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The long wait and rapid rise of deep magma

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ABSTRACT

Magma erupted from a volcano in Iceland was stored at the boundary between the crust and the mantle for thousands of years before travelling to the surface in a matter of days. This improves our understanding of how magma behaves before eruption.

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Simple textbook models have suggested that single bulbous magma chambers feed volcanoes. However, geological studies have shown that volcanoes are underlain by a complex system of chambers and conduits going through the Earth's crust. The crust is the rigid outer layer of the Earth and can range in thickness from 6 to 50 km. It covers the mantle which is a 2900 km thick, predominantly solid rock layer. Partial melting of the mantle generates magma, a mixture of liquid rock, crystals and gas, which travels through the multi-level volcanic maze in the crust until it reaches the surface. Knowing how long magma can be stored at each crustal level and how quickly it can get to the surface could help forecast volcanic eruption and understand how volcanoes influence long-term climate. Many studies have estimated storage times at shallow depths (less than 10 km), which ranges from 100 to 100 thousand years. However, we know little about how long magma can stay in the deepest parts of the crust, particularly near the crust-mantle boundary called the Moho. Using mineral records from an Icelandic eruption we estimated, for the very first time, magma storage time deep in the Earth's crust.

Mineral records from eruptions are like mini geological hard drives that store information about the conditions inside the volcanoes. But the information about storage deep in the crust can be erased during shallow storage. To overcome this issue, we looked at the Borgarhraun lava field in Northern Iceland. It formed in a basalt (a black volcanic rock poor in silica and rich in magnesium) lava eruption 8000 years ago. Previous geological studies showed strong evidence that is was once stored near the Moho (around 20 km under Northern Iceland) and underwent minimal shallow crustal storage. The hardened volcanic rock contains many crystals including olivine, spinel and other minerals, which we can use to reconstruct the conditions under which the magma formed.

Local magmatic conditions such as temperature, pressure and the composition of the liquid rock determine the chemistry of minerals. If minerals encounter a new set of conditions as they grow, they start to change their composition and become chemically zoned. This means that the concentration of elements varies from the edge to the centre. In our spinel crystals the aluminium concentration decreased and chromium increased. Crystals hate to be zoned and prefer to be fully homogeneous. They rely on diffusion to remove the concentration differences. For the spinels, aluminium is diffusing into the crystals and is exchanging with chromium as it diffuses out. Since we know how fast this exchange is at a given temperature, we used the data from the spinels like a stopwatch to estimate the time of magma storage. We modelled the diffusion of aluminium and chromium in the spinels at a temperature of 1215°C (the temperature at which we estimated the magma was stored) and calculated the storage time to be approximately 1500 years.

Looking at iron and magnesium diffusion in olivine crystals from the same volcanic rock, we also found that the magma only took 10 days to travel 20 km upwards from near-Moho storage depths to the surface. Combined our results suggest that magma can stay at the base of the crust for thousands of years before rushing up to the shallow crust for further storage or eruption.

Besides the basalt lava volcano we studied, other volcanic systems exist. The storage of magmas in the deep crust of Iceland is much shorter than in the shallow, silica-rich volcanic systems that can feed large explosive eruptions, such as Mount St. Helens, USA. If results from other places confirm our data for Iceland, then this would mean that the storage periods get longer as magmas move higher in the crust. This could be due to different thermal and physical properties of magma at different depths. Our results also suggest that magma may move through the magmatic system in a punctuated manner; long periods of storage (thousands of years) at different levels in the crust interspersed with periods of rapid transport (days to months). Are our deep storage timescales representative of all volcanic systems? What is the link between deep storage and eruptive activity at the surface? We will need further work to address these questions.