and geologist Latisha Brengman, as well as a few others (including yours truly), the students arrived, two hours later and still before daybreak in the Minnesota Northwoods, at the visitor center and museum for the historic Soudan Iron Mine. The mine began operations in 1882 as an open pit mine, but moved underground about 20 years later and ceased mining in 1962.

After hustling into the (mercifully warm) visitor center to watch a video about the former mining operations 800 meters belowground at Soudan, everyone in the group suited up with hard hats and head lamps for a pitch-black, claustrophobia-inducing three-minute descent into the mine aboard a loud, clanging elevator cage — the original mine elevator built around 1900. This was followed by a kilometer-plus-long ride aboard the original mine railway to the deepest part of the mine, and then a guided tour.

The mine and its history are fascinating, as is the buried ore exposed on the walls of the mine — a banded iron formation featuring thinly layered swirls of black and red rock shot through with veins of white quartz. But on this day, the students and their instructors weren't touring the mine simply to admire some striking Precambrian geology, or to get in out of the cold. There was science to be done.

Sheik and his collaborators have traveled to Soudan several times as part of their microbiology research, and as the sampling techniques they employ are straightforward, Sheik and Brengman saw this trip as a perfect learning opportunity for their students. The group spent the day collecting samples

The headframe of the historic Soudan Iron Mine on a frigid day in northern Minnesota. The mine, which ceased operations in 1962, is now operated as a state park and also hosts scientific research.

Credit: Josh Knackert

from a rivulet of water running along one side of the mine tunnel. The water was stained bright red, as was pretty much every other surface in sight. The coloration was from iron that had oxidized when exposed to air in the tunnel, essentially rusting the entire mine. Trickles of groundwater running down the tunnel walls concentrated this oxidized iron in the small stream, making the reds extra sharp. Meanwhile, the streambed also displayed a stringy mix of oranges, yellows and browns, almost as if someone had smeared oil paints along its length. These bright, mottled streaks — formed by mats of microorganisms — were what most interested Sheik and Brengman. The group sampled the stream and its populations — filtering suspended microbes out of the water and scraping up portions of the slimy biofilms and mineralized solids in the microbial mats — to take back to their university lab. The sampling was part of a larger effort not only to study the collection of microorganisms inhabiting the mine's deep tunnels today, but also to address longstanding questions about the origins of life on Earth.

Beyond Soudan, a surprising variety of groundbreaking — and often otherwise impossible — research is being conducted underground all over the world, from investigations of natural resources, seismic activity and carbon sequestration, to less obvious topics like biofuel development and how life began on Earth — and, maybe, on other planets as well. These modern research efforts have their roots in mining: As centuries of ingenuity took us deeper into Earth, scientists realized that subterranean depths and isolation offered conditions and phenomena not available on the surface, either naturally or artificially in laboratories. This holds true today, with established underground research facilities offering scientists from numerous fields unique ways to answer some of science's biggest questions.

Capitalizing on the Quiet

Worldwide, there are about 20 deep, underground laboratories — including 10 in Europe and four in the U.S. — buried at depths varying from a few hundred to several thousand meters. Most are former mines, though some have been excavated for the sole purpose of research. One such lab is the European Organization for Nuclear Research's Large Hadron Collider near Geneva, Switzerland, likely the most renowned subterranean lab facility, which is buried at a relatively shallow depth of about 100 meters. For roughly the last 60 years,

Students from the University of Minnesota-Duluth collect samples from a rivulet of water in an underground tunnel in the former Soudan Iron Mine.

Credit: K. Cantner

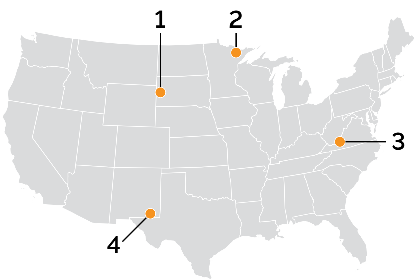
Selected Underground Research Facilities

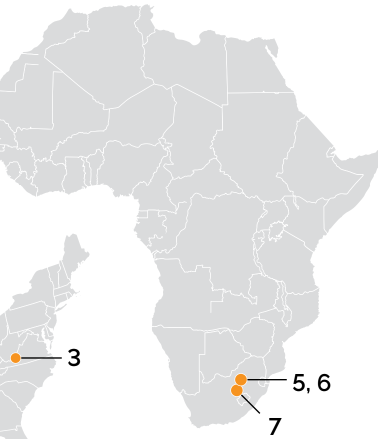
1 Sanford
Original use: Gold mine
Active mining: No
Research began: 1960s
Research depth: 1,500 meters (m)

2 Soudan
Original use: Iron mine
Active mining: No
Research began: 1981
Research depth: 713 m

3 Kimballton
Original use: Limestone mine
Active mining: Yes
Research began: 2007
Research depth: 518 m

4 Waste Isolation Pilot Plant
Original use: Radioactive waste disposal
Active mining: No
Research began: 1999
Research depth: 655 m





5 Driefontein
Original use: Gold mine
Active mining: Yes
Research began: ≤1990s
Mine depth: 3,300 m

6 Kloof
Original use: Gold mine
Active mining: Yes
Research began: ≤1980s
Mine depth: 3,347 m

7 Beatrix
Original use: Gold mine
Active mining: Yes
Research began: ≤1980s
Mine depth: 2,155 m

Credit: K. Cantner, AGI

researchers from different fields have been drawn to underground facilities for many of the same reasons.

One benefit of underground mines, particularly for physics research, is that thick layers of soil and rock provide what can be referred to as statistical quiet, blocking or attenuating background signals present at Earth's surface, such as solar radiation, that often drown out or otherwise interfere with the target signal. A kilometer and a half worth of ground cover can reduce the noise from cosmic rays by a factor of roughly 10 million, for example. Physicists often shield their underground experiments further, blocking trace radiation emanating from rocks and even from the human body by encasing detectors in water, lead or other protective materials.

Another benefit is that underground environments like mines typically remain unchanged for longer periods of time than surface environments. In some deep mines, like the gold mines of South Africa, the same groundwater can remain trapped in a small area for millions of years; and temperatures remain remarkably consistent as well, always staying above freezing. (Tour guides at the Soudan Mine highlight this as a year-round draw for tourists — with temperatures hovering around a comfortable 10.5 degrees Celsius, it's cooler than muggy Minnesota summers and much warmer than the biting chill of winter.) Furthermore, some mines are located in areas where seismic activity is minimal, reducing their vulnerability to ground shaking. These relatively stable conditions mean that subterranean research facilities can last a long time.

Researching the Origins of Life

Limitations on oxygen, organic carbon and sunlight deep underground offer conditions thought to be similar to those when life began on early Earth. Subterranean environments also offer analogs for conditions under which life may have begun on other planets, like Mars. Along with high pressure, and sometimes very acidic or dry conditions, these factors create environments that typically make it difficult for anything to survive, much less thrive. Yet even in such places, bacteria and archaea known as extremophiles do thrive; and these microbes may be the closest living relatives to those that first populated the planet.

At Soudan, Sheik and his team find surprisingly complex microbial communities given the limitations of the mine environment. The inherent resilience of these organisms is what interests the researchers most. "We look at what biology can do today [in these extreme environments] and apply that to what we know about Earth 4 billion years ago," Sheik says. After collecting microbial samples from the mine, they characterize them in the lab using various growth conditions and by sequencing their DNA. The goal is to better understand the mechanisms and key genes that allow the bacteria to grow and replicate in natural environments where resources are sparse.

The slow rate of change and movement in deep subterranean environments may also affect microbial evolution. It's common for deep-living extremophiles to not encounter other living species for

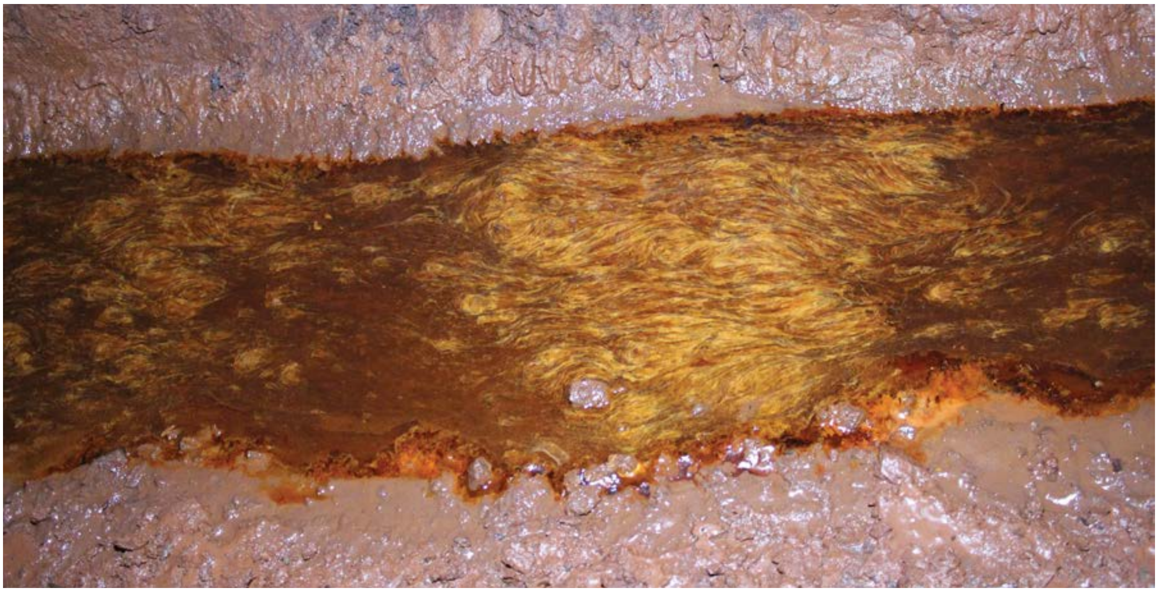
Soudan has hosted several large physics experiments, including the Main Injector Neutrino Oscillation Search (MINOS) project. MINOS ended in 2016, and the large neutrino detector housed in this excavated hall in the former mine has since been dismantled.

Credit: Josh Knackert

hundreds or even thousands of years. This means there are low rates of predation, symbiosis and gene transfer in these communities. Survival in low-resource environments can also mean slow replication or even long stretches of senescence, conditions that likely affect how genes in these extremophiles activate and change over time. "We don't fully know how [these microorganisms] eat, reproduce or evolve," Sheik says. "Advanced genomic tools are helping us understand evolution and the flow of energy through these complex communities."

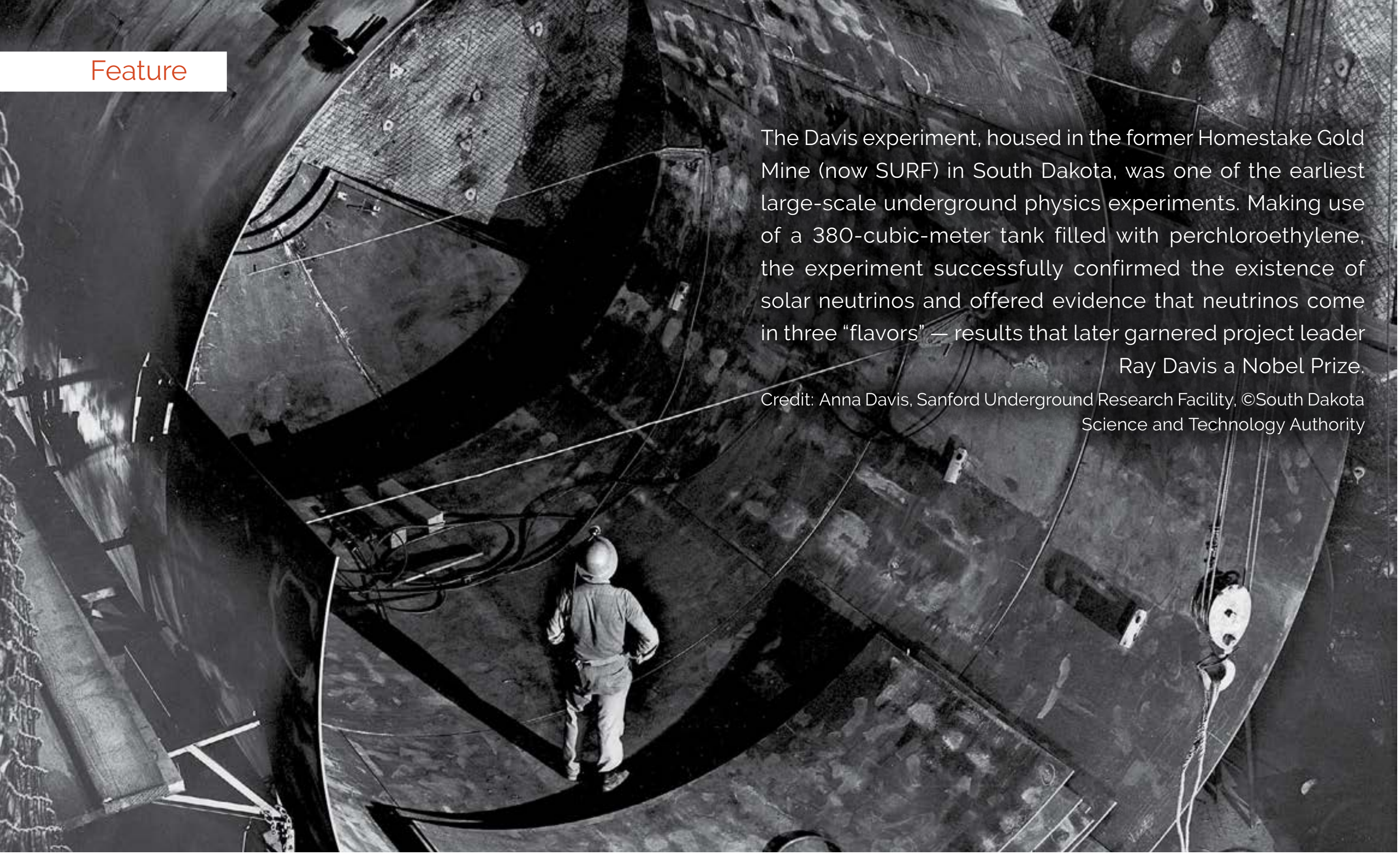
Tullis Onstott, a geomicrobiologist at Princeton, studies life in environments even deeper than Soudan, collecting microorganisms in active gold mines in South Africa. The cluster of four active gold mines where he works — the East and West Driefontein mines and the Kloof Mine near Carletonville, plus the Beatrix Mine near Welkom — are some of the deepest excavations in the world, reaching down as far as 3.4 kilometers below the surface. These depths offer even more challenging living conditions, including elevated temperatures due to increased geothermal activity. And the pressure is so great at these depths that boreholes drilled by the mining company close in a matter of months; most significant cracks or fissures formed by gradual rock movement and seismic activity meet similar fates.

