

An Alaskan volcano, climate change, and the history of ancient Rome

In the first century BCE, political instability set the Roman Republic on edge. Researchers have found evidence of an eruption that may have catalyzed the republic's end.

The assassination of Julius Caesar on the Ides of March in 44 BCE marked the beginning of a 17-year power struggle for control over the greater Mediterranean region. Roman law remained in force, but societies were in tumult. Civil wars broke out, the Senate and its consuls were ousted, and in 31 BCE Julius's grandnephew and heir Octavian emerged as the first emperor of the Roman Empire.

Accounts of the time reveal that inclement weather, crop failure, widespread famine, and disease accompanied the political upheaval. Recent climate reconstructions have borne out those accounts: On average, 43 and 42 BCE were among the coldest of the past 2500 years in the Northern Hemisphere.¹

A team of climate scientists, volcanologists, and historians led by Joseph McConnell of the Desert Research Institute in Reno, Nevada, has now compiled persuasive evidence pinpointing the source responsible for the extreme environmental conditions: a powerful eruption from Alaska's Okmok volcano (figure 1), 9300 kilometers from Rome.²

To reach that conclusion, the researchers measured the volcano's ancient fallout sequestered in six well-dated Arctic ice cores. Their geochemical analysis of volcanic tephra—small shards of cooled magma—in the cores revealed a near-perfect match to basalt found around the volcano today. Climate proxies, such as tree rings and stalagmite layers, provided a complementary record of temperatures and rainfall at the time of the ancient event. So did historical chronicles and climate modeling.

The research represents one of a growing number of interdisciplinary projects that seek to reconstruct an era's climate and better understand the history



FIGURE 1. THE 10-KM-WIDE CALDERA on Alaska's Umnak Island was formed during the 43 BCE eruption of the Okmok volcano. The massive eruption produced some of the most extreme Northern Hemisphere weather conditions of the past 2500 years. (Courtesy of Kerry Key, Columbia University.)

of a civilization in its proper environmental context.

Fire and ice

Several factors influence the variability of Earth's climate. The Sun's activity rises and falls with its 11-year sunspot cycle. Earth's tilt, spin, and orbit likewise oscillate through so-called Milankovitch cycles, which influence the amount and distribution of solar energy that reaches Earth's surface (see the article by Mark Maslin, *PHYSICS TODAY*, May 2020, page 48). The Milankovitch cycles induce ice ages, which take thousands of years to develop—hardly a rapid response. By contrast, volcanic eruptions are sudden, dramatic events that can shock a society for years.

During a large eruption, billions of tons of rock, gas, and ash are thrust into the atmosphere. Small, insoluble particles of tephra rain out within days to weeks. But the gas, much of which is sulfur dioxide, can reach the stratosphere, where it may linger for years. In the thin dry air, SO₂ slowly becomes oxidized to sulfate aerosols. Depending on the eruption's location, those sulfates can get caught up in stratospheric winds, which disperse them throughout one or both of Earth's hemispheres. Extremely reflective, the sulfates scatter incoming solar radiation and cool Earth's surface. But eventually they, too, fall out, some

settling on snow near one of the poles.

As the snow becomes compressed into ice over the millennia, gases and molecular compounds become trapped, layer by layer, and form a rich, time-stamped record of the atmosphere's chemical composition. Industrial pollution, dust, pollen, ash from biomass burning, and volcanic residue can all be found there. Since the 1960s, researchers have drilled cylindrical ice cores in glaciers and ice sheets to mine that archive.

Early on, the ice cores were cut into short slices, and individual layers were melted and analyzed one by one as a function of ice depth. But the technology has matured; today, researchers can continuously melt and analyze ice cores simultaneously for much more accurate dating. "Each year is much more clearly resolved," McConnell says. "And because nearly everything we measure in the ice shows seasonal variation, we can use multiple parameters to identify those annual layers." His system, shown in figure 2, holds an ice core over a heated ceramic plate. Grooves in the plate channel meltwater from the innermost part of the core to a mass spectrometer to measure the concentration of dozens of elements.

