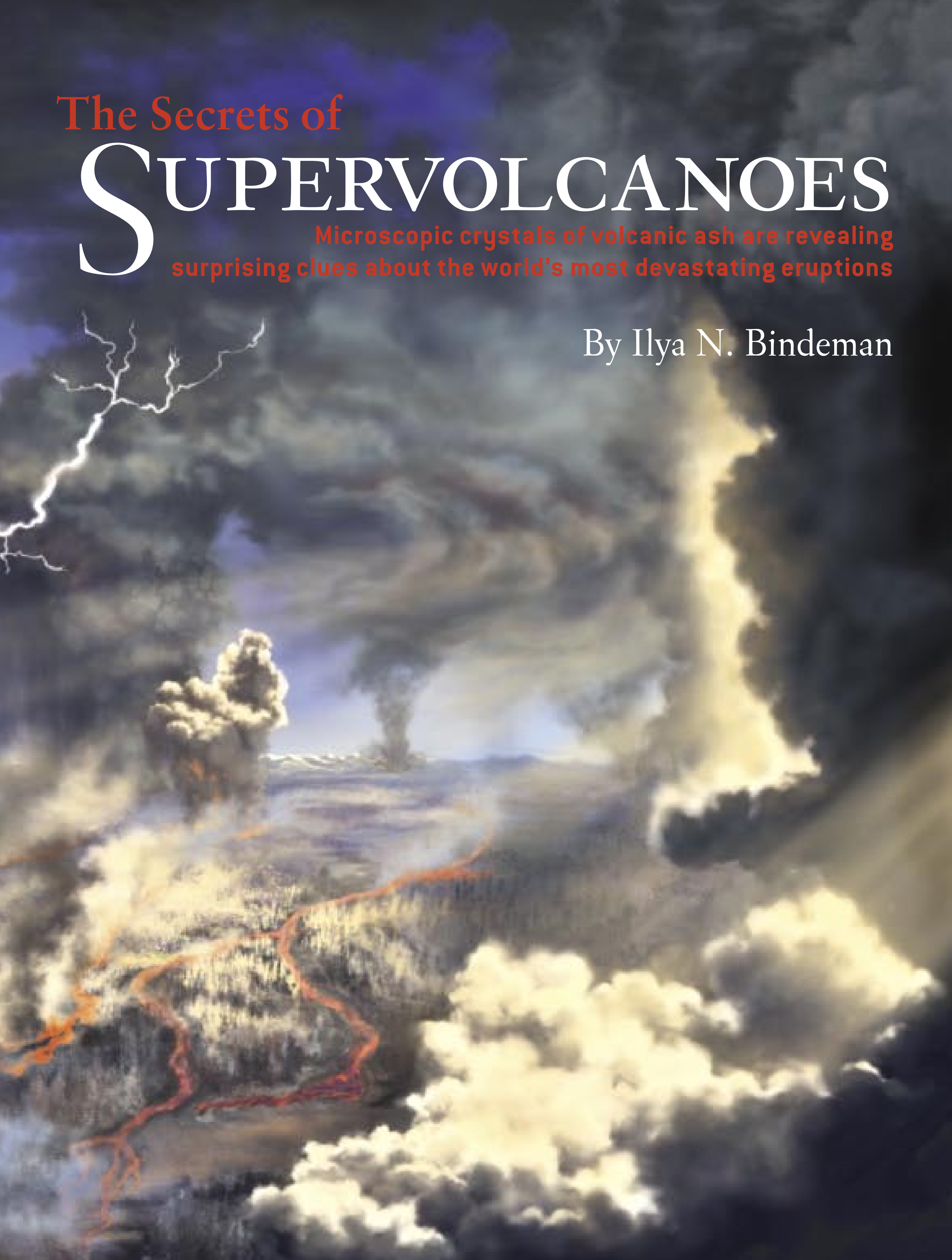
RING OF FIRE: Mountain-size vents exploding around the outer edge of an active supervolcano smother the landscape in clouds of hot gas and ash.

The Secrets of SUPERVOLCANOES

Microscopic crystals of volcanic ash are revealing surprising clues about the world's most devastating eruptions

By Ilya N. Bindeman



Lurking deep below the surface in California and Wyoming are two hibernating volcanoes of almost unimaginable fury. Were they to go critical, they would most likely bury the western half of the U.S. under ash many centimeter thick within a matter of hours. Between them, they have done so at least four times in the past two million years. Similar supervolcanoes smolder underneath Indonesia and New Zealand.

