

GEOPHYSICS

Probing the underbelly of a supervolcano

Seismic imaging of Yellowstone provides a better understanding of large volcanic systems

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Human civilization remains vulnerable to volcanic eruptions. For example, the moderate eruption of Eyjafjallajökull volcano in Iceland in 2010 was responsible for the total disruption of air traffic in Europe for several days. The largest eruptions known in human history (such as that of Mount Tambora, Indonesia, in 1815) ejected enormous volumes of volcanic material, ranging from 25 to 150 km³, and caused serious worldwide climate changes, leading to huge loss of life even in countries located far from volcanoes. Even greater eruptions that have spewed out more than 1000 km³ of ash and volcanic gases into the atmosphere have occurred in the recent geological past (1). The ash of such supereruptions covered

huge areas, polluted the atmosphere, and caused notable climate changes throughout the world with marked effects on the biosphere (2). Evaluating whether such strong volcanic eruptions will occur in the future requires an understanding of the geological processes and physical mechanisms that led to them. Such an understanding can be gained from studies of the volcanic systems known to produce these supereruptions in the near past. On page 773 of this issue, Huang *et al.* (3) present a new seismic tomography study of the crust and the uppermost mantle beneath the Yellowstone volcanic field that provides insights into the functioning of supervolcanoes.

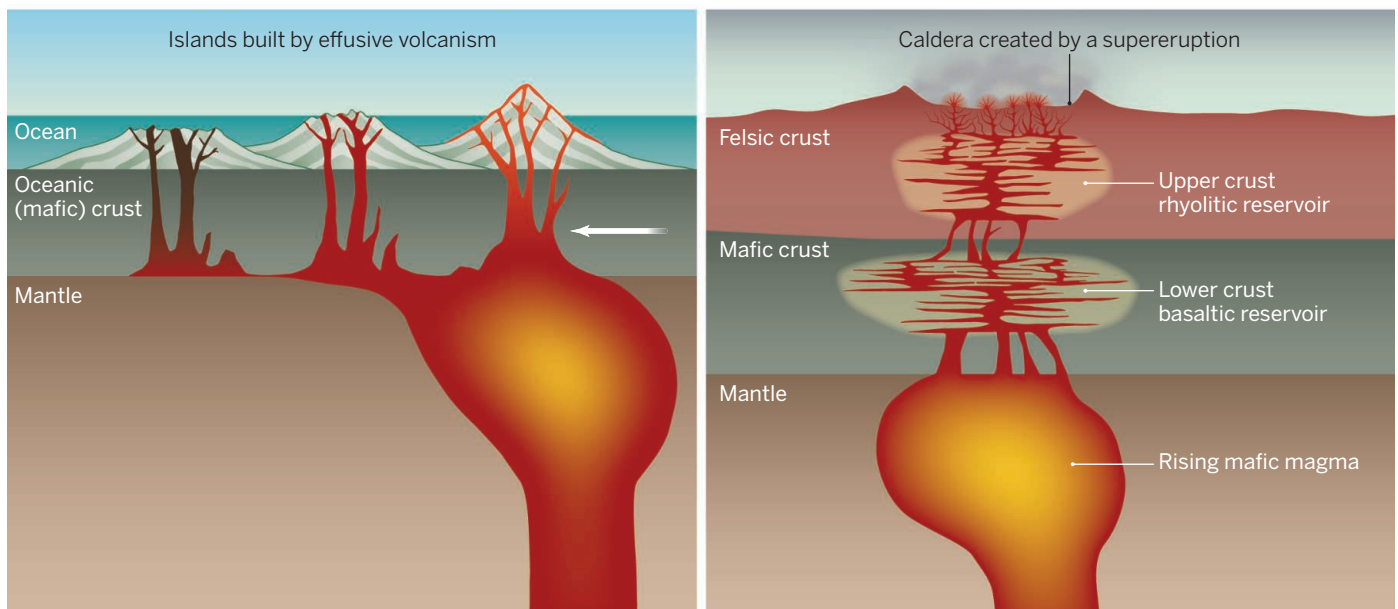
Located in North America, this volcanic system is the youngest manifestation of the Yellowstone hotspot (4, 5) and is among the most active supervolcanic sites of the Quaternary period [the other two are Toba in Indonesia (2) and Taupo in New Zealand (6)]. It is characterized by extensive earthquake activity, episodic ground deformation, high fluxes of heat and CO₂ emission, and a vigorous hydrothermal system. The Yellowstone complex is made of large calderas generated by several explosive eruptions. The three largest eruptions occurred

2.1 million years ago (Ma), 1.3 Ma, and 640,000 years ago, forming the Island Park caldera, the Henry's Fork caldera, and the Yellowstone caldera, respectively. The Island Park caldera supereruption produced the Huckleberry Ridge Tuff and was the largest with ~2500 km³ of ejected material. The younger Henry's Fork caldera is associated with the smaller Mesa Falls Tuff (~280 km³). The latest supereruption formed the Yellowstone caldera and produced the Lava Creek Tuff (~1000 km³).

In comparison, volcanoes fed by the Hawaii hotspot have erupted ~300,000 km³ of lava in the past 5.5 Ma (7). Despite the larger output rate compared to Yellowstone, these volcanoes did not generate appreciable explosive eruptions and are characterized by a relatively steady sequence of many thousands of effusive eruptions.

