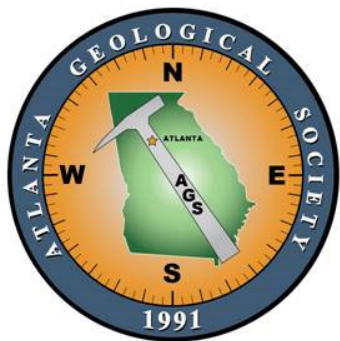




Atlanta Geological Society Newsletter

ODDS AND ENDS

Dear AGS members,

I was wondering about this month's topic; perhaps the water found at the Martian north pole, or some continued tectonic activity offshore near Portugal. What about something tied to this month's speaker, Nils Thompson and his presentation about climate change and the data associated with it. You may have heard a couple of weeks ago about an 84° F temperature recorded in Arkhangelsk, Russia. That's just south of the Arctic Circle in northwest Russia and about 30° above normal. Yes, it does seem high but its only one data point. I suspect what is happening in the public understanding is they don't see the long-term trend, not geologic in length but the 200 years since the start of the Industrial Revolution. We've fired many a steam boiler with coal and run our engines with petroleum, unleashing a lot of carbon that's been sequestered for millions of years. Let's hear what Nils has to say.

I wonder if you could do the Society a favor, please? Would you take the newsletter and forward it to 2 or 3 geologist friends? Please let them know we have a very diverse interesting program where we also get to enjoy standing in the shadow the dinosaurs nearly every month. How great is that? Please share your enthusiasm with some like-minded geologists.

Hope to see you on Tuesday.

Ben Bentskowski, President

May Meeting

Join us **Tuesday, May 28, 2018** at the Fernbank Museum of Natural History, 760 Clifton Road NE, Atlanta GA. The meeting/dinner starts at 6:30 pm and the meeting starts approximately 7 p.m.

This month our presentation is **“Why is Applied Geology Important for Nuclear Power Plant Siting?”** presented by Dave Fenster AEG President. Please find more information about the presentation and Mr. Fenster bio on the next page.

Please come out, enjoy a bite to eat, the camaraderie, an interesting presentation and perhaps some discussion on the importance of applied geology.

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This Month's Atlanta Geological Society Speaker

“Why is Applied Geology Important for Nuclear Power Plant Sitting?”

Speaker Mr. Dave Fenster's Bio:

Dave retired as a general consulting engineering geologist in January 2018 after a 44-year career working primarily for large consulting firms. After starting at the City College of the City University of New York (CUNY) as an engineering major, he was graduated with a BA in History in 1967. He received an MA in history from the University of Illinois in 1968. Dave started taking geology courses at Queens College of CUNY while teaching in the South Bronx. He was awarded a teaching assistantship (Lecturer Part-time) and received a Masters in Geology in 1975. He is a Licensed Professional Geologist (PG) in California; Certified Professional Geologist in Virginia and was previously certified in Indiana and Missouri.

As an engineering geologist, Dave applied geologic principals to investigate sites for: geologic and seismic hazards assessments; critical facility site selection; radioactive and hazardous waste management; nuclear facility licensing, LNG facility permitting and certification; and NEPA compliance. His project experience includes: site investigations; report preparation; project management; and business development. Many projects have included Federal, state, and local regulatory compliance; permit acquisition and nuclear facility licensing. Prior to retiring, he had been a Principal Geologist and the Engineering Geology Supervisor and was recognized as an Elite Technical Specialist for Bechtel Power Corporation in Fredrick, MD and Reston, VA. (2006-2018). Most of his work for Bechtel included site investigations and report preparation for the current generation of commercial nuclear power plants. Dave began his career as a geologist with Dames & Moore in 1974 investigating sites for nuclear power plants, working on foundation and groundwater investigations and other aspects of applied geology. His experience with geologic field mapping led to interpretations of surface and subsurface data to develop the regional and site geology sections of Safety Analysis Reports filed with the US Nuclear Regulatory Commission in support of nuclear power plant licensing. As this work declined, Dave conducted environmental geologic investigations to characterize site groundwater and soil conditions and to determine whether clients were in compliance with environmental regulations. After leaving Dames Moore, Dave worked on the geologic isolation of high-level radioactive wastes while with Argonne National Laboratory (1982-1985), Roy F. Weston Inc. (1985-1991) and with Woodward Clyde/URS (1991-2006). At URS he supported FEMA while working on the Pre-Disaster Hazard Mitigation Program and other geology-related programs.

Dave joined the North-Central Section of AEG in 1982. He served as North-Central Section Program Chairman (1982-1984) and Secretary (1984-1985). He was appointed as Chairman of the Committee on Rock Mechanics and AEG's representative to the U.S. National Committee on Rock Mechanics (1984-1989). He was Chairman of the Committee on Radioactive Waste Management (1989-1991) and Chairman of the Committee on High-Level Radioactive Waste Management (1991-1994). Dave served as Chairman of the Baltimore-Washington-Harrisburg Section (current DC-Maryland-Virginia Chapter) (2002-2004). He was an initial member of the Section Chapter Support Committee. He served on the Board of Directors of the AEG Foundation from 2006-2016 as Secretary for two years and as President for 2015. Dave was appointed as interim Vice President of AEG in 2017 and was elected as Vice President/President-elect for 2017-2018.

Dave has served as a peer reviewer for AEG's Environmental & Engineering Geology Journal. His term as Overseas Reviewer of the Quarterly Journal of Engineering Geology and Hydrogeology (Geological Society of London) expired in 2018.

This Month's Atlanta Geological Society Speaker

“Why is Applied Geology Important for Nuclear Power Plant Sitting?”

Abstract:

Nuclear power plants are critical facilities in more ways than one. Initial siting and detailed site characterization require the input of experienced engineering geologists. The U.S. Nuclear Regulatory Commission (NRC) is charged with protecting the health and welfare of the public and the environment. As consultants working for industry, we are charged with obtaining geologic data from the region within which the site is located. We need to obtain even more detailed data from the site and surrounding area. Our careful documentation of geomorphic processes, stratigraphy, geologic and tectonic history, seismicity, the hydrologic setting and groundwater modeling, geologic hazards, and soil and rock properties are essential to providing the NRC with the data they need to make a finding, with reasonable assurance, that the site is suitable for the safe construction and operation of a nuclear power plant. Detailed site investigations are necessary to define in our understanding of uncertainties regarding site characteristics. Ages of faulting in the site vicinity or at the site, the age and extent of karst and the presence of other geologic hazards are key aspects of determining site suitability.

Ship Spies Newborn Underwater Volcano

Last week, Marc Chaussidon, director of the Institute of Geophysics in Paris (IPGP), looked at seafloor maps from a recently concluded mission and saw a new mountain. Rising from the Indian Ocean floor between Africa and Madagascar was a giant edifice 800 meters high and 5 kilometers across. In previous maps there had been nothing. “This thing was built from zero in 6 months!” Chaussidon says.

His team, along with scientists from the French national research agency CNRS and other institutes, had witnessed the birth of a mysterious submarine volcano, the largest such underwater event ever witnessed. “We have never seen anything like this,” says IPGP's Nathalie Feuillet, leader of an expedition to the site by the research vessel *Marion Dufresne*, which released its initial results last week.

The quarter-million people living on the French island of Mayotte in the Comoros archipelago knew for months that something was happening. From the middle of last year they felt small earthquakes almost daily, says Laure Fallou, a sociologist with the European-Mediterranean Seismological Centre in Bruyères-le-Châtel, France. People “needed information,” she says. “They were getting very stressed, and were losing sleep.”

The authorities knew little more. Mayotte has a seismometer, but triangulating the source of the rumblings would require several instruments, and the nearest others are several hundred kilometers away in Madagascar and Kenya. A serious scientific campaign started only in February, when Feuillet and her team placed six seismometers on the ocean bottom 3.5 kilometers down, close to the activity.

Data from the seismometers, retrieved by the expedition this month, show a tightly clustered region of earthquake activity, ranging from 20 to 50 kilometers deep in Earth's crust. The team suspects a deep magma chamber fed molten rock to the sea floor and then contracted, driving the cracking and creaking of surrounding crust. GPS measurements on Mayotte also suggest a shrinking magma chamber: They show the island has sunk by 13 centimeters and moved 10 centimeters east in the past year.

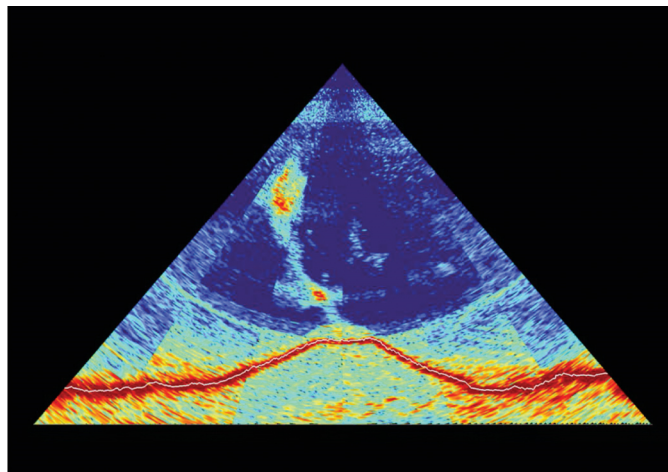
The map of the sea floor, made by the ship's multibeam sonar, indicates that as much as 5 cubic kilometers of magma erupted onto the sea floor. The sonar also detected plumes of bubble-rich water rising from the center and flanks of the volcano. Feuillet says her team didn't see the shoals of dead fish that fisherman reported, but they did collect water samples from the plumes. The chemistry of the water will give clues about the composition of the magma, the depth from which it came, and the risk of an explosive eruption.

The crew also dredged up rocks from the flanks of the newborn volcano. “They were popping as we brought them on board,” Feuillet says—a sign of high-pressure gas trapped inside the black volcanic material.

Explaining the eruption isn't easy. Most submarine volcanoes are found along midocean ridges, where tectonic plates in Earth's crust slowly spread apart, allowing magma from relatively shallow magma chambers to ooze up in rifts. Others mark deep mantle plumes that periodically burst through the crust, forming a chain of volcanoes, as plate tectonic forces drag it over the hot spot. The islands of Hawaii, the Galápagos, and nearby Réunion—on the opposite side of Madagascar from Mayotte—are all thought to have formed this way.

The Comoros are clearly volcanic. Mount Karthala on Grande Comore, at the west end of the chain, erupted as recently as 2007. Petite Terre, the volcano nearest to Mayotte, last erupted 7000 years ago. But there are competing explanations for the volcanism, and the new eruption will intensify the debate. To some, the exceptional depth of the collapsing magma chamber, tens of kilometers down, offers a clue. “A really deep chamber might be consistent with melting by a plume from below,” says Mike Cassidy, a volcanologist

Ship Spies Newborn Underwater Volcano (Continued)



Multibeam sonar waves, reflecting off the sea floor near the French island of Mayotte, reveal the outline of an 800-meter-tall volcano (red) and a rising, gas-rich plume.

at the University of Oxford in the United Kingdom. But Cindy Ebinger, a geologist at Tulane University in New Orleans, Louisiana, who studies African tectonics, sees rifting at work—related to the spreading in the East African Rift Valley that is slowly separating Somalia from the rest of the continent. “Historic earthquake patterns suggest that Africa is splitting into a number of rigid blocks separated by rifts and volcanic zones,” she wrote in an email. The Comoros Islands, she adds, appear to run along the northern edge of one of these suspected blocks.

Feuillet and her team are reserving judgment until they have a complete analysis ready to publish. Meanwhile, anxieties persist on Mayotte. The continuing earthquake activity, now much closer to the island, along with the possibility of a tsunami triggered by an undersea landslide from the flank of the new volcano have both alarmed the population.

Cassidy says the new volcano is probably too deep to cause a dangerous tsunami onshore. But he is worried by the westward migration of the small earthquakes toward Mayotte, which could potentially trigger a collapse of the submarine flank of Mayotte itself. “This scenario could certainly create a tsunami,” he says.

Feuillet wants to extend her team's mission by several months to monitor this geological mystery as it develops.

Read more about this article at: <https://science.sciencemag.org/content/364/6442/720>

The 2018 Rift Eruption and Summit Collapse of Kīlauea Volcano

Volcanic eruptions at basaltic shield volcanoes can threaten communities and infrastructure with a variety of hazards, including lava flows, gas emissions, explosions, and tephra fall, as well as damaging seismicity, ground collapse, and tsunamis. Eruption impacts can become global if sufficient ash or gas are transported through the atmosphere or if ocean-crossing tsunamis are generated. The 2018 eruption of Kīlauea Volcano in Hawai‘i included both a summit caldera collapse and a flank fissure eruption, a complex event observed only a handful of times in modern history. Other large and well-documented caldera-forming eruptions at basaltic systems worldwide have been partially obscured or occurred over periods of hours to a few days. Thanks to excellent accessibility and a dense network of geological, geochemical, and geophysical instrumentation, large datasets from the 2018 events at Kīlauea will prompt new scientific understanding of, for example, how calderas

The 2018 Rift Eruption and Summit Collapse of Kīlauea Volcano (Continued)

collapse and how caldera and rift zone systems interact. In addition, the eruption and emergency response underscore the value of long-term observations to the science of volcanology and to risk mitigation.