A supervolcano eruption packs the devastating force of a small asteroid colliding with the earth and occurs 10 times more often—making such an explosion one of the most dramatic natural catastrophes humanity should expect to undergo. Beyond causing immediate destruction from scalding ash flows, active supervolcanoes spew gases that severely disrupt global climate for years afterward.

Needless to say, researchers are eager to understand what causes these giants to erupt, how to predict when they might wreak havoc again, and exactly what challenges their aftermath might entail. Recent analysis of the microscopic crystals in ash deposits from old eruptions has pointed to some answers. These insights, along with improved technologies for monitoring potential disaster sites, are making scientists more confident that it will be possible to spot warning signs well before the next big one blows. Ongoing work hints, however, that supervolcano emissions could trigger alarming chemical reactions in the atmosphere, making the months following such an event more hazardous than previously suspected.

Almost all volcano experts agree that those of us living on the earth today are exceedingly unlikely to experience an active supervolcano. Catastrophic eruptions tend to occur only once every few hundred thousand years. Yet the sheer size and global effects of such episodes have commanded scientific attention since the 1950s.

Early Awe

ONE OF GEOLOGISTS' first discoveries was the existence of enormous circular valleys—some 30 to 60 kilometers across and several kilometers deep—that looked remarkably similar to the bowl-shaped calderas located atop many of the planet's most well-known volcanoes. Calderas typically form when the chamber of molten rock, or magma, lying under a volcanic vent empties out, causing the ground above it to collapse. Noting that these calderalike valleys sit close to some of the earth's largest deposits of volcanic rocks laid down during a single event, those early investigators realized they were seeing the remnants of volcanoes hundreds or even thousands of times larger than the familiar Mount St. Helens in Washington State. From the extreme scale of the calderas and the estimated volume of erupted material, researchers knew that the magma chambers below them had to be similarly monstrous.

Because the needed to create such massive magma chambers are rare, supervolcanoes themselves are also uncommon. In the past two million years, a minimum of 750 cubic kilometers of magma has exploded all at once in only four regions: Yellowstone National Park in Wyoming, Long Valley in California, Toba in Sumatra and Taupo in New Zealand. The search for similarly large eruptions continues in other areas of thick continental crust, including in western South America and far eastern Russia.

By the mid-1970s, investigations of past events revealed some ways that the chambers can form and become dangerous. Under the surface of Yellowstone, the North American tectonic plate is moving over a buoyant plume of warm, viscous rock rising through the mantle, the 2,900-kilometer-thick layer of the earth's interior that is sandwiched between the molten core and the relatively thin veneer of outer crust. Functioning like a colossal bunsen burner, this so-called hot spot has melted enough overlying crust to fuel catastrophic eruptions for the past 16 million years. In Toba, the source of the chamber is different. That region lies above a subduction zone, an area where one tectonic plate is slipping under another; the convergence produces widespread heating, mainly through partial melting of the mantle above the sinking plate.

