SUPERVOLCANOES AND THEIR EXPLOSIVE SUPERERUPTIONS

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Earth's largest volcanic eruptions were an order of magnitude larger than any witnessed by humans since the advent of civilization. These "supereruptions" have played an important role in our species' past and they pose a serious future threat. In this issue of *Elements*, we consider key issues that reflect both the scientific and social importance of these awe-inspiring phenomena: the products and processes of the eruptions themselves, the nature and evolution of the shallow magma chambers that feed them, the monitoring of active supervolcano systems, and the potential consequences to humans of future supereruptions.

KEYWORDS: supervolcano, supereruption, explosive volcanism, rhyolite, magma chamber, caldera

SUPERVOLCANO!

In the year 2000, a BBC documentary introduced to the general public—and to the scientific community—the term "supervolcano." The documentary addressed the consequences of explosive "supereruptions" (a term that had recently entered the scientific lexicon) and pointed to the fact that three such eruptions had occurred in the geologically recent past at a popular tourist destination in the middle of North America: Yellowstone National Park. A BBC/Discovery Channel dramatization that followed in 2005 portrayed a near-future supereruption at Yellowstone, and captured the imagination of the public by showing the dramatic processes and potential consequences of a gigantic eruption. This docudrama presented plausible eruption processes, the people who study them, and the responses of officials and the public. Other works of popular science and science fiction have continued to build on the supervolcano concept, some serious and informative and others decidedly not (Lowenstern 2005). For the most part, volcano scientists have grudgingly welcomed this publicity (and the new term "supervolcano"), hoping to use it as a pathway to greater awareness of how volcanoes work and the threats they present to society—and of the excitement and importance of volcano research. In this issue, a group of experts summarize what we know, and don't know, about what is arguably the most catastrophic of all natural processes on Earth.

WHAT MAKES A VOLCANO SUPER?

Although the term "supervolcano" was not formally defined when introduced by the BBC, it arose from recognition that Earth's volcanoes occasionally produce gigantic, explosive eruptions, far larger than any that have been observed during recorded human history. Evidence for such eruptions was first described by van Bemmelen (1949), who recognized the volcanic origin of thick ash deposits around Lake Toba, on the island of Sumatra (Indonesia). It wasn't until 1992 (Rampino and Self 1992), however, that the term "supereruption" was applied. Essentially undefined until recently, supereruptions are now considered to be those that eject magma (molten, or partly molten, rock) with a mass greater than 10^{15} kg, equivalent to a volume greater than 450 km^3 (Sparks et al. 2005; Self 2006). Although ancient eruptions of lava (flowing rather than explosively fragmented magma) have yielded similar volumes with impressive consequences, the term supereruption has been applied almost exclusively (as it is here) to relatively short-term, explosive events (e.g. Francis and Oppenheimer 2004; Mason et al. 2004). Explosive eruptions of this magnitude have a volcanic explosivity index (VEI) of 8 or above and produce fragmental deposits with volumes of 1000 km^3 or greater (SEE BOX 1). In this issue, we define "supervolcano" as a volcano that has produced at least one explosive supereruption.

SUPERVOLCANOES AND SUPERERUPTIONS

How do supervolcanoes differ from other volcanoes that produce explosive eruptions? Their eruptions are bigger (FIGS. 1, 2), and hence their destructive capacity is far greater. The size distinction, however, is arbitrary—1000 km^3 of fragmental material is a convenient dividing line. The appearance of the volcano itself after eruption is also distinctive: it doesn't conform to the common image of a volcano as a lofty, symmetrical, conical structure. Rather than being giant versions of the classic cone, supervolcanoes are calderas, which are subcircular, *negative* topographic features (FIG. 3 and cover illustration). As supervolcanoes rapidly emit material during eruption, whatever surface structure existed before the eruption collapses into the evacuating chamber to form the characteristic caldera. The caldera size correlates with eruption size (Smith 1979), and supervolcano calderas are appropriately gigantic: some are nearly 100 km across.