Buildup to 2018 activity

Kīlauea Volcano (Figure. 1), on the southeast side of the island of Hawai‘i, is supplied with mantle-derived magma that enters the shallow magma plumbing system below the summit caldera. Summit area magma can be stored, erupted, or transported laterally at shallow depth (~3 km) up to tens of kilometers along the volcano’s rift zones—long, narrow areas of persistent eruption that are a hallmark of shield volcanoes. Before 30 April 2018, Kīlauea had been erupting from two vents: (i) a lava lake within Halema‘uma‘u crater at the summit, active since 2008, and (ii) Pu‘u ‘Ō‘ō cone and nearby vents in the East Rift Zone (ERZ, Figure. 1), ~20 km from the summit, active since 1983. The summit lava lake was characterized by emission of gas and small amounts of ash, whereas the ERZ eruption produced ~4.4 km³ of lava over 35 years.

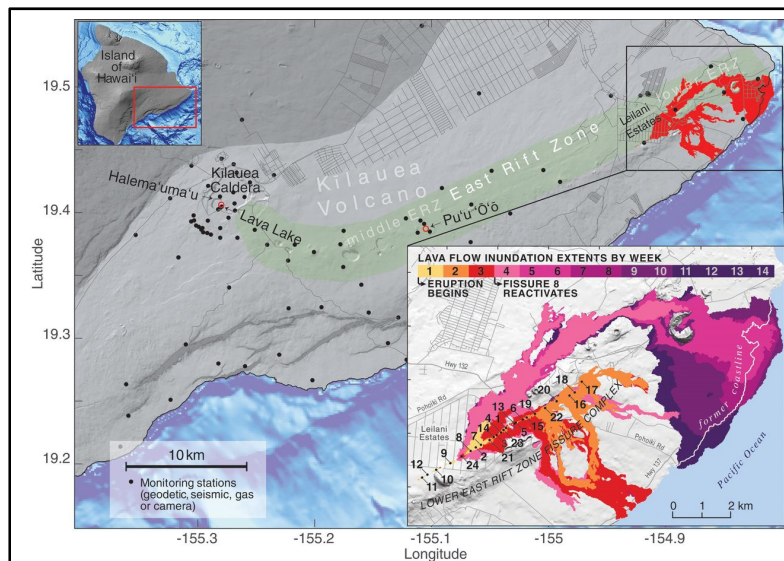


Figure. 1 Map showing the location of Kīlauea Volcano on the island of Hawai‘i and the general geographic features of the volcano.

Kīlauea Volcano is indicated in light gray. Gray lines are roads, and dots mark the locations of monitoring stations (geodetic, seismic, gas, or camera). Locations of summit and Pu‘u ‘Ō‘ō eruptive vents are indicated with red circles. The green area indicates the ERZ. The inset on the bottom right is a magnified view of the LERZ, showing a map of LERZ lava flows, with colors indicating the week during which a particular part of the flow was active. The labels 1 to 24 indicate eruptive fissure locations numbered according to the order of their formation.

In mid-March 2018, tiltmeters at Pu‘u ‘Ō‘ō began to record inflationary ground deformation that was probably due to accumulation of magma. Previous episodes of pressurization at Pu‘u ‘Ō‘ō resulted in the formation of new eruptive vents within a few kilometers, for example, in 2007, 2011, and 2014. The pressure increase continued through March and April, causing the lava pond at Pu‘u ‘Ō‘ō to rise and prompting the Hawaiian Volcano Observatory (HVO) to issue a warning on 17 April that a new vent might form “either on the Pu‘u ‘Ō‘ō cone or along adjacent areas of the East Rift Zone.” The pressure increase eventually affected the entire magma plumbing system, causing the summit lava lake to rise and ultimately overflow onto the floor of Halema‘uma‘u crater on 21 April, with another hazard notice issued by HVO on 24 April.

Lower ERZ eruption

At 2:15 p.m. Hawaii Standard Time (HST) on 30 April (Figure. 2), geophysical data began indicating rapid changes occurring in the middle ERZ (MERZ) magma system. Collapse of the Pu‘u ‘Ō‘ō crater floor was followed by ground deformation and eastward-propagating seismicity that indicated downrift intrusion of a dike toward the populated lower ERZ (LERZ). On 1 May, HVO issued a warning to residents downrift that an eruption was possible. Seismicity and ground deformation provided indications of extensional deformation

The 2018 Rift Eruption and Summit collapse of Kīlauea Volcano (Continued)

associated with a magmatic intrusion. Ground deformation was measured with borehole tiltmeters, real-time Global Navigation Satellite System (GNSS), and satellite interferometric synthetic aperture radar (InSAR), the latter of which included an acquisition by the European Space Agency's Sentinel-1 satellite on 2 May. These data indicated that the intrusion was approaching the Leilani Estates subdivision, about 20 km downrift from Pu'u 'Ō'ō. The first of 24 eruptive fissures opened within the subdivision just before 5:00 p.m. HST on 3 May.

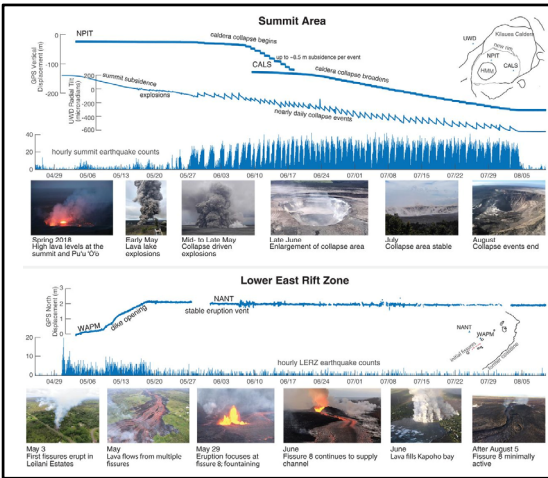


Figure. 2 Timeline of Kīlauea's 2018 eruptive activity with representative geodetic and seismic data.

On the map, triangles marked with three- and four-letter codes (NPIT, CALS, UWD, WAPM, and NANT) are geodetic station locations. **(Top)** Activity in the summit area of Kīlauea through the time series of GNSS sites located near the initial focus of collapse (NPIT) and farther away (CALS). Near-daily collapse events are manifested as spikes on the UWD tiltmeter and in hourly summit-area earthquake counts. HMM, Halema'uma'u crater. **(Bottom)** LERZ activity, where deformation was observed by two GNSS sites (WAPM and NANT) on the north side of the fissures. The initial intrusion produced more than 2 m of northward displacement at WAPM and coincided with substantial seismicity. After a swarm of about 100 earthquakes at Pu'u 'Ō'ō on 30 April to 1 May, MERZ seismicity rates were around one to two events per hour, much less than rates at the summit and LERZ.

The eruptive fissures that formed during the first week of the LERZ eruption were up to several hundred meters long and generally short-lived (minutes to hours), with spatter and lava accumulating within a few tens of meters of individual vents. The sluggish lava was of a composition (≤ 5 weight % MgO) that suggested long-term storage before eruption. It was also chemically similar to lava erupted in the same area in 1955, implying that the magma had been stored in the rift for decades.

On 4 May, the largest [moment magnitude (M_w) 6.9] earthquake on the island in 43 years occurred beneath Kīlauea's south flank at a depth of ~ 6 km based on seismic data (Figure. 3). Focal mechanism analysis suggests that the earthquake was probably located on the subhorizontal basal décollement fault between the volcanic pile and the preexisting seafloor. Ground deformation models indicate up to ~ 5 m of seaward fault slip (Figure. 3) based on up to 0.7 m of coseismic seaward displacement at GNSS stations. The aftershock pattern was consistent with our geodetic model, with a slip patch extending 25 km offshore and spanning an area of about 700 km². The earthquake may have been motivated by the dike intrusion—a hypothesis that is supported by stress models showing that rift-zone opening promotes décollement fault failure. Earthquakes (usually in the magnitude 4 to 5 range) have also occurred during and immediately after past Kīlauea ERZ intrusions.

We modeled Advanced Land Observing Satellite 2 (ALOS-2) and Sentinel-1 interferograms spanning the first few days of the LERZ eruption and found contraction along much of the MERZ, along with up to ~ 4 m of subsurface opening in the LERZ (Figure. 3). After the onset of eruption, we found evidence of downrift propagation of the intrusion from earthquake activity and deformation. On 10 May, HVO issued a status report suggesting that more lava outbreaks were likely, and on 12 May, a new fissure opened 1.6 km downrift of the previous eruptive activity in a location where earthquakes had clustered in the previous 2 days. On 18 May, hotter and less viscous lava began erupting (movie S1), resulting in long, fast-moving lava flows that

The 2018 Rift Eruption and Summit Collapse of Kīlauea Volcano (Continued)

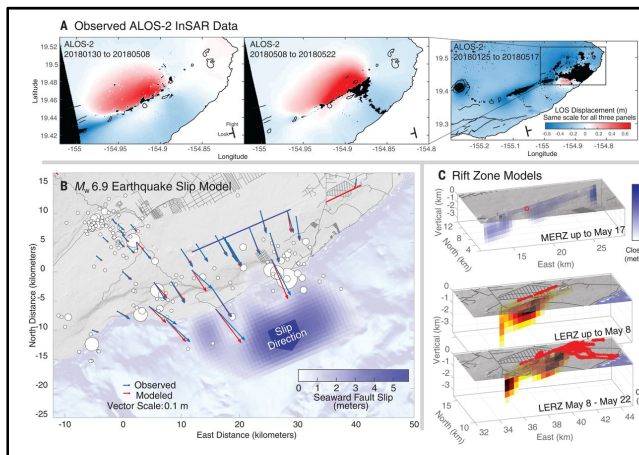


Figure. 3 Surface deformation and models of 2018 eruptive and earthquake activity.

(A) Example InSAR line-of-sight (LOS) displacement data from the ALOS-2 satellite used during the eruption (scale bar is the same for all three images). (B) GNSS displacements and model of the 4 May M_w 6.9 earthquake (vector uncertainties are smaller than the arrowheads). White circles are earthquakes. (C) Example models of rift-zone deformation utilizing the ALOS-2 data in (A). The top model shows a cross section along the blue line in (B), whereas the section covered by the lower two models is shown by the red line in (B). In the models, fault slip and rift-zone deformation are represented by simple elastic half-space solutions and were produced following previously published inversion methodologies.

reached the ocean on the southeast side of the island 5 days later. This change in eruptive character provided an indication, supported by changes in chemical composition, that “fresh” magma derived from the summit and MERZ was now beginning to erupt from the LERZ fissures.

To assess changing lava hazards to now-threatened surrounding communities, HVO produced rapid preliminary lava flow path forecasts based on steepest-descent path modeling (Figure. 4). Throughout the eruption, lava flow path simulations that utilized updated topography were run from active flow fronts, new fissures, and channel overflow locations, yielding maps of likely future flow directions (Figure. 4).

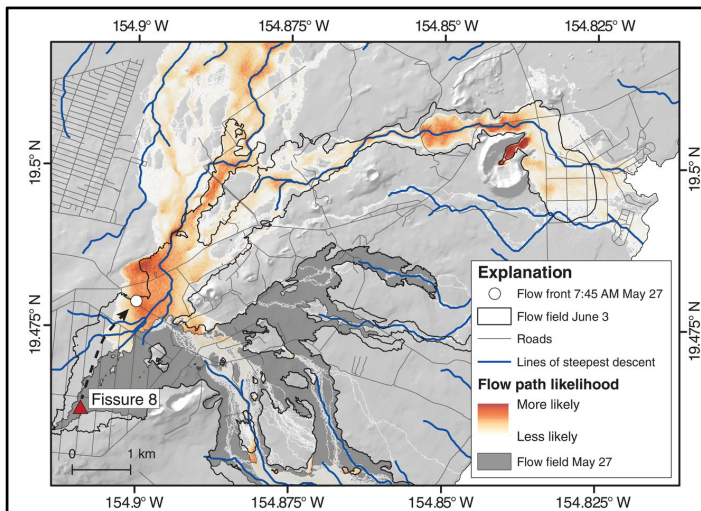


Figure. 4 Example lava flow forecast map.

Initial lava flow path forecast for the fissure 8 (red triangle) flow on 27 May (light orange to red colors) compared to the mapped flow extent on 3 June (black outline) and pre-eruptive lines of steepest descent. Potential flow paths were simulated with DOWNFLOW from approximate flow-front positions reported by field crews (in this case, at the flow margin on the road, rather than from the true inaccessible flow front further east) and pre-eruptive topography updated within the extent of new flows. Resulting maps were preliminary for operational use and produced on-demand as the flows progressed, following decades of syn-eruptive flow mapping and expanding the past use of steepest-descent paths for flow modeling. The dashed arrow indicates the approximate initial flow from which the flow-front emanates.

