**Original Article (DOI)**: – **DOI: 10.1126/science.aax4092,**

**Related article (DOI):** [**https://doi.org/10.1038/s41561-019-0376-9**](https://doi.org/10.1038/s41561-019-0376-9)

**Author(s):** – Euan J. F. Mutch1,2

**Position:** – **Postdoctoral Research Fellow**

**Affiliations:** – **1Department of Earth Sciences, University of Cambridge, U.K.; 2Department of Geology, University of Maryland, College Park, U.S.**

**Corresponding Author:** – Euan J. F. Mutch ([em0242@my.bristol.ac.uk](mailto:em0242@my.bristol.ac.uk),ejfm2@cam.ac.uk)

**Word count (700-750 max):** – 748 words (main article).

**Field:** – Earth Sciences, Geology, Geochemistry, Igneous Petrology, Volcanology

**Twitter handle:** -- @euanjfmutch @EarthSciCam

**Keywords**: -- Magma, Volcano, Iceland, Crystal, Storage

**--The long wait and rapid rise of deep magma**

*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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--Text

Our understanding of volcanic systems has undergone a recent paradigm shift. The simple textbook model of volcanoes being fed by a single bulbous magma chamber has now been superseded by complex trans-crustal magmatic systems. Magma (a mixture of liquid rock or melt, crystals and gas) can be stored at multiple levels in the crust extending from the mantle, where magma is generated, all the way to the surface. Knowing how long magma can be stored at each level in the crust is important for understanding how quickly magma, volatile compounds (e.g. CO2 and H2O) and heat can be transferred from the mantle to the surface. This in turn, is crucial for understanding how volcanoes can modulate long-term climate and for volcanic eruption forecasting. Many studies have estimated storage times in shallow magmatic systems (< 10 km depth), which can range from 102-105 years. However, we have little understanding of how long magma can be stored in the deepest parts of the crust, particularly near the crust-mantle boundary called the Moho. This is because mineral records (mini geological hard drives) of deep crustal storage can be erased during shallow storage.

To overcome this issue, we looked at the Borgarhraun eruption from Northern Iceland. It is an 8000 year old basalt lava flow that shows strong evidence that is was once stored near the Moho (~20km under Northern Iceland) and underwent minimal shallow crustal storage. The eruption contains crystals of olivine, plagioclase, clinopyroxene and spinel, which can be used to reconstruct the conditions under which the magma formed. These minerals can be found in crystalline nodules, which represent the accumulation of crystals that formed from the magma. The composition of clinopyroxene and olivine told us that the magma crystallised at 24 km depth from the very first melts that left the mantle.

The compositions of minerals are controlled by the local magmatic conditions including the temperature, pressure and the composition of the liquid. If minerals are exposed to a new set of conditions, they start to change their composition and become chemically zoned. In our work published in *Science*, we found that spinel crystals contained in the crystalline nodules were zoned in terms of their aluminium (Al) and chromium (Cr) concentrations. This means that the composition of the crystals changed from the edge into the centre; Al decreased and Cr increased. Crystals hate to be zoned and prefer to be fully homogeneous and in chemical equilibrium with their surroundings. Diffusion acts to remove any compositional zoning by smoothing chemical gradients. For the spinels, Al is diffusing into the crystals and is exchanging with Cr which is diffusing out. The rate of this exchange has been experimentally determined meaning we could use the diffusive exchange in the spinels like a stopwatch to estimate the timescale of magma storage.

By modelling the diffusion of Cr and Al in the spinels at a temperature of 1215 °C , we found that the compositional gradients in the spinels could be fit with a storage timescale of approximately 1500 years. This was the very first estimate of deep crustal magma storage time at any tectonic setting. We also found using iron and magnesium diffusion in olivine crystals from the same crystalline nodules that the magma only took 10 days to travel from near-Moho storage depths to the surface. This was published in an article in *Nature Geoscience*. Combined our results suggest that magma can be stored for thousands of years at the base of the crust before being rapidly mobilised and transported to the shallow crust for further storage or eruption.

We found that our storage time of magmas in the lower crust of Iceland are much shorter than the timescales of storage in shallow, silica-rich volcanic systems that can feed large explosive eruptions, such as Mt St Helens, USA. If the lower crustal storage times of Iceland are representative of other places, then this would mean that storage times would increase as magmas move higher in the crust. This could be due to different thermal and physical properties of different types of magma. Our results also suggest that magma may move through the trans-crustal 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? More work will be needed to address these questions.