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Box 1 Sizes of Eruptions

VOLUME

The amount of material in an eruption can be described in terms of mass or volume of material. *Volume*, often of greater interest, can be described in the following ways:

- **dense rock equivalent (DRE)** – estimate of the pre-vesiculation, pre-eruption volume of erupted magma (densities range from ~2.2–2.8 × 10^3 kg m^{-3}). Note that this volume is somewhat greater than that of equivalent crystallized (glass-free) rocks, which have densities ranging from ~2.6 to 3.0 × 10^3 kg m^{-3}.
- **the volume of pyroclastic material** (for explosive eruptions) – this vesiculated, often loosely packed material is much less dense than the magma (its density is highly variable but averages roughly 10^3 kg m^{-3})

The volume of pyroclastic material deposited at Earth's surface, commonly used to characterize explosive eruptions, is thus two to three times greater than that of the magma necessary to form the material.

MAGNITUDE

The magnitude of an eruption has been defined by the mass of erupted material (lava or pyroclastic), as follows (Pyle 2000):

$$\log_{10}(\text{erupted mass in kg})-7$$

This calculation yields a value similar to the VEI (see following table)

VOLCANIC EXPLOSIVITY INDEX (VEI)

VEI	Plume height (km)	Ejected volume (km^3)	Frequency on Earth	Example
0	<0.1	>~10^{-6}	daily	Kilauea, Hawai'i
1	0.1–1	>~10^{-5}	daily	Stromboli, Italy
2	1–5	>~10^{-3}	weekly	Galeras, Colombia, 1993
3	3–15	>~10^{-2}	yearly	Nevado del Ruiz, Colombia, 1985
4	10–25	>~10^{-1}	~every 10 y	Soufrière Hills, West Indies, 1995
5	>25	>~1	~every 50 y	Mount St. Helens, USA, 1980
6	>25	>~10	~every 100 y	Pinatubo, Philippines, 1991
7	>25	>~100	~every 1000 y	Tambora, Indonesia, 1815
8	**>25**	**>~1000**	**~every 10,000–100,000 y**	***Supereruptions:* Toba, 74 ka**

Modified after Newhall and Self (1982)

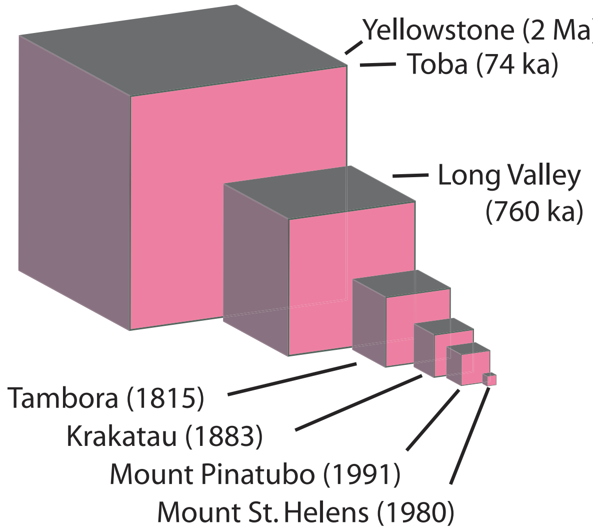

Figure 1 Relative volumes of pyroclastic material erupted at four young volcanoes, compared with volumes of three supereruptions discussed in this issue. The two most recent eruptions shown, from Mount St. Helens and Mount Pinatubo, each caused extensive damage and received intense media interest. Ejected volumes, however, were only about 1/10,000 (St. Helens) and 1/500 (Pinatubo) of the volumes associated with either the 74 ka Toba or the 2 Ma Yellowstone supereruptions. Even the 1883 Krakatau eruption, which accounted for over 35,000 deaths, was smaller than the Toba and Yellowstone eruptions by two orders of magnitude. The 1815 Tambora eruption, which had an ejected volume less than 5% of those of Toba or Yellowstone and was distinctly less than "super," affected global climate and was responsible for over 50,000 deaths.