No matter the heat source, pressure

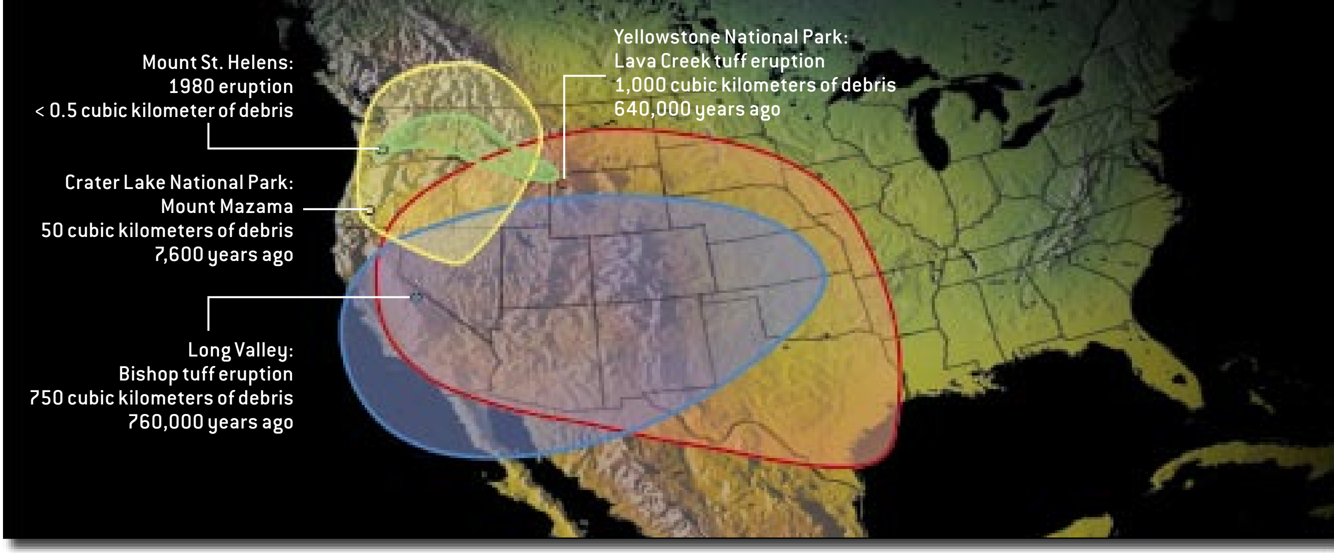
Overview/*Mighty Eruptions*

- **Recent analysis of the composition of tiny crystals inside ash deposits from prehistoric eruptions is overturning old beliefs about supervolcano behavior—and revealing new surprises about the aftermath.**
- **The inner workings of the magma chambers that fuel supervolcanoes can evolve in ways that influence the style of future eruptions.**
- **The volcanic winter that grips the planet in the wake of a supereruption is probably shorter than once suspected, although chemical reactions in the atmosphere may be much more dangerous.**

JULIA GREEN (*preceding pages*)

BIG, BIGGER, BIGGEST

Supervolcanoes (*red* and *blue*) spread ash much farther than even large versions of what most people think of as "normal" volcanoes (*yellow* and *green*), because the behemoths, with their massive magma chambers, eject so much more material.



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in the magma chambers builds over time as more magma collects under the enormous weight of overlying rock. A super-eruption occurs after the pressurized magma raises overlying crust enough to create vertical fractures that extend to the planet's surface. Magma surges upward along these new cracks one by one, eventually forming a ring of erupting vents. When the vents merge with one another, the massive cylinder of land inside the ring has nothing to support it. This "roof" of solid rock plunges down—either as a single piston or as piecemeal blocks—into the remaining magma below. Like the roof of a house falling down when the walls give way, this collapse forces additional lava and gas out violently around the edges of the ring [*see box on pages 40 and 41*].

Fingerprinting Eruptions

YET MYSTERIES REMAINED. Notably, as researchers soon realized, not every large magma chamber will necessarily erupt catastrophically. Yellowstone, for example, is home to three of the world's youngest supervolcano calderas—they formed 2.1 million, 1.3 million and 640,000 years ago, one nearly on top of the other—but in the gaps between these explosive events, the underlying chamber released similar volumes of magma slowly and quietly. Why magma sometimes oozes slowly to the surface is still uncertain.

A look at the composition of tiny crystals trapped inside erupted lava and ash at Yellowstone has suggested a partial answer, by providing new insight into how magma forms. For decades, geologists assumed that magma sits as a pool of liquefied rock for millions of years at a time and that each time some of it pours out onto the earth's surface, new liquid rises up from below to refill the chamber immediately. If that conception were correct, one would expect many more catastrophic, voluminous eruptions, because it is mechanically and thermally infeasible to keep monster magma bodies in the crust without emptying them frequently.

The old idea was based largely on so-called whole-rock analyses in which researchers would obtain a single set of chemical measurements for each fist-size piece of volcanic rock they collected. Those data provided important general patterns of magma evolution, but they were insufficient for determining the age of the ejected magma and the depth at which it formed.

Every chunk of rock is actually made up of thousands of tiny crystals, each with its own unique age, composition and history. So when technological advances made it possible in the late 1980s to analyze individual crystals with good precision, it was like being able to read individual chapters in a book rather than relying on the jacket blurb to explain the story. Investigators began to see that some crystals—and thus the magmas in which they originally formed—arose much earlier than others, for instance, and that some formed deep underground, whereas others formed near the earth's surface.

