Magma chambers have a sponge-like structure

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The Wheeler Monument, Colorado, USA, is a classic example of volcanic deposits formed by a super eruption. Credit: Dave Minkel, flickr. com CC BY-NC-ND 2.0

ETH researchers show that magma chambers under supervolcanoes are more like soggy sponges than reservoirs of molten rock. Before a volcano of this kind erupts, such mush must slowly be reactivated by heat input following deep magma recharge ultimately derived from the Earth's mantle.

Supervolcanoes are superlative in every respect. The eruption of the Toba caldera in modern-day Indonesia approximately 74,000 years ago was so powerful that it led to a period of global cooling and, possibly, a drastic fall in the population of humankind. Around 2.1 million years ago, the first of three eruptions of the Yellowstone supervolcano in the USA formed a crater with an area of 50 x 80 kilometres. Approximately 2,800 cubic kilometres of material were ejected in the process – around 10 to 20 times as much as in the 1815 eruption of Mount Tambora in Indonesia. Even this relatively small eruption, considered the largest in recent times, produced effects that could be felt around the world.

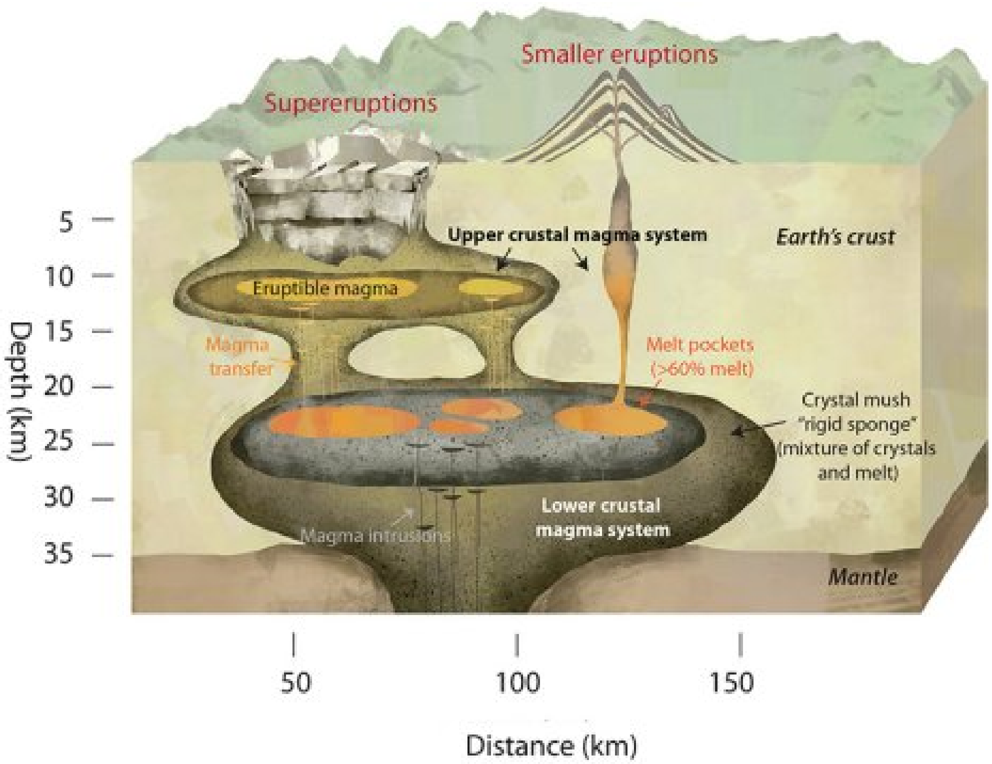
However, supervolcanoes are difficult to study and therefore continue to baffle researchers to this day. For example, scientists agree that there must be a chamber of magma at a depth of a few kilometres in the Earth's crust, containing material that escapes during an eruption. However, the experts do not agree on the form and consistency of such a reservoir.