Supereruptions require a very large volume of magma with strong explosive potential. Explosive potential results from a high content of volatile constituents (mostly H_2O) that can form gas bubbles, combined with high viscosity to inhibit escape of the bubbles from the magma; it is the bursting of these trapped bubbles that drives an explosion (see Zhang and Xu 2008 this issue, regarding the physics of bubble growth from a lighter perspective). Supervolcano magmas have high water contents[1], and their silica-rich dacitic and rhyolitic magmas are highly viscous, not unlike the magmas of many other volcanoes (Fig. 4). What sets them apart, however, is simply the enormous amount of eruptible magma that accumulates in shallow chambers, which are in turn only a minor component of even larger magma reservoirs (see Bachmann and Bergantz 2008 this issue; Reid 2008 this issue). As suggested by all the papers in this issue, deeper-level, hotter, less silicic basaltic and andesitic magmas, though rarely evident in the products of the eruptions themselves, provide the thermal energy that drives the supervolcano system and contribute at least some of their mass to the silicic erupting magmas (Lowenstern and Hurwitz 2008 this issue; Fig. 5). Key to growth of large-volume, silicic magma reservoirs seems to be thick, relatively low-density crust of the type found in continents and old island arcs. Such crust inhibits buoyant ascent of dense, low-silica magma, thereby promoting reservoir growth and facilitating differentiation processes (see Bachmann and Bergantz 2008).

Explosive eruptions, whether super or "normal" size, may be triggered by any perturbation that leads either to extensive bubble growth or to failure and fracturing of the rocky container that surrounds and overlies the magma chamber, producing conduits to the surface. Expansion of magma—either through bubble growth or through addition of new magma—increases pressure, and if this overpressure exceeds the strength of the surrounding rock, the container will fail and magma will inject into the resulting fractures, potentially reaching the surface and erupting. This results in rapid decrease of pressure in the magma, causing bubble growth and commonly explosion. Possible triggers for explosive eruptions include (1) gas saturation in crystallizing magma (volatiles are partitioned into remaining liquid); (2) replenishment by fresh drafts of magma; (3) escape of gas-rich, crystal-poor magma from crystal mush and storage of this low-density, low-strength magma beneath the chamber roof; and (4) earthquakes and faulting, which may fracture chamber walls or destabilize a stagnant mush (e.g. Anderson 1976; Pallister et al. 1992; Eichelberger and Izbekov 2000; Bachmann and Bergantz 2003, 2008; Walter and Amelung 2007; Davis et al. 2007). A central question in understanding supervolcanoes is why their chambers *escape* triggering perturbations for long enough to accumulate the gigantic quantities of magma that eventually erupt.

[1] It is noteworthy that, despite the availability of abundant magmatic water as well as enormous amounts of heat, supervolcano systems are not unusually productive in terms of hydrothermal mineral deposits (John 2008 this issue).