During the past 10 years, geochemists have been paying particular attention to an especially durable type of volcanic crystal called zircon. Knowing that zircons can withstand extreme changes

THE AUTHOR

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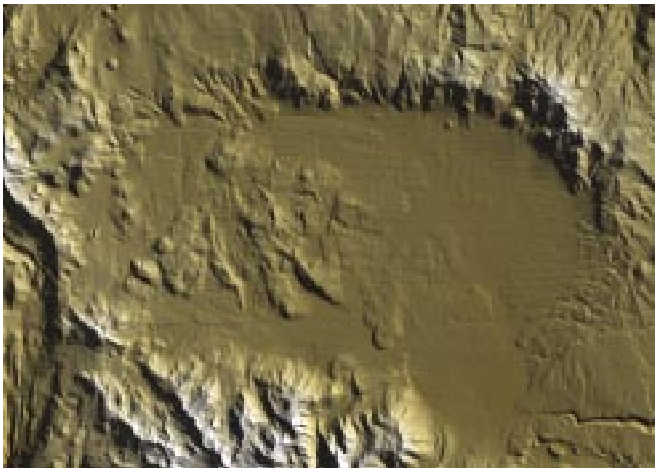
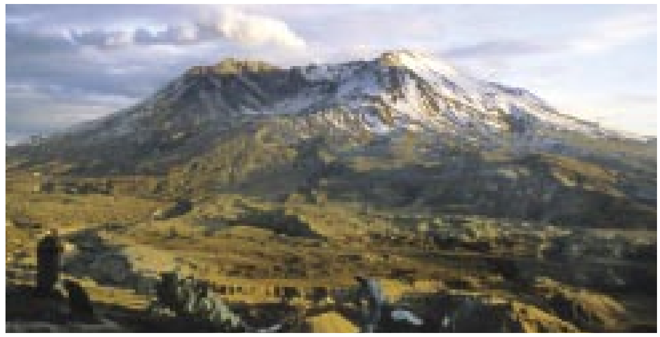




SLEEPING SUPERVOLCANOES, such as that in Long Valley in California (*left*), are not obvious cone-shaped peaks like Washington State's Mount St. Helens (*above*). Instead they are marked by enormous calderas, depressions in the earth's surface that formed when the land collapsed into the magma chambers that fed the most recent supereruptions.

COURTESY OF J. S. LACKEY *College of Wooster;* DATA FROM U.S. GEOLOGICAL SURVEY (*left*); TODD CULLINGS *National Park Service* (*right*)

in heat and pressure without compromising their original composition, a few researchers—among them John W. Valley of the University of Wisconsin–Madison—have been using them to study the early evolution of the earth's crust [see "A Cool Early Earth?" by John W. Valley; Scientific American, October 2005]. When I joined Valley's team as a postdoctoral fellow in 1998, we used Yellowstone zircons to trace the history of their parent magma—which in turn revealed important clues about how the volcano may behave in the future.

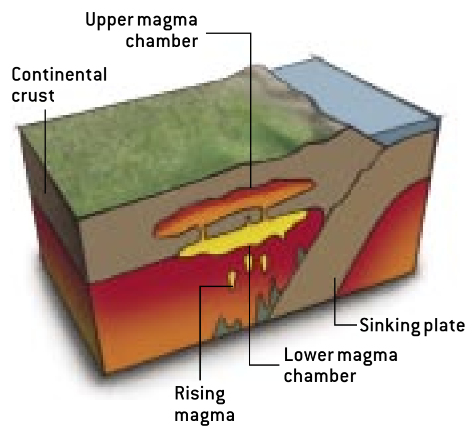
The first step was to measure the ratios of different forms of oxygen in zircons from the youngest Yellowstone supereruption—which after exploding 640,000 years ago gave rise to the Lava Creek tuff, a fossilized ash deposit 400 meters thick in some places—as well as younger deposits that were expelled during milder eruptions since then. When I finished my initial analyses, Valley and I were both surprised to see that oxygen composition of those zircons did not match that of deep, hot mantle, as would be expected if drained chambers always filled from below. Zircons born of mantle-derived magmas would have had a distinctive signature: as elements that are dissolved in magmas come together to form a zircon, that crystal takes on a notably high proportion of oxygen 18, a heavy isotope of oxygen that has 10 neutrons in its nucleus instead of the usual eight.