Despite the harsh conditions, "we find very active communities adapted to their environment," Onstott says. Single-celled life living several kilometers down once seemed unlikely enough, but in 2011, Onstott and his collaborators discovered microscopic worms called nematodes living in the extreme conditions of the Beatrix Mine. "We were startled to find multicellular organisms," he says. "They're feeding off the bacteria," and the worms may also have bacterial symbionts, which altogether suggests a more complex food web in the subterranean than was previously assumed. His team has also found a surprising diversity of viruses underground, increasing the complexity of potential flows of genes and nutrients among organisms.



Microbial colonies form a stringy mix of orange, yellow and brown hues in a small stream running through a tunnel at the former Soudan Iron Mine. Researchers have found surprisingly complex communities of microorganisms here, considering the limitations of the deep mine environment.

Credit: Josh Knackert



The Davis experiment, housed in the former Homestake Gold Mine (now SURF) in South Dakota, was one of the earliest large-scale underground physics experiments. Making use of a 380-cubic-meter tank filled with perchloroethylene, the experiment successfully confirmed the existence of solar neutrinos and offered evidence that neutrinos come in three "flavors" — results that later garnered project leader Ray Davis a Nobel Prize.

Credit: Anna Davis, Sanford Underground Research Facility, ©South Dakota Science and Technology Authority

The unexpected level of diversity and complexity in life deep underground is offering researchers an array of opportunities to ask key questions about the origins of life on this planet and others, like how the genetic building blocks common to all life came into being and how cells gained the ability to produce energy through respiration. Researchers are also looking into whether multiple forms of life might have evolved in parallel here on Earth — and, thus, if one early form of genes outcompeted others — as well as what life on Mars might have looked like if it did evolve.

From the Origins of Life to the Origins of the Universe

While biologists are exploring the origins of life, physicists are using underground research facilities to ask questions about the origins of the universe. They were drawn underground by the radioactive quiet after finding that a thick layer of rock blocks the vast majority of cosmic radiation that continually falls on Earth from the sun and other celestial sources.

This radioactive quiet allows incredibly sensitive detectors to record the trajectories of subatomic particles called neutrinos, which are produced by the decay of radioactive elements in the sun and in distant, high-energy events like supernovae, black holes and gamma ray bursts. Because the particles are unaffected by magnetism due to their lack of charge, and because they typically pass unimpeded through matter, they travel, essentially unchanged and along straight trajectories, through the universe at near the speed of light. In the rare instances, however, when neutrinos collide with atomic nuclei, the collisions produce quick flashes of light that can be picked up by detectors. Physicists thus consider neutrinos as messenger particles coming directly from whatever high-energy event created them and use the particles to learn more about those sources and other aspects of the universe that we know little about, like the balance between matter and antimatter and the origin of the universe.

Neutrino research is one of the primary objectives of the Sanford Underground Research Facility (SURF) in Lead, S.D., the deepest research facility in the U.S. at about 1.5 kilometers depth. The lab is in the former Homestake Gold Mine, where gold was mined from 1876 to 2002, after which it was converted into a dedicated research facility. However, the mine has a long history of physics experiments, beginning with the Davis experiment in the mid-1960s. Led by Brookhaven National Laboratory physicist Ray Davis, who was awarded a Nobel Prize in 2002 for the work, researchers looked to confirm that the sun emits neutrinos. The instrument built by Davis' team at SURF did indeed detect solar neutrinos, but, oddly, only at one-third of the predicted

Historic core samples and cataloging of information at the old Homestake Gold Mine have helped engineers and scientists at SURF better understand physical features of the local rock, which saves time and money when it comes to contemporary excavation efforts there. The headframe of the Yates Shaft (seen here), which opened in 1938, serves as the main access for people and equipment to get deep underground.

Credit: Matthew Kapust, Sanford Underground Research Facility, ©South Dakota Science and Technology Authority

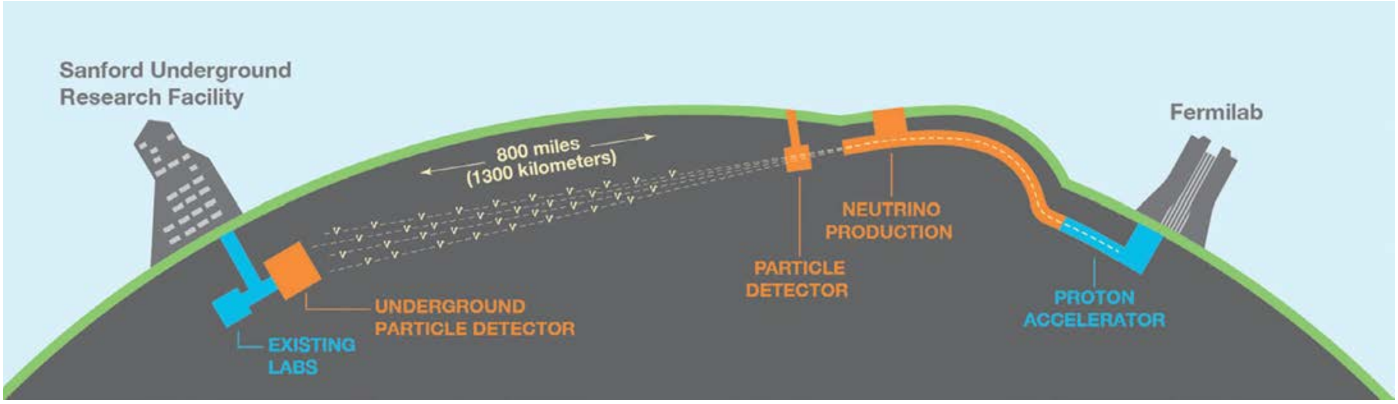
rate. As subsequent experiments would confirm, this wasn't a case of an inaccurate detector, but rather one of the first signs that neutrinos come in three types, or flavors: electron neutrinos, the type observed by the SURF detector, as well as muon and tau neutrinos.

Construction of a next-generation detector broke ground in 2017 at SURF. The new detector will take a decade to build and is part of a massive, international research collaboration known as the Deep Underground Neutrino Experiment (DUNE), which brings together roughly 1,000 scientists from more than 160 laboratories in 30 countries. In addition to the detector at SURF, the other main piece of DUNE is the source of neutrinos, which is a particle accelerator at the Fermi National Accelerator Laboratory (Fermilab) in Batavia, Ill. The accelerator will send a concentrated beam of neutrinos through Earth to the detector at SURF, about 1,300 kilometers away, where only a small fraction of the original neutrinos is expected to be detected. Researchers are interested in how these neutrinos scatter and change after interacting with other subatomic particles during their underground trip. The detector at SURF will also be able to observe high-energy neutrinos passing through Earth from cosmic sources like supernovae.

"DUNE is designed to be maximally sensitive based on current limitations," says Jonathan Paley, an associate scientist at Fermilab. The high-resolution detector at SURF, the largest of its kind, "can see neutrino interaction events in three dimensions with unprecedented resolution," Paley says. This level of detail will help the DUNE collaboration elicit as much information as possible from these messenger particles, including their energy, flavor and even potentially their incoming direction, among other features. The more researchers can determine about the features of a given neutrino, the better they can understand where it came from and the intense physical events that created it. The neutrino researchers involved with DUNE hope to answer outstanding questions about the universe regarding the balance between matter and antimatter, the stability of matter and what happens inside supernovae, as well as to expand our understanding of fundamental physics in our universe and reveal processes we haven't yet observed.

Excavations and Records

Mining operations have proved, on the whole, to be a major blessing for underground research efforts. In his research studying deep-dwelling microbes, Onstott says he appreciates having access to unsullied portions of rock as mining operations continually expose fresh surfaces through drilling and blasting. Fresh exposures sometimes provide access to organisms only recently exposed to oxygen and that



The DUNE project, construction of which is underway, involves four massive detectors 1.5 kilometers below the surface at SURF that will study neutrinos produced by an accelerator roughly 1,300 kilometers away at the Fermi National Accelerator Laboratory in Illinois. The current timeline calls for two of the detectors to be online by 2026.

Credit: Fermilab

may have been undisturbed for tens of thousands of years. However, for scientists working in active mines, ongoing operations can be a nuisance as well. When and where research can be conducted is up to the discretion of mine owners; and the same blasting that exposes fresh rock also limits the amount of time researchers can spend in the mine. “Everything has to be planned in advance and we’re running a lot of the time. We want to get in as much [sampling and placement of collection equipment] as possible before the mine is cleared for blasting at the end of the day,” Onstott says.

That’s not an issue at decommissioned mines, though. At the Homestake Mine, which houses SURF, “there are no competing interests, and research is what it’s all about,” says Constance Walter, communications director at SURF.

Past mining efforts can tell researchers a lot about the physical features of rock surrounding a mine, as well as about how the rock formed, past seismicity in the area and other useful information. “The Homestake Mining Company did a tremendous job of cataloging the rock,” Walter says. “We’re lucky to still have their historic core samples.” And researchers working at Soudan have benefitted in the same way, with historical core samples inherited after the mine was taken over by the state. Being able to use these past records offers essential time and financial savings compared to drilling new holes or excavating from scratch. William Roggenthen, a geological engineer at the South Dakota School of Mines and Technology, studies the mechanical properties and behavior of soil and rock as part of the SURF collaboration. Such work is relevant in understanding expected behaviors of materials in applications related to construction, mining, dams and geothermal development, as well as in developing new materials. Conducting this type of research on deep natural rock formations is typically very difficult to justify economically. But at SURF, he “can get up close and personal with the rock mass I want to investigate in a cost-effective manner,” Roggenthen says.

Sometimes, though, further excavation is necessary once a mine is turned into a research facility. At SURF, for example, engineers must still excavate a volume of rock the size of a small warehouse more than a kilometer underground to house the massive detectors required for DUNE. To accomplish such feats, underground research facilities bring in civil engineers, including many who typically cut tunnels for roads and subways.

“Typical mining excavation values the volume of rock moved and doesn’t care much about the quality of the walls or long-term stabilization of large caverns,” says David Vardiman, a geotechnical engineer who is in charge of the SURF excavation. Every step of the process for creating these research facilities requires more precision, especially in the blasting patterns. Rock walls are meticulously smoothed and stabilized with cable and concrete. The final product looks more like an airplane hangar than a cave. While the construction deviates from typical mining protocols, knowledge of a mine’s history is vital. The 140-year history of excavation at the Homestake Mine provides “a better understanding of how the rock mass will react to excavation,” Vardiman says. The historical drilling cores also helped engineers select the region of the old Homestake Mine that was most amenable to a large-scale excavation. Such engineering and attention to detail lead to huge underground spaces that can last several decades.

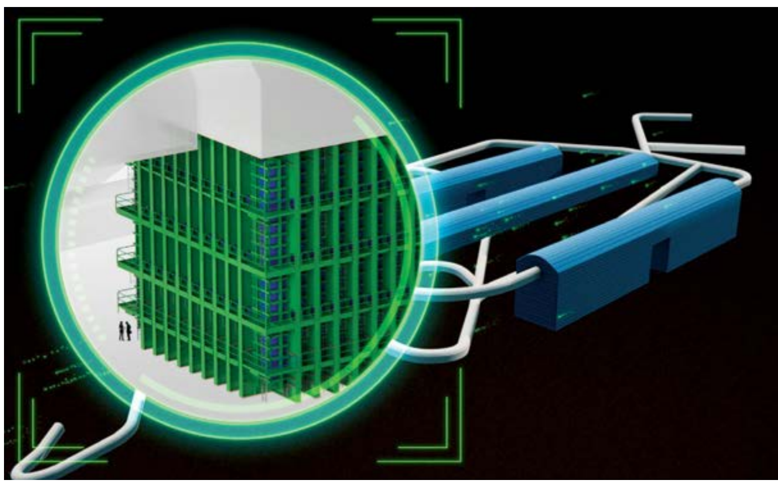
Before the DUNE detectors can be built at SURF, roughly 875,000 tons of rock must be removed, requiring detailed planning, test excavations, as seen here, and careful execution.

Credit: Sanford Underground Research Facility, ©South Dakota Science and Technology Authority

An Uncertain Future

Many subterranean experiments generate a lot of buzz given their unorthodox settings and their engagement in answering fundamental science questions. This attention offers a certain amount of staying power for these projects, with many of the larger ones slated to run for several decades. "DUNE is a very exciting program," Paley says. "It offers a broad research program, touching on a number of key topics, that will keep us busy for a long time to come."

In addition to those studying the origins of life and particle physics, researchers in many fields are capitalizing on the accessibility of unique underground environments to undertake a variety of investigations. Computer hardware companies have placed hard drives underground to evaluate whether cosmic rays damage data storage; seismologists have installed geophysical arrays sensitive enough to detect ripples from tsunami waves reaching the West Coast of the U.S. from as far away as the Indian Ocean; and microbiologists have isolated bacteria from rotting mine timbers that could help produce more efficient



The Neutrino-sensing DUNE detectors will each hold 70,000 tons of liquid argon.

Credit: Fermilab

Maintaining public support for underground research facilities, most of which are supported at least in part by public funding, is vital for labs' survival, so outreach and education efforts are typically a high priority. SURF is home to a visitor center full of exhibits (above) and hosts occasional public outreach events such as an annual "Neutrino Day" (top right). At Lake Vermilion-Soudan Underground Mine State Park (right), visitors can take guided tours of the historic mine operations and ride the original mine railway.

Credit: clockwise from top left: Matthew Kapust, Sanford Underground Research Facility, ©South Dakota Science and Technology Authority; Laura Howard, Sanford Underground Research Facility, ©South Dakota Science and Technology Authority; Josh Knackert

biofuels. The isolation that draws researchers underground also offers an appealing trap for things that need to stay put for a long time, like radioactive waste or carbon captured from power plants or the atmosphere.

Despite the wealth of potential from underground research, there are persistent challenges for facilities hosting such work. As with virtually all research, funding is the big unknown. Researchers working in active mines are often dependent on a mine's profitability. Maintenance of deep excavations is incredibly costly. If a pumping system isn't maintained, mines slowly fill up with groundwater. For example, between the time the Homestake Mine was fully decommissioned in 2003 and when it became a full-time research facility in 2007, the mine slowly filled with water. Before construction could begin on the research spaces, the mine had to be pumped out and refurbished.

Combined with other bare necessities, like circulating fresh air, performing regular safety checks and operating mine cages, costs can easily reach hundreds of thousands of dollars per year for individual mines. "The South Africa mines are beginning to shut down [due to decreasing profitability], meaning we will eventually lose our access," Onstott notes.

Soudan and SURF each depend on a mix of public and private funding, but those sources are also finite and prone to fluctuation. Soudan relies heavily on state funding as a state park, meaning budget cuts or low tourist attendance could close the mine and spell the end of research there. SURF was established with a private $70 million donation from T. Denny Sanford combined with $40 million from the state of South Dakota, but it continues to get grants from the National Science Foundation and the Department of Energy as well.

Underground research facilities house scientific investigations beyond just particle physics and microbiological experiments. At SURF, for example, researchers have begun studying rock mechanics and geothermal systems as part of the Stimulation Investigations for Geothermal Modeling and Analysis project. The project involves drilling several boreholes for injection and production of geothermally heated water, as well as for monitoring.