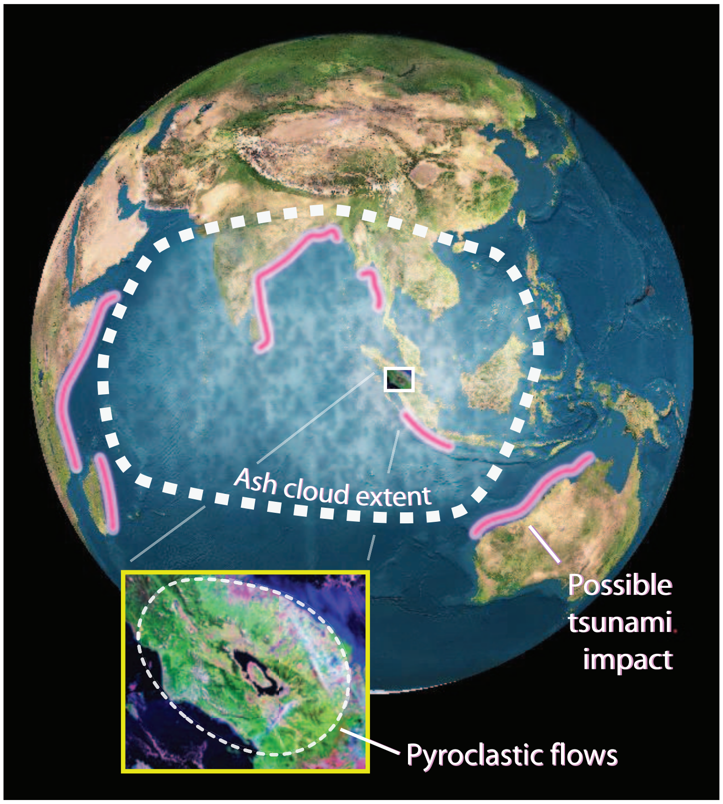

FIGURE 2 Likely extent of ash cloud (thick dashed line) and of pyroclastic flows (inset Landsat image; thin dashed line) produced during the 74 ka supereruption from the Toba caldera, Sumatra. Lake Toba (visible in center of inset) fills the 100 km long by 40 km wide depression formed during caldera collapse. Also shown is the possible impact zone of a tsunami generated by Toba pyroclastic flows entering the sea 150–200 kilometers from the source vents, but note that sea level was about 60 m lower at 74 ka than now. Figure based on original illustration by S. Self and S. Blake.

Explosive eruptions tear apart the frothy, gas-rich magma, producing fine pyroclasts (hot fragments) composed of solidified melt (i.e. glass) and crystals. Copious quantities of hot, buoyant, pyroclast-bearing gas and the enormous Plinian eruption column that they form are the signatures of large explosive eruptions (Wilson 2008 this issue; Self and Blake 2008 this issue). The mixture of gas and pyroclasts leaves the volcanic vent and enters the atmosphere at near-magmatic temperatures. It immediately entrains and heats air, rises buoyantly to heights that may exceed 35 km, and then spreads laterally as a giant "umbrella" cloud in the stratosphere. The fragments return to Earth in two very different ways (Wilson 2008). Some fall gently like snow from the eruption column and blanket the land surface (forming fall deposits). More energetic and immediately devastating, however, are the hot and highly fluid pyroclastic flows that can move across the ground surface at speeds up to hundreds of kilometers per hour, covering areas of many thousands of square kilometers with ash-flow deposits.

IMMEDIACY AND MAGNITUDE OF THE THREAT?

The consequences of future supereruptions, which were portrayed in dramatic fashion in the movie *Supervolcano*, are discussed by Self and Blake (2008). In short, supereruptions are "the ultimate geologic hazard," in terms of the immediate and devastating impact of eruption products on our social infrastructure, and with regard to the longer-term climatic effects that will arise from loading the stratosphere with sulfur-rich gases. There is, however, a silver lining of sorts: the global frequency of volcanic eruptions correlates inversely with eruption size. Supereruptions, then, occur extremely infrequently (from a human perspective), on average one about every 100,000 years (Decker 1990; Mason et al. 2004). Moreover, the youngest well-documented supereruption, Oruanui in the Taupo Volcanic Zone of New Zealand, occurred only (!) 26,000 years ago (26 ka) (Wilson 2008). This event was preceded by Toba's cataclysmic eruption roughly 50,000 years earlier, and several lesser-known, post-100 ka candidates for supereruption status are under study.

FIGURE 3 Views of (**A**) the Long Valley caldera, USA, which collapsed during the 760 ka supereruption that formed the Bishop Tuff (photo by Colin Wilson), and (**B**) Cascada de Basaseachic, a waterfall over 300 m high cutting through a single, thick ~28 Ma ignimbrite typical of those elsewhere in the Sierra Madre Occidental of western Mexico. Because of good exposure, ancient supereruption products—like those in Mexico (McDowell and Clabaugh 1979) and elsewhere in western North America (e.g. Lipman et al. 1972)—have provided a valuable framework to better understand modern supervolcano systems.