Valley and I saw immediately that the magma must have originated in rock once near the earth's surface. The zircons we studied were depleted in oxygen 18 relative to the mantle, and such depletion occurs only if the crystals formed from rocks that interacted with rain or snow. We thus suspected that the collapsed roof rock from one of the two oldest Yellowstone supereruptions must have melted to form the bulk of the magma that was ejected during the younger Lava Creek catastrophe and smaller eruptions since. This hypothesis gained strength when we learned that the ages of the zircons from post–Lava Creek eruptions span the entire two-million-year duration of Yellowstone volcanism. Such old zircons could exist in the youngest ash only if they originated in material that was ejected during the oldest eruptions and if that material later collapsed back into the magma chamber and remelted to help fuel the youngest eruptions.

Our findings mean that scientists can now expect to make certain predictions about how the Yellowstone supervolcano, and possibly those elsewhere, will behave in the future. If a new round of small, precursor eruptions begins in Yellowstone—and they usually do so weeks to hundreds of years before a catastrophic explosion—testing the oxygen fingerprint of those lavas and the ages of their zircons should reveal what type of magma is abundant in the chamber below. If the next eruption is depleted in oxygen 18, then it is most likely still being fed by stagnant remnants of the original magma, which by now is probably more of a thick crystal mush than an explosive liquid. On the other hand, if the new lava carries the fingerprint of fresh magma from the mantle and does not contain old zircons, then it very likely came from a large volume of new magma that has filled the chamber from below. Such findings would imply that a new cycle of volcanism had commenced—and that the newly engorged magma chamber had more potential to explode catastrophically.

SUPERCYCLES

The vast chambers of molten magma that feed supervolcanoes form above hot spots (buoyant plumes of rock rising from deep



1 Partial melting of the mantle rock above the sinking plate of oceanic crust produces magma that works its way up toward the base of the continental crust and pools there. This lower magma chamber acts as a colossal bunsen burner that eventually melts parts of the continental crust, which has a lower melting point than the rock below. Some magma also rises via small, vertical conduits between the two chambers.

Immediate Aftermath

TINY CRYSTALS and their isotopic signatures have also revealed surprises—good and bad—about the aftermath of supereruptions. One of the best-studied examples of supervolcano aftermath is the Bishop tuff, a volcanic layer tens to hundreds of meters thick that is exposed at the earth's surface as the Volcanic Tablelands in eastern California. This massive deposit represents what is left of the estimated 750 cubic kilometers of magma ejected during the formation of the Long Valley supervolcano caldera some 760,000 years ago.

For decades, many geologists assumed that a series of distinct eruptions over millions of years must have occurred to produce the extensive Bishop tuff. But careful studies of microscopic, magma-filled bubbles trapped inside tiny crystals of quartz tell a different story. The rate at which magma leaves a chamber depends primarily on two factors: the magma's viscosity, or ability to flow, and the pressure difference between the chamber and the earth's surface. Because the pressure inside a bubble matches that of the chamber where the magma formed, the bubble acts like a mini version of the chamber itself.

Aware of this correspondence, Alfred Anderson of the University of Chicago and his colleagues studied the size of the bubbles under a microscope to estimate how long it took the magma to leak out. Based on these and other experiments and field observations from the 1990s, geologists now think that the Bishop tuff—and probably most other supererupted debris—was expelled in a single event lasting a mere 10 to 100 hours.

Since that discovery, investigators have had to modify their reconstructions of supervolcano eruptions. Here is what they now generally expect from an event the scale of those that struck Long Valley and Yellowstone: Instead of a slow leak of red-hot lava as is seen creeping down the sides of Kilauea Volcano in Hawaii, these eruptions feature supersonic blasts of superheated, foamlike gas and ash that rise buoyantly all the way into the earth's stratosphere 50 kilometers high. As the land above the magma chamber collapses, immense gray clouds called pyroclastic flows burst out horizontally all around the caldera. These flows are an intermediate stage between lava and ash, so they move extremely rapidly—up to 500 kilometers an hour, some sources say; cars and even small airplanes would have no chance of outrunning them. These flows are also intensely hot—600 to 700 degrees Celsius—so they burn and bury everything for tens of kilometers in every direction.