Lead pollution and volcano hunting

McConnell and his collaborators did not set out to look for the source of sudden

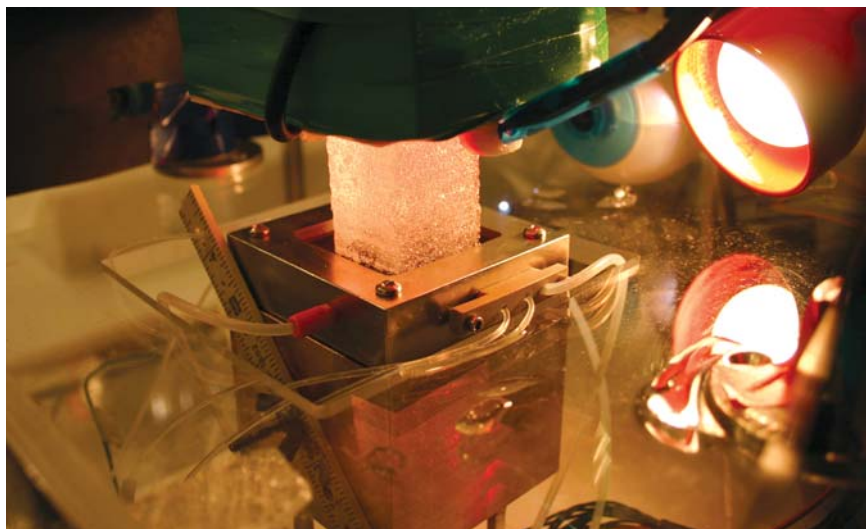


FIGURE 2. AN ICE-MELTER PLATE holds a 3 cm × 3 cm block from an ice core. As the ice melts, its water is pumped into two mass spectrometers and vaporized for elemental and chemical analysis in real time. The system can resolve concentrations at the level of parts per quadrillion and age as a function of depth to within ±2 years. (Courtesy of Joseph R. McConnell.)

climate change in the ancient Mediterranean region. Two years ago, they were analyzing lead pollution in ice cores for a project on the history of silver production. Silver mining and smelting operations waxed and waned in the ancient

world. (About 10000 g of argentiferous lead ore was used to produce 1 g of silver.) McConnell's team used the rise and fall of lead's concentration in the cores as a marker of ancient economic activity, war, and plague.³

While reviewing data for that project, McConnell and his former postdoc Michael Sigl (now at the University of Bern) came across an unusually well-preserved layer of tephra in one of the ice cores used in the pollution study. Excited about finding possibly unknown volcanic eruptions, they decided to investigate it further. Their subsequent mass spectrometry measurements of ice cores (figure 3) revealed volcanic fallout from two distinct eruptions—the first starting in early 45 BCE and the second in early 43 BCE, almost a year after Julius Caesar's assassination. The first eruption probably took place in Iceland, the collaboration surmised. But it was short-lived and likely had little climate impact. The second, attributable to the Okmok volcano, was a whopper: It had a greater fallout of sulfuric acid, which persisted for 2.5 years.

The sharp spike in 3–10 μm insoluble tephra shards that McConnell and Sigl had spotted early on coincided with the early stages of the 43 BCE sulfur peak. The temporal narrowness of the spike pinned the eruption to January or February of that year, before the growing season in the Northern Hemisphere.

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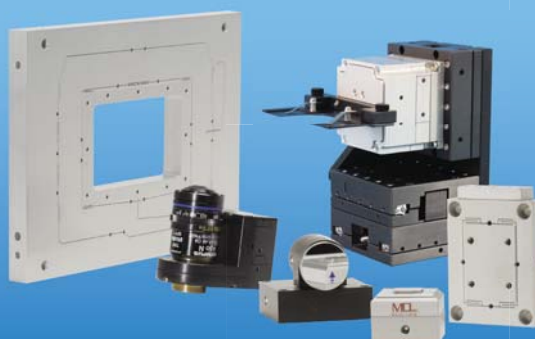
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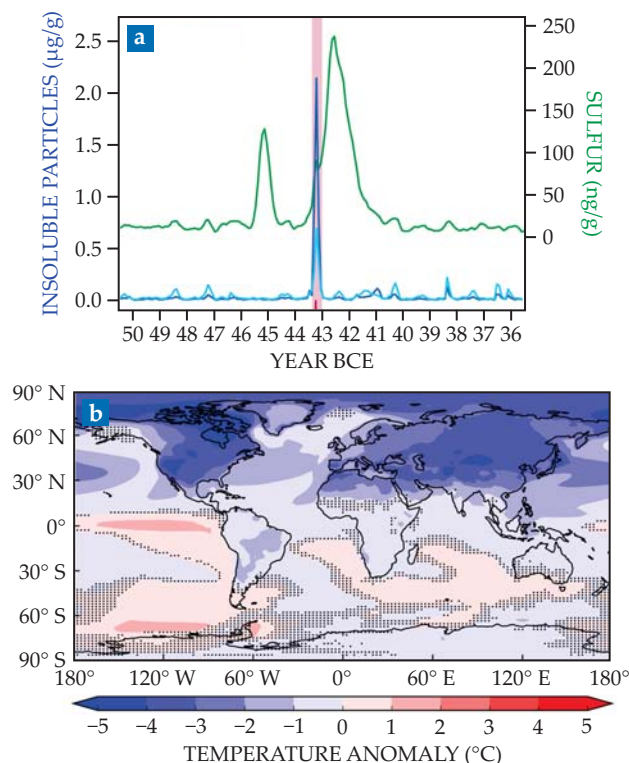