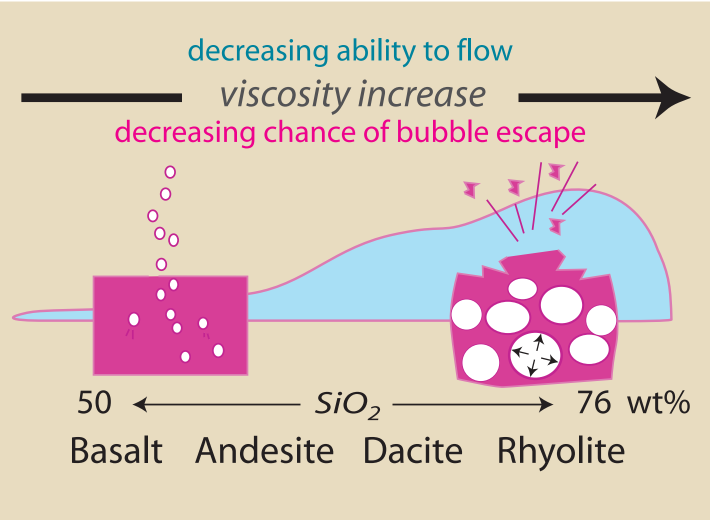

FIGURE 4 Classification of volcanic magmas (and their solidified rock equivalents), corresponding silica (SiO_2) contents, and associated changes in physical properties. The explosivity of supereruption magmas (indicated by red container on right) results from high gas contents and silica-rich compositions: their high viscosity inhibits escape of expanding bubbles, leading to pressure build-up. Gas-poor magmas, in contrast, may erupt passively as lava (blue), with viscosity playing a role here, too: viscous, silica-rich lavas do not travel as easily or as far as their silica-poor counterparts, forming thick flows or domes. Compositionally equivalent intrusive rocks include granite (rhyolite), granodiorite (dacite), diorite and tonalite (andesite), and gabbro (basalt).

Does this average recurrence interval, together with relatively recent events, mean that we are not due for another supereruption and are therefore off the hook? Unfortunately not: although the statistical probability of another supereruption in any given year, or century, is very small, the estimated average recurrence rate is just that—an average. There is no reason to believe that, globally, supereruptions should occur regularly, and therefore there is no predictive value in knowing when the last supereruption occurred. It is possible that processes at individual supervolcanoes might result in some regularity in eruption interval, but existing data are ambiguous, and in any case a large fraction of supereruptions are first-time events (Reid 2008; Wilson 2008). We can take comfort in their rarity—but the probability of a supereruption in our lifetime is not zero.

SUPERVOLCANOES: QUESTIONS AND THE FUTURE

Supereruptions are fascinating, frightening phenomena. Many critical questions remain, both scientific and related to minimizing the associated risks to humanity. Why, for example, are these eruptions so large, and what distinguishes the superscale process from the smaller, more familiar eruptions that have been described and directly studied (Wilson 2008)? How are these eruptions triggered, and, equally important, why do they fail to trigger before their chambers achieve gargantuan proportions (Bachmann and Bergantz 2008; Reid 2008)? How can we detect and assess the threat of a slumbering magma reservoir that has achieved supervolcano dimensions (Lowenstern et al. 2006)? And finally, how might mankind develop a strategy for coping with a supereruption and its aftermath (Self and Blake 2008)? This issue highlights both the great strides that are currently being made in understanding these systems and their impacts and what must be done to solve the critical puzzles that remain.