As bad as the pyroclastic flows are, the ash injected into the atmosphere can have even more far-reaching consequences. For hundreds of kilometers around the eruption and for perhaps days or weeks, pale-gray ash would fall like clumps of snow. Within 200 kilometers of the caldera, most sunlight would

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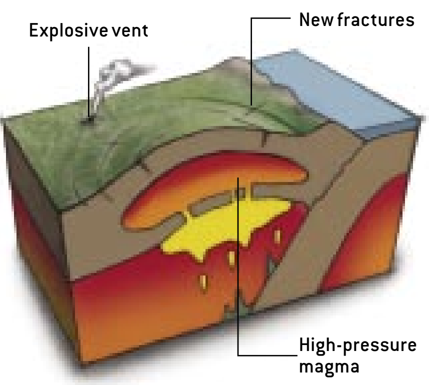
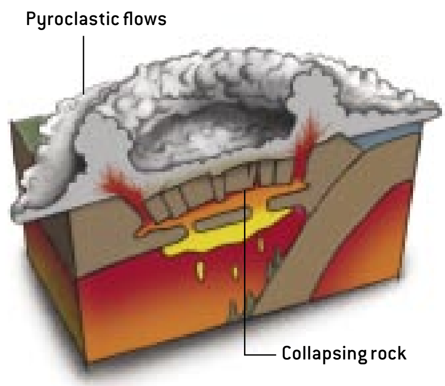
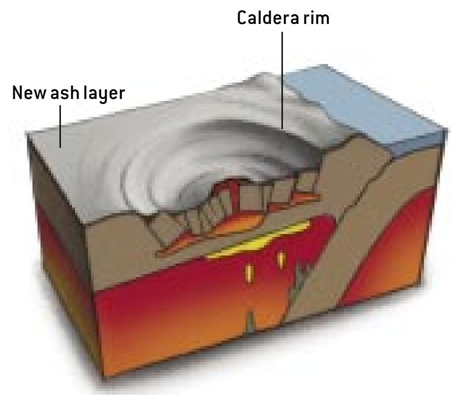
within the earth) and subduction zones (regions where one tectonic plate is slipping underneath another). In both cases, the giant volcanoes tend to follow an eruption cycle that is now far better understood than it once was. Here are the four basic steps, beginning with initial formation of the magma chamber, depicted for a subduction zone:



2 As the upper magma chamber grows, the land above bulges and cracks. The silica-rich composition and low temperature of this magma relative to those that form in the mantle make it particularly flow-resistant, so water and gas have trouble rising through it. Thus, when a plug of the sticky magma suddenly works its way to the surface along a vertical crack, the high-pressure material underneath tends to explode violently rather than oozing slowly.



3 The earth's strained surface eventually shatters as new explosive vents form a ring as wide across as the magma chamber. The fractured pieces of rock plunge down into the chamber, forcing additional magma up the outside edges of the ring. The sudden release of this magma transforms it into vast, scalding clouds of ash, gas and rock known as pyroclastic flows, which decimate the landscape for tens of kilometers in all directions.



4 After the eruption, a craterlike depression called a caldera sits above the partially drained magma chamber. Over time, the collapsed land inside the chamber begins to melt from the inside, creating a smaller batch of magma that, along with other forces, creates a dome in the caldera's center. Slow-moving lava may leak from this region many times before enough magma accumulates to fuel a new supereruption.

TWO EXTENSIVE DEPOSITS (*dark parallel layers*) are visible along a steep slope near Yucca Mountain in Nevada. They are the remains of scalding ash flows resulting from supereruptions that struck nearby between approximately 11.8 million and 12.8 million years ago.

MASSIVE WALL of gray rock in western Nebraska originated as a suffocating pile of ash left by a supereruption at an unknown site 28 million years ago. Elements in the ash suggest that such explosions can damage the ozone layer in the stratosphere.

be blocked out, so the sky at noon would look like that at dusk. Homes, people and animals would be buried, sometimes crushed. Even 300 kilometers away, the ash could be half a meter thick; mixed with rain, the weight would be plenty sufficient to collapse roofs. Less ash than that would knock out electrical power and relay stations. As little as a millimeter, which could well dust the ground halfway around the globe, would shut down airports and dramatically reduce agricultural production.