Eruptive activity resumed at fissure 8, in east-central Leilani Estates, late on 27 May (Figure. 4), and activity became focused there within 12 hours, on 28 May. Lava fountains reached heights of 80 m and fed a rapid channelized flow that ultimately entered the ocean near the eastern tip of the island (following potential routes indicated in the initial forecast, Figure. 4). SO_2 emissions climbed to more than 50,000 metric tons per day, severely affecting air quality across the island and reaching as far as Guam (>6000 km). Estimated effusion rates ranged from 50 to 200 m^3/s (dense-rock equivalent) during this part of the eruption. Effusion of large amounts of lava ended abruptly on 4 Aug 2018. On the basis of a combination of topographic differences and fissure 8 vent flux over time, we estimate a preliminary bulk erupted volume of $\sim 0.8 \text{ km}^3$ to possibly greater than 1 km^3 of lava. The volume of the 2018 intruded dike (Figure. 3C and Figure. S2) is about 10% of the erupted volume.

The 2018 Rift Eruption and Summit Collapse of Kīlauea Volcano (Continued)

Summit collapse

Summit subsidence and lava lake withdrawal began gradually on 1 May and accelerated in the days after the M_w 6.9 earthquake (Figure. 2). The summit lava lake level, which in previous years rose and fell in concert with summit deformation and adjustments in vent elevation of Pu‘u ‘Ō‘ō, dropped more than 300 m and was no longer visible from the crater rim by 10 May. In 1924, a substantial drop in lava level associated with a LERZ intrusion was followed by explosive activity that included ash emissions and ejection of blocks onto the caldera floor. The hypothesis for the 1924 explosions had been that they resulted from groundwater mixing with the hot rock of the recently evacuated magma conduit. On the basis of this analogy, HVO issued a warning of “the potential for explosive eruptions in the coming weeks” on 9 May.

By 10 May, sporadic ejections of mixed juvenile and lithic ash reached heights of ~2000 m above the summit eruptive vent (e.g., see Figure. 2), accompanied by hundreds of magnitude 3 to 4 summit earthquakes per day. Most of Hawai‘i Volcanoes National Park closed on 11 May because of the increase in seismicity and in anticipation of further explosive activity. On 16 May, 1 day after HVO issued a notice of the potential for stronger explosions, the first of several small explosive events occurred, ejecting nonjuvenile ash that was transported southwest by the wind, while small (<1 m) ballistic blocks landed within a few hundred meters of the vent.

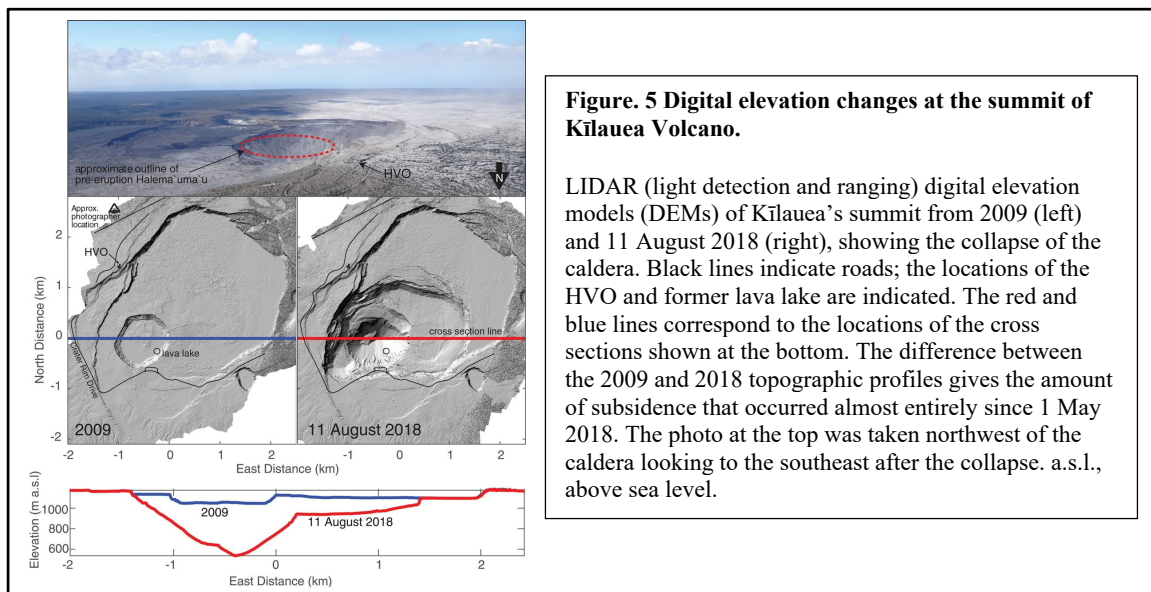
Minor explosions continued, and slope failures widened the former eruptive vent that had contained the lava lake as summit deflation progressed through May. From 16 to 26 May, 12 explosions occurred at intervals of 8 to 45 hours. Each early event was characterized by an inflationary tilt step, very-long-period (VLP) seismic signals of M_w 4.7 to 5.1, and a small amount of high-frequency shaking. Moment tensor inversions reveal a complex source process dominated by changes in volume rather than the slip on a planar fault that is typical of a tectonic earthquake. Plume heights from small explosions varied because of eruption intensity and atmospheric conditions, with the largest reaching about 8100 m above ground level on 17 May. Summit SO_2 emission rates increased by two to three times and peaked during this stage of explosive activity. This trend is not compatible with the groundwater origin for the source of the explosions and also calls into question the hypothesis put forth for the 1924 activity.

Starting near the end of May, the floor of Kīlauea caldera around Halema‘uma‘u crater began to subside as the walls of the crater slumped inward (movie S2). As the vent filled with rock-fall rubble, the background plume of ash from the vent greatly diminished, magmatic gas emissions decreased markedly, and ash eruption gradually slowed. A total of 62 collapse events occurred between May and early August. Seismic, infrasonic, and geodetic signals settled into a notably consistent pattern characterized by M_w 5.2 to 5.4 VLP collapse events occurring almost daily, with intervening escalating earthquake swarms exceeding 700 earthquakes of magnitude ≤ 4.0 per day. During this phase, higher-frequency seismic energy and strong infrasound signals accompanied the notably consistent VLP signal originally associated with explosions, and the caldera floor dropped several meters during each of the large events, ultimately deepening in places by more than 500 m (Figure. 5). The persistent high levels of seismicity caused substantial damage to infrastructure in Hawai‘i Volcanoes National Park, including to the by-then-evacuated HVO facility.

The episodic subsidence of the caldera floor was likely driven by the nearly constant magma withdrawal from the summit reservoir system to feed the LERZ eruption. Starting in July, transient tilt signals were detected at downrift instruments following summit collapse events, suggesting that the collapses were driving pressure increases that propagated down the ERZ. Some of these pressure transients were followed by observations of increased effusion rate at the LERZ eruption site. The summit subsidence largely stopped by 4 August—about the same time as the end of major LERZ effusion—and the last collapse event occurred on 2 August. The

The 2018 Rift Eruption and Summit Collapse of Kīlauea Volcano (Continued)

0.825-km³ volume of the collapse (based on topographic differences; Figure. 5) is similar to the bulk volume of LERZ effusion.



Synthesis of 2018 activity

The 2018 activity at Kīlauea reflects changes in a well-connected magmatic plumbing system from the volcano's summit to its lower flank (Figure. 6). The summit magmatic system consists of at least two magma storage areas, one centered about 1 to 2 km beneath the former east margin of Halema'uma'u crater and another larger one 3 to 5 km beneath the south part of the caldera Figure. 6. Deformation associated with the 2018 collapse suggests substantial drainage of the shallower reservoir.

Caldera collapses have been observed under challenging circumstances at only a few volcanoes worldwide [e.g., Miyakejima, Piton de la Fournaise, Fernandina, and Bárðarbunga;]. At Kīlauea, substantial, protracted, incremental caldera collapse occurred in the midst of a strong monitoring infrastructure, providing abundant opportunity for observation and investigation and helping to refine models of hazardous volcanic activity. As an example, the 1924 explosions were interpreted as being the result of the interaction of water with hot rock. The 2018 explosions of lithic ash were accompanied by heightened SO₂ emissions, suggesting the collapse and rockfalls may have agitated the magmatic system and released gas that entrained rockfall debris. These observations are not only a window into activity in 2018 but will also facilitate reinterpretation of past events.

The high effusion rate of the LERZ vents was sustained longer than that of any observed Kīlauea eruption. Although past eruptions have produced more total lava, the effusion rates were much lower, and the eruptions lasted for years to decades. The voluminous 2018 eruptive activity was probably driven by a combination of factors, foremost among these being the pressurized pre-eruptive state of the summit and ERZ and the relatively low elevation of the eruptive vent. Past eruptions on the ERZ have demonstrated a correlation between the magnitude of total coeruptive summit deflation and vent elevation, with the greatest summit deflation coinciding with the lowest-elevation vents. The summit collapse, however, might also act as a mechanism to drive magma toward the rift zone, as suggested by the ERZ pressure pulses. Additionally, LERZ effusive surges were occurring, of which some in July followed collapse events at the summit. These observations reflect a complex feedback process between the LERZ eruptive vent and the summit collapse.

The initiation mechanism for the extraordinary 2018 LERZ eruption and summit collapse remains enigmatic.

The 2018 Rift Eruption and Summit Collapse of Kīlauea Volcano (Continued)

Previous episodes of inflation at Pu‘u ‘Ō‘ō resulted in the formation of new eruptive vents nearby, but not in the downrift transport of large amounts of magma. One explanation is that the initial rupturing of a barrier in the MERZ allowed substantial volumes of magma to move into the LERZ for the first time since 1960, and the highly pressurized state of the magmatic system probably facilitated downrift transport of magma from the summit. Long-term flank slip and deep ERZ opening promotes extension in the shallow rift, so the LERZ was already primed for an intrusion by 2018, given that almost 60 years of extension had accumulated since the last intrusion. The 4 May M_w 6.9 earthquake may have also aided magma transport, because décollement fault slip can result in rift-zone opening. The strong hydraulic connection between the summit and LERZ, once established, remained until the summit magmatic system drained to a point at which the LERZ eruption could no longer be sustained.

The 4 May M_w 6.9 earthquake marked an important event in the magmatic cycle of Kīlauea Volcano. Major flank slip events occur frequently on Kīlauea. A suggested cycle, in which the flank progressively stiffens as it nears the next flank earthquake, results in gradually increasing magmatic head and more frequent eruptive activity. Once the flank slips, the magmatic head drops, and eruptions become smaller and less frequent. The latest example of such a period occurred after the 1975 M_w 7.7 Kalapana earthquake. Between that earthquake and the beginning on the Pu‘u ‘Ō‘ō eruption in 1983, only three small eruptive events occurred, although there were at least a dozen intrusive events.

The loss of magmatic head due to the earthquake, coupled with the evacuation of magma from the summit in 2018, suggests that it may take several years before enough magma can accumulate beneath the summit to erupt. After the 1924 summit collapse, which may also have been associated with flank instability, only a few small eruptions confined to Halema‘uma‘u crater occurred in the ensuing 10 years, and there was a total absence of eruptions anywhere on the volcano for another 18 years. If future activity at Kīlauea follows a similar pattern, the next several years will see little, if any, sizeable eruptive activity. However, it is also possible that reduced summit magma pressure may promote higher rates of magma supply from depth owing to a pressure imbalance between the deep and shallow parts of Kīlauea’s magma plumbing system, which could result in renewed eruptive activity sooner than expected. The next several years offer an exceptional and exciting opportunity to study the evolution of magmatism following a major perturbation to Kīlauea’s plumbing system.

Volcano observatory science and emerging technology

Since HVO’s founding in 1912, its scientists have been committed to better understanding how Hawaiian volcanoes work, deciphering eruption histories, and improving strategies for responding to eruptions and issuing public hazard notifications. Indeed, HVO’s founder, Thomas Jaggar, held that earthquake and volcano processes must be studied not only after the event but also before and during their occurrence. Only by such long-term study, he reasoned, could such processes be understood sufficiently to allow for effective risk reduction, including forecasting. The 2018 LERZ eruption and summit collapse of Kīlauea challenged HVO like never before to apply the lessons learned in more than 100 years of study. Intensive observations of historical eruptions provided a framework (but not absolute constraints) for interpreting the activity and associated hazards. Eruptions in Kīlauea’s LERZ in 1955 and 1960 were both accompanied by large summit subsidence (although not to the degree of the current episode), and withdrawal of a lava lake in 1924 preceded explosions at the summit. This knowledge of Kīlauea’s geology was augmented by a comprehensive instrumental monitoring network of geological, geochemical, and geophysical sensors spread across the volcano and deployed in response to the unfolding eruption and summit collapse (Figure. 1).