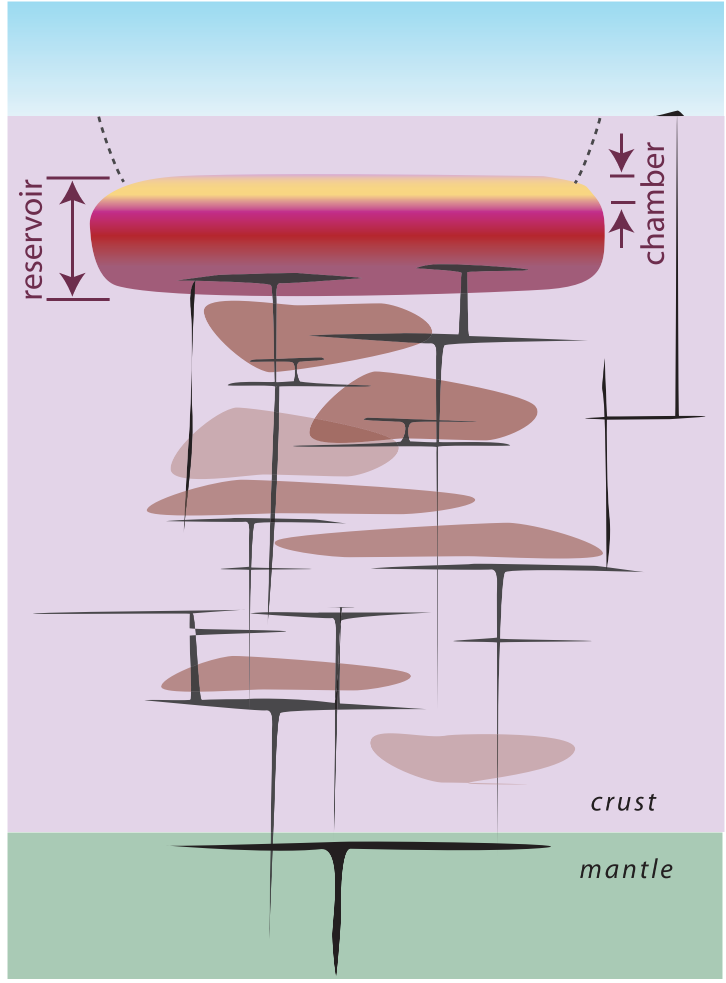

FIGURE 5 Simplified cross-sectional view of a large-volume magma reservoir in the upper crust and the underlying magma system that feeds it. Only the magma in the topmost part of the reservoir (termed a "chamber") is likely to erupt. Beneath this chamber, the reservoir comprises crystal-rich zones and less-differentiated (lower silica content) magma bodies. Mantle-derived basaltic melts (black) are a critical part of this assemblage, providing the heat to maintain the partially molten state of the crustal magma reservoirs. Due to density contrasts, these basaltic melts cannot penetrate the shallow, partially molten reservoir, although they can reach Earth's surface and erupt outside the perimeter of the supervolcano system as shown. Dashed lines indicate where the "lid" of the magma chamber may fail, leading to caldera collapse and a supereruption.

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GLOSSARY

Caldera – A large depression formed by collapse of the roof rock above an erupting (evacuating) magma chamber

Crystal mush – A mixture of crystals and silicate liquid whose mobility, and hence eruptibility, is inhibited by a high fraction of solid particles

Devitrification – Conversion of glass, which lacks a continuous internal structure, to structured crystalline solids. Glass, initially the dominant material in the deposits of supereruptions, is metastable and converts into crystals at a highly variable rate.

Magma – Material with a high enough proportion of silicate liquid (typically >40–50%) to be mobile; usually contains crystals and may contain gas bubbles (which are critical to supereruptions!)

Magma chamber – A discrete region beneath Earth's surface in which mobile (and eruptible) magma is stored

Magma reservoir – A magma reservoir encompasses all of the liquid-bearing regions within a magmatic system, including crystal-rich, uneruptible zones; it may include one or more chambers (or none).

Plinian eruption – A large, violent, highly explosive eruption that sends a column of pyroclastic ejecta into the stratosphere. Named for Pliny the Elder, the Roman sage who died in the 79 AD Plinian eruption of Vesuvius, and for his nephew Pliny the Younger, who wrote an insightful and widely read account of the eruption. The supereruptions that are the subject of this issue are classified as Plinian.