Credit: Sanford Underground Research Facility, ©South Dakota Science and Technology Authority

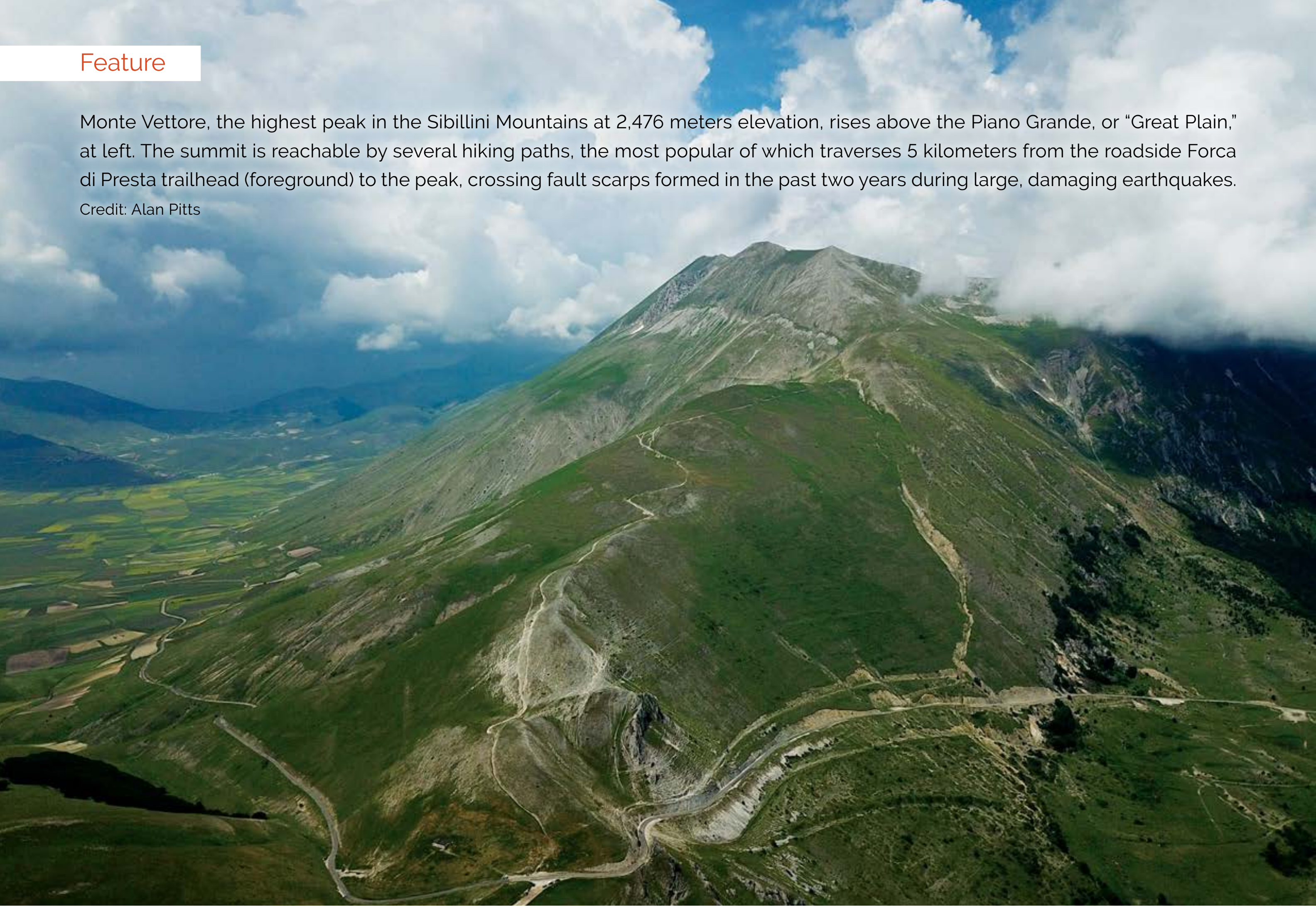
Fostering collaboration and highlighting return on investment are keys in maintaining public support for these facilities, a point often reiterated by the people involved in their operation. As part of his donation, Sanford required that SURF promote education and outreach. That directive is fulfilled with a visitor center offering detailed information to guests, as well as with internships, fellowships, activities for student groups, and collaborations with several nearby universities that support a variety of local jobs. A dedicated education and outreach staff has also developed curriculum kits that are sent to classrooms in South Dakota and beyond. These kits "are especially popular as they give teachers … the opportunity to incorporate hands-on, inquiry-based science units into their classrooms," Walter says, noting that other national and international laboratories have contacted SURF for help in developing their own educational lesson plans.

At Soudan, Sheik, Brengman and the retired miners who still work at the site, giving tours and running the museum, all hope that enough tourists visit the mine to keep it going, perhaps lured by curiosity about the captivating iron-rich rocks 800 meters below the surface or the chance to eat lunch in a historic mining operation while sitting on boxes labeled "TNT/explosives." They also hope that more researchers realize the upside of working underground — where the potential science to be done is as exciting as the subterranean environment itself.

"These are such unique environments to ask important questions," Onstott says. "It's the lack of access that always kills us," never a lack of new questions.

Knackert is a science communicator at the University of Wisconsin-Madison and a freelance science writer who enjoys writing about geoscience.

Feature



Monte Vettore, the highest peak in the Sibillini Mountains at 2,476 meters elevation, rises above the Piano Grande, or "Great Plain," at left. The summit is reachable by several hiking paths, the most popular of which traverses 5 kilometers from the roadside Forca di Presta trailhead (foreground) to the peak, crossing fault scarps formed in the past two years during large, damaging earthquakes.
Credit: Alan Pitts

Travels in Geology

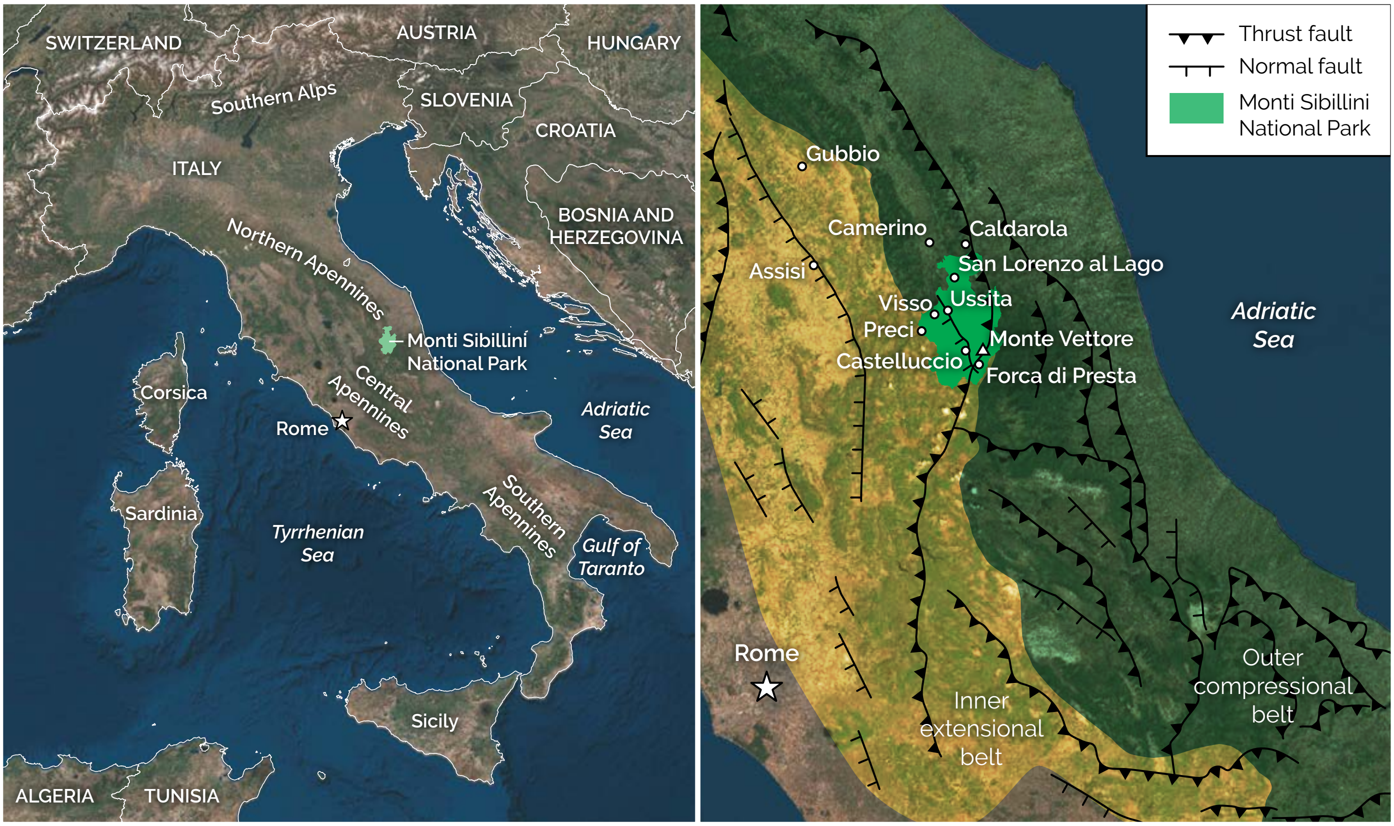
JEWEL OF THE APENNINES

Italy's Monti Sibillini National Park

Callan Bentley and Alan Pitts

The Apennine Mountains form the exposed, rocky backbone of Italy. In northwestern Italy, the mountains are linked to the Maritime Alps; from there, they wind sinuously southward in the form of several arcuate chains all the way to the southern terminus of the Italian Peninsula, where they disappear under the Gulf of Taranto before reappearing on Sicily as part of the Calabrian Arc. In the central Apennines, roughly three hours from Rome by car, Monti Sibillini National Park straddles the border between the regions of Umbria to the west and Marche to the east. The park offers exemplary views into the formation of Italy's limestone spine, as well as several chilling lessons about the relationship between humans and the unstable land on which we live.

The landscape of the central Apennines is a manifestation of the geological processes that have acted on this region for more than 200 million years. It is a place where human history is closely tied to the terrain: a relationship that has produced terrific rewards of agriculture and art, as well as great catastrophes from earthquakes and landslides.



The Apennine Mountains run the length of the Italian Peninsula. In the central Apennines, Monti Sibillini National Park straddles the border between the regions of Umbria and Marche. Two main stages of Cenozoic tectonism shaped the Apennines: Compression along thrust faults during the upper Eocene and Oligocene that contorted and uplifted rocks in the western portion of the range, followed by extension along normal faults in the Pliocene and Quaternary that has created high flat basins surrounded by steep mountain topography.

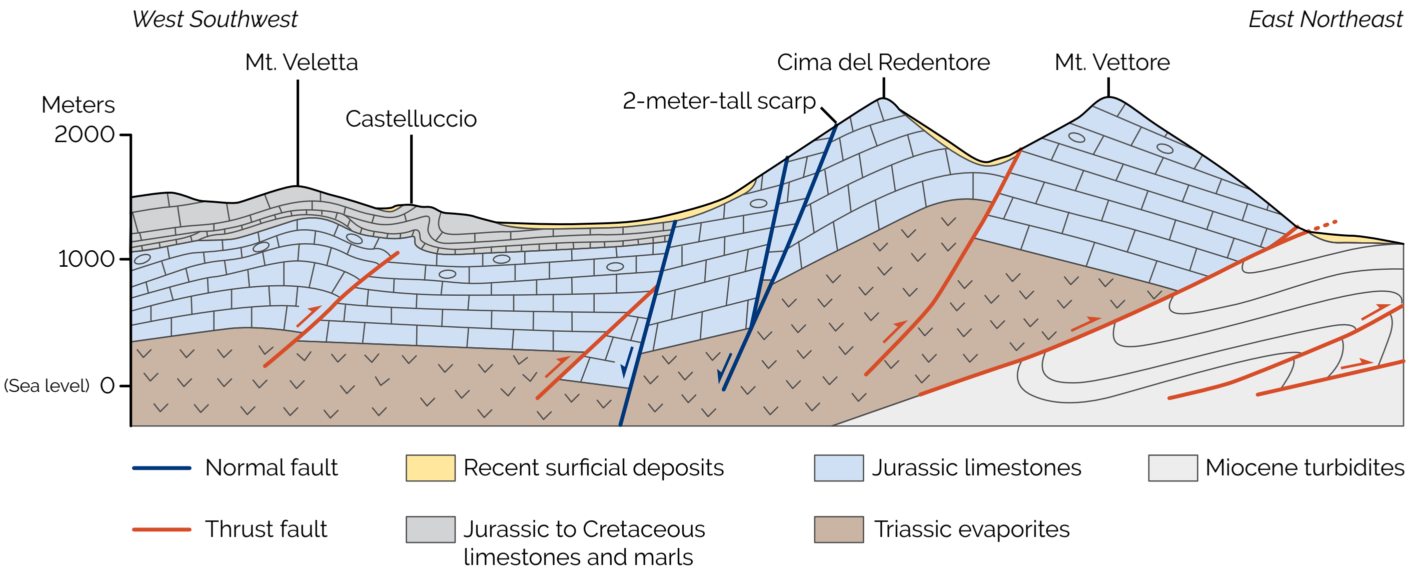
Credit: both: K. Cantner, AGI, after Vezzani et al., GSA Special Paper, vol. 469, 2010

A Story Only a Sibylline Oracle — or a Geologist — Can Tell

The Sibillini Mountains, with their high pristine peaks and occasionally intense shaking, have for centuries evoked a sense of enchantment, both benevolent and sinister, in the minds of locals and visitors alike. The rugged terrain was named after a legendary medieval oracle, a sibyl, who, like the prophets of classical Greece, had the power to see the future and the past. Stories tell of a particular oracle who lived in this part of the Apennines, surrounded by treasures, in an underground paradise that could be accessed only through a high cave entrance at the top of Monte Sibilla, one of the highest peaks in the range. As the legend goes, quite a few European explorers ventured in search of the cave, and many never returned.

The story of the rocks of Monti Sibillini National Park begins in the Late Triassic with the opening of the Tethys Ocean between the supercontinents of Gondwana and Laurasia. In the Early Jurassic, warm and shallow Tethys waters along a passive continental margin in the vicinity of modern Italy created conditions ripe for the deposition of ample calcareous sediments, which piled up into a thick carbonate platform — an environment closely resembling the present-day Bahamas. Over time, the calcite shells of deceased organisms — particularly microscopic foraminifera — contributed more and more to these sediments, and thus to the eventual limestones that formed from them.

The Italian naming convention for many of these limestones is straightforward. The Calcare Massiccio, for example, translates to "massive limestone." The "scaglia" units are named for the "scaly" or flaky way that they weather, along with their color. The Scaglia Bianca is white, the Scaglia Rossa is red, and the Scaglia Variegata is mixed in color. Once you learn this naming code, you'll recognize these limestones where they have been used in constructing buildings and towns of the central Apennines. For instance, the Basilica of St. Francis in Assisi has a distinctive pink color because it was built from the Scaglia Rossa.