The 2018 Rift Eruption and Summit Collapse of Kīlauea Volcano (Continued)

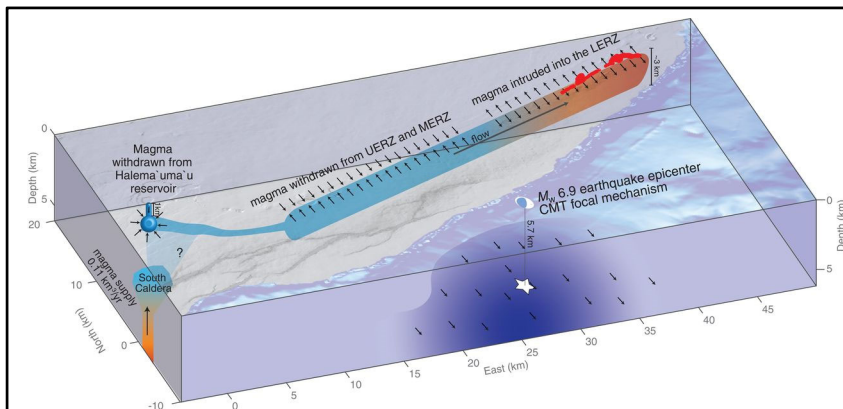


Figure. 6 Schematic representation of the subsurface redistribution of magma during the 2018 Kīlauea eruptions.

Orange colors depict areas that inflated, whereas turquoise indicates areas from which magma was withdrawn. Dark blue shading shows the approximate extent of the slip model from [Figure. 3](#).

This eruption also enabled the broader use of emerging technologies, such as the use of unoccupied aircraft systems (UAS), infrasound arrays, inexpensive webcam networks, real-time GNSS, multimedia communication systems, and alarm systems for automatic notification of specific parameters. For example, infrasonic alarms were developed to alert on changes in summit or rift-zone eruption location or vigor, complementing existing seismic alarms. These were integrated into an enhanced real-time communication system (voice, text, images, and video), which enabled transparent and instantaneous information transfer between field observers and scientists monitoring data. On-demand lava flow path modeling (Figure. 4) based on topography updated during the eruption augmented steepest-descent paths to identify changes in potential flow paths. SO_2 emission rates were continuously used to update air-quality forecasts for the island, and gas compositions were tracked in nonevacuated areas along the fissure axis to monitor for potential signs of ascending magma. Rapid chemical and petrographic lava sample analysis provided information on changing magma compositions while the eruption progressed. Frequent UAS flights facilitated much of this work, for example, by enabling gas emission measurements and topographic data collection from areas that would not otherwise be accessible. Simultaneously, the geologic record guided thinking about potential outcomes of the eruption and collapse, including the size and type of summit explosions and the duration and volume of the LERZ eruption. Application of these methods has the potential to aid in future eruption responses in Hawai‘i and elsewhere.

Concluding remarks

The protracted 2018 summit collapse and flank eruption at Kīlauea provided an outstanding opportunity to observe and measure hazardous volcanic phenomena using an array of techniques with exceptional resolution in both space and time. These observations have already yielded new insights into poorly known processes such as caldera collapse, small-scale explosive basaltic volcanism, vigorous lava effusion and degassing, and magma transport and flank stability at shield volcanoes. Continued exploitation of these rich datasets will undoubtedly yield additional discoveries that will refine understanding of Kīlauea Volcano and volcanic processes and hazards in general. The success of HVO in detecting and, to the extent possible, forecasting various elements of the 2018 eruptive activity is a strong argument for continuous and intensive ground-based monitoring of geologic processes to inform hazards assessment and risk mitigation. Furthermore, the collective scientific response and lessons learned during this most recent Kīlauea eruption offer emphatic validation of Thomas Jaggar’s vision for the role and value of a volcano observatory.

Read more about this article at: <https://science.sciencemag.org/content/363/6425/367?intcmp=trendmd-sci>

Managing Injection-induced Seismic Risks

Heat transported from deep within Earth's crust can be used to generate electricity or provide direct heating by circulating fluid through permeable fracture networks in hot rock. Because naturally permeable systems are rare, enhanced geothermal system (EGS) technology stimulates the creation of permeable pathways in otherwise impermeable rock by means of the injection of water under high pressure, creating new fractures and causing preexisting fractures to open. But several EGS projects have encountered problems of induced seismicity, particularly the moment magnitude (M_w) 5.5 earthquake in 2017 that occurred near an EGS drill site in Pohang, Republic of Korea (South Korea). Here we explore the implications of, and derive lessons from, the Pohang experience. The Pohang earthquake provides unequivocal evidence that EGS stimulation can trigger large earthquakes that rupture beyond the stimulated volume and disproves the hypothesis that the maximum earthquake magnitude is governed by the volume of injected fluids. Because that hypothesis tacitly underpins hazard-based methods used for managing induced seismicity, those methods must be revised and based on considerations of risk.

EGS is a promising source of clean energy for a decarbonizing world and an important source of energy in natural resource-poor countries. The Pohang EGS project was intended to create an artificial geothermal reservoir within low-permeability crystalline basement by hydraulically stimulating the rock to form a connected network of fractures between two wells, PX-1 and PX-2. If successful, about 1.2 MW of electricity would have been generated.

On the afternoon of 15 November 2017, the half-million residents of Pohang experienced violent shaking in a M_w 5.5 earthquake (U.S. Geological Survey). The earthquake injured 135 residents, displaced more than 1700 people into emergency housing, and caused more than \$75 million (USD) in direct damage to more than 57,000 structures and more than \$300 million of total economic impact, as estimated by the Bank of Korea.

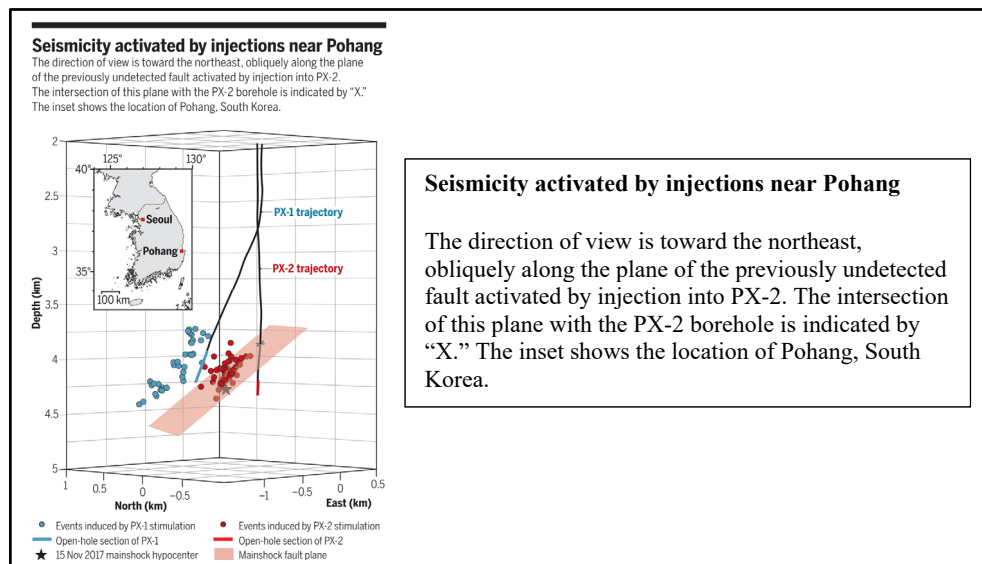
Questions soon arose about the possible involvement in the earthquake of the Pohang EGS project, because the preliminary epicenter of the quake reported by the Korean Meteorological Administration was located a few kilometers from the project's drill site. The EGS project was suspended, and, on behalf of the South Korean government, the Geological Society of Korea (GSK) conducted an investigation whose findings have recently been released. The GSK's analysis of the tectonic stress conditions, local geology, well-drilling data, hydraulic characteristics of the five high-pressure well stimulations undertaken to create the EGS reservoir, and seismicity associated with stimulation produced definitive evidence that small earthquakes induced by high-pressure injection into the PX-2 well activated the fault that ultimately ruptured in the M_w 5.5 earthquake (see the figure). Injection into PX-1 also induced seismicity, but in a spatially and hydraulically distinct volume of rock, and is not believed to have played a role in the earthquake.

The Pohang EGS project is not the only geoenery project to have encountered problems of induced seismicity. In recent years, small earthquakes induced during the drilling or stimulation phases of EGS projects in Europe exceeded predefined safety thresholds, leading to the termination of those projects. Although none of the quakes in those cases were as large as in Pohang, they caused alarm among the local communities and minor damage. Earthquakes induced during the development of hydrocarbon resources by hydraulic fracturing and by the disposal of wastewater have also led to the scaling back or termination of projects in several jurisdictions and led to regulatory changes.

Stimulation and Seismicity

It is useful to segment the analysis of the Pohang event into three sequential phases of the project: site assessment, drilling of the injection boreholes, and stimulation through the high-pressure injection of water.

Managing Injection-induced Seismic Risks (Continued)



The selection of the EGS site near a major city, port, and industrial center inherently posed an issue of seismic risk. Predrilling site investigations did not identify any large faults in the vicinity of the EGS project but did indicate that the faults in the region capable of generating moderate or large earthquakes were critically stressed, as shown by stress-state investigations. Even before the start of the drilling, it should have been clear that if the EGS project intersected a large fault susceptible to slip, it would pose a specific hazard that needed to be factored into the risk assessment and mitigation strategy.

During drilling of PX-2, the borehole intersected a fault at about 3.8-km depth, as noted in drilling records of the on-site geologists, resulting in loss of more than 160 m³ of drilling fluid that transferred an additional pressure of >20 MPa to the formation, triggering microearthquakes. Triggering of earthquakes in this manner is unusual and points again to the critical stress condition of the fault crossed by the borehole. This microseismicity, however, was noted only after the M_w 5.5 earthquake, and the importance of the previously unknown fault was not appreciated at the time and did not lead to changes being made to the operational plan.

The EGS project monitored seismicity induced during each well stimulation to determine each earthquake's magnitude and approximate location. It was only learned during the GSK investigation that injection into PX-2 had activated a fault (see the figure). The affected part of the fault grew to more than 1 km in length during the second stimulation of PX-2 in April 2017 when a M_w 3.2 earthquake occurred. The induced earthquakes delineate a planar structure that projects to the fault zone encountered at 3.8-km depth in PX-2, which subsequent seismological and geodetic observations indicated was the mainshock fault. The abrupt resurgence of seismicity releasing tectonic strain during each stimulation phase indicates that this fault was very sensitive to perturbations.

The focal mechanisms (which describe the geometry of the faults that slipped and the corresponding directions of slip) of the largest earthquakes that occurred during stimulation, of the foreshocks, and of the mainshock all display the same geometry. This again shows that this fault was critically stressed, meaning that it was susceptible to slip with only a small stress perturbation. Destabilization of the fault continued after the final PX-2 stimulation in September 2017, with foreshock activity initiating on 14 November and the M_w 5.5 mainshock occurring the next day and rupturing more than 10 km of the fault.

Managing Injection-induced Seismic Risks (Continued)

Had the presence of the fault and its susceptibility to slip in the prevailing stress regime been recognized at the time, it would have been clear that injection into PX-2 posed a substantial hazard and greatly increased the risk because of the proximity to Pohang.

To manage the potential for inducing unwanted earthquakes, the Pohang EGS project team monitored seismicity during injection and adjusted operations when specific magnitude thresholds were exceeded. Such an approach is often referred to as a “traffic light system” (TLS), with green, amber, and red states representing seismicity at background, anomalous, and increased levels, respectively. At Pohang, this approach focused on keeping induced seismicity below a threshold magnitude of 2 (later raised to 2.5) and did not address the potential for a larger earthquake triggered by injection, as ultimately occurred.

Neither Too Late Nor Too Large

Shortly after the M_w 5.5 earthquake, comments reported by the Korean media suggested that the earthquake was unrelated to EGS activities because it occurred almost 2 months after the final stimulation had ended and was disproportionately large, given the volumes of fluid injected. But it has been well known since the 1960s that induced earthquake hazard does not end when injection stops. The induced M_w 4.8 earthquake that shook Denver, Colorado, in 1967 occurred more than a year after injection in a deep well nearby had ended. At Basel, Switzerland, seismic activity including multiple M_w 3 earthquakes continued for several months after pressure was bled off.

It has been argued that the size of earthquakes induced by stimulation can be managed by controlling the volume, pressure, rate, and location at which fluid enters the rock mass and by allowing time for pressure to diffuse when seismicity rates escalate. The threshold magnitudes for TLSs have often been set to avoid earthquakes that pose a shaking nuisance and/or risk of damage.