Pyroclast – A fragment ejected during an explosive eruption

Pyroclastic – Adjective related to explosive eruptions and their products, as in pyroclastic fall or flow deposits

Pyroclastic flow, ash flow, ignimbrite – A *pyroclastic flow* is a hot, fluidized mass of fragmental material from an explosive eruption that moves across the ground surface at high speed. Pyroclastic flows are dominated by fine (<2 mm) particles of volcanic ash and so are sometimes called *ash flows*. An *ignimbrite* (or *ash-flow tuff*) is the deposit formed by a pyroclastic flow. Supereruptions typically form very large ignimbrites that are in part *welded* (glassy ash particles fused together within thick flows that retain heat for long periods).

Supereruption – An eruption that expels more than 10^{15} kg (~450 km^3) of magma; in this issue, and in common usage, the term refers to explosive eruptions that invariably involve silicic magma. 450 km^3 of unvesiculated magma is equivalent to approximately 1000 km^3 of low-density eruption products. Such eruptions invariably form large calderas.

Supervolcano – A volcano that produces one or more supereruptions.

Tuff – A consolidated deposit of generally fine-grained pyroclastic material, formed either from a pyroclastic flow or from hot fallout from an eruption cloud

Time (units) – In this issue, *ages* are given in Ma and ka (millions of years ago, thousands of years ago, respectively); *durations* of episodes are in My and ky (periods of millions of years and thousands of years, respectively).

Volatile constituents, gas – *Volatile constituents* are chemical species that tend to enter into a gas phase at low pressure (e.g. H_2O, CO_2; S, F, Cl species). *Gas* is strictly a low-density, highly compressible, non-condensed phase; as pressure (P) and temperature (T) increase, gas and liquid phases of the same composition become indistinguishable and merge into supercritical fluid, but for simplicity in this issue we refer to both low- and high-P fluids that are made up mostly of volatile constituents as "gas."

(Potentially) Frequently Asked Questions About Supervolcanoes and Supereruptions

(RESPONSES BY CALVIN MILLER, DAVE WARK, STEVE SELF, STEVE BLAKE, AND DAVE JOHN)

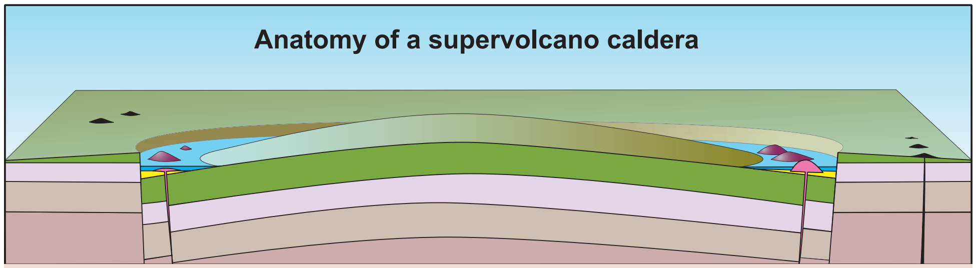
1 How many supervolcanoes/supereruptions are known? Are there many more than are mentioned in the papers in this issue?

There have been far more supereruptions than are mentioned in this issue. Those discussed here are the most famous, best documented, and best known to the authors. A minimum total number cited by Mason et al. (2004) is 47. Many other candidates with less well-documented deposit volumes are known, many others are as yet unrecognized, and many more, we can assume, have had their record obliterated. Natural processes cover the tracks of supereruptions. Their erupted products are spread over enormous areas, in some cases including the seafloor and distant continents, and they are easily eroded or turned into soil. Much of their deposits may be retained within the caldera, where their great thickness is easily underestimated. Thus, the enormous erupted volumes—and therefore their "super" character—may not be recognized.

2 What are their ages? Are they all "young" geologically speaking? Which is the oldest known? Will we start recognizing them in older and older rocks?