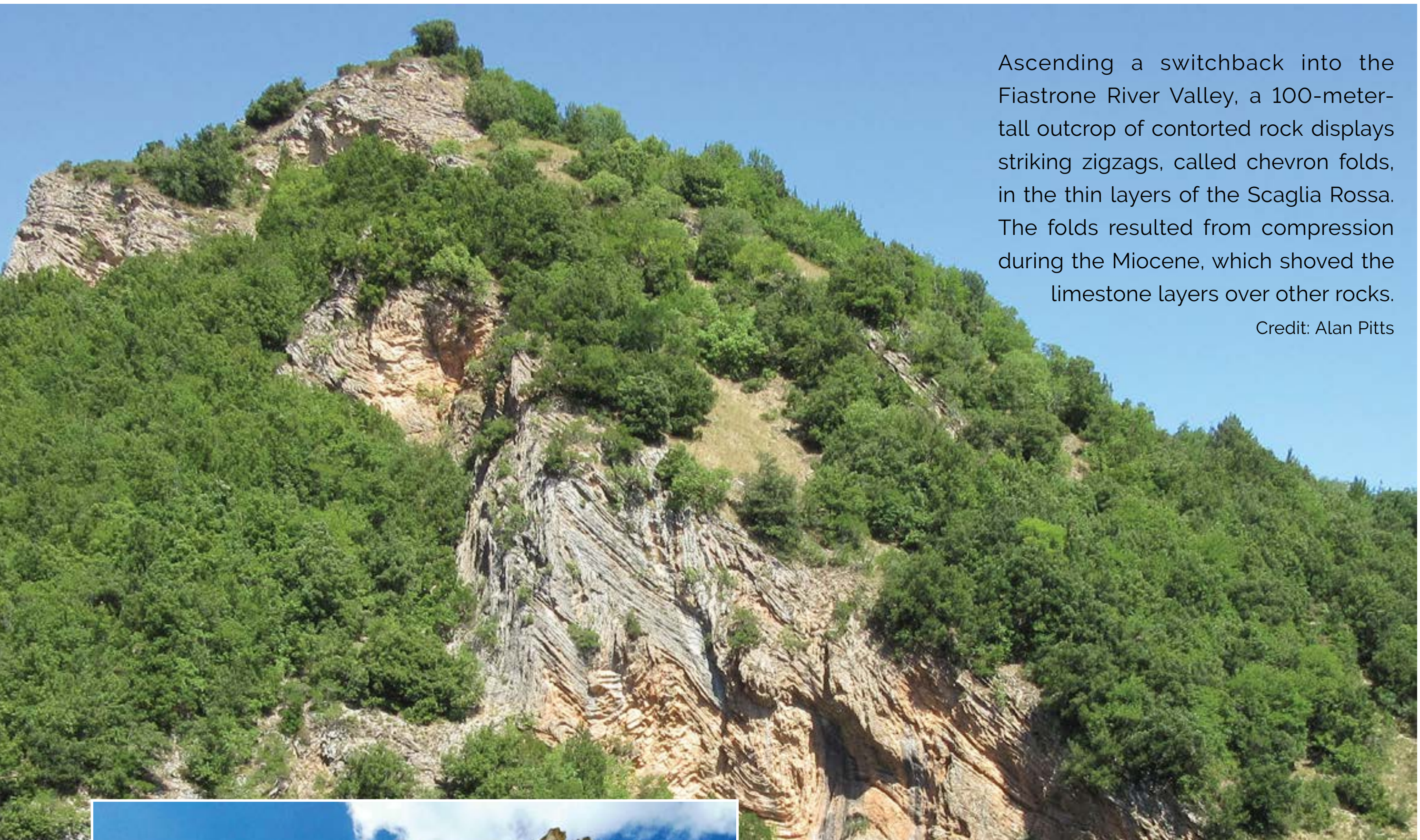
A geological cross section through the central Apennines in the vicinity of Monte Vettore and the Piano Grande.
Credit: K. Cantner, AGI, after Pierantoni et al., Italian Journal of Geosciences, vol. 132, 2013

Within the Scaglia Rossa is the Cretaceous-Paleogene boundary dating to 66 million years ago. The sudden drop in the diversity, size and ornamentation of foraminifera at the boundary tells of a cataclysmic global event that happened at the time: the end-Cretaceous mass extinction. At Bottaccione Gorge near Gubbio, about 60 kilometers northwest of the national park, the famous outcrop where scientists identified an iridium anomaly in the rock — which was later linked to the massive Chicxulub impact implicated in the mass extinction — remains a pilgrimage site for geologists.

A Tale of Two Tectonics

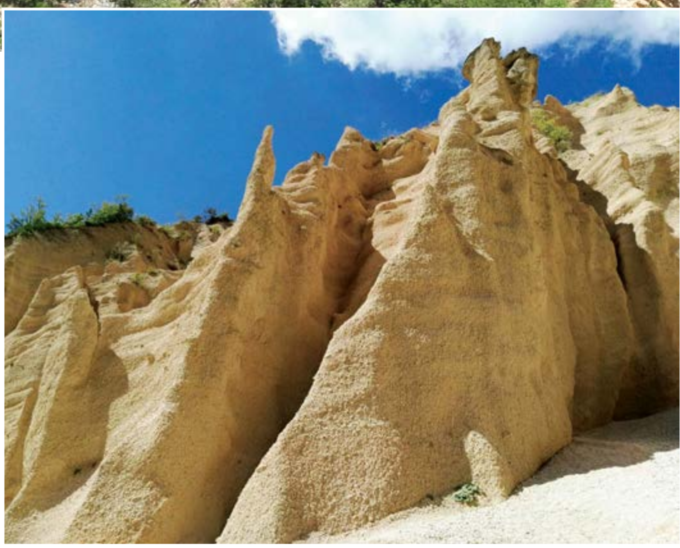
Two main stages of Cenozoic tectonism shaped the Apennines, partly overlapping in space and time. Beginning roughly 35 million years ago in the upper Eocene and continuing into the Oligocene, the older limestones in the western portion of the Apennines were compressed and contorted into folds and uplifted above the surrounding topography along thrust faults. As this compressional belt propagated eastward, arriving in the interior portion of the chain during the Miocene, thrust faulting generated deep marine sedimentary basins that became the

The Basilica of St. Francis in Assisi, about 40 kilometers west of Monti Sibillini National Park, has a distinctive pink color because it was built from the Scaglia Rossa limestone.
Credit: both: Callan Bentley



Ascending a switchback into the Fiastrone River Valley, a 100-meter-tall outcrop of contorted rock displays striking zigzags, called chevron folds, in the thin layers of the Scaglia Rossa. The folds resulted from compression during the Miocene, which shoved the limestone layers over other rocks.

Credit: Alan Pitts



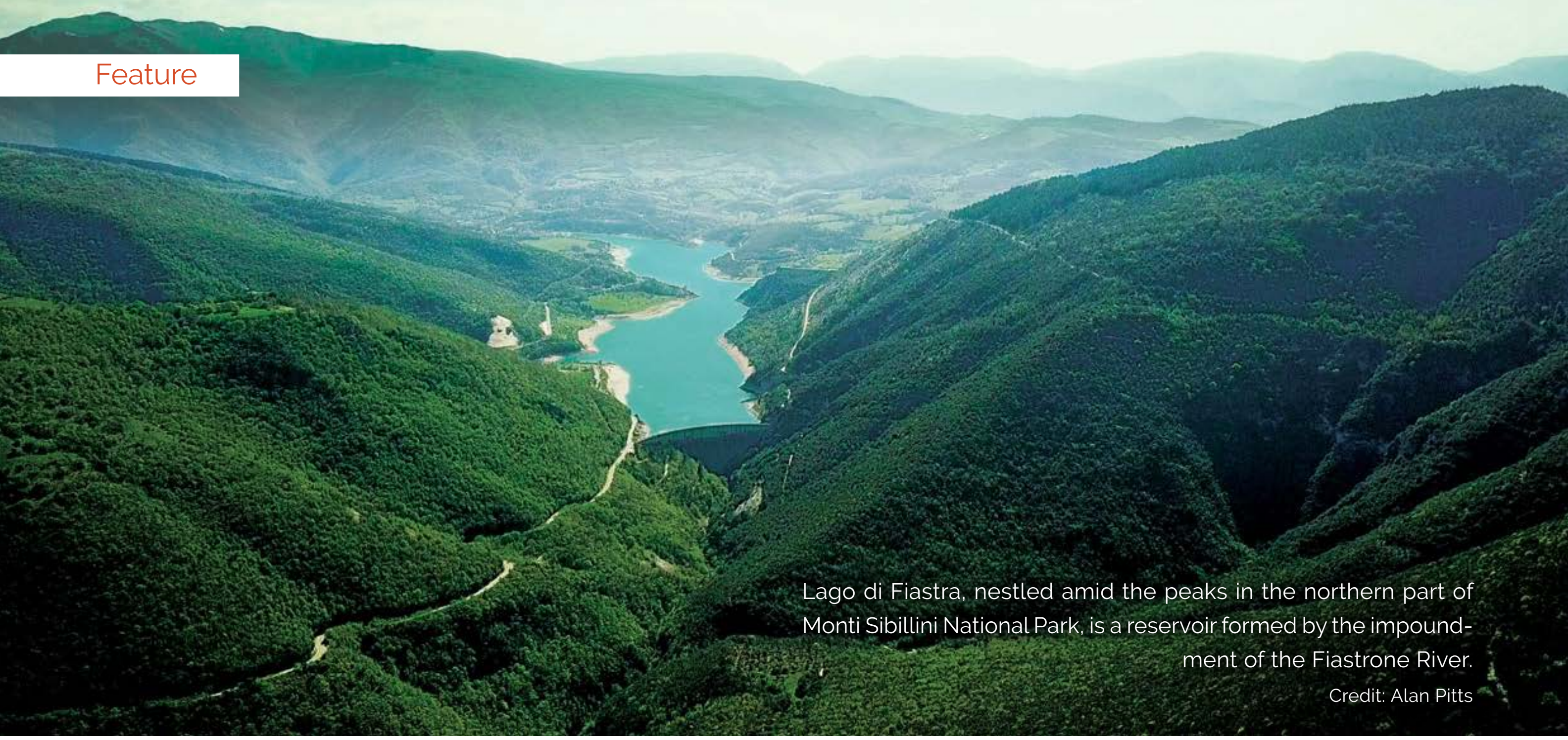
Amid the Lame Rosse, hoodoos rise from eroded Holocene sandstones and conglomerates.

Credit: Isabella Vitali, public domain

repository for sediment that cascaded down along the ancient seafloor as turbidity currents, forming thick packages of sandstone and shale. These Miocene turbidites are syntectonic, meaning they formed at the same time that the compressional stresses were deforming the limestones.

The eastern portion of the Apennine chain, where this compressional activity is still occurring, is called the outer compressional belt, a naming convention likely due to the fact that Italian geology tends to be viewed from the perspective of Rome (which lies west of the mountains). The area around Lago di Fiastra, a reservoir in the far north of Monti Sibillini National Park, is a great place to examine the tectonic structures produced during the main compressive phase of Apennine mountain building, such as wonderful examples of folding and thrust faulting on both large and small scales.

Closer to Rome is an extensional belt on the western flank of the chain, where the Apennines are being stretched. In this zone, Pliocene- to Quaternary-aged normal faults dissect the previously uplifted landscape, creating basins in the mountains that make for high flat plains surrounded by steep topography. Active movement on these faults continues today, sometimes with catastrophic results. Every time a fresh earthquake creates offset along these faults, it increases the local relief. Some rocks rise higher into the sky, while others sink lower. This encourages the breakdown of the mountains and the filling of the basins. The Piano Grande ("Great Plain") of the Castelluccio Basin is a unique location to see the evidence of these active mountain-sculpting processes, such as ground surface ruptures along the trace of long extensional faults and the vast, flat intermontane plain.



Lago di Fiastra, nestled amid the peaks in the northern part of Monti Sibillini National Park, is a reservoir formed by the impoundment of the Fiastrone River.
Credit: Alan Pitts

Contemplating Compression Around Lago di Fiastra

Approaching the northern part of Monti Sibillini National Park from the northeast, you'll climb Strada Provinciale ("provincial road" or SP) 91 into the mountains. Ascending a switchback into the Fiastrone River Valley, a prominent 100-meter-tall contorted rock will catch your attention. The striking zigzags in this rock are chevron folds in the thin limestone layers of the Scaglia Rossa. The strata date to the early Late Cretaceous, roughly 100 million years ago, but the folding that overprints them only occurred in the Miocene, about 15 million years ago or less. This is a fine place to contemplate the first stage in the tectonic evolution of the Apennines, when compressional stresses shoved older rocks atop the Miocene turbidites. Also visible here, if you gaze across the valley, are several thrust faults and recumbent anticlines, as well as the tracks of recent debris flows and small landslides.

If you're interested in stratigraphy, you'll want to check out the Bonarelli Level, a 3-meter-thick interval of organic-rich black shales within the Scaglia Bianca. A dark sliver of rock within a stack of white limestone thousands of meters thick, the Bonarelli Level is a key marker-bed for geologists amid the contorted structure of the region, sliced and diced as it is. The level marks the stratigraphic boundary 93.9 million years ago between the Cenomanian and Turonian ages of the Cretaceous. It can be seen in many locations throughout the Apennines and Alps, although it's an expression of a global-scale oceanic anoxic event — a time when oxygen levels in the oceans dropped, allowing undecayed organic matter to build up on the seafloor. The cause of the ocean anoxia — whether tectonic or climatic in origin — is still disputed. The best place to view the Bonarelli Level in this area is from the roadside, about 10 kilometers down the road from the chevron folds viewpoint.