Part of the rationale for selecting the magnitude thresholds comes from an empirical hypothesis that the largest magnitude of induced earthquakes is bounded by a function of the injected volume. If correct, this “volume hypothesis” would enable the hazard to be managed prescriptively by simply maintaining the net injection volume below a certain value (the concept underlying magnitude-based TLSs). However, an alternative analysis of the same data found that the largest event in an induced seismicity sequence is not related to the injection volume, but rather to preexisting tectonic conditions and the number of earthquakes induced. The greater the number of earthquakes, the higher the odds of one of them being large.

The Pohang earthquake violated the volume hypothesis, as the injected volume was less than 1/500th of the amount expected to produce an earthquake of M_w 5.5. Once initiated, the Pohang earthquake grew through the release of tectonic strain rather than being limited by the pressure perturbation induced by the injected fluids or confined to the perturbed volume of rock. The earthquake was almost two magnitude units larger than the M_w 3.7 predicted by one model; by rupturing beyond the volume affected by stimulation, it exceeded the maximum “arrested” earthquake size predicted by the other and constituted a “runaway” earthquake in their terminology.

How to Proceed

The Pohang EGS project was located close to a major city, port, and industrial center. This proximity raises clear issues of seismic risk, governance, and mitigation. It is crucial that strategies and tools for monitoring, mitigating, and communicating the risk of induced seismicity are established together with responsible

Managing Injection-induced Seismic Risks (Continued)

authorities. Seismic risk scenarios should be developed to evaluate possible consequences and to identify risk mitigation measures. Best practice involves a formal process of risk assessment, with input from competent authorities, and the updating of this assessment as knowledge of the potential hazard evolves. Implementation of a comprehensive risk framework should incorporate scenarios of a triggered large earthquake.

The analyses and investigations carried out as part of the GSK investigation were done only after the Pohang earthquake, but they would have been possible during the sequence of stimulations, which lasted almost 2 years before the earthquake. All the data required for this analysis were collected during that 2-year period, and the most important evidence was available in April 2017 after the second stimulation in PX-2.

Evaluations of seismic risk of possible relevance to the different stakeholders in the area could have been performed and communicated months before the mainshock.

In future EGS projects, the project team and the scientific institutions involved should engage in comprehensive and ongoing efforts to monitor, analyze, and understand the evolving seismic hazard. They should prioritize an open-access policy and clear channels of communication to maximize their contribution to the mitigation of seismic risk and to update information to the public authorities on the changing seismic risk conditions.

The Pohang earthquake had a complex origin. Seismicity induced by stimulation activated portions of a previously unknown fault that ultimately triggered the mainshock. The Pohang earthquake reinforces the conclusion that induced earthquake magnitudes are not limited by injected volume, and runaway earthquakes do occur. Models of earthquake nucleation do not adequately forecast the pre-mainshock evolution of a fault or the possibility of pressure perturbations triggering runaway slip. Further work is required to develop physical and statistical models of induced and triggered seismicity to provide appropriate bases for risk assessment.

As in many projects involving injection of water to stimulate permeability, the emphasis of the monitoring program in the Pohang EGS project was on the avoidance of earthquake magnitudes that would breach TLS thresholds, rather than on obtaining accurate hypocenters and documenting the evolution of the seismicity sequence. This narrow focus meant that the evolving risk was neither recognized nor communicated. It is essential that EGS and related stimulation activities use a risk-based TLS that adapts to evolving hazards such as fault activation from multiple stimulations.

Earthquakes are heavy-tailed phenomena, with the hazard concentrated in the large-magnitude, low-probability events. However, the risk that this hazard poses depends on exposure and vulnerability. The siting of the Pohang EGS project close to a major population and industrial center should have emphasized the need to consider risk rather than simply hazard. Such considerations are likely to be increasingly problematic if EGS activities are to be located near the population centers they are intended to power. The Pohang experience emphasizes the critical importance of formal processes of risk assessment and ongoing review that involve responsible authorities and appropriate independent oversight and scrutiny.

Read more about this article at: <https://science.sciencemag.org/content/364/6442/730>

Project Traces 500 Million Years of Roller-coaster Climate

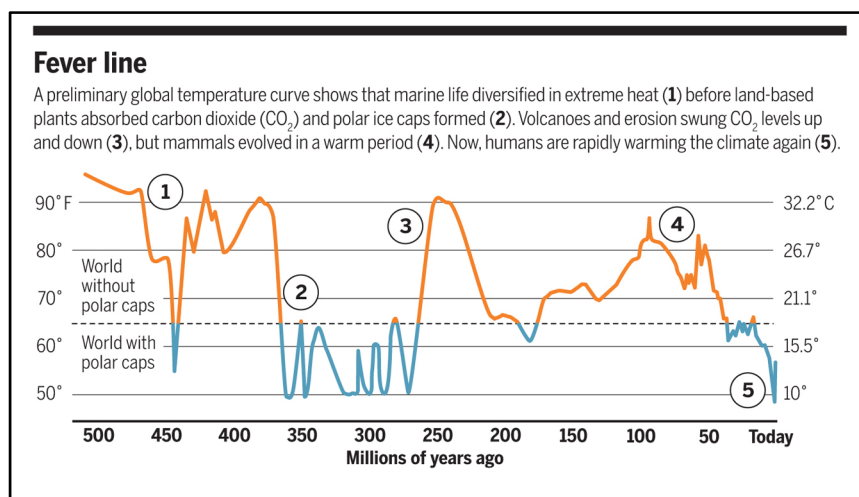
When it opens next month, the revamped fossil hall of the Smithsonian Institution's National Museum of Natural History in Washington, D.C., will be more than a vault of dinosaur bones. It will show how Earth's climate has shifted over the eons, driving radical changes in life, and how, in the modern age, one form of life—humans—is in turn transforming the climate.

To tell that story, Scott Wing and Brian Huber, a paleobotanist and paleontologist, respectively, at the museum, wanted to chart swings in Earth's average surface temperature over the past 500 million years or so. The two researchers also thought a temperature curve could counter climate contrarians' claim that global warming is no concern because Earth was much hotter millions of years ago. Wing and Huber wanted to show the reality of ancient temperature extremes—and how rapid shifts between them have led to mass extinctions. Abrupt climate changes, Wing says, “have catastrophic side effects that are really hard to adapt to.”

But actually making the chart was unexpectedly challenging—and triggered a major effort to reconstruct the record. Although far from complete, the research is already showing that some ancient climates were even more extreme than was thought.

Ancient glaciations are easy enough to trace, as are hothouse periods when palms grew near the poles. But otherwise little is certain, especially early in the Phanerozoic, which spans the past 541 million years. Paleoclimate scientists study their own slices of time and use their own specialized temperature proxies—leaf shape, say, or growth bands in fossilized corals—which often conflict. “We don't talk to each other all that much,” says Dana Royer, a paleoclimatologist at Wesleyan University in Middletown, Connecticut. So at a meeting last year, Wing and Huber assembled a loose-knit collaboration, dubbed Phantastic, dedicated to putting together a rigorous record. “Most people came away quite inspired to do something about this,” says Dan Lunt, a paleoclimate modeler at the University of Bristol in the United Kingdom.

The value of a deep-time temperature curve extends beyond the exhibit. Similar curves exist for atmospheric carbon dioxide (CO₂). Combine the two and you can see how much warming CO₂ caused in the past, says Jessica Tierney, a paleoclimatologist at the University of Arizona in Tucson. Because the latest climate models seem to forecast more warming than earlier ones, “using paleoclimate to constrain the models is becoming much more important,” she says. “We feel we have to step up.”



Project Traces 500 Million Years of Roller-coaster Climate (Continued)

But ancient global temperatures are elusive because they varied with location and season, and because the gauges drop away as you move deeper in time: Tree rings go back only thousands of years and ice cores only a million years or so. Still, oxygen isotopes in tiny fossilized shells on the ocean floor give a fairly reliable longer-term record. Because water molecules with lighter oxygen variants evaporate faster and end up locked in ice sheets, the ratio of light to heavy isotopes in the fossils indicates the volume of global ice, a rough guide to temperatures.

However, ocean floor older than 100 million years or so is scarce, devoured by the constant churn of plate tectonics. To go deeper in time, Ethan Grossman, a geochemist at Texas A&M University in College Station, looks for marine fossils found on land—mostly teeth and once-common bivalves called brachiopods. They tend to be from the shallow, isolated seas that formed inside ancient supercontinents. To glean temperatures from those fossils, scientists have to assume those seas had a balance of oxygen isotopes similar to the ocean today.

This “water problem” is decades old. But scientists in Phantastic are attacking it with a second thermometer, based on a new technique, called clumped isotopes, that measures the abundance of two or more rare isotopes. Using sensitive mass spectrometers, they analyze the fossil shells for carbonate molecules that contain a heavy isotope of oxygen bound to a heavy carbon, which form more frequently at lower temperatures. The results will be misleading if the fossil has been exposed to heat and pressure during its burial, but researchers have learned how to identify altered specimens. “We’ve moved into the place where we can apply it,” says Kristin Bergmann, a geobiologist at the Massachusetts Institute of Technology in Cambridge, who is using clumped isotopes to prepare a temperature record of the past billion years.

In collaboration with Gregory Henkes, a geochemist at the State University of New York in Stony Brook, and others, Grossman has gone through his samples, tossing out those that show signs of alteration, and analyzed their clumped isotopes. The results match his existing oxygen-isotope measures, and they tell a startling story, he and Henkes reported last year in *Earth & Planetary Science Letters*. Some 450 million years ago, ocean waters averaged 35°C to 40°C, more than 20°C warmer than today. Yet marine life thrived, even diversified. “It’s unsettling for the biologists, these warm temperatures we’re proposing,” Grossman says. “These are extreme for modern organisms.”

To turn such data into a global temperature curve, researchers need to fill gaps in geography and time. One Phantastic collaborator, Christopher Scotese, a geologist at Northwestern University in Evanston, Illinois, has come up with a simple way to spread limited data into a global picture. He uses the presence of polar ice caps to indicate whether the world had a steep temperature differential between the equator and its poles.

Other collaborators are using the sparse data to calibrate computer simulations of the ancient climate, the way weather models use satellite data as a reality check. Lunt and Paul Valdes, also at Bristol, are ground-truthing a suite of several hundred paleoclimate simulations. They’ve been able to extrapolate temperatures across the planet for broad stretches of the Phanerozoic.

Although Wing and Huber are pleased with the work they’ve seeded, they also ran out of time. The temperature curve they’re presenting at the museum opening is a beta, Wing says. “It’s sort of jamming together different kinds of observations, different kinds of models, different kinds of procedures, and probably different assumptions.” The plan is to replace it once the Phantastic team’s efforts reach maturity. But even the draft version should open eyes, Grossman says. “This kind of work gives people a sense of how easy it is to tip into a warm period. Because the world has been warm.”

Humans Held Responsible for Twists and Turns of Climate Change Since 1900

While industry and agriculture belched greenhouse gases at an increasing pace through the 20th century, global temperature followed a jagged course, surging for 3 decades starting in 1915, leveling off from the 1950s to the late 1970s, and then resuming its climb. For decades, scientists have chalked up these early swings to the planet's internal variability—in particular, a climatic pacemaker called the Atlantic Multidecadal Oscillation (AMO), which is characterized by long-term shifts in ocean temperatures. But researchers are increasingly questioning whether the AMO played the dominant role once thought. The oceanic pacemaker seems to be fluttering.

It is now possible to explain the record's twists and turns almost entirely without the AMO, says Karsten Haustein, a climate scientist at the University of Oxford in the United Kingdom and lead author of a new study published this month in the *Journal of Climate*. After correcting for the distinct effects of pollution hazes over land and ocean and for flaws in the temperature record, Haustein and his colleagues calculated that the interplay of greenhouse gases and atmospheric pollution almost singlehandedly shaped 20th century climate. "It's very unlikely there's this ocean leprechaun that produces cyclicity that we don't know about," Haustein says—which means it is also unlikely that a future cool swing in the AMO will blunt the ongoing human-driven warming.

Others aren't convinced the "leprechaun" is entirely vanquished. "They are probably right in that [the AMO] is not as big a player globally as has sometimes been thought," says Kevin Trenberth, a climate scientist at the National Center for Atmospheric Research in Boulder, Colorado. "But my guess is that they underestimate its role a bit."

The AMO arose from observations that sea surface temperatures in the North Atlantic seem to swing from unusually warm to cold and back over some 20 to 60 years; the ancient climate appears to have had similar swings. Researchers theorized that periodic shifts in the conveyor belt of Atlantic Ocean currents drive this variability. But why the conveyor would regularly speed and slow on its own was a mystery, and the evidence for grand regular oscillations has slowly been eroding, says Gabriele Hegerl, a statistical climatologist at the University of Edinburgh. "Those are harder to defend."