Only gradually would rain (made acidic by volcanic gases) wash away the thick blanket of ash. And because volcanic rock and ash float, it would clog major waterways. Transportation along big rivers could grind to a halt. Indeed, recent oil drilling in the Gulf of Mexico struck a surprisingly thick layer of supervolcanic debris near the Mississippi Delta—more than 1,000 miles from its source in Yellowstone. Only by floating down the Mississippi River and then sticking to sediment that sank to the ocean bottom could that amount of debris have accumulated from a volcano so far away.

The Long Haul

INVESTIGATORS HAVE reason to believe that other consequences, arising from the great volumes of problematic gas expelled into the upper atmosphere, would also transpire and could persist for many years. New work suggests that some of these outcomes may not be as bad as once feared but that others may be worse. Once again, looking at the composition of small by-products from past eruptions has been illuminating.

Of the varied gases that make up any volcanic eruption, sulfur dioxide (SO_2) causes the strongest effect on the environment; it reacts with oxygen and water to produce tiny droplets of sulfuric acid (H_2SO_4). These droplets are the main sun-blocking source of the dramatic climatic cooling that would grip the planet in the wake of a supereruption. Knowing that the planet's hydrological cycle takes months or years to fully wash away the acid droplets, many researchers made apocalyptic estimates of "volcanic winters" lasting decades, if not centuries. But in recent years other investigators have uncovered evidence that drastically reduces that calculation.

Almost always, traces of the sulfuric acid produced after large volcanic eruptions are trapped in snow and ice as the acid precipitates out of the contaminated atmosphere. In 1996 investigators studying ice cores from Greenland and Antarctica found the sulfuric acid peak that followed the supereruption of Toba 74,000 years ago. That eruption ejected 2,800 cubic kilometers of lava and ash and reduced average global temperatures

SKELETONS OF ANIMALS buried in ash from a catastrophic eruption in Idaho 12 million years ago are now exposed in northeastern Nebraska's Ashfall Fossil Beds State Historical Park. Most of the animals probably died slowly as the falling ash—which is essentially powdered glass—filled their lungs and abraded their teeth. Toxic chemicals in the ash may have poisoned their drinking water as well.

U.S. DEPARTMENT OF ENERGY (*top left*); ILYA N. BINDEMAN (*top right*); RICK OTTO *University of Nebraska State Museum* (*bottom*) by five to 15 degrees C. The consequences of such a chill were undoubtedly severe, but not for as long as once thought; sulfuric acid in the ice record disappeared after only six years; some researchers suggest that it vanished even earlier.

That volcanic winters are probably shorter than expected is the good news. But a new method developed in the past five years for studying the composition of the oxygen atoms in the volcanic acid rain is revealing an entirely different, alarming sign about the long-term effects of sulfur dioxide in the atmosphere. For SO_2 to become H_2SO_4, it must be oxidized—in other words, it must acquire two oxygen atoms from other compounds already existing in the atmosphere. Exactly which compounds play the key role is a hotly debated topic of current research, so when I started working with John M. Eiler as a staff scientist at the California Institute of Technology in 2003, he and I looked for evidence in my samples of ashes from the prehistoric Yellowstone and Long Valley eruptions.

We began our analyses with a focus on a particularly efficient oxidant, ozone. Ozone is a gas molecule made up of three oxygen atoms best known for shielding the earth from the sun's dangerous ultraviolet rays. Because of rare chemical transformations that certain gases undergo in the presence of that intense solar radiation, ozone is characterized by an anomaly in its so-called mass-independent oxygen isotope signature, which in simple terms can be thought of as an excess of oxygen 17.