Nearby, the sediments and formations of the Lame Rosse ("Red Blades") badlands are another spectacular site. Looking more like southern Utah

Lago di Fiastra's emerald green to blue waters and the abundance of activities for visitors make the area a popular summertime retreat for locals.
Credit: Alan Pitts

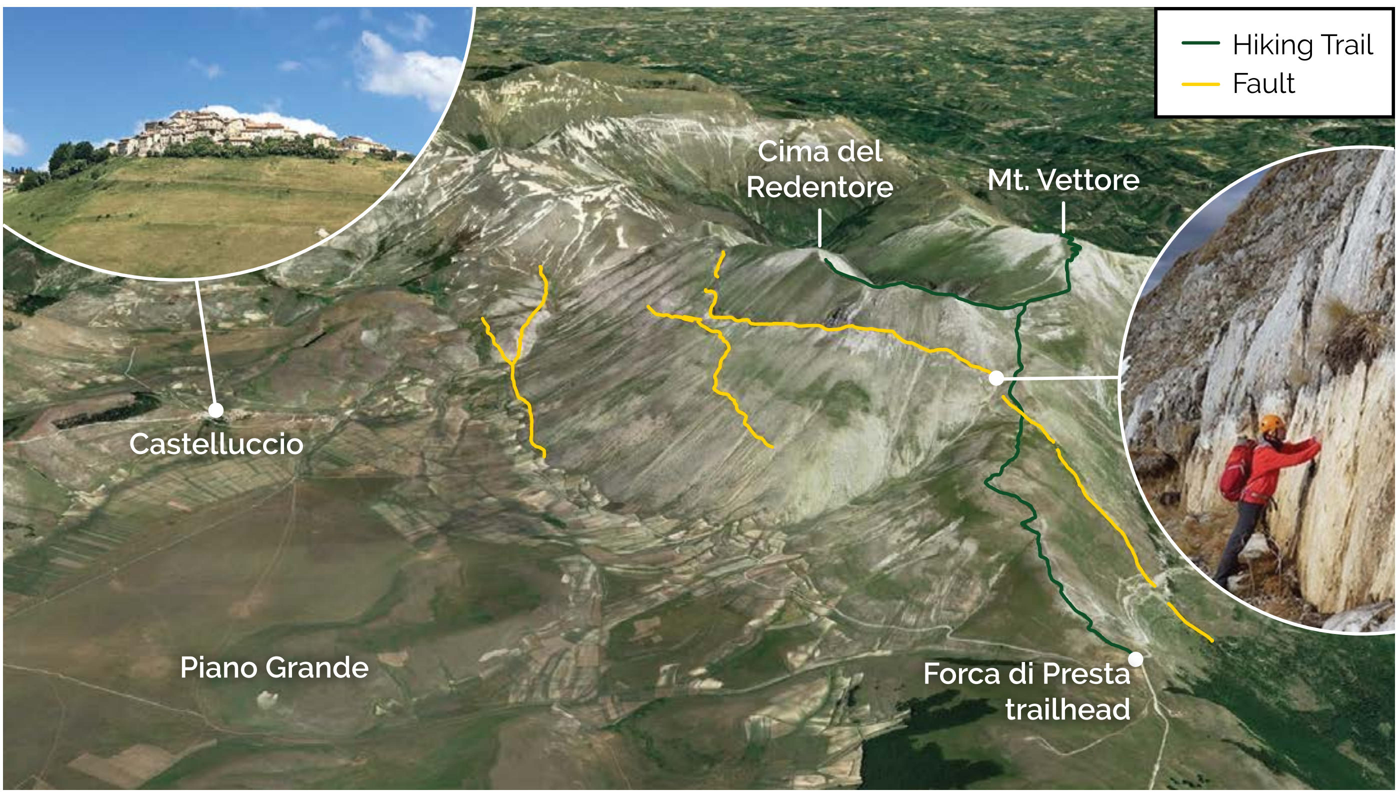
than central Italy, it's a site that will impress even nongeologists. Here, towering hoodoos rise from extremely young (Holocene) sandstones and conglomerates — most tinted varying shades of orange — that don't neatly fit into the overall story of the formation of the Apennines, but rather represent periods of intense erosion of previously unvegetated rocky slopes. A scenic hiking trail from the Lago di Fiastra Dam will take you to the outcrops.

A gem of this part of Monti Sibillini National Park, Lago di Fiastra is a reservoir on the impounded Fiume Fiastrone (Fiastrone River) with milky, emerald green to blue waters that is a classic summertime retreat for locals. In addition to plenty of hiking and biking (both road and mountain), the village of San Lorenzo on the eastern shore of the lake hosts several tourist facilities offering opportunities to boat, paddleboard, kayak, swim or just lounge on the beach with a gelato or drink in hand. After the recent earthquake sequence that hit the region in 2016 and 2017, officials lowered the reservoir level to reduce the risk of a landslide-induced tsunami overtopping the dam. The low water levels can make for a steep descent to the beach, which adds to the surreal beauty of the location.

Downstream of the reservoir, the Fiastrone River scours through the Scaglia Rossa limestone, revealing several older stratigraphic units of the Apennines. Visitors can wade through the river in the Gole del Fiastrone (Fiastrone Gorge) in an experience reminiscent of the Narrows in Zion National Park or Arizona's Antelope Canyon. However, thanks to the buffering of water flow provided by the dam at the northeast end of the lake, there is little risk of being swept away in a flash flood.

Hitting High Notes in Piano Grande

About 25 kilometers south of Lago di Fiastra, the Piano Grande is a high plain sitting about 1,200 meters above sea level and surrounded by the highest peaks in the central portion of the national park. Guarding the Piano Grande from above is the village of Castelluccio, the highest in the region and



Tectonic extension along normal faults that bound the Piano Grande on its eastern edge continues to drop the floor of the basin, and the town of Castelluccio, downward with respect to the mountains to the east, including Monte Vettore. Hiking along the trail that ascends to Vettore's summit from the Forca di Presta trailhead takes you across fault scarps created during recent earthquakes, including a particularly impressive 2-meter-tall scarp.

Credit: K. Cantner, AGI, based on an image from EMERGEO working group

The Piano Grande is a high plain about 1,200 meters above sea level and surrounded by the highest peaks in the central portion of Monti Sibillini National Park.
Credit: Alan Pitts

formerly home to some 130 people who have since been relocated to newly built anti-seismic structures until the town is reconstructed. This location is famous for producing lentils and distinctively cured salamis.

Even higher above the Piano Grande sits Monte Vettore, which tops out at 2,476 meters. This summit is reachable by several hiking paths of varying difficulty, the most popular of which starts at the Forca di Presta trailhead off SP477 and traverses 5 kilometers to the peak. The trail crosses new fault scarps formed in the past two years during large, damaging earthquakes. Hikers looking to extend their trek for a more challenging climb can continue on the trail to see the crystal blue waters of the Lago di Pilato, one of the few natural lakes in the region. This lake, which sits at 1,941 meters elevation, rests in the trough of a broad, glacially carved valley, one of the most notable glacially derived landscapes on display in the Sibillini Mountains. Though the water may seem inviting after a long hike up the mountain, swimming is strictly prohibited, as Lago di Pilato hosts a rare species of freshwater crustacean that is found only in this tiny mountain lake.

In late summer, a vibrant mosaic of colors arises from the lentil fields in the Piano Grande in a spectacle known as the Fioritura, or "flowering," of Castelluccio.
Credit: Stefano Avolio, CC BY-SA 2.0

Hiking, mountain biking and horseback riding are popular activities for tourists in the Piano Grande. In late summer, the area hosts a vibrant mosaic of colors that burst from the lentil fields, a spectacle known as the Fioritura, or "flowering," of Castelluccio that attracts visitors from all over Italy. The rich cultural and culinary traditions (see sidebar, page 47) born in this region are at risk of being lost, however. Due to heavy damage from the recent earthquakes, several of the towns and commercial enterprises, once thriving, are now struggling to remain active.

The village of Castelluccio, perched atop a hill overlooking the Piano Grande, was heavily damaged during a magnitude-6.6 earthquake that occurred in October 2016 along a normal fault roughly 10 kilometers northwest of the town.
Credit: Alan Pitts

Apennine Earthquakes Reshape the Landscape

Aside from being one of the most picturesque locations in Monti Sibillini National Park, and a treasured recreational location, the Piano Grande is also an active extensional basin. The natural beauty of this landscape derives from a system of normal faults that bound the basin on its eastern edge and drop the floor of the Piano Grande downward with respect to Monte Vettore. But motion on faults in this region can have severe consequences. In October 2016, the magnitude-6.6 Norcia earthquake struck near here, damaging many nearby towns, including Castelluccio. Stone buildings partially collapsed and much of the town was reduced to rubble.

That quake was just one in a string of earthquakes that struck central Italy in 2016 and 2017. This seismic sequence consisted of three large shocks each greater than magnitude 6.0, along with thousands of aftershocks, occurring between August 2016 and January 2017 along the central Apennine fault system. To this day, the central portion of Castelluccio is closed to traffic, with only residents allowed into the "red zone" for short periods of time. The towns of Amatrice, Caldarola, Camerino, Ussita, Visso and many

Lago di Pilato, a natural high-elevation lake, sits at 1,941 meters elevation in the trough of a glacially carved valley between Monte Vettore and another peak, Cima del Redentore. Swimming is prohibited in the lake as it hosts a rare species of freshwater crustacean.
Credit: Shutterstock.com/Stefano Buttafoco

Many towns in the central Apennines were damaged during the 2016–2017 seismic sequence that hit the region. Here, rubble from a toppled building remains along a roadside in the town of Visso.
Credit: Callan Bentley

others also sustained substantial damage and now have similar exclusion zones where access is limited.

The drive from Preci to Visso along the Strada Statale ("state highway" or SS) 209 (local signage denotes this area as "Valnerina") in the western part of the park takes you through part of the Nera River Valley, offering views of a large landslide triggered by the Norcia earthquake; the slide dammed the Nera River and closed this road for almost a year. Meanwhile, high above, freshly exposed limestone gleams white and a frighteningly large amount of rubble can be seen on both sides of the river on the valley floor.

Though these earthquakes are destructive in the short term, they are also responsible for sculpting the landscape of the central Apennines. The mythological sibyls had the power to see into the future and the past, and the same could be said for geological travelers to this special place: The past is revealed in outcrops and landscapes that tell a story of sedimentary deposition, compressional mountain building and tectonic extension.

Bentley teaches geology at Northern Virginia Community College and is a contributing editor to EARTH. He is a GSA Fellow and the president of the two-year-college division of the National Association of Geoscience Teachers. Pitts is a doctoral candidate at the University of Camerino in Italy, where he conducts research on the evolution of the Apennines. He is a former student of Bentley's and has lived in Italy since 2012. He is the Coordinator of the George Mason University/University of Camerino Field Camp in the central Apennines.

A large landslide triggered by the October 2016 Norcia earthquake dammed the Nera River in the western part of the park and closed state highway 209 for almost a year. Gleaming white limestone, freshly exposed by the landslide, can be seen high above the road.
Credit: both: Callan Bentley

Getting There & Getting Around

For those traveling internationally by air to Italy to visit Monti Sibillini National Park, flying into Rome's Leonardo da Vinci–Fiumicino Airport (FCO) is likely the best option. Florence is another option, but Rome is closer and hosts more flights. There are several routes into the park from different directions; all the entrance points on the western side of the park are a two-and-a-half- to three-hour drive east of Rome. Bus tour services run out of Rome, but the best way to reach the park is via rental car. Rental cars are plentiful, and the good news is that, unlike driving in some parts of Italy such as around Naples or in Sicily (which is not for the faint of heart), driving in the Apennines is much more like driving in the U.S. In this part of Italy, drivers are more courteous and generally adhere to road signage and lane guidelines. All countries have driving norms that are not immediately clear to foreign drivers, however. In Italy, to avoid scorn from your fellow drivers, it's important to remember to never pass another car on the right. Italians consider it a severe breach of driving etiquette.

On your flight to Italy, consider reading Walter Alvarez's 2009 book "The Mountains of St. Francis," which covers the geologic evolution of central Italy in the context of a memoir of his own career studying these rocks. Alvarez, together with his father, Luis, and other colleagues, were the first to detect the iridium anomaly at the famous end-Cretaceous boundary outcrop near Gubbio.

A wide variety of lodging is available in the vicinity of Monti Sibillini National Park. Luxury travelers can stay at the Palazzo Seneca in Norcia. There are also plenty of smaller cabins, hostels and bed-and-breakfasts that provide a more authentic experience in the Apennines. For a quiet and family-friendly stay in the foothills just outside the northern boundary of the park, we recommend Al Respiro nel Bosco bed-and-breakfast. The English-speaking owners, Luca and Matilde, will likely offer guests a glass of their homemade Verdicchio wine. And Luca operates a tour-guide service for those interested in an expert tour of the many different sights within the national park.

Views of hillside orchards and the nearby Sibillini Mountains await visitors to the Al Respiro nel Bosco bed-and-breakfast in the foothills just outside the northern boundary of Monti Sibillini National Park.

Credit: Callan Bentley

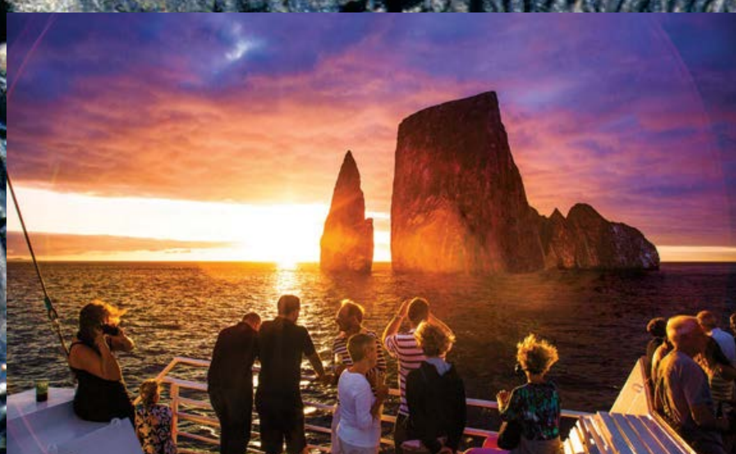
While visiting the Piano Grande/Castelluccio area, be sure to try the lenticchie e salsiccia. This very popular regional dish features locally grown lentils cooked together with local sausage and is an example of the simple, rustic culinary traditions that make this region so special. This corner of Umbria and Marche is also famous for its cured pork products, so you won't go wrong with any salami, prosciutto, lonza or other such products you find. Another local specialty not to be missed is the cold-smoked salami, ciauscolo (also spelled ciavuscolo), a soft, spreadable treasure unique to the mountains of Umbria and Marche and generally unknown throughout the rest of Italy. Order a panino (sandwich) with ciauscolo and pecorino cheese (made from sheep milk) and you'll instantly impress the local shop owners.

Although this region is best known for its pork products, the area is also a mecca for black truffles. A delectable dish you'll find at any osteria or ristorante is Tagliatelle al Tartufo — normally handmade fresh pasta with black truffles and olive oil.

CB & AP


NATIONAL GEOGRAPHIC ENDEAVOUR II



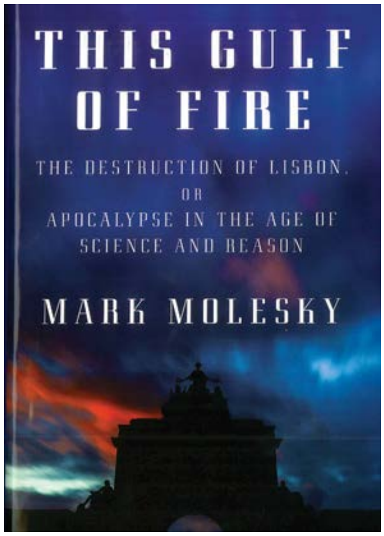



Books: "This Gulf of Fire" Recounts the 1755 Lisbon Disaster

Callan Bentley

In the panoply of history-altering natural disasters, Lisbon's destruction on All Saints' Day, Nov. 1, 1755, stands out. You may have heard of this Portuguese calamity in the context of tsunami coverage, but it was a sequence of three disasters — an earthquake, a tsunami and a fire — that combined to level much of the city and claim tens of thousands of lives. Some scholars suggest a fourth calamity was the way the aftermath was handled, but author Mark Molesky seems more charitably inclined on that front. In "This Gulf of Fire: The Destruction of Lisbon, or Apocalypse in the Age of Science and Reason," Molesky, a historian at Seton Hall University in New Jersey, has written the definitive scholarly account — if not the most accessible one — of that fateful day and its historical aftermath.