The new skepticism kicked off with work led by Ben Booth, a climate scientist at the Met Office Hadley Centre in Exeter, U.K.. In 2012, he reported in *Nature* that pollution hazes, or aerosols, began thickening the clouds over the Atlantic in the 1950s, which could have cooled the ocean with little help from an internal oscillation. In the past year, several independent models have yielded similar results. Meanwhile, most global climate models have been unable to reproduce AMO-like oscillations unless researchers include the influence of pollutants, such as soot and sulfates produced by burning fossil fuels, says Amy Clement, a climate scientist at the University of Miami in Florida.

Now, it seems plausible that such human influences, with help from aerosols spewed by volcanic eruptions, drove virtually all 20th century climate change. Haustein and his co-authors tweaked a relatively simple climate model to account for the fact that most pollution originates over land, which heats and cools faster than the ocean—and there's much more land in the Northern Hemisphere. And they dialed back the cooling effect of volcanic eruptions—a reasonable move, says Booth, who is not affiliated with the study. "We've known models respond too strongly to volcanoes."

The also adjusted the global temperature record to account for a change in how ocean temperatures are measured; during World War II, the British practice of measuring water samples in buckets gave way to

Humans Held Responsible for Twists and Turns of Climate Change Since 1900 (Continued)

systematically warmer U.S. readings of water passing through ships' intake valves. Past efforts to compensate for that change fell short, Haustein and his team found, so they used data from weather stations on coastlines and islands to correct the record.

As input for the model, the team used greenhouse gas and aerosol records developed for the next U.N. climate report, along with records of historical volcanic eruptions, solar cycles, and El Niño warmings of the Pacific. Comparing the simulated climate with the adjusted temperature record, they found that multidecadal variability could explain only 7% of the record. Instead, soot from industry drove early 20th century warming as it drifted into the Arctic, darkening snow and absorbing sunlight. After World War II, light-reflecting sulfate haze from power plants increased, holding off potential warming from rising greenhouse gases. Then, pollution control arrived during the 1970s, allowing warming to speed ahead.

It's a compelling portrait, but it could have been substantially different if the team had used other, equally justifiable assumptions about the climate impact of aerosols, Booth says. Trenberth thinks the team's adjustments had the effect of fitting the model to an uncertain record. "There is considerable wiggle room in just what the actual record is," he says.

Haustein disputes that the team tailored the model to explain the 20th century warming. "All we did was use available data in the most physically consistent way," he says. The researchers ran the model from 1500 to 2015, and he says it matches paleoclimate records well, including Europe's Little Ice Age.

If a grand ocean oscillation isn't shaping climate, a future ocean cooling is unlikely to buy society time to address global warming. But the demise of the AMO also might make it easier to predict what is in store. "All we're going to get in the future," Haustein says, "is what we do."

Read more about this article at: <https://www.sciencemag.org/news/2019/05/humans-held-responsible-twists-and-turns-climate-change-1900>

Theorist Calculates the Incalculable Siren Song of Merging Black Holes

Just a month into a renewed observing campaign with a trio of detectors, physicists today announced they have spotted more gravitational waves—fleeting ripples in space set off when two massive objects such as black holes spiral into each other. The collaboration has now bagged 13 merging black hole pairs, as well as two pairs of neutron stars. But even as detections accumulate, one theorist has made an advance that could change how the team analyzes the signals and make it easier to test Albert Einstein's theory of gravity, general relativity.

To interpret their signals gravitational wave hunters compare them to computer simulations. Now, Sean McWilliams, a theoretical astrophysicist at West Virginia University in Morgantown, has calculated an exact mathematical formula for the signal, or waveform, produced by two merging black holes.

"It's a big step forward," says Neil Cornish, a gravitational wave astronomer at Montana State University in Bozeman who was not involved in the work. "It's going to allow for more accurate waveforms for doing analysis. But it also gives us more insight into what's going on" in a black hole merger.

In 1916, Einstein predicted that as two stars orbit each other they'd radiate gravitational waves, although he figured the waves would be too feeble to detect. In 2015, physicists with the Laser Interferometer Gravitational-Wave Observatory (LIGO) spotted a burst of waves from two black holes that merged 1.3 billion

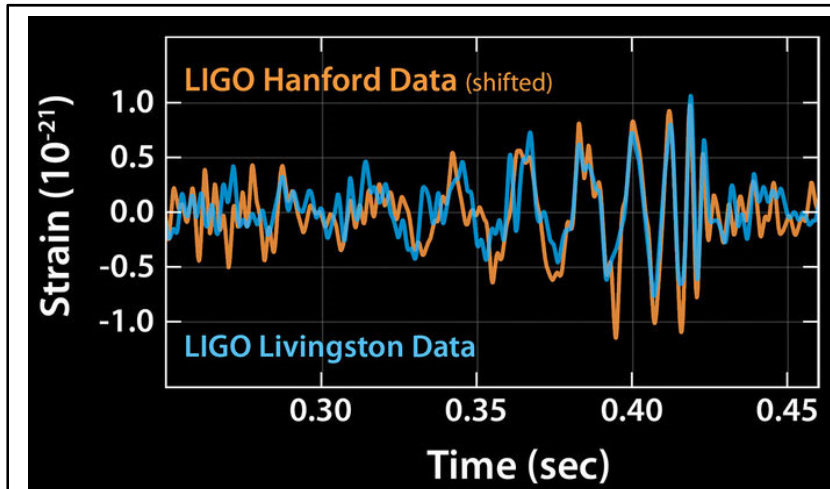
Theorist Calculates the Incalculable Siren Song of Merging Black Holes (Continued)

two black holes that merged 1.3 billion light-years away, using their huge optical instruments in Hanford, Washington, and Livingston, Louisiana. The Virgo detector near Pisa, Italy, joined the hunt in August 2017, enabling the collaboration to triangulate to the sources of the events on the sky.

As two black holes spiral ever closer, they emit ripples in space that speed up. The waves' intensity peaks as the two objects collide, and then peter out as the final, merged black hole undulates and settles down. To decipher the signal and determine the black holes' masses and other parameters, scientists compare it to a catalog of simulated signals, a task they have taken because of the complexity of the problem.

According to general relativity, gravity arises when mass and energy warp spacetime. And a black hole is the ultraintense gravitational field left behind when a massive star collapses to an infinitesimal point. So when two black holes swirl together, warping begets warping and renders the mathematics "nonlinear" and intractable.

Or so many scientists assumed. McWilliams says he has found a way to calculate the signal mathematically after all, as he reports in a paper in press at *Physical Review Letters*.



Two relatively simple formulas describe the peak and reverberation of gravitational wave signals like the first ones the Laser Interferometer Gravitational-Wave Observatory saw.

The calculation involves special distances from the center of the black hole. Famously, nothing can escape a black hole if it draws closer than a characteristic distance called the event horizon. At a distance about 1.5 times that of the event horizon, the black hole's gravity will bend passing light into a circular orbit, defining the "light ring." A distance roughly three times that of the event horizon marks the limit for a massive object to maintain a circular orbit and not spiral in, a threshold called the innermost stable circular orbit (ISCO).

Previous attempts to calculate the exact waveform from a black hole merger relied on a standard mathematical transformation, turning the problem of two orbiting black holes into one of a single body spiraling in a funnel-shaped energy landscape. But within the ISCO, the body stops spiraling, forcing researchers to correct its path with numerical simulations. McWilliams realized he could avoid that problem by skipping to the final merged black hole. He then used general relativity to calculate how a tiny test mass spirals into and perturbs the final black hole, enabling him to calculate the radiated signal from the ISCO inward.

Once the test particle reaches the light ring, tracing its trajectory becomes mathematically untenable. But McWilliams says the physics there can be ignored for a simple reason: All the churning of spacetime within

Theorist Calculates the Incalculable Siren Song of Merging Black Holes (Continued)

the light ring cannot escape to influence the spreading gravitational waves. Essentially, the black hole itself slurps up all the nasty nonlinearities. McWilliams provides a pair of formulas that neatly match the simulations. “I’ll be honest,” he says, “I was rather floored how well it agrees with the results of numerical relativity.”

Those formulas could prove valuable in tests of general relativity, McWilliams says, especially as black holes are objects made of pure gravitational energy, with no messy matter to get in the way. LIGO’s and Virgo’s observations have already confirmed general relativity’s accuracy to an unprecedented level, but researchers should be able to push further as they hone their instruments’ sensitivity. They’ll need more precise predictions of the waveforms from general relativity, McWilliams says, and the exact formulas should be more accurate than the numerical simulations.

Lionel London, a gravitational wave theorist and LIGO team member at the Massachusetts Institute of Technology (MIT) in Cambridge, isn’t so sure. McWilliams still has to rely on simulations to model the spiraling outside the ISCO, he notes, and that part of the signal is key to determining the masses of the initial black holes. The calculations also depend on certain simplifying assumptions, but do not provide estimates of the uncertainties carried with them, he says. The formulas are more of an “ansatz”—an educated guess at how the signal should look—than an exact solution to the problem, London says.

Cornish agrees it’s too early to replace numerical relativity. Still, he says, the formulas will be useful and should spur physicists to explain why black hole mergers seem to be simpler than they had anticipated. “There’s more to be learned.”

In the meantime, LIGO and Virgo researchers will have no shortage of signals. During the first month of their third observing run, they have detected five new candidate events, including three black hole mergers, a second neutron star merger, and a possible black hole-neutron star merger spotted last week. The mixed merger would be another gem for scientists, as they lack even good estimates of how often such things should occur. “Because it’s such an interesting astrophysical object, it’s generating a lot of excitement, which I think it deserves,” says Jessica McIver, a physicist and LIGO team member from the California Institute of Technology in Pasadena.

Still, the tantalizing signal is relatively weak. Researchers estimate that random noise should produce a similar spurious signal about once every 20 months, and there’s a 14% chance that it originated in terrestrial vibrations. “If you ask me, ‘Would you bet a coffee, your car, or your house on this?’ I would say, ‘I’d bet *your* car,’” says Salvatore Vitale, a physicist and LIGO member from MIT. To nail the case for the supposed mixed merger, astronomers would likely have to spot light and electromagnetic waves from it.

Read more about this article at: <https://www.sciencemag.org/news/2019/05/theorist-calculates-incalculable-siren-song-merging-black-holes>

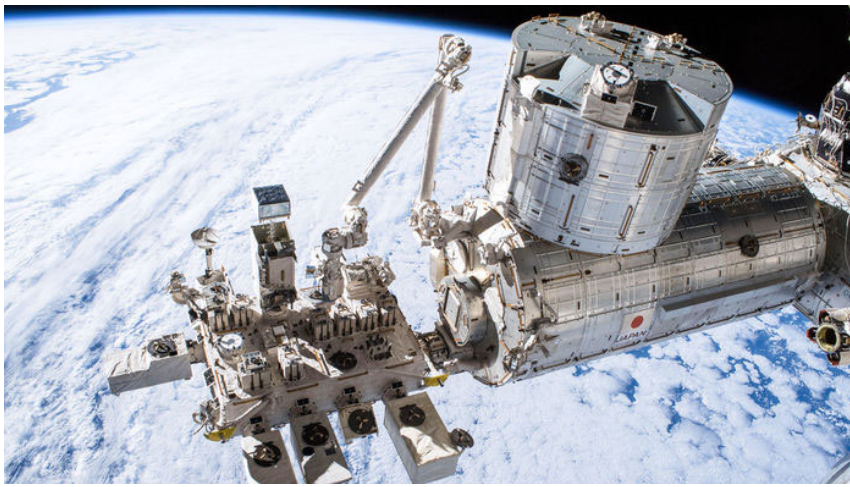
The International Space Station Has Found its Scientific Calling

The International Space Station (ISS) has never been known as a hotbed of science, even though the United States and partner nations spent more than \$100 billion to build it. Inside its cramped bays, astronauts study the biological effects of microgravity, and a few astrophysical experiments are mounted to its exterior. But 2 decades after it started to take shape, the ISS has finally found a scientific calling: looking down at its home planet.

The ISS is now home to five instruments that observe Earth, with two more set to join this year. One, NASA’s

The International Space Station Has Found its Scientific Calling (Continued)

Orbiting Carbon Observatory 3 (OCO-3), was scheduled for launch this week from Cape Canaveral, Florida, aboard a routine resupply mission. Its launch marks a political victory: President Donald Trump has proposed canceling OCO-3 several times, only to be rebuffed each time by Congress. It also marks a victory of expedience over perfection.



Earth-observing instruments roost on a platform attached to a Japanese module.

The ISS is not the ideal platform for OCO-3, which was built to fly on a stand-alone satellite. In fact, "It's probably not the perfect platform for almost anything," says Michael Freilich, who led NASA's earth science division in Washington, D.C. for 12 years until his retirement in February. "It's big. It flexes. It travels around in a cloud of contaminants." And, most important, its orbit misses the poles and revisits sites at a different time each day. But compared with launching a satellite, mounting the instrument on the ISS is vastly cheaper: At \$110 million, OCO-3 costs a quarter as much as OCO-2, which launched as a stand-alone mission in 2014.