Both the Hawaii and the Yellowstone volcanoes are fed by mafic melts generated in the mantle. Therefore, the reason(s) for the striking difference in their styles of volcanism is not related to the deepest magma sources but must be sought in the structures through which magma passes on its way to the surface. In the case of Hawaii, the hot basaltic melts rise through a thin

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Influence of the crust on the style of volcanism. Mafic magmatic fluids remain buoyant within the oceanic crust and traverse it almost without obstacles, leading to a quasi-open system generating the steady effusive volcanism. Within the continental crust, basaltic magmas cannot easily ascend through the low-density felsic rocks and are accumulated in sill complexes at depth. This accumulation leads to a formation of intermediate magma reservoirs and differentiation of silicic magmas that, in turn, ascend to shallow depths and produce explosive eruptions.

and mostly mafic oceanic crust in which they remain relatively buoyant, leading to a fast ascent directly to the surface (see the figure) and an effusive volcanism dominated by basaltic lava flows.

Magma ascent through thick continental crust proceeds in more complex ways. Basaltic melts are denser than most of the felsic rocks that make up the upper crust. They therefore tend to stall within the lower or middle crust, where they form magma reservoirs that grow over many thousands or a few millions of years (8) by accretion of many individual sills (9, 10). Silicic magmas that are enriched in volatiles and cause explosive eruptions are believed to be produced by magma differentiation during the long-term evolution of these crustal reservoirs (11).

In most cases, the information about the origin and evolution of these crustal magmatic reservoirs is deduced from petrological analysis of the erupted volcanic rocks, though their location and size remain poorly known.

Huang *et al.*'s seismic tomography survey of deep parts of the Yellowstone volcanic system combined local and teleseismic data. This information allowed them to unveil a 46-km³ basaltic reservoir in the lower crust that is a factor of about 4.5 times larger than a shallower rhyolitic reservoir. This lower-crustal reservoir absorbs a large part of the magmas generated by the mantle plume, and only a reduced volume of evolved magmas ascends to the surface and generates large explosive eruptions. The results of Huang *et al.* show that further understanding of the functioning of the largest volcanic systems requires information about their roots in the lower crust that can be obtained via large-scale geophysical studies, including seismic and magnetotelluric (12) imaging. ■

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OCEAN CHEMISTRY

The missing link in oceanic phosphorus cycling?

Rapidly recycled reduced phosphorus compounds play a key role in phosphorus biogeochemistry

By Claudia Benitez-Nelson

Nutrient limitation plays a central role in the productivity of marine systems and long-term atmospheric carbon dioxide uptake by the oceans (1). Marine organisms are adept at changing their biochemical physiology to take advantage of scarce resources (2). Thus, changes in the ocean environment affect the biodiversity of organisms within those waters and the efficiency by which material is transported from the surface to the sea floor (3). On page 783 of this issue, Van Mooy *et al.* (4) report their discovery of a large, rapidly recycled pool of reduced phosphorus compounds that play a key role in ocean phosphorus biogeochemistry.

Phosphorus is a critical nutrient for all forms of life (5). Altered environmental conditions associated with human-induced and natural climate dynamics may cause the ocean's plankton community to become increasingly phosphorus-stressed (6, 7). Yet the composition of marine phosphorus and the factors that determine the timing and extent of phosphorus use and storage by marine organisms are incompletely understood. Van Mooy *et al.* now show that oceanic phosphorus is recycled through a previously unrecognized and vast pool of reduced forms of phosphorus at an unprecedented rate.

For decades scientists have assumed, on the basis of thermodynamics and cellular transport across membranes, that organisms only consume phosphorus in the form of phosphate for their cellular requirements. However, organisms can also break down and use a variety of other dissolved phosphorus forms, even when phosphate concentrations are relatively high (5) (see the figure). This dissolved phosphorus is a mixture of phosphate, phosphorus esters, polyphosphate, and phosphonates (8). High concentrations of the reduced phosphorus compound phosphonate in the dissolved phosphorus pool are unexpected, given the energy required to break the C–P bond (5). Yet various heterotrophic bacteria, cyanobacteria, and even archaea are now known to contain the molecular machinery for producing and using phosphonates as well

as another reduced phosphorus compound, phosphite (5, 9). Multiple lines of evidence thus suggest the importance of reduced phosphorus compounds in marine phosphorus biogeochemistry. But one last piece of information has been missing: How rapidly are they produced and used?

Van Mooy *et al.* provide a definitive answer to this question. They show that the production of reduced phosphorus compounds in cells may be as high as 15% of phosphate uptake in biological communities. In some cases, much of this phosphorus is rapidly released to the surrounding environment. Thus, the amount of phosphorus recycled through redox reactions equals or even exceeds oceanic phosphorus inputs via continental and atmospheric sources (see the figure). The rapid synthesis and release of reduced phosphorus

“...the amount of phosphorus recycled through redox reactions equals or even exceeds oceanic phosphorus inputs via continental and atmospheric sources...”

compounds in low-nutrient marine environments helps to explain the large divergence from predicted N:P ratios in marine organisms (10). This redox cycle further explains why phosphonates are present in seawater (8) and how cyanobacteria and archaea can sustain carbon fixation in increasingly stratified, phosphorus-poor waters.

Why organisms produce energetically expensive, reduced phosphorus compounds remains a mystery, particularly given that these compounds are subsequently released to surrounding waters. Van Mooy *et al.* and others have shown that phosphorus recycling is often independent of inorganic and organic phosphorus concentrations

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