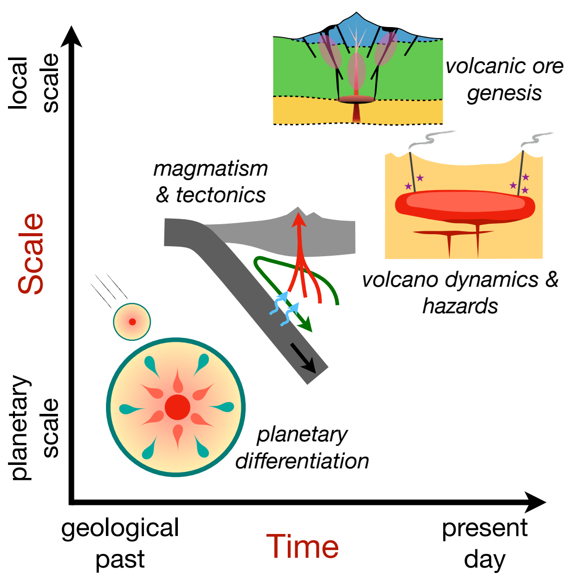
Magma matters

Modelling the complex generation and transport of magma beneath volcanoes

Magmatism shapes our planet, but we know relatively little about magma generation or transport. Dr Tobias Keller, University of Glasgow, studies these processes using computer simulations. Modelling magma is non-trivial because it is a complex mixture of liquid rock melt, mineral grains, and gas bubbles and involves dozens of elements. Its large-scale behaviour depends on how materials are interconnected at the microscale. Dr Keller's work provides a new framework for models that provide a simplified representation of a complex reality for the sake of better understanding magma generation and transport.



Magma is at the core of numerous geological processes, from Earth's differentiation (i.e., into core, mantle, and crust), to interactions between plate tectonics and ocean-atmosphere systems that control long-term climate, to volcanic activity posing both terrible hazards and providing rich agricultural, energy, and mineral resources.

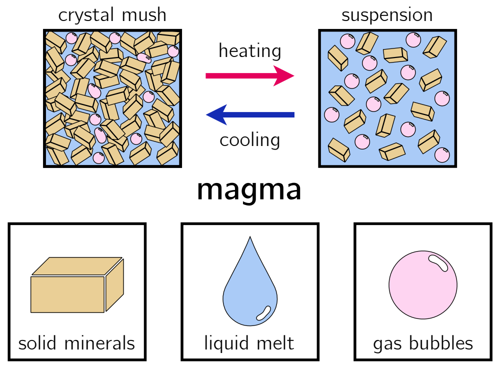
Despite this significance, we still understand relatively little about how these processes play out in the subsurface. What we do know is derived from studying long-dead magmatic systems whose igneous rocks (i.e., rocks formed by magmatic processes) have been exposed at the surface by erosion, complemented by crude imaging afforded by geophysical surveys and the monitoring of active volcanoes. However, we continue to lack detailed understanding of the dynamic processes involved when magma is generated in the Earth's mantle, is focused into narrow magmatic zones in the crust, and ascends toward the surface to be emplaced as plutonic rocks (e.g., 'unerupted' or 'intrusive' igneous rocks such as granite) or erupted at the surface in spectacular displays of fire and ash from the volcanoes that dot our continents and ocean floors.

To address this gap in knowledge, Dr Tobias Keller of the University of Glasgow has spent the past decade studying these processes through the lens of physics-based numerical models. With support from the Swiss National Science Foundation and the European Research Council, Dr Keller has been at the forefront of rapid developments in modelling techniques to dig deep below the surface, revealing the incredible hidden world of magma.

MODELS ARE SIMPLE, MAGMA IS NOT

Modelling magma is non-trivial, primarily because magma is not a simple one-phase material; it is a multi-phase mixture of liquid molten rock, solid mineral grains, and bubbles of gas that determine the dynamic evolution of igneous systems at a sub-millimetre scale. However, the dynamics relevant for human- to planetary-scale perspectives happen on scales from tens of metres to hundreds of kilometres.

Reactions between the solid, liquid, and gas phases involve dozens of chemical elements; modelling such a system requires that each of these reactions is tracked. The proportions of phases in the mixture must be accounted for, along with the structure of the melt. Magma, far from being the simple liquid of peoples' imagination, can range from porous medium, to granular slurry or mush, to dilute suspension, emulsion, or foam. The connectivity of phases is critical—in some cases, even in magma with a very low melt proportion, liquid remains interconnected and mobile; in others, melt forms isolated droplets separated by solid phases, rendering the melt immobile. To complicate matters further, magma is embedded in solid rock (i.e., 'country rock'), the properties of which determine how it behaves in response to the magma; for example, country rock may deform through slow creeping flow or sudden fracture, or both. Together, these challenges present a problem of extraordinary complexity.