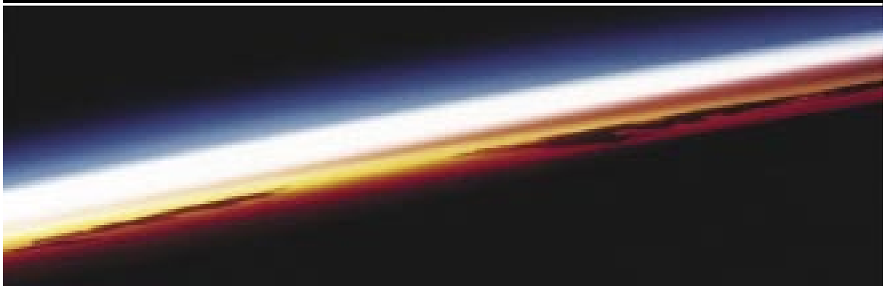
When ozone or any other oxygen-rich molecule in the stratosphere interacts with SO_2, it transfers its oxygen isotope signature to the resulting acid—that is, the oxygen 17 anomaly persists in the new acid. In 2003 geochemists at the University of California, San Diego, found the first evidence that this signature is also preserved in the oxygen atoms of the acid that later falls as rain and in the sulfate compounds that form as the acid rain reacts with ash on the ground.

The oxygen 17 excess and other chemical patterns that we found in sulfate from the Yellowstone and Long Valley ash samples thus implied that significant amounts of stratospheric ozone were used up in reactions with gas from the supereruptions in those regions. Other researchers studying the acid layers in Antarctica have demonstrated that those events, too, probably eroded stratospheric ozone. It begins to look as if supervolcano emissions eat holes in the ozone layer for an even longer period than they take to cool the climate.

This loss of protective ozone would be expected to result in an increased amount of dangerous ultraviolet radiation reaching the earth's surface and thus in a rise in genetic damage caused by rays. The magnitude and length of the potential ozone destruction are still being debated. Space observations have revealed a 3 to 8 percent depletion of the ozone layer following the 1991 eruption of Mount Pinatubo in the Philippines. But what would happen after an event 100 times larger? Simple arithmetic does not solve the problem, because the details of atmospheric oxidation reactions are extremely complex and not fully understood.

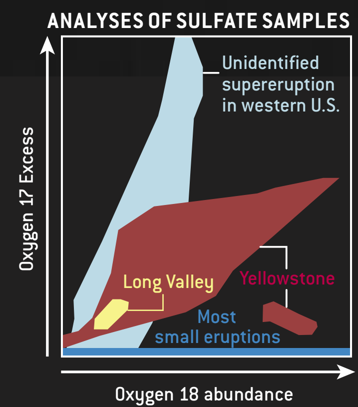
Scientific techniques for studying and monitoring volcanoes of all sizes are developing with all deliberate speed. But no matter how much we learn, we cannot prevent an eruption. And what can be said about the aftermath of the most catastrophic occurrences is still speculative at best. The good news, though, is that researchers now know enough about the sites of possible eruptions to predict with reasonable assurance that no such catastrophe will happen anytime soon. SA

UPPER ATMOSPHERE



Dangerous gases spewed from Mount Pinatubo in the Philippines in 1991 appeared as bright colors in satellite images of the earth's upper atmosphere (*background*). New evidence suggests that such gases emitted from future supervolcanoes may significant deplete the planet's protective ozone layer before falling as acid rain and mixing with ash to form sulfate.

Sulfate samples extracted from four supervolcano deposits carry an unusual excess of oxygen 17 (*warm colors in graph represent collections of measurements*); such abundance occurs only in compounds that have acquired the rare atoms during reactions with special gases in the earth's upper atmosphere, very likely ozone. Materials that originate on the ground, including the products of most small eruptions, show no such anomaly (*blue*).



MORE TO EXPLORE

Low-$\delta^{18}O$ Rhyolites from Yellowstone: Magmatic Evolution Based on Analyses of Zircon and Individual Phenocrysts. Ilya N. Bindeman and John W. Valley in *Journal of Petrology*, Vol. 42, pages 1491–1517; 2001.

Sulfate Oxygen-17 Anomaly in an Oligocene Ash Bed in Mid-North America: Was It the Dry Fogs? Bao Huiming, Mark H. Thiemens, David B. Loope and Xun-Lai Yuan in *Geophysical Research Letters*, Vol. 30, pages 1843–1848; 2003.

Rare Sulfur and Triple-Oxygen Isotope Geochemistry of Volcanogenic Sulfate Aerosols. Ilya N. Bindeman, John M. Eiler, Boswell Wing and James Farquhar in *Earth and Planetary Science Letters* (in preparation, 2006).

NASA JOHNSON SPACE CENTER (*atmosphere spectrum*); GRAPH; SOURCE: ILYA N. BINDEMAN