Swimming pool vs solidified block

Some geologists assume that calderas, as supervolcano craters are known, sit on top of a gigantic reservoir of liquid magma embedded in the Earth's crust. The mantle supplies this reservoir with material and heat, and a supervolcano of this kind can erupt explosively at any time.

Others deem it more plausible that the magma chamber has cooled down completely and solidified, and that it is only made liquid by a massive influx of heat from the mantle. Only then can an eruption take place.

"Probably neither theory is correct," says Olivier Bachmann, Professor of Volcanology at ETH Zurich. Bachmann and his group have published two articles in the journal *Nature Geoscience*, in which they demonstrate that the truth may lie somewhere between these two extremes.



This is how volcanic researchers imagine the magma chamber under a supervolcano. Credit: from Bachmann & Huber, American Mineralogist, 2016

The truth somewhere in the middle?

"The magma chamber of a supervolcano does not resemble a pot of soup that can boil over at any time and at the slightest provocation," Bachmann explains. Similarly, he says it is wrong to assume that the magma has cooled down to form a completely solidified body, as reactivating a body of this kind would require an enormous influx of heat within a very short time. In addition, volatile substances such as water and CO2 would escape from the body during cooling and solidification. However, these substances are essential for an eruption as they serve to build up the corresponding pressure in the magma chamber.

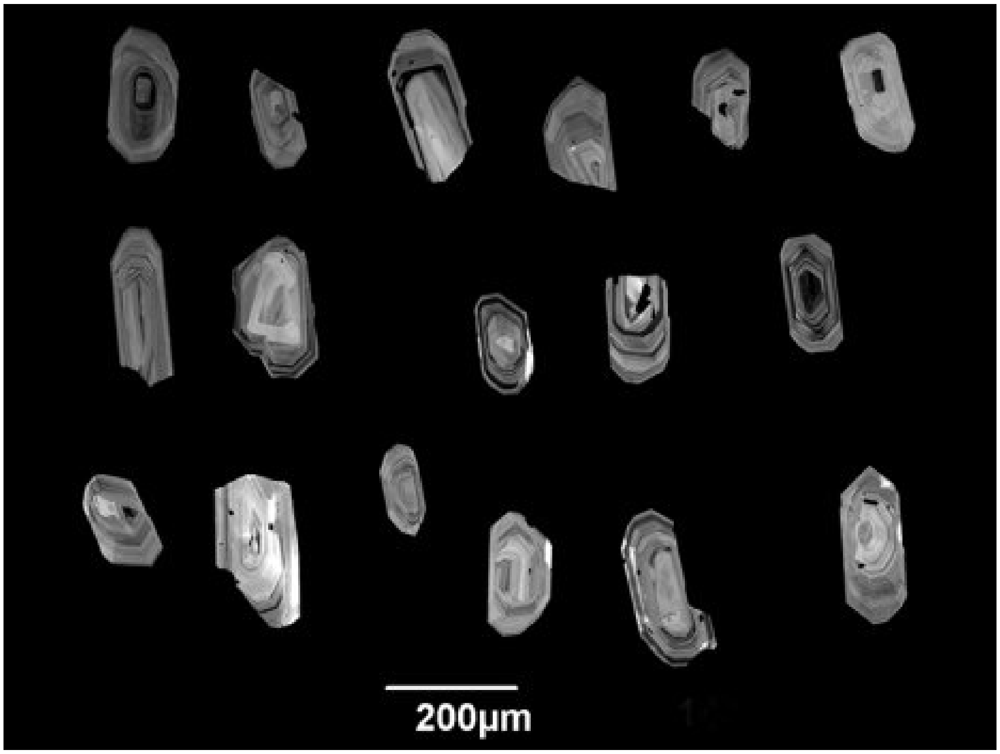
Taking the supervolcano eruption of the "Kneeling Nun Tuff" in New Mexico as an example, studies by Bachmann's doctoral student Dawid Szymanowski demonstrated that a supervolcano's magma chamber contains a mixture of liquid and crystalline – that is, solidified – magma. More than 40 to 50 percent of the reservoir is present in crystalline form. In the ETH researcher's view, the chambers may exhibit a sponge-like texture, with a mesh structure of crystallised rock and pores containing molten material – crystal mush, as Szymanowski calls it.