"This Gulf of Fire" is a comprehensive and impressively researched work with hundreds of citations and 75 pages of footnotes. Molesky seemingly leaves no stone unturned. However, in this attempt to be exhaustive, the book becomes exhausting. Molesky includes every detail, chaff along with wheat, listing, for example, dozens of estimates — ranging from 10,000 to 40,000 — of the death toll from a wealth of sources. In the discussion of death registers from the various churches in the city, there is list after list of names and occupations of those who succumbed. Similarly, there are interminable lists of buildings, streets and other sites that experienced varying degrees of damage. This is doubtless useful material for the historian interested in plotting things out block by block. However, for the nonspecialist reader, especially one who hasn't visited Lisbon, it is overwhelming. This list mania gets downright silly when Molesky enumerates all the things that burned in the fire: "trunks, dressers, chairs ... barrels of fish, gunpowder, butter ..." etc. (I'll spare you the full list.)



"This Gulf of Fire: The Destruction of Lisbon, or Apocalypse in the Age of Science and Reason," by Mark Molesky, Knopf, Hardcover 2015, ISBN-13: 978-0307267627

But if you skip over many of those lists, you will find a compelling story, with perhaps the most interesting aspect of the disaster being the influence it had on the Enlightenment. The destruction of Lisbon occurred in the middle of this period of flowering of human intellect in a very Catholic city that was one of the last redoubts of the Inquisition. It was a wealthy place, overflowing with riches from Portugal's colony in Brazil, and attendant levels of indulgence.

Molesky has ready foils to represent both the church and secular forces: the Jesuit priest Gabriel Malagrida and the Marquis of Pombal, an advisor to the king. Like a modern televangelist, Malagrida blames the earthquake on God's displeasure at the city's sinful ways to gain followers. Pombal uses the destruction of Lisbon as an opportunity to diminish the influence of the church and advance the cause of secular government, as well as to settle some old scores. He's a ruthless ruler, and the book opens with him orchestrating the execution of Malagrida. It reads like a scene straight out of "Game of Thrones."

The tension between religion and reason extended far beyond Portugal's borders: Across Europe, Lisbon's apocalypse was a vital prompt for discussion. An entire city had been destroyed by a trio of violent events: What did it mean? Kant, Rousseau, Leibniz and Voltaire all chimed in. Molesky recounts their published discourse in context, and thus furnishes his reader with a sense of the intellectual fallout of the event.

Another bright spot is the book's illustrations, including maps, that help document conditions on the day of the earthquake, as well as conditions preceding the disaster and during the subsequent reconstruction. Molesky estimates the quake's magnitude to have been "between 8.5 and perhaps 9.2" and notes that "it was the largest earthquake to affect Europe in the last 10,000 years." He offers interesting speculation on the source fault for the earthquake and makes the case (for the first time) that the culminating fire qualified as a "firestorm," a fire so hot and intense that it produced its own wind system. The blaze lasted for weeks and burned the city to its foundations.

If you enjoy European history flavored with tectonic drama, you will likely enjoy "This Gulf of Fire." And, if you can avoid getting bogged down in the minutiae, you'll find it offers a rich retelling of an event that could be an exemplar of how societies react to catastrophic natural disasters — complete with lessons to bear in mind when the next great earthquake, tsunami or hurricane strikes.

Bentley, an EARTH contributing editor, is an assistant professor of geology at Northern Virginia Community College in Annandale, Va. He is the 2018 recipient of the National Association of Geoscience Teachers Shea Award for exceptional contributions in earth science writing for the public and/or teachers. He blogs about geology at http://blogs.agu.org/mountainbeltway. The views expressed are his own.

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It's already time to plan for our 2019 Annual Meeting in Phoenix, Arizona, USA. Help ensure that your area of research and expertise is represented at next year's annual meeting. Any individual or geoscience organization is welcome to submit proposals. The proposal form is online at **www.geosociety.org/amnext.**

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CLUES

- This formation, a triplet of sandstone pinnacles, can be seen from a cable car that offers expansive views of a national park and a 10,000-square-kilometer UNESCO World Heritage site. The park features a rare, endemic species of pine tree that has existed since the time of Pangea and was thought extinct until living specimens were discovered here in 1994.
- Deep valleys and steep cliffs up to 1,200 meters tall in this area — which is about 100 kilometers inland from the largest city in this Southern Hemisphere country — are remnants of a Paleozoic quartzite plateau that was uplifted and deeply incised. Spires like these three were further sculpted by wind and rain.
- The heritage site, national park and mountain range in which the pinnacles lie all share a name that references the misty azure haze that usually blankets the region. The haze is caused by airborne droplets of oil emitted by eucalyptus trees.

August 2018 Answer:

Located in a rift valley, Lake Baikal in Russia holds more than 20 percent of the world's surface freshwater and has a maximum depth of more than 1,600 meters. Photo by Dave Boden.

August 2018 Winners:

Jerilyn Bachowski (Lackawanna, N.Y.)
Edward S. Grew (Orono, Maine)
John J. Hebberger Jr. (Jackson, Wyo.)
Jim Hensel (Tonawanda, N.Y.)
Stephen McKay (Niagara Falls, Ontario, Canada)

HOW TO PLAY

NAME THE GEOLOGIC FEATURE, ITS HOST MOUNTAIN RANGE & 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 (November 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.

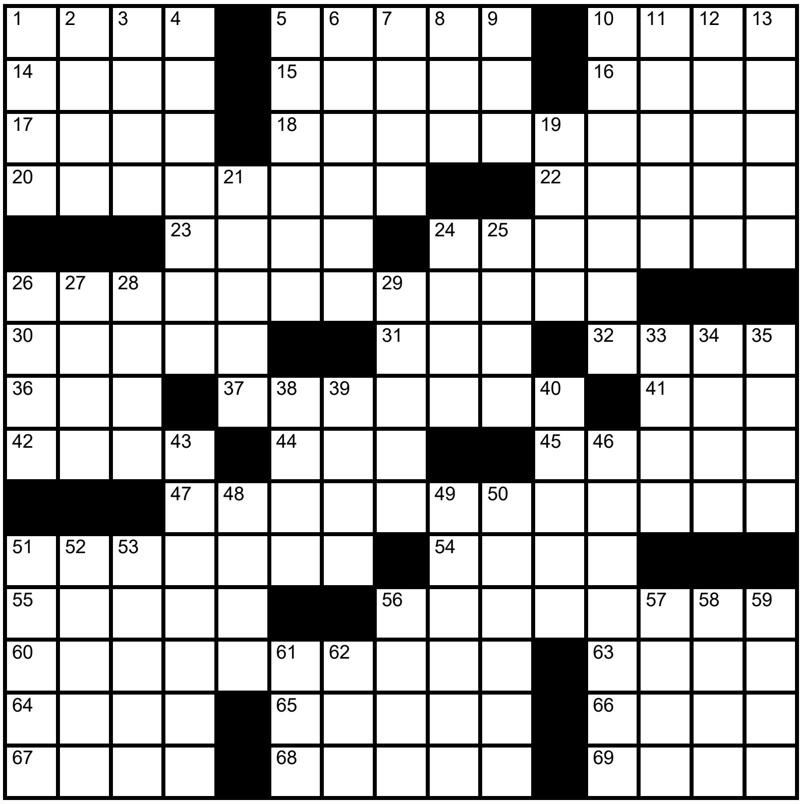
You can also submit entries to Where on Earth? EARTH, 4220 King Street, Alexandria, VA 22302 (postmarked dates on letters will be used). EARTH also welcomes your photos to consider for the contest. Find out more about submitting your photos at www.earthmagazine.org/whereonearth/submit, and send them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

Across

1. Forbidden: Var.
5. Circa
10. Top cover?
14. Biology lab supply
15. Grand ___
16. "___ bitten, twice shy"
17. Bumpkin
18. Reversal of conviction
20. Elementary particle
22. Pub order
23. "Catch!"
24. Craft
26. Deep critter?
30. Escalator feature
31. Coke's partner
32. ___ of the Unknowns
36. "Wheels"
37. X-mas burner
41. Grassland
42. Mass number
44. Born
45. Calculator, at times
47. Asia expert of old?
51. Bumblers
54. Freudian topics
55. Runner Jesse
56. Door feature
60. Minnesota resource
63. Pudding fruit
64. "Mi chiamano Mimi," e.g.
65. High up
66. Hokkaido native
67. Contradict
68. Hearty laughs
69. Wood pegs for a brick wall

Down

1. Mountain pool
2. Chill
3. Hindu Mr.
4. Path from bladder
5. Ratify
6. Jungled island
7. Sundae topper, perhaps
8. Arthur Godfrey played it
9. Cooking meas.
10. Princess gear?
11. Provide, as with a quality
12. Desktop pictures
13. Advances
19. Seed cover
21. High-pitched
24. Saturday school?
25. Airport pickup
26. Carve in stone
27. Inside shot?
28. Course
29. To groom feathers
33. Cutlass, e.g.
34. Convene
35. Blocks
38. Condo, e.g.
39. Bottom of the barrel
40. Dance
43. Mid-day
46. ___ hands
48. Gift on "The Bachelor"
49. Irritate
50. Operatives
51. Rot
52. Cognizant
53. Red Square figure
56. Faculty membr.
57. Assortment
58. Air bag?
59. Flightless flock
61. Apply gently
62. 1969 Peace Prize grp.



Puzzle solution appears in the Classifieds section.

With Geologist Robert Brinkmann

Bethany Augliere

As a child, Robert Brinkmann was always curious about rocks. He wondered how they got where they were and why they were different from each other. Brinkmann grew up in the farm country of southeastern Wisconsin, as well as in the woods in the northern part of the state. After one of his first geology classes in college, he went home and finally understood what he was looking at. "It was such an eye-opening experience to be able to read the landscape," Brinkmann says.

Brinkmann received his bachelor's degree in geology from the University of Wisconsin-Oshkosh before earning both a master's in geology and a doctorate in geography from the University of Wisconsin-Milwaukee, studying human impacts on the environment and lead pollution in soils. Now, as vice provost for scholarship and research and dean of graduate studies at Hofstra University in New York, Brinkmann pursues science communication to reach broader audiences beyond his students and colleagues. He has authored several books, including "Sinkholes of Florida: Science and Policy," and the textbook "Introduction to Sustainability." For nearly a decade, he's also maintained a blog called "On the Brink," in which he writes about topics related to the environment, sustainability and higher education.

Brinkmann recently sat down with EARTH to discuss his work in sustainability, the geology and sinkholes of Florida, and how he became interested in science communication.

BA: How would you describe your research interests?

RB: They involve human modification of Earth, and the measurable ways we can make a difference. So, I do a lot of work on a variety of issues related to sustainability, from water issues to economic development. It's a holistic approach to sustainability.

So many fascinating sustainability issues in the suburbs are emerging at this moment. For example, suburbs are facing serious water issues — whether related to quality or quantity — all over the United States. In my own area of Long Island [New York], we have dozens of suburban water districts in control of a single source aquifer that has serious regional pollution issues.

BA: As a geologist interested in human impacts, what do you think are some of the biggest issues we need to be concerned with in the future?

RB: There is no doubt that climate change is the most existential issue we are facing right now. Of course, the broad cause of this issue is anthropogenic pollution. But climate change is not the only serious pollution problem confronting us. We also have issues with plastics, nutrients and pharmaceutical pollutants as well. We are just now starting to understand how these pollutants impact earth systems.

BA: How did you first become interested in this field?

RB: When I was a graduate student in geology, I worked for a mineral exploration firm that sent me out to collect samples in streams to look for heavy minerals. The areas they sent me to were very heavily altered landscapes, with, for example, sediment coming into a stream from a railroad bridge or roadway. So, what I was collecting was not really a true representation of what would've been there naturally.

I became curious and started reading more about human impacts. This was back in the 1980s when very few people were writing about human impacts in the field of geology. I started talking to my professors too, who told me they didn't do that kind of work. Then I talked

Geologist Robert Brinkmann is vice provost for scholarship and research and dean of graduate studies at Hofstra University in New York.

Credit: Robert Brinkmann

to a professor by the name of Robert Eidt, who was a physical geographer trained in Germany. He was studying human-altered soils through time, and he had developed some chemical techniques to measure human impacts of abandoned settlements. So, he totally understood what I was interested in. That was my big "aha" moment that defined my career and steered me a little bit away from traditional geology.

I started to work with Eidt, and that's how I began researching lead pollution for my doctorate. I ended up managing a state soils lab at the University of Wisconsin-Milwaukee, which was one of the first of its kind. That led me to thinking about cities and human impacts on cities. Eventually, I moved to Florida for a faculty position and to research Florida geology and sinkholes. Florida is full of sinkholes.

BA: What's interesting about Florida geology and sinkholes?

RB: When I first moved to Florida, people would tell me: "Oh, there's no geology here, it's just a flat featureless plane." Many rough and tumble geologists who feel the mountains call to them often avoid spending time getting to know the geology of flat places like Florida. However, if one takes a closer look, they will find that Florida holds clues to understanding the geologic and environmental history of the Cenozoic. There is a nearly continuous fossil record in the state, and the rocks contain assemblages of a fascinating array of plants and animals. It's incredible what you can learn by studying the geology of Florida.

In many parts of the country, in the 19th century and earlier, geologists spent a considerable amount of time puzzling out the lithology, mineralogy, structural geology, geomorphology and other issues. Many regions were described in tremendous detail: Geologic maps were created, and articles and books were written about local geologic conditions. This didn't happen in Florida. While there were some early writers, the geologic literature on Florida prior to the 1950s is relatively slim. My research in Florida focused on puzzling out the complex geologic history of the state through the study of karst landforms. I'm very proud of that work because it was some of the first research on Florida geology.

As far as sinkholes, Florida is lucky because of the early aviation history of the state. There are great aerial photos that go back to the 1920s, and you can see fantastic evidence of these very complicated sinkhole features. Today, many of these [sinkhole-prone] places are covered with houses, so it's not really a surprise that there is regular property damage in some of these areas because these sinkholes are still forming.

BA: What's a common misconception about sinkholes?

RB: Well, a sinkhole is a depression on the surface that forms as a result of dissolution of the bedrock beneath the surface. Florida has so many sinkholes because conditions are perfect for their development. What I mean by that is that Florida is underlain by soluble limestone; it is in a wet, warm environment, and there is an abundance of plant life to produce the needed chemistry that aids in dissolution. Often, people think of sinkhole formation as occurring in a single event. But they can take hundreds of years to form because of the nature of the karst geology.