Among the 47 eruptions listed in the Mason et al. compilation, only four are older than 50 Ma and three older than 100 Ma (three gigantic, altered ash-fall tuff deposits in the eastern United States and Europe, all about 454 Ma). Ages cited by Mason et al. (2004) range from 26 ka (Oruanui) to these Ordovician tuffs. Candidates dating back to almost 2 billion years are known, but their volumes or the nature of the eruptions remain open to question (e.g. Hildebrand 1984; Allen et al. 2003). The relative paucity of ancient supereruptions is certainly due to a lack of preservation. The older the deposit, the likelier it is to be buried or eroded. Furthermore, volcanologists typically focus on younger deposits because of their closer link with active volcanism and because of their better preservation. It is likely that the products of supereruptions will be recognized in older and older rocks, but because of their vulnerability they will always be underrepresented in the ancient rock record.

Given the current estimates of frequency of supereruptions (on the order of 10 per million years), it is nonetheless reasonable to infer that there have been many thousands—probably tens of thousands—over the course of Earth history.



This cartoon illustrates the main components of a resurgent caldera like those that form during explosive supereruptions from large-volume, crustal magma systems (see Fig. 5 on page 14). *Precaldera rocks* are shown as three layers (shaded lavender) that are offset along faults (*ring fractures*) defining the caldera margins. Overlying the precaldera rocks are pyroclastic deposits (green) laid down during the supereruption that accompanied caldera collapse. These include (a) thick *intracaldera* deposits (reaching thicknesses of 1000s of meters in some instances) that accumulated as the caldera was forming, and (b) thinner *outflow* deposits, which blanket the surrounding countryside. Thinning with increasing distance from the source, the outflow deposits can be tens to hundreds of meters thick near the caldera margin.

In this example—as in most large calderas—a *resurgent dome* formed sometime after collapse as the caldera floor was pushed upward by rising residual, unerupted magma in the underlying chamber. Surrounding the resurgent dome, and separating it from the caldera margins, or *walls*, is a lowland known as the *moat*. The moat often fills at least partially with water (leaving the resurgent dome exposed as an island), and traps sediments eroding from adjoining highlands as well as ash erupted from nearby volcanoes. The lowermost (oldest) *moat sediments* (yellow) often tilt radially outward (away from the resurgent dome), indicating deposition before dome uplift had ceased.

The *ring fractures* bounding the collapsed region of the caldera are zones of weakness through which lavas are often extruded. *Ring-fracture lavas* (red in figure) are typically composed of viscous, highly differentiated melt (rhyolite) from the same magma chamber that fed the earlier supereruption. Flowing only short distances, these lavas pile up, forming steep-sided, dome-shaped hills. Also shown are the less-differentiated *basalt lavas* (in black) often associated with (and at depth, critical to the survival of) supervolcano systems, but which only erupt some distance from the caldera margin, where they form small domes, flows, and cinder cones.

3 You mention several post 100 ka candidates. What are they?

In addition to Oruanui and Toba, possible candidates include the Los Chocoyos eruption from Lake Atitlan caldera, Guatemala (84 ka), and several in Japan [from Aso (90 ka), Kikai-Akahoya (7 ka), and Aira (~25 ka) calderas—Blake and Self 2007]. The eruption of the Campanian Tuff from Campi Flegrei (39 ka) is of particular interest because it demonstrates the threat of a great eruption to a nearby city (Naples, Italy), but it falls short of the criteria for a true supereruption (Marianelli et al. 2006).

4 What is the tectonic setting of supervolcanoes?

One common characteristic is that all known supereruptions occurred within thick, continental-type crust. As suggested in the papers in this issue, input of hot, mantle-derived basaltic magma into this thick, more-silicic crust appears to be required. Supereruptions occur in subduction zone settings, like Japan, Indonesia, New Zealand, and the Andes, and in plate interiors, both at hot spots like Yellowstone and in zones of extension like Long Valley, California. In fact, even where they occur in broadly convergent regions—subduction zones—supereruptions appear to be commonly and perhaps invariably associated with local extension.

5 Do calderas always indicate supereruptions?

No. While all well-known supervolcanoes have calderas, this does not mean that calderas necessarily indicate a supereruption. In fact, calderas range widely in size, and a great majority formed during more modest eruptions (well-known examples: Crater Lake, Oregon, United States; Laacher See, Germany; Santorini, Greece).

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