FIGURE 3. ICE-CORE AND CLIMATE ANALYSES.

(a) Continuous mass spectrometry of sulfur and insoluble-particle (tephra) concentrations—in units of nanograms and micrograms of material per gram of water, respectively—sync'd to the years that volcanic fallout settled into snow. **(b)** This snapshot of an air-temperature simulation captures the average air-temperature anomalies during 43 and 42 BCE. As inputs, the researchers relied on the Okmok eruption's location, timing, and sulfur yield to estimate its cooling effect and the extent and persistence of the climate response into the late 30s BCE. (Adapted from ref. 2.)

Coauthor Gill Plunkett of Queen's University Belfast conducted electron microprobe analyses on 35 tephra shards filtered from the melted ice cores to confirm the volcano's identity.

Earth has about 1500 potentially active volcanos, not counting the belt of spreading centers on the ocean floor. But their magmas have geochemical fingerprints that reflect each one's distinct location in Earth's crust. The geochemistry of the ice-laden shards and Okmok's contemporary basalt matched well enough for Plunkett to rule out several other possible volcanos.

The 2.5-year spread of the volcanic fallout coincides with air-temperature anomalies recorded in tree rings and cave stalagmites. Those climate proxies confirmed that the eruption's effects were pervasive in the Northern Hemisphere. The ring widths of temperature-sensitive trees in Scandinavia and Austria each revealed summertime cooling of more than 2 °C in 43 and 42 BCE. Radiocarbon dating of stalagmite layers in China's Shihua Cave showed a similarly pronounced temperature drop. And a rare frost ring found in bristlecone pine trees from the mountains of North America confirmed below-freezing temperatures there in early September of 43 BCE.

The researchers' simulations suggest that in some regions those cooling trends persisted into the early 30s BCE. Indeed,

the simulated temperature dropped by as much as 7 °C in parts of southern Europe and northern Africa. Rainfall patterns shifted as well, with summer precipitation levels some 50–120% above normal throughout southern Europe and autumn precipitation in some regions reaching 400% above normal.

The Nile fails to flood

The strong temperature gradient between the Northern and Southern Hemispheres could have shifted the intertropical convergence zone, the region where tropical trade winds meet. That shift, in turn, would have moved the East African monsoon rainfalls southward. The headwaters of the Blue Nile in the Ethiopian Highlands are the source of more than 85% of the summer floods that year after year delivered irrigation and silt to the lower reaches of the Nile in Egypt. With those highlands drier than normal, according to the simulations, little flooding likely occurred in 43 or 42 BCE.

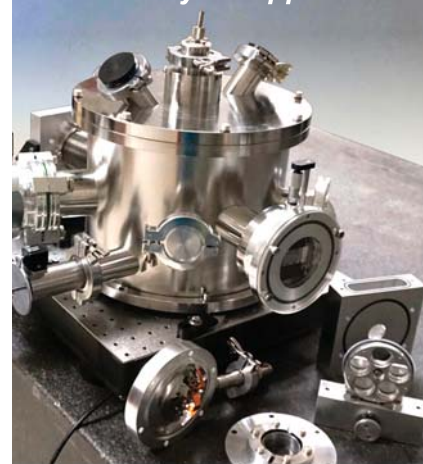
Greek historian Appian recorded the lack of flooding; he cited Cleopatra's reluctance to provide help to Rome due to Egypt's famine and pestilence. Although establishing direct causal linkages between crop failures and political decisions is difficult, McConnell and collaborators argue that Okmok's severe environmental impact likely contributed to social unrest. Rome's interest in Egypt as a

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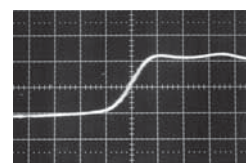
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breadbasket was magnified, no doubt, by the stress on a largely agrarian society, and Egypt's ability to withstand Rome was diminished by famine.² Egypt was absorbed into the Roman empire after Cleopatra's suicide in 30 BCE.