Rare minerals as data-loggers

This mush is likely to remain in the magma chamber for a very long time before being hurled to the surface. Szymanowski derives this conclusion from the analysis of zircon and titanite, two trace minerals that are present in the magma. Zircon is the crystalline material of the oldest known rock samples on Earth – some crystals found in Australia are approximately 4.4 billion years old.

Zircon and titanite crystals record not only the time at which they were formed but also the temperature during their formation, as this temperature influences the incorporation of chemical elements into the crystal lattice. After crystal formation, the chemical composition of these minerals in a magma chamber remains essentially unchanged even if the conditions in the magma chamber change significantly.

By analysing the age and chemical composition of zircon and titanite crystals from different rocks in the laboratory, the researchers obtain information about how a magma chamber's temperature has changed over time. The eruption brings these two minerals up to the surface, where they can be found in corresponding rock strata.



Zirconium crystals under the microscope: These minerals log the temperature of a magma chamber that prevailed during their crystalization. Credit: Dawid Szymanowski Dawid / ETH Zurich

From these analyses, the volcanologists from ETH concluded that the temperature in the magma chamber that fed the Kneeling Nun Tuff eruption must have remained between 680 and 730 degrees Clesius for over half a million years. From the minerals, the researchers could determine that it took the supervolcano a very long time to become fully "charged" and to reach the point of eruption.

Numerical model supports mineral analyses

The mineral analyses are also supported by a computer model created by Ozge Karakas, a postdoc in Bachmann's group. This model was published in June – also in the journal *Nature Geoscience* – and describes a system made up of a magma chamber in the upper crust that is connected with further chambers in the lower crust.

Hot "source" magma forms in the mantle at a temperature of approximately 1,200 degrees before rising through cracks and chimneys into the upper crust. Once there, it forms a reservoir, which cools down and partially crystallises but can survive as a crystal mush for hundreds of thousands of years.

Using the model, the scientists were able to show that the formation of a permanent reservoir in the upper crust does not require gigantic quantities of material from the mantle in short periods of time. "The conditions in the upper crust are not suitable for collecting and storing that much material very quickly," says Karakas. Nevertheless, the geologist says that the reservoir does need a connection with magma in the lower mantle in order to ensure the transport of heat, and she emphasises that, until now, researchers had not included the lower crust in their considerations. "Without it, however, there would be no supervolcanoes."

Very rare events

Both the model and the mineral analyses therefore point to the idea that supervolcanoes form and mature over very long periods of time, and that they can only erupt at intervals of tens of thousands of years. "The magma is primarily preserved as a type of crystalline, sponge-like structure. And it must always be reactivated by an influx of heat before it can erupt," says Olivier Bachmann, summing up the findings.

It is not possible to predict when the next supervolcano eruption is about to occur based on the new findings, as the system is not yet understood in sufficient detail. However, mechanisms of growth and reactivation of giant magma reservoirs become clearer, and that may help to better assess the reawakening signs of those systems in the future. "In any case – and fortunately for us – a supervolcano eruption is a very rare event," says Bachmann.

More information: Dawid Szymanowski et al. Protracted near-solidus storage and pre-eruptive rejuvenation of large magma reservoirs, *Nature Geoscience* (2017). DOI: 10.1038/ngeo3020

Ozge Karakas et al. Lifetime and size of shallow magma bodies controlled by crustal-scale magmatism, *Nature Geoscience* (2017). DOI: 10.1038/ngeo2959

Provided by ETH Zurich