Brinkmann poses with students studying sustainability at Hofstra University.
Credit: Robert Brinkmann

Also, holes in the ground are often called sinkholes even if they aren't [technically] geologic sinkholes. It's a challenging terminology issue because, to the public, a sinkhole is any hole in the ground that just suddenly forms. For example, newspapers in New York will report that a sinkhole formed due to a water main break or something. And I'll get all these calls from people asking what I can tell them about the sinkhole; but it's not a geologic sinkhole, just a collapse in the ground.

BA: Has your research brought you to other interesting field sites?

RB: I think the most exotic place I ever did fieldwork was in Yemen. When I was working on my doctorate, my advisor, who researched human impacts on soil chemistry, got a call from the American Foundation for the Study of Man, which does work in Yemen, [inviting him along] to go into the field. He didn't want to go and asked if I did. I said, "Sure!" It was the first time I was ever out of the country aside from visiting parts of Canada. It was such a great trip, and I ended up going for two full field seasons.

We were in remote parts of Yemen, which is such a beautiful country. There's so much history that we don't really know about. Yemen was part of the camel caravan for the Queen of Sheba during that era [roughly the fifth century B.C.], and there were all these settlements along the edge of the desert, along the edge of the mountains, and the pre-Islamic people built dams and huge agricultural fields.

These soils are now topographic highs, because people essentially created these elevated deltas. The silt would blow from the desert into the mountains, mountain streams would carry the silt downstream, and it would become captured behind the dams. The dams brought silt-laden water to the fields, and the fields got higher and higher over time. Now, these fields have this tremendous prehistoric record of the region. I was doing a lot of descriptive work, and a lot of lab work afterward in basic soil chemistry and sediment analysis. It was some of the first description of those agricultural fields.

Brinkmann, in 1989, doing fieldwork in Yemen, where he studied the soils of ancient agricultural fields and dam sites built by pre-Islamic settlements.
Credit: Robert Brinkmann

BA: You now do less research and more writing. How did that happen?

RB: I always liked writing. But I hadn't thought much about it until I was in Miami in the mid- to late '90s visiting a friend, and he dragged me to a writing seminar with him. I didn't want to go, but that seminar changed how I wrote. The seminar was with Julia Cameron, who wrote "The Artist's Way: The Spiritual Path to Higher Creativity." She provides a number of really interesting writing techniques that help people like me — people who never really considered themselves writers — turn their ideas into something bigger and more substantial. I started thinking I could write articles that can impact my discipline. Then, I realized that my interests were more interdisciplinary, and I could reach more people by writing more comprehensive books, and that's what I decided to do.

Augliere (www.bethanyaugliere.com) is a freelance writer and photographer and a former editorial intern with EARTH. She is a graduate of the science communication program at the University of California, Santa Cruz, and holds a master's degree in marine biology from Florida Atlantic University.

November 16, 1990: Florida Keys National Marine Sanctuary Is Established

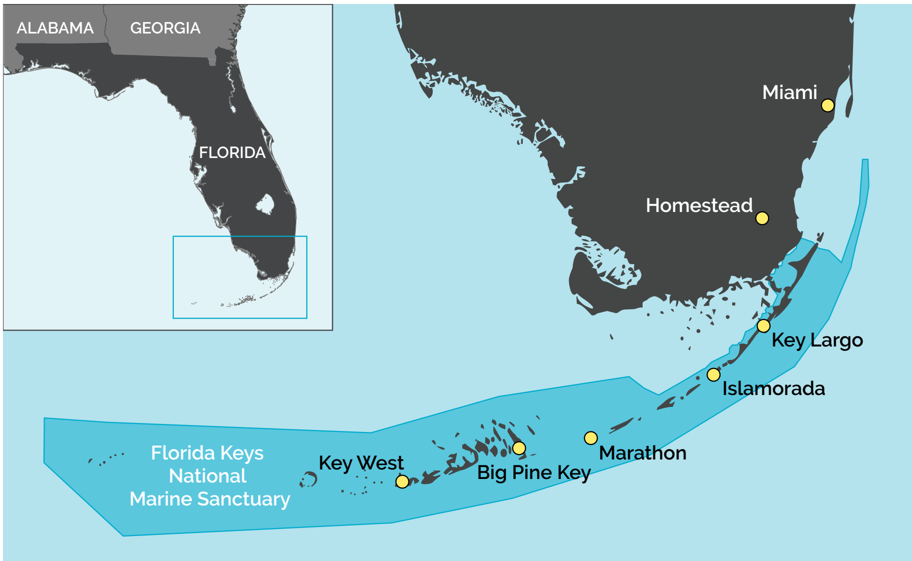
Bethany Augliere

Off the tip of the Florida Peninsula lies the world's third-largest living coral reef, the Great Florida Reef. The only barrier reef system in North America, it is composed of a system of individual reefs that together extend 270 kilometers south of Miami through the Florida Keys, a crescent-shaped chain of more than 1,500 islands, about 30 of which are inhabited. This ecological treasure is home to more than 6,000 species of marine life, including colorful fish and endangered sea turtles, as well as extensive seagrass beds, mangrove islands and about 1,000 shipwrecks.

On Nov. 16, 1990, amid mounting human-caused threats to the reef's well-being, President George H.W. Bush officially recognized the reef's value to Florida's marine ecosystem — and to the state's economy — establishing the Florida Keys National Marine Sanctuary. The marine sanctuary — the country's second, and one of 15 marine protected areas in the National Marine Sanctuary System — protects nearly 10,000 square kilometers of waters surrounding the Keys, including coral reefs, seagrass meadows, mangroves, sand flats and "hardbottom" seafloor habitats.

The crescent-shaped island chain of the Florida Keys (western end shown here) extends south of Miami to Key West, spanning 240 kilometers.

Credit: NASA/GSFC/METI/ERSDAC/JAROS and U.S./Japan ASTER Science Team



Designated in November 1990, the Florida Keys National Marine Sanctuary protects nearly 10,000 square kilometers of ocean surrounding the islands, including North America's only barrier reef.

Credit: K. Cantner, AGI

Underwater Firsts

In 1872, the U.S. established its first national park: roughly 9,000-square-kilometer Yellowstone. The first marine equivalent wasn't established for more than another century, following a series of environmental protections put in place during the early 1970s, including the Endangered Species Act, the Marine Mammal Protection Act, and the Coastal Zone Management Act.

The first national marine sanctuary, Monitor National Marine Sanctuary off the coast of North Carolina, was established in 1975, after researchers discovered the wreckage of the USS Monitor, the United States' first ironclad warship, built during the Civil War. The Monitor's discovery prompted North Carolina Gov. James E. Holshouser Jr. to nominate the final resting place of the war vessel for national marine sanctuary status, recognizing its importance in maritime history and the need to protect it from further damage.

The reefs of the Florida Keys face several threats, including pollution and warming water temperatures, which can make corals, like this diseased brain coral, susceptible to bleaching events.

Credit: Bethany Augliere

Since then, the national marine sanctuary system has grown considerably. It now includes 13 marine sanctuaries and two national monuments, totaling 1.5 million square kilometers of marine

On Aug. 4, 1984, the M/V Wellwood, a cargo ship carrying chicken feed, ran aground on the reef near Key Largo, damaging 75,000 square meters of reef habitat and 5,800 square meters of living coral. Also visible in this photo is the classic "spur and groove" reef formation, with high ridges of coral separated by sand channels.

Credit: NOAA/Florida Keys National Marine Sanctuary

and Great Lakes waters, ranging from the Florida Keys to American Samoa. In 2015, President Barack Obama added two new marine sanctuaries, one off the coast of Maryland and the other in Lake Michigan, which were the first protected marine areas designated by the federal government in 15 years. Sanctuaries require protective measures that place limits on human activity, including commercial fishing, shipping traffic and recreational use.

In the 1950s, growing threats to the Florida Keys reef's health, such as overfishing and seagrass die-offs, began alarming scientists and conservationists. This led to legislative action at the state level, including the creation of America's first underwater park, John Pennekamp Coral Reef State Park in Key Largo. Later, in 1975 and 1981, two small national marine sanctuaries were designated, Key Largo National Marine Sanctuary and Looe Key National Marine Sanctuary, respectively.

Despite designating these protected areas, the reef still faced trouble. In 1983, for example, periods of weak winds and high air temperatures caused ocean warming and widespread coral bleaching on the reef along the southernmost islands of the Florida Keys. Bleaching events along with seagrass die-offs continued into the late 1980s. In 1987, amid the ongoing decline in reef health, the Department of the Interior approved oil and gas development off the Florida coast, which began in late 1988.

Also, in the late 1980s, three large merchant vessels ran aground on the reef, damaging the sensitive coral. One ship, the M/V Wellwood, a cargo ship carrying chicken feed, damaged 75,000 square meters of reef habitat and 5,800 square meters of living coral off Key Largo. Restoration of that area continues today.

Eventually, the combined threats prompted Congress to act, passing the Florida Keys National Marine Sanctuary and Protection Act. And, on Nov. 16, 1990, President Bush formally established the sanctuary, which incorporated both the Key Largo and Looe Key sanctuaries.

Within the boundaries of the sanctuary, visitors can fish, snorkel and scuba dive. However, there are rules and regulations to protect the reef and other marine life. For instance, in all areas of the sanctuary, visitors cannot move, remove, injure, break or possess coral or live rock. Boaters are not allowed to anchor on the coral reefs in less than 12 meters of water, and public mooring balls anchored to the seafloor that boaters can tie up to are in place at certain sites to reduce anchor damage. Furthermore, no dredging or drilling is allowed. To regulate fishing, the sanctuary uses a strategy of marine zoning in which no fishing is allowed in parts of the area, while size and catch limits, established by the Florida Fish and Wildlife Conservation Commission, are in place in other areas.

The Rocks and Reefs

The Florida Keys island chain is geologically young and predominantly made of limestone. About 125,000 years ago, water levels were roughly 30 meters higher. The Upper Keys, from Bahia Honda Key north, are remnants of an ancient reef that existed during this time, while the Lower Keys formed later from old sandbars.

The economy of the Keys is driven by tourism. Recreational activities, like boating, fishing and diving, are allowed within the sanctuary with certain restrictions.

Credit: both: Bethany Augliere

During the last ice age, starting about 100,000 years ago, sea levels dropped, exposing the reef and sandbars, which lithified into the rock that makes up the islands today. The rock underlying the Upper Keys is mainly Pleistocene-aged Key Largo Limestone. This white and light gray limestone is characterized by coral heads in a calcarenitic matrix — limestone composed of more than 50 percent detrital, sand-sized carbonate grains. The formation is very porous and permeable, and as such, is part of the Biscayne Aquifer, a shallow aquifer that provides South Florida with much of its freshwater.

In the Lower Keys, the exposed bedrock is the Miami Limestone, also Pleistocene-aged but younger than the Key Largo Limestone. Additionally, rather than being composed of lithified corals, this limestone is mainly made of ooids — spherical, millimeter-scale grains that form as carbonate minerals precipitate around existing shell fragments or sand grains — along with some quartz and mollusk fossils.

The current living barrier reef is about 5,000 to 7,000 years old and lies about 9.5 kilometers seaward of the Florida Keys in waters ranging from 4 to 9 meters deep. The reef exhibits what's known as a "spur and groove" formation, with coralline ridges and channels perpendicular to the shoreline, shaped, in part, by wave energy. There are about 50 types of coral that make up the reef — such as sea fans, brain coral, star coral and the critically endangered staghorn coral — which together represent about 80 percent of all coral reef species in the Tropical Western Atlantic.

Scientists have also documented more than 500 species of fish that call the Great Florida Reef home. One common fish family along the reef is parrotfish, which are characterized by bright colors and a bird-like beak that helps the fish scrape algae, their food source, off coral. In doing so, parrotfish also contribute sand to the beaches of the Florida Keys. As the fish scrape algae from the coral, they also ingest bits of the coral's calcium carbonate skeleton, which they later expel undigested. One large parrotfish can release up to a ton of sand each year.

A Spanish hogfish swims near a reef in Florida Keys National Marine Sanctuary.
Credit: NOAA/Florida Keys National Marine Sanctuary

Fueled by Tourism

The turquoise waters and vibrant reefs of the Florida Keys bring in about $2.7 billion a year, from snorkelers, divers, fishermen, boaters and other tourists. And 3.5 million people visit the area each year, supporting 54 percent of all jobs there, according to Monroe County, which includes the Keys. Nearly everything in the Florida Keys is linked to the health of the reef — and the reef is struggling.

Decades of overfishing, disease, pollution and coastal development, as well as introductions of invasive species, have caused a prolonged decline in reef health. In the last 240 years, reef coverage on the seafloor has declined by 54 percent, according to a 2017 study that used historical nautical maps to determine the changes. Nearshore reefs — those at the 4-meter depth contour — experienced the largest decline, with a loss of 87.5 percent of reef coverage.

In 2014 and 2015, the Great Florida Reef experienced back-to-back major bleaching events because of warmer-than-average sea-surface temperatures, triggered by a strong El Niño. Then, in 2015 and 2016, the corals experienced back-to-back disease outbreaks. Additionally, a disease known as "white plague," first discovered in 2014 off the port of Miami, has spread north and south, including into the Florida Keys. Overall, it has impacted half of the Great Florida Reef, as of a 2017 assessment.

Around the world, from the Great Barrier Reef off the coast of northeastern Australia to the Mesoamerican Barrier Reef off Central and South America, climate change is considered the greatest threat to coral reef health. Increasing temperatures lead to coral bleaching and disease outbreaks. Stronger and more frequent storms destroy reef structure while ocean acidification due to increasing atmospheric and oceanic carbon dioxide levels makes it difficult for young coral polyps, as well as other vital reef organisms that make shells, like snails and crabs, to build their calcium carbonate skeletons.

The dour trends in the health of reefs worldwide, including the Great Florida Reef, bode ill for both marine ecology and local and regional economies. But there is hope. As vulnerable as reef systems are to climate change impacts, they are also dynamic and sometimes resilient ecosystems. In some places around the world, new coral growth has been observed in as little as two years after bleaching events. And scientists, nonprofit organizations like the Coral Restoration Foundation, and others are also working to restore reefs in the Florida Keys and elsewhere by growing coral in captivity and reintroducing it in the wild. Whether these efforts will be enough to reinvigorate the reef system remains to be seen.

Augliere (www.bethanyaugliere.com) is a freelance writer and photographer and a former editorial intern with EARTH. She is a graduate of the science communication program at the University of California, Santa Cruz, and holds a master's degree in marine biology from Florida Atlantic University.

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CAREER OPPORTUNITIES

COLLEGE OF CHARLESTON
The College of Charleston Department of Geology and Environmental Geosciences is accepting applications for a tenure-track faculty position at the Assistant, Associate, or Full Professor rank to begin in August 2019. The successful candidate will hold a Ph.D. in Geosciences or closely-related field with teaching experience and research activity in paleobiology that complement our existing strengths. The candidate must be able to teach introductory geology courses, especially Earth History, develop and teach one or more courses in their field of specialty, and mentor student research. The candidate is expected to develop his/her own research program and to seek external funds to support their research activities, with relevant fields being vertebrate or invertebrate paleobiology, microevolutionary and/or macroevolutionary patterns, response of organisms to global climate variability through time, and/or taphonomy. The candidate will be expected to mentor students and direct student-driven research projects. The candidate must also be able to serve as curator of the Mace Brown Museum of Natural History at the College of Charleston by demonstrating evidence of past curation, collections management, using collection specimens in their research, and/or museum experience. A Ph.D. is required at the time of employment. For those attending, we can arrange to meet with interested applicants at the 2018 GSA Annual Meeting in Indianapolis and the 2018 AGU Fall Meeting in Washington, D.C. Contact Tim Callahan (callahant@cofc.edu) for information about this position.