The savings have helped NASA preserve the breadth of its earth science missions, after two spectacular launch failures: the loss of the original OCO satellite, which crashed into the Indian Ocean in 2009, and the 2011 demise of Glory, meant to track atmospheric particles. Although Freilich marshaled support to build OCO-2, costs doubled for several other planned satellites, putting smaller missions in jeopardy.

Around this time, Japan added a module to the ISS. Its flat terrace, jutting off its human-habitable module, was a good perch for 10 plug-and-play instruments. If putting Earth-observing instruments there would let NASA get much of the science for a fraction of the cost, that seemed like a good deal, Freilich says. "Everybody benefits. [NASA's human program] gets to show the utility of the station," while the earth science division flies more experiments.

OCO-3 will be the third prominent NASA mission to be mounted on the Japanese module within the past year. Ecostress, attached in July 2018, measures the heat given off by plants to gauge the impact of heat waves and drought. The Global Ecosystem Dynamics Investigation (GEDI), launched in December 2018, uses a laser to probe the height of tree canopies and understories. Later this year, a Japanese hyperspectral imager that can detect land use and forest type will take a fourth spot. Other instruments mounted elsewhere on the ISS in the past 2 years measure lightning, incoming sunlight, and ozone.

Like OCO-2, OCO-3 carries a spectrometer that spies on wavelengths of light absorbed by carbon dioxide (CO₂), providing a count of all CO₂ molecules on a path from the ISS to the surface. Based on how

The International Space Station Has Found its Scientific Calling (Continued)

CO₂ concentrations vary from place to place, the missions can map some emission sources along with absorption by plants. But the measurements are difficult given the vast background of CO₂ already in the atmosphere.

At first the OCO-3 team wasn't thrilled to end up on the ISS, says Annmarie Eldering, the mission's project scientist at the Jet Propulsion Laboratory (JPL) in Pasadena, California. But they came to see advantages. The erratic timing of its observations will make it challenging for OCO-3 to infer trends over weeks or months but will allow the instrument to explore how plant carbon emissions vary over the course of the day. "That's going to be very useful," Eldering says, especially when combined with measurements taken simultaneously by GEDI and Ecostress.

OCO-3's angled perch on the ISS also required a pivoting mount to allow it to see straight down. By pivoting, it can map CO₂ over large regions, roughly the size of the Los Angeles, California, basin, during a single pass. Such regional maps could capture emissions from local sources such as cities and industry, says Christopher O'Dell, an atmospheric scientist at Colorado State University in Fort Collins, and enable OCO-3 to test the promise of verifying CO₂ cuts from space. "That's the goal," O'Dell says. "We don't know if that's possible."

The ISS has one key constraint: space. After 3 years, OCO-3 is likely to be displaced on the Japanese module. NASA and Japan are already talking about what will go next to take its slot, Eldering says. Afterward, she says, "They will take us off and burn us up in the atmosphere."

Yet the promise of a space-based platform for making multiple simultaneous measurements of Earth at lower cost will live on. Rudranarayan Mukherjee, a JPL engineer, is developing a concept called the Science Station: a robotic mini-space station with trusses and a robotic arm that could host a dozen Earth-observing instruments in low orbit. The space station, he says, "has shown the benefit of having a platform in lower Earth orbit that's a shared resource." NASA hasn't yet committed to the concept, he says. But he adds, "People can instantly see, yeah, I could see how that could work."

Read more about this article at: <https://www.sciencemag.org/news/2019/05/international-space-station-has-found-its-scientific-calling>

First Marsquake Detected by NASA's InSight Mission

Mars is shaking. After several months of apprehensive waiting on a quiet surface, NASA's InSight lander has registered a sweet, small sound: the first marsquake ever recorded. On 6 April, the lander's seismometer detected its first verifiable quake, NASA and its European partners announced today.

The quake is tiny, so small that it would never be detected on Earth amid the background thrum of waves and wind. But Mars is dead quiet, allowing the lander's sensitive seismometer to pick up the signal, which resembles similar surface ripples detected traveling through the moon's surface after moonquakes. The quake is so small that scientists were unable to detect any waves tied to it that passed through the martian interior, defying efforts to estimate its exact location and strength, says Philippe Lognonné, a planetary seismologist at Paris Diderot University who leads the mission's seismometer experiment. Still, it was gratifying to observe, he says. "It is the first quake. All the time, we were waiting for this."

The detection is a milestone for the \$816 million lander, kicking off a new field of "martian seismology," added Bruce Banerdt, InSight's principal investigator and a geophysicist at NASA's Jet Propulsion Laboratory (JPL) in Pasadena, California, in a news release. It proves Mars is seismologically active, and marks NASA's

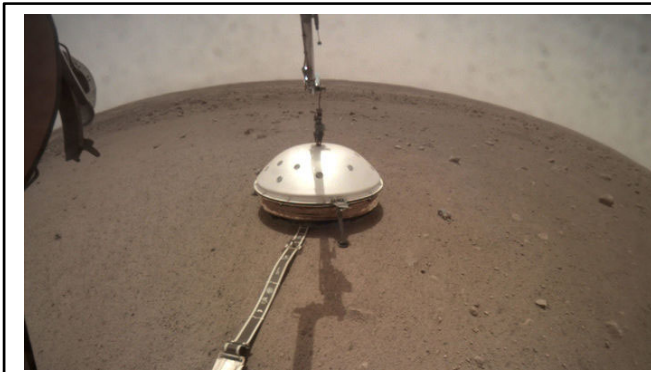
First Marsquake Detected by NASA's InSight Mission (Continued)

marks NASA's return to planetary seismology after more than 4 decades. The mission is intended to peer through the planet's rust-colored shell, gauging the thickness and composition of its crust, mantle, and core. But while on Earth, the lander was plagued by delay and cost overruns; since landing on Mars in a sand-filled hollow, the lander's second instrument, a heat probe, got stuck soon after it began to burrow into the surface.

Scientists had good reason to believe that Mars hosted such quakes even though it lacks plate tectonics, the force that drives most earthquakes. The moon suggested so: Seismometers deployed by the Apollo program had detected quakes caused by meteorite impacts, the solar-driven thermal expansion of its crust, and the gravitational tug of Earth. But the frequency was unknown. The InSight team estimated it might see one a month, but that number could be much higher or lower. And so, after deploying the volleyball-size seismometer and its shield in early February, the researchers waited. The seismometer was working well, they found: It was picking up background vibrations, called microseisms, in the martian surface that were induced by wind. But still, as the weeks ticked by, no quakes.

The team now believes the seismometer needed time to settle on the surface. Week after week, background noise during martian nights has dropped. That allowed the 6 April detection and three other signals that could (or could not) be other marsquakes, detected on 14 March, 10 April, and 11 April. The 6 April quake is the only event to rise above minimum requirements set by the mission for detection, and it was observed by both the primary seismometer and a smaller, less sensitive sensor.

The quake reminds Yosio Nakamura, a planetary seismologist at the University of Texas in Austin who worked on Apollo seismology, of what the seismometer that Apollo 11 brought to the moon revealed during its 3 weeks of operation. The quakes the device recorded were mysterious, and it wasn't until NASA's Apollo 15 team established a network of three seismometers that scientists realized that some of what Apollo 11 recorded had actually been quakes from the moon's deep interior.



InSight's seismometer is protected from wind and heat swings by a dome-shaped shield.

"With a seismometer of better quality and better analysis techniques than what we had 50 years ago, I hope they can do better than what we did with the Apollo 11 data," he says. "This may take a while, but we can wait."

While listening for quakes, InSight's seismometer has had another pressing engagement, serving as a diagnostic tool for the stuck heat probe. Engineers at JPL and the German Aerospace Center in Darmstadt, which designed and built the instrument, have spent several rounds tapping the probe's rod with a tungsten hammer at its tip and using the seismometer to listen to the noise, hoping to understand the ground the heat probe is trapped in. It's possible the probe's rod is stuck in gravel, but the sandy ground could also not be providing enough friction for the probe to gain traction. Testing is continuing, with JPL's engineers seeing

First Marsquake Detected by NASA's InSight Mission (Continued)

whether a nudge from the lander's robotic arm might help.

Meanwhile, this marsquake detection is just the start. As the lander's 2-year primary mission continues, larger and larger quakes will likely be detected, Lognonné says. These will ultimately allow InSight to peer beneath the planet's surface. "We're starting to have many small quakes," he says. By the end of the mission, he hopes, "we'll have a super big quake."

Read more about this article at: <https://www.sciencemag.org/news/2019/04/first-marsquake-detected-nasas-insight-mission>

First Fossil Jaw of Denisovans Finally Puts a Face on Elusive Human Relatives

Thirty-nine years ago, a Buddhist monk meditating in a cave on the edge of the Tibetan Plateau found something strange: a human jawbone with giant molars. The fossil eventually found its way to scientists. Now, almost 4 decades later, a groundbreaking new way to identify human fossils based on ancient proteins shows the jaw belonged to a Denisovan, a mysterious extinct cousin of Neanderthals.

The jawbone is the first known fossil of a Denisovan outside of Siberia's Denisova Cave in Russia, and gives paleoanthropologists their first real look at the face of this lost member of the human family. "We are finally 'cornering' the elusive Denisovans," paleoanthropologist María Martínón-Torres of the National Research Center on Human Evolution in Burgos, Spain, wrote in an email. "We are getting their smiles!"

Together, the jaw's anatomy and the new method of analyzing ancient proteins could help researchers learn whether other mysterious fossils in Asia are Denisovan. "We now can use this fossil and this wonderful new tool to classify other fossil remains that we can't agree on," says paleoanthropologist Aida Gomez-Robles of University College London, who reviewed the paper, which appears in *Nature* this week.

The international team of researchers also reports that the jawbone is at least 160,000 years old. Its discovery pushes back the earliest known presence of humans at high altitude by about 120,000 years.

A massive search for Denisovans has been underway ever since paleogeneticists extracted DNA from the pinkie of a girl who lived more than 50,000 years ago in Denisova Cave and found she was a new kind of human. Max Planck Society researchers have since sequenced DNA from several Denisovans from the cave, but the fossils—isolated teeth and bits of bone—were too scanty to show what this enigmatic hominin looked like. Denisovans must have been widespread, because many living people in Melanesia and Southeast Asia carry traces of DNA from multiple encounters between modern humans and Denisovans. But although intriguing fossils across Asia could be Denisovan, they have not yielded the DNA that could confirm their identity.

Enter the new jawbone, found by an unidentified monk in Baishiya Karst Cave in Xiahe county in China at an altitude of 3200 meters on the margins of the Tibetan Plateau, according to co-author Dongju Zhang, an archaeologist at Lanzhou University in northwestern China. She traced the jawbone's discovery by interviewing local people in Xiahe, who told her they remembered human bones from the large cave, which is next to a Buddhist shrine and is still a holy place as well as a tourist attraction. Recognizing the jaw's unusual nature, the monk gave it to the sixth Gung-Thang living Buddha, one of China's officially designated "living Buddhas," who consulted scholars and then gave the jaw to Lanzhou University. The jawbone was so "weird" that researchers there didn't know how to classify it, and it sat on shelves for years, Zhang says.

First Fossil Jaw of Denisovans Finally Puts a Face on Elusive Human Relatives (Continued)

She and geologist Fahu Chen, also from Lanzhou University and the Institute of Tibetan Plateau Research in Beijing, showed the jaw to paleoanthropologist Jean-Jacques Hublin of the Max Planck Institute for Evolutionary Anthropology in Leipzig, Germany. After seeing its large molars—as big as ones found in Denisova Cave—Hublin immediately suspected it was Denisovan.

Max Planck paleogeneticists couldn't get DNA from the jaw, but Hublin's graduate student Frido Welker had found in his doctoral work that Neanderthals, modern humans, and Denisovans differ in the amino acid sequence of key proteins. Welker, now a postdoc at the University of Copenhagen, was able to extract collagen, a common structural protein, from a molar of the Xiahe jawbone. He found its amino acid sequence most closely matched that of Denisovans.



Other team members dated a carbonate crust that had formed on the skull by measuring the radioactive decay of uranium in the carbonate. They got a date of 160,000 years ago—a "firm minimum date" for the skull, says geochronologist Rainer Grün of Griffith University in Nathan, Australia, who is not a member of the team.

The date suggests Denisovans would have had tens of thousands of years to adapt to the altitude of Tibet by the time modern humans arrived in the region, some 30,000 to 40,000 years ago. Encounters between modern humans and Denisovans adapted to high altitude could explain how the Tibetans of today came by a Denisovan gene that helps them cope with thin air. "It seems likely that ancestral Tibetans interacted with Denisovans, as they began to move upslope," archaeologist David Madsen of the University of Texas in Austin wrote in an email.

The jaw's features could be a template for spotting other Denisovans. "Its distinct large molars and premolar roots differ from those of Neanderthals," and the jawbone "is very primitive and robust," says Hublin, who sees a resemblance to a jawbone found off the coast of Taiwan known as the Penghu mandible.