No one knows whether the birth of the Roman Empire would have happened without Okmok's influence. But the extreme climate the volcano produced could have hastened it.

Mark Wilson

References

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2. J. R. McConnell et al., *Proc. Natl. Acad. Sci. USA* **117**, 15443 (2020).
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Mechanically stressed phytoplankton light up

The bioluminescent intensity depends on the rate and amplitude of the micro-organism's deformation.

English naturalist Henry Baker in 1753 identified the source of the phosphorescent "burning of the seas," like the glow off the Taiwanese coast in figure 1, that had mesmerized nautical explorers for centuries. His prowess in microscopy led him to identify a unicellular "illuminous animal," *Noctiluca scintillans*, that emits light when disturbed, perhaps by a ship's bow or a rower's oar. Understanding of the biochemical processes that generate luminescence in *N. scintillans* and other bacteria or dinoflagellates in marine and freshwater environments progressed rapidly. But what mechanisms ultimately trigger bioluminescence? American zoologist E. Newton Harvey in 1920 commented, "That problem must be left to the physicist."

The complex series of chemical reactions through which bioluminescent marine organisms produce light begins when calcium ions enter the cell through channels in the cell wall. Biologists hypothesize that fluid flow outside the cell causes the cell's outer wall to stretch, which opens those ion channels. One puzzle, however, arises from experiments that use different methods of stimulating the cell to elicit a bioluminescent flash: How exactly do those methods, which involve both fluid and mechanical perturbation, lead to a distribution of forces over the cell body that cause the cell to stretch?

Maziyar Jalaal, Raymond Goldstein, and colleagues at the University of Cambridge now have taken a step toward solving that puzzle. In a series of experiments, the researchers pinpoint the mechanical stresses that deform the viscoelastic membrane of the dinoflagellate *Pyrocystis lunula* and trigger light emission.¹ Linking macroscopic flows to microscopic cellular processes could im-

FIGURE 1. SWARMS OF THE DINOFLAGELLATE *Noctiluca scintillans* emit blue light that illuminates the coastline in Taiwan. In historical accounts of nautical adventures, mariners marveled at the milky seas caused by bioluminescence. (Photo by RobbinChang.)



prove understanding of the ecology and evolution of bioluminescent organisms.

Poking and prodding

P. lunula has occupied the spotlight for bioluminescence studies for several decades. The large (130 μm long) organism, shown in figure 2, has a rigid cell wall, has limited mobility, has a density greater than that of seawater, and is transparent. Because of those properties, handlers can easily manipulate the dinoflagellate's position and observe its internal activity. Experiments by several research groups in the 1960s demonstrated that stirring or bubbling water around the creature could cause it to emit flashes of light from its central cytoplasmic area.² That work motivated quantitative investigations of how fluid motion triggers bioluminescence.

Subsequent studies using improved flow visualization tools have shed light on the process. In the early 2000s, Michael Latz and colleagues at the Scripps Institution of Oceanography estimated the magnitude of stress required to trigger light production in *P. lunula* under different methods of forcing. In one study, they poked a cell at a single point using an

atomic force microscope until the cell lit up.³ In other studies, they pumped water alongside the cell and found that emitted light intensity depends on the shear.⁴ And zoophysiology experiments performed by Latz's group have shown how much stress is required to trigger stretch-activated proteins in dinoflagellate bioluminescence signalling pathways.⁵

But there are discrepancies in bioluminescent responses to different forms of stimulation. Those variations are likely based on the unknown distribution of sensors in the cell that respond to mechanical stimulation and on how the sensors' activity is integrated into a whole-cell response.

Jalaal and his colleagues have now performed a quantitative study that could help resolve the discrepancies. Their experiments explored two ways of stimulating *P. lunula* cells to flash. In the first protocol, the researchers pumped a liquid through a microscopic pipette to create a shearing force along the surface of a cell (figure 3a and b). Tiny particles in the liquid traced the flow lines near the cell surface, revealing the velocity and the resulting distribution of forces on the cell. A high-speed camera recorded the