TWO-YEAR TEACHING POST-DOCTORAL POSITION MINERALOGY/PETROLOGY DEPAUW UNIVERSITY
DePauw University invites applications for a two-year teaching post-doctoral position in the Department of Geosciences beginning August 2019. We are seeking a broadly-trained geoscientist with specialties in Mineralogy and/or Petrology to complement our existing strengths in sedimentology/stratigraphy, structural geology/tectonics, and environmental geoscience. Candidates should demonstrate the potential to be an outstanding teacher in the liberal arts context, an active scholar in their field, and a contributor to a vibrant, student-centered curriculum in the Department and the University. Evidence of effective and inclusive pedagogy is essential.

Ideal candidates will have the desire and the ability to teach courses at all levels of the curriculum, including first-year seminars, and to provide a balance of classroom, laboratory, field and research experiences for our students. Candidates should have broad interests beyond their specialty. We are especially seeking a person who can develop and teach environmentally-themed courses for both majors and non-majors. The teaching assignment for this position is two lab courses and one non-lab course per year. Candidates are encouraged to maintain a productive research program that involves undergraduate students.

The successful candidate will have access to the full range of available faculty development opportunities including teaching, writing, speaking and critical thinking workshops, funding for research and travel to professional conferences, mentoring by current faculty members, and summer stipends for course development or research

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with students. Department funds are available to support course-related field trips during the academic year and field-based courses during our January and May terms.

Candidates should submit the following material through Interfolio (http://apply.interfolio.com/54222): a cover letter, curriculum vitae, one-page teaching philosophy, one-page summary of research interests, graduate transcripts, and three letters of recommendation. In their application materials, candidates should demonstrate a commitment to fostering an engagement with a diversity of ideas and experiences both in the classroom and at the University. Review of applications will begin on October 22, 2018 and will continue until the position is filled. We will meet with selected candidates, if attending, at the 2018 GSA Annual Meeting in Indianapolis, November 5-7, 2018. Questions may be directed to the search committee chair, Dr. Frederick M. Soster, at fsoster@depauw.edu.

DePauw University is an equal opportunity/affirmative action employer; women, members of underrepresented groups, and persons with disabilities are encouraged to apply.

SAM HOUSTON STATE

The Department of Geography and Geology at Sam Houston State University invites applications for a full-time, nine-month, tenure-track faculty position in groundwater hydrogeology beginning August of 2019. A Ph.D. degree in Geology or related Earth Sciences is required. The appointment will be at the Assistant Professor level. More experienced candidates may be considered at the Associate Professor level. The position will teach a standard 3-3 load consisting of two sections of an introductory, general education course and an upper-division specialty or elective course per semester.

The ideal candidates will have the interest and ability to teach Hydrogeology, Environmental Geology, and serve in a leadership role in the nascent, interdisciplinary Environmental Sciences degree. The successful candidate would ideally serve as the primary advisor/coordinator for the Environmental Sciences degree and must have a commitment to a high-quality undergraduate teaching program that values both field and laboratory instruction, involve undergraduate students in research, and the ability to work with a diverse student body.

Review of complete applications will begin December 1, 2018 and will continue until the position is filled. Preference will be given to applicants who have submitted all required materials listed below by that date.

Application Process: Interested applicants should submit a letter of interest, current vita, contact information for three professional references, and statements of teaching philosophy and research interests online at http://shsu.peopleadmin.com/postings/20523.

Questions regarding the position may be directed to: Dr. Joseph Hill, Search Chair (email: geojoe@shsu.edu; 936-294-1560), Department of Geography and Geology, Box 2148, Sam Houston State University, Huntsville, TX 77341-2148.

Applicants selected for the on-campus interview process will be asked to supply transcripts showing appropriate conferred degrees. Official transcripts will be required for appointment.

About SHSU: Sam Houston State University was founded in 1879 and named after Texas' greatest hero, General Sam Houston. With a total enrollment of approximately 21,000 students, SHSU is classified as a Doctoral Research Institution by the Carnegie Commission on Higher Education and offers 79 undergraduate degree programs, 54 masters programs, and five doctoral programs. The department has approximately 70 geology majors and offers degrees in geology and geoscience. More information is available on the department's website at www.shsu.edu/~gel_geo.

Sam Houston State University is an Equal Opportunity/Affirmative Action Plan Employer and Smoke/Drug-Free Workplace. All qualified applicants will receive consideration for employment without regard to race, creed, ancestry, marital status, citizenship, color, religion, sex, national origin, age, veteran status, disability status, sexual orientation, or gender identity. Sam Houston State University is an "at will" employer. Security sensitive positions at SHSU require background checks in accordance with Education Code 51.215.

ASSISTANT PROFESSOR OF GEOLOGY UTAH VALLEY STATE

The Department of Earth Science at Utah Valley University (UVU) invites applications for a tenure-track assistant professor position in geology, to begin August 2019. In our broad search of talented candidates, we seek a committed educator with expertise in geoscience education, a proven record of effective pedagogy, and a passion for teaching lower-division Earth science courses. Expertise in applied geophysics and/or engineering geology is a plus but is not required. The successful candidate must have a Ph.D. in geology or a closely related field at the time of appointment. Responsibilities will include: 1) designing and teaching introductory-level Earth science courses using various delivery methods (i.e., face-to-face, flipped, hybrid, and online courses); 2) assisting other faculty in designing courses and in developing learning activities that follow sound pedagogical principles; 3) supervision of undergraduate research (in science education and/or a geological discipline); and 4) service to the institution. Other possible responsibilities may include participation in our multi-instructor summer field geology capstone course, development of new upper division course(s) in the successful applicant's area of expertise, and coordination of curricula design among full-time faculty and adjunct instructors. A strong commitment to an evidence-based approach to teaching and to undergraduate research are necessary.

UVU, located in Orem, Utah, is a fast-growing comprehensive state institution of higher education with over 36,000 students and strong support for engaged learning. The main campus sits at the western front of the Wasatch Mountains, with superb opportunities for field-based teaching and research. The Department of Earth Science has a 14-member faculty with a strong record of mentoring undergraduate research and offers B.S. programs in Geology, Earth Science Education, Geography, and Environmental Science & Management. It has excellent facilities, including a GEODE seismograph, pXRF, ICP-OES, SEM (EDX, EBSD, and CL-capable), petrographic teaching microscopes, electrical resistivity and magnetometer instruments, as well as a range of other geochemical, remote sensing, surveying, and computing resources. The department also has strong ties to the University of Utah, Brigham Young University, Utah State

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University, local industry and governmental organizations.

The Provo-Orem metropolitan area has a population of over 500,000 and excellent access to numerous outdoor recreational activities such as snow sports, hiking, mountain biking, kayaking, fishing, and hunting. Salt Lake City is 45 minutes north by high-speed commuter rail; it has an international airport and a vibrant cultural scene including highly acclaimed symphony, opera, ballet, outdoor concert series, professional sports and more (see https://www.visitsaltlake.com/). In addition, Utah boasts world famous National Parks and Monuments. For more information, please see https://www.uvu.edu/earthscience/or contact the search committee co-chairs Alessandro Zanazzi (alessandro.zanazzi@uvu.edu) and Michael Stearns (mstearns@uvu.edu).

To apply, please visit http://www.uvu.jobs/postings/9182. Applications deadline: 1/7/19.

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AGIF american geosciences institute foundation

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Currently, AGIF is engaged in a capital campaign to support the AGI Center for Geoscience and Society. The Center's mission is to enhance AGI's existing partnerships and build new relationships across all sectors of society, within and outside of the geosciences.

The Center has two distinct, but coordinated efforts:

1. The **Critical Issues Program (CIP)** provides decision makers, educators, industry professionals, and the general public with scientifically-based information to understand important contemporary issues that involve the geosciences.
2. The **Education Resources Network (ERN)** provides resources that help teachers and informal educators build geoscience awareness across kindergarten through grade 12 (K-12) populations — the people who will make decisions at personal, societal, and global levels in the future.

Specific programs and services of the Center include:

- Information Resource Development
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If you are interested to learn more about AGIF, or support the Center's campaign, please contact us at: agif@agifoundation.org

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A Cautionary Tale About "Sleeping" Natural Hazards

Wendell Duffield

Despite its lugubrious climate, the rugged, verdant landscape of the greater Seattle/Puget Sound area, to which I moved five years ago, is a natural attraction for humans and their many activities. The forested chain of Cascade volcanoes provides recreation and business opportunities. The Salish Sea, with its many islands and ready access to the Pacific Ocean, invites tourism and marine industries.

But powerful geologic forces have shaped this part of North America in multiple earth-shaking events — and they will do so again. Not far offshore, the Juan de Fuca tectonic plate pushes beneath the western margin of the North American Plate, building up stress on this massive fault that is released in earthquakes. And as portions of the descending plate heat up and melt in the subduction zone, the buoyant magma that results rises and feeds eruptions of Cascade volcanoes, several of which are still active on geologic and human timescales.

As a career geologist, I came to my new home with an understanding of its geological history and the future natural events that may further shape it. The most recent powerful Cascadia quake, about a magnitude-9 event, occurred on Jan. 26, 1700 — a fact we know from the testimony of drowned forests and tsunami deposits in the region, and from historical records documenting the arrival of tsunami waves across the Pacific in Japan. If today's infrastructure and population had existed then, the physical damage and death toll would have been catastrophic. Another event as powerful as that will undoubtedly shake the Pacific Northwest again, but predicting exactly when is impossible. Considering such uncertainty, wisdom dictates that we practice the Boy Scout motto and be prepared, both as a community and personally. Government agencies in the Pacific Northwest appear to be taking steps in the right direction, by retrofitting bridges for instance and building rooftop evacuation sites atop schools, but there's still a long way to go. My wife and I keep a multiweek supply of food and water on hand, and we feel as prepared as possible for a Cascadia "sleeper."

It's not the first time we've lived with risk from natural hazards. From 1969 to 1972, we lived on the Big Island of Hawaii when I worked at the U.S. Geological Survey's Hawaiian Volcano Observatory. Earlier this year, the eruption activity along the East Rift Zone of Kilauea, which destroyed hundreds of homes and forced evacuations, brought to mind an experience we had with another "sleeping" natural hazard — one that still exists but seems absent from current public reports about Kilauea's restlessness: local earthquake-generated tsunamis and landslides.

Kilauea is built against the south-sloping flank of its older and much larger volcanic neighbor, Mauna Loa, whose mass buttresses and stabilizes the north side of Kilauea. As magma rises into the reservoir beneath Kilauea's summit caldera, it lifts the ground surface and shoulders the south side of Kilauea toward the ocean. This process triggers a constant background of relatively small-magnitude earthquakes, as well as occasional larger ones. At the onset of this year's East Rift eruption, a magnitude-6.9 earthquake shook the area, moving land seaward of the lower East Rift Zone to the south by about a meter. Over time, large pieces of the south flank become unstable and fall toward the sea, resulting in the shape of Kilauea's south flank, from sea level to near the summit caldera, being a giant staircase of landslide headwalls. Some of these "risers" are hundreds of meters tall and are partially draped by younger lava flows that spilled over them — cumulative evidence of multiple landslide events as Kilauea has grown into the volcano it is today.

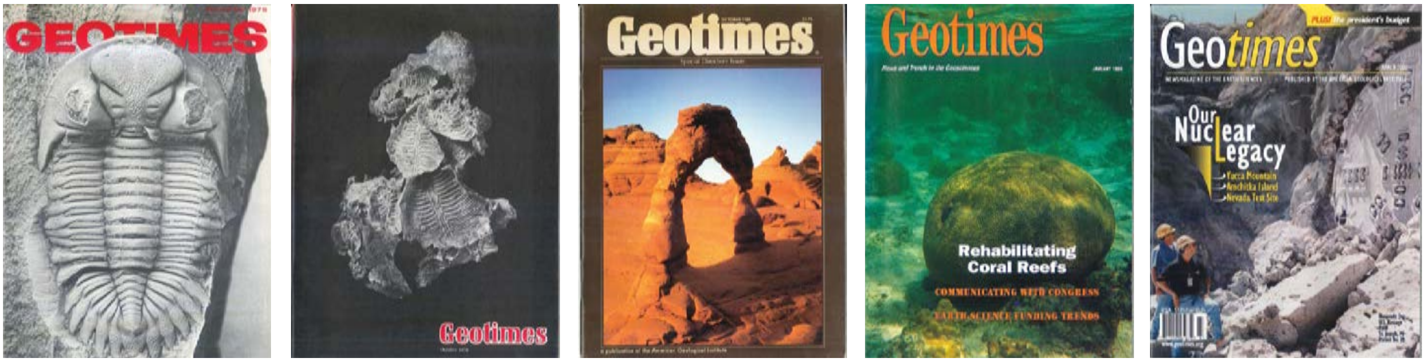
In 1972, my wife and I and two friends camped for a long weekend along the south coast of Kilauea at a primitive national park campground called Halape. In the typically humid tropical weather, we sweated profusely carrying heavy backpacks on the hike to the site, traversing 800 meters down the landslide staircase. As the only people at the camp, we enjoyed the privacy and cool breezes of a small beach, which lay adjacent to a grove of coconut palm trees at the base of an ominously tall landslide headwall.

Three years later, on Nov. 29, 1975, a Boy Scout troop and counselors were camped at Halape when a shallow magnitude-7.7 earthquake shook Kilauea. Some of the landslide staircase blocks moved tens of meters downward and seaward, triggering a local tsunami that washed across the campsite and through the coconut grove. Two of the campers died and 28 more were injured. Several of their pack horses were also killed. When the waters calmed, the campsite was about a meter below sea level, where it remains today.

Events of this sort are an integral part of the life of the volcano. Though rare, they are unpredictable, and like the history of major Cascadia events, should never be forgotten during long-range planning of how and where to live safely on active landscapes.

Credit: Anne Knowles

After completing his doctorate in geology at Stanford University in 1967, Duffield studied volcanoes at the U.S. Geological Survey for 30 years. In retirement, he has authored several books on volcanoes, including "Chasing Lava," about his time at Kilauea. The views expressed are his own.



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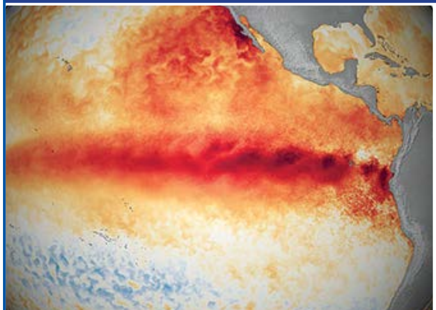

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