What anatomy can't confirm, proteins might. "The protein analyses allow us to see landscapes where DNA cannot reach"—from warmer climates or much more ancient sites where fragile DNA doesn't persist, Martínón-Torres says. Other researchers have a half-dozen fossils they want to test for proteins or compare with the Xiahe jaw.

The implications are far-reaching. "Forget the textbooks," says archaeologist Robin Dennell of the University of Sheffield in the United Kingdom. "Human evolution in Asia is far more complex than we currently

First Fossil Jaw of Denisovans Finally Puts a Face on Elusive Human Relatives (Continued)

understand, and probably does involve multiple lineages, some of which probably engaged with our species."

Meanwhile, Chen and Zhang did their first excavation at the cave in December 2018, with permission from local villagers and Buddhists. They dug two small trenches where they have already found stone tools and cut-marked rhino and other animal bones. "We do have hope we'll find more Denisovans," Zhang says.

Read more about this article at: <https://www.sciencemag.org/news/2019/05/first-fossil-jaw-denisovans-finally-puts-face-elusive-human-relatives>

Two-thirds of The World's Longest Rivers No Longer Run Free

About two-thirds of the world's longest rivers are no longer free flowing, compromising their ability to move sediment, facilitate fish migration, and perform other vital ecosystem services, according to a new study. And with more than 3700 large dams in the works, the future of free-flowing waterways looks even bleaker, researchers say.

To get a global perspective on river conditions, Bernhard Lehner, a hydrologist at McGill University in Montreal, Canada, who for years has studied the effects of dams on entire watersheds, teamed up with researchers from the World Wildlife Fund (WWF), based in Washington, D.C., and elsewhere. Using aerial, satellite, and other data, the team examined 12 million kilometers of waterways, evaluating their flows in 4.5-kilometer segments.

Traditionally, researchers focused on dams when assessing a river's free flow. But in this assessment, the team also considered the impacts on flow created by riverbank levees, other flood control structures, and water diversions for power, irrigation, or drinking supplies. "It's a more comprehensive analysis of global hydrology than we have had before," says N. LeRoy Poff, a hydroecologist at Colorado State University in Fort Collins who was not part of the project.

In particular, the researchers focused on the 246 longest rivers encompassing more than 1000 kilometers of flowing water—think the Nile and Mississippi rivers—because of their huge ecological impact. Just 90 of those big rivers are still unencumbered, they report today in *Nature*. Most of the remaining unblocked rivers are in the Amazon, the Arctic, and Africa's Congo basin.

"In the U.S., Europe, and more developed areas, these longer, free-flowing rivers don't really exist," Poff says. And those free rivers that remain "are some of the most important places for freshwater species," says Michele Thieme, a WWF freshwater ecologist. Freshwater plants and animals are declining twice as fast as terrestrial and marine populations, WWF has found. And rivers in general have a lot of hidden value not fully appreciated by policymakers, Thieme notes.

Thieme and Bernhard hope this assessment will have an effect on both global and local policymaking. It provides a ready source of data for countries working to meet international sustainable management goals, which include protection for freshwater systems. And the study's methodology can be applied more locally with finer scale data to help guide where to site—or remove—dams to maintain or restore free flows.

WWF, for example, is advocating increased use of solar or wind power to cut down on the need for more hydroelectric dams, which could help protect areas such as Asia's Mekong delta. The group has also worked with Myanmar and the World Bank's International Finance Corporation to try to keep dams off the Irrawaddy

Two-thirds of The World's Longest Rivers No Longer Run Free (Continued)

and the Salween river, two of that country's major free-flowing waterways. And it's helping establish baseline monitoring of the water quality of Canada's Liard River, which runs from the Yukon into the Northwest Territories and is one of that country's last long free-flowing rivers.

Already, the increased awareness of the value of free-flowing rivers is leading to policy changes, WWF notes. In February, Slovenia agreed to stop hydropower development on that country's Mura River, one of the last refuges with otters and the Danube salmon. Last year, Mexico established water reserves in about 300 river basins—water reserved for nature and not stored behind dams.

Bernhard would like to see more such decisions. "We hope that our data can be used to find smarter and more sustainable solutions in how we manage rivers," he says.

Read more about this article at: <https://www.sciencemag.org/news/2019/05/two-thirds-world-s-longest-rivers-no-longer-run-free>

These Tiny Microbes are Munching Away at Plastic Waste in the Ocean

Plastic makes up nearly 70% of all ocean litter, putting countless aquatic species at risk. But there is a tiny bit of hope—a teeny, tiny one to be precise: Scientists have discovered that microscopic marine microbes are eating away at the plastic, causing trash to slowly break down.

To conduct the study, researchers collected weathered plastic from two different beaches in Chania, Greece. The litter had already been exposed to the sun and undergone chemical changes that caused it to become more brittle, all of which needs to happen before the microbes start to munch on the plastic. The pieces were either polyethylene, the most popular plastic and the one found in products such as grocery bags and shampoo bottles, or polystyrene, a hard plastic found in food packaging and electronics. The team immersed both in saltwater with either naturally occurring ocean microbes or engineered microbes that were enhanced with carbon-eating microbe strains and could survive solely off of the carbon in plastic. Scientists then analyzed changes in the materials over a period of 5 months.

Both types of plastic lost a significant amount of weight after being exposed to the natural and engineered microbes, scientists reported in April in the *Journal of Hazardous Materials*. The microbes further changed the chemical makeup of the material, causing the polyethylene's weight to go down by 7% and the polystyrene's weight to go down by 11%. These findings may offer a new strategy to help combat ocean pollution: Deploy marine microbes to eat up the trash. However, researchers still need to measure how effective these microbes would be on a global scale.

Read more about this article at: <https://www.sciencemag.org/news/2019/05/these-tiny-microbes-are-munching-away-plastic-waste-ocean>

Fernbank Events & Activities Calendar

In addition to a wide array of permanent and special exhibitions and movies on the 4-story giant screen, Fernbank Museum also hosts a variety of special events and programs, as well as drop-in programs offered on weekends and school holidays.

Excellent Experiments

Sunday, May 26, 2019 3:00 PM

Explore the amazing world of chemistry through fun experiments in a live presentation.

Tadpole Tales

Monday, May 27, 2019 11:30 AM

Preschoolers will enjoy a story and special activity with a Fernbank educator.

Cosmic Quest

Monday, May 27, 2019 2:30 PM

Blast off for an exploration of space that will take you from Earth through the universe.

Geology Rocks

Friday, May 31, 2019 2:30 PM

Discover how the rocks of Georgia formed with hands-on experiments and touchable specimens.

Dog Days of Summer

Sunday, June 2, 2019 6:00 PM

Join us for a paw-tastic evening of family fun celebrating Superpower Dogs 3D.

Monster Fish Opening Day

Saturday, June 8, 2019 10:00 AM

Join us for hands-on activities and live animal encounters to celebrate the new summer exhibit, Monster Fish: In Search of the Last River Giants.

Fernbank After Dark: The Great Outdoors

Friday, June 14, 2019 7:00 PM

Get your outdoors on and quench your thirst for nature with hands-on activities and demonstrations.

Adult Summer Camp

Friday, June 21, 2019 7:00 PM

Get in on the summer fun and enjoy outdoor games and entertainment like the good old days of summer camp.

Sensory Morning

Saturday, June 29, 2019 9:00 AM

Join us for a series of special sensory events, designed for guests with sensory sensitivities, special needs or various physical abilities who might benefit from a less-crowded environment.

Reptile Day

Saturday, July 13, 2019 10:00 AM

Come face to face with live reptiles and amphibians at this popular annual event. Learn about and interact with unique creatures, including snakes, tortoises, lizards and many more.

Double Feature: Monster Fish & Jaws

Friday, July 19, 2019 7:00 PM

For one night only, see Jaws swimming across Fernbank's 4-story giant screen. Before being terrorized by a giant man-eating great white shark, experience Fernbank's newest special exhibit, Monster Fish: In Search of the Last River Giants.

Moon Landing Celebration

Saturday, July 20, 2019 10:00 AM

Usher in the 50th anniversary of man's first steps on the moon in a special celebration of NASA's 1969 moon landing with interactive activities and special screenings of Apollo 11: First Steps Edition.



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of NATURAL HISTORY



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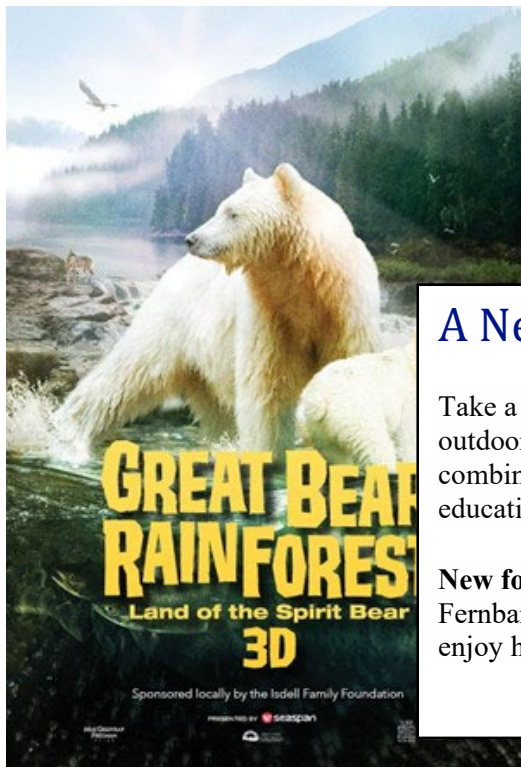
FERNBANK MUSEUM

of NATURAL HISTORY

Fernbank Museum of Natural History

(All programs require reservations, including free programs)

Now showing in the Fernbank IMAX movie theater:



A New Way to Museum

Take a walk on the wild side as you explore 75 acres of new outdoor nature adventures. WildWoods and Fernbank Forest combine to highlight the natural world through immersive trails, educational programming, hands-on exhibits and beautiful scenery.

New for Summer! Experience the wonders of nature on Fernbank's giant 4-story screen with Backyard Wilderness 2D, and enjoy hands-on nature adventures outside in WildWoods.

Great Bear Rainforest 3D

Showing May 3 through October 31

Visit a magical environment, unchanged for 10,000 years, home to one of the rarest animals on Earth—the fabled Spirit Bear. Great Bear Rainforest is one of the planet's most extraordinary and largest temperate coastal rainforests in the world and has remained forest for millennia. Embark on a remarkable journey to discover the secret world of the Spirit Bear. Narrated by

Giants of the Mesozoic

A prehistoric battle of gigantic proportions unfolds in the permanent exhibition *Giants of the Mesozoic*, filling the Museum's Great Hall. This exhibition recreates life in the badlands of Patagonia, Argentina, where the largest dinosaurs in the world were unearthed.

Giants of the Mesozoic includes additional fossil casts to further demonstrate the diversity of prehistoric life in Patagonia. The simulated rockwork beneath the dinosaurs contains casts of animals and plants that lived during the Cretaceous period. Visitors will also find pterosaur and dinosaur tracks, remnants from an *Auracaria* tree, a fossilized crocodile and a turtle shell.

Superpower Dogs 3D

Showing May 17 through September 16

Join an immersive giant screen adventure to experience the most amazing dogs in the new IMAX® movie, *Superpower Dogs 3D*. In this inspiring true story narrated by Chris Evans, our best friends are also real-life superheroes. Journey around the globe to meet remarkable dogs who save lives and discover the powerful bond they share with their human partners. Follow 'Halo,' a rookie puppy training to join one of the most elite disaster response teams in America. Meet 'Henry,' an avalanche rescue expert in the mountains of British Columbia, 'Reef,' a Newfoundland lifeguard with the Italian coastguard, 'Ricochet,' a Californian surf legend helping people with special needs, and the Bloodhound brothers, 'Tipper and Tony,' who are leading the fight to save endangered species in Africa.

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AGS 2019 Meeting Dates

Listed below are the planned meeting dates for 2019. Please mark your calendar and make plans to attend.

2019 Meeting Schedule

June 25

July 30

August 27

September 24

October 29

2019 PG Study Group Meetings

June 29

July 27

August 31

September 28

October 26

AGS Committees

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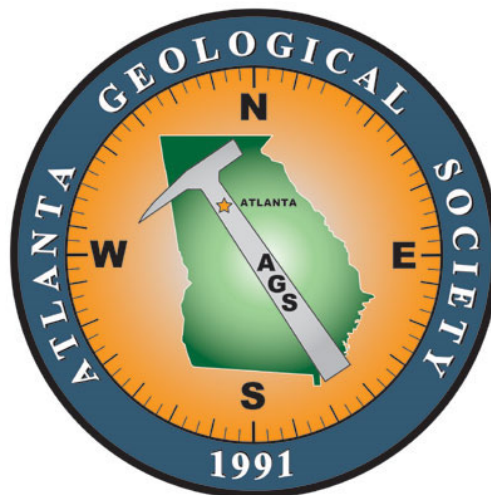
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