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Just 10 years ago, mathematical models were relatively simple and could not address these challenges. Dr Keller has been at the forefront of developing the next generation of igneous process models. Over this time, Dr Keller and his collaborators have published three theoretical studies presenting numerical models and computer simulations that have the potential to greatly expand our understanding of how magma shapes the world that we inhabit, as well as other worlds we are now discovering.

MAGMA MOVEMENT ON A CRUSTAL SCALE

The first of these studies, co-written with Prof Dave May (University of California, San Diego) and Prof Boris Kaus (University of Mainz), explored numerical modelling of magma dynamics in conjunction with large-scale tectonic deformation of Earth's crust. The finite element model was run in two-dimensions and assumed a simple two-phase material—solid mineral grains and melt. The model calculated both the transport of the melt and the deformation of country rock; in contrast to many other 'two-phase' models, which focus on a two-phase liquid (e.g., oil and gas or oil and water) within a porous rock that is assumed to be static. Such two-phase models had been used before, but in general they focused on flow within the mantle, which behaves very differently from the Earth's crust—hot mantle is viscous and flows like a sticky fluid ('viscous creep'); deformation of the cooler crust shows a complex range of styles from ductile creep to brittle fracturing.

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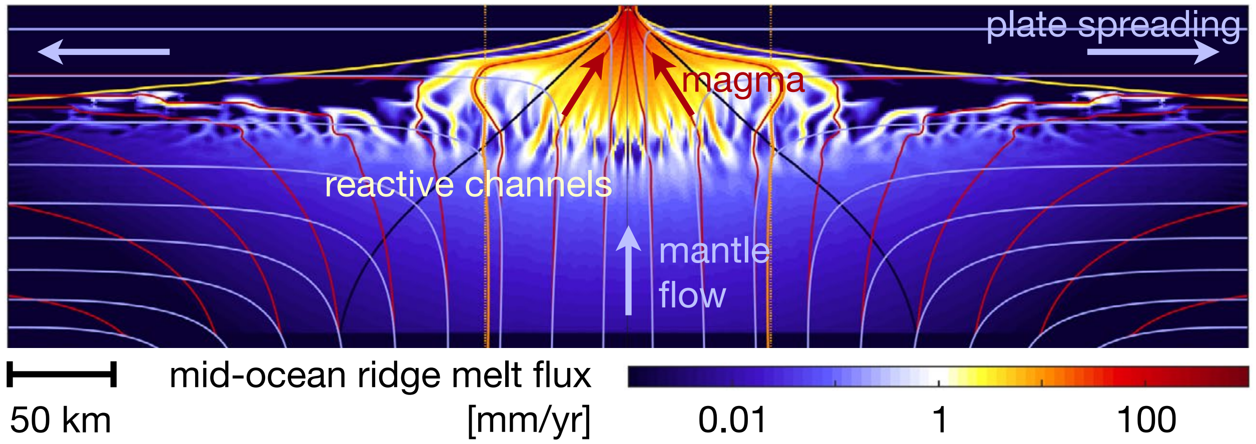
The team built on these existing models by considering a visco-elasto-plastic rock rheology (i.e., the relationship between rock deformation rate and the forces applied) in terms of shear deformation (i.e., deformation where there is no net volume change) and compaction (deformation involving equal and opposite volume change in either of the two phases—the solid and/or melt). Past models only considered shear deformation; In contrast, Dr Keller's approach allows parts of the model to have a solid matrix compacting while melt is being squeezed out (like squeezing a sponge), and other parts where the solid is 'decompacting' while melt is accumulating (like pumping up an air mattress).

This unique model captures the most important characteristics of melt generation and movement in Earth's crust. The viscosity (i.e., resistance to deformation) of country rock increases from depth towards the surface, owing to decreasing temperature. This causes changes in behaviour from depth to the surface: (1) melt diapirism (i.e., magma rises into the ductile crust by ductile creep), (ii) decompaction channelling (i.e., elongated bands of localised melt flow and rock deformation) and (iii) tensile fracturing (i.e., growth of magma-filled cracks). These processes, through which magma-rock interactions are controlled, determine the geometry of magma chambers and conduits, the emplacement of plutonic rocks, and the rates of magma ascent, from millimetres per year to metres per day.

EXPLORING A VOLATILE ENVIRONMENT

The second study, co-authored by Prof Richard Katz (Oxford University) stepped up the level of complexity by taking into account volatiles, species like H_2O and CO_2 that tend to be gaseous at atmospheric pressure but are dissolved in silicate melts during reactive transport of magma in the viscous upper mantle. Volatiles significantly depress the temperature at which a rock will first melt, but what is less known is the impact on 'reactive transport'—systems where the dynamic transport of a liquid through the pores of a solid is intimately linked to the chemical reactions between them. Unlike ice, rock does not melt at one fixed temperature; rather, different minerals melt under different conditions. In reactive transport, melt flowing through pore spaces can be 'corrosive', carving out ever deepening channels. Dr Keller's models show that just very small concentrations of H_2O and CO_2 (e.g., 100 parts per million) can control both the amount of magma generated and the dynamics of subsequent transport through such channels.

Magma generation is related to a positive feedback mechanism: an increase in volatile-rich magma enhances melt production, in turn increasing permeability and promoting



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new melt generation. Previous models assumed highly simplified chemical interplays of one or two components, but did not consider the effects of multi-chemical melting reactions (most importantly volatiles); as such, they likely underestimated magma transport rates, and could not capture the significant chemical variability of these magmas.

ONWARDS AND UPWARDS

In 2019, Dr Keller and collaborator Prof Jenny Suckale (Stanford University) took a step back, recognising that the previous models still fell short of capturing key aspects of igneous processes. An entirely new framework was needed. They went back to the drawing board in an attempt to rephrase igneous process models in a much more general and flexible way.

Magma is multi-phase, making it highly non-linear, subject to abrupt changes in behaviour, and at the mercy of complex feedbacks causing temporally and spatially localised heterogeneity, both chemically and physically. The 2019 study shifted focus to a multi-phase model framework that opens the door to investigating processes on a variety of scales, from small(ish), including volcanic conduits and shallow magma reservoirs, to regional-scale development of economically valuable ore deposits (e.g., iron, copper, gold, etc.), and finally to planet-wide perspectives (e.g., plate tectonics, planetary differentiation).

One the most challenging aspects was the diversity in physical magma structures, ranging from porous (i.e., dominated by solids) to suspension (i.e., dominated by liquid), with strongly contrasting and highly uncertain parameters impacting on flow dynamics (e.g., flow velocity, scale of transport, etc.). The new model took an *n*-phase approach, in which multiple solid, liquid, and gas (i.e., 'volatiles') phases can be included. The model, which is based on Mixture Theory (i.e., macroscopic behaviour results from averaged microscopic phase interactions) and the principles of thermodynamics, considers the transfers of entropy (i.e., degree of disorder or randomness), mass, momentum, and volume in the system. These transfers express how the phases within the system interact—for example, melt in disconnected pockets on grain corners will mechanically and chemically interact differently than the *same amount* of melt present as thin films forming an interconnected network between grains.

The gold-standard for model development is validation (did we build the *right model*?) and verification (did we build the *model right*?) through comparison to observations and known analytical benchmarks; however, given the scale and nature of Earth's subsurface and the limitations of field- and geophysics-based observations, it is challenging to find sufficient, high quality data for comparison. When applying the model framework developed by Dr Keller and team, users will need to use data from observations and experiments (e.g., field observations, geochemical sampling, geological mapping, geophysical imaging, remote sensing, volcano monitoring) in two main ways: (1) calibrating problem-specific model parameters; and (2) validating model outputs. The paradox is that consistency between a model and observations depends on the model calibration; that is, calibration and validation of the model cannot be independent. As such, modelling outputs cannot be taken as a representation of reality; rather, Dr Keller and his colleagues hope that they provide a simplified representation of a complex reality and are a tool for formulating new and testable hypotheses.

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Models are a critical tool for visualising magmatic processes normally hidden in deep time and deep below the surface—epic animated movies where magma is the superhero and its powers are the real laws of physics. Using these models, we are able to glimpse the weird and wonderful world of volcanoes and their deep magmatic roots; gaining a better, more nuanced understanding of the planet we call home.

Behind the Research

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Research Objectives

Dr Keller is a Computational Geoscientist passionate about all matters magma. He uses computer simulations to study the physical and chemical processes active in volcanoes and their deep magmatic roots.

Detail

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Bio

Tobias Keller completed his university education at ETH Zürich, his BSc Earth Sciences in 2006, MSc Geophysics in 2009, and Ph.D. in Sciences in 2013. He held two three-year positions as Postdoctoral Research Associate at the University of Oxford (2013-2016) and at Stanford University (2016-2019). He has been a Lecturer for Computational Geosciences at the University of Glasgow since 2019.

Funding

The Swiss National Science Foundation (snf.ch) who funded Dr Keller's Ph.D. and second postdoc research, and the European Research Council (erc.europa.eu) who funded his first postdoc position.

Collaborators

Jenny Suckale (Stanford Univ., postdoc mentor), Richard Katz (Univ. Oxford, postdoc mentor), Boris Kaus (Univ. Mainz, Ph.D. advisor)

University of Glasgow

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Personal Response

Can your models be used to inform hazard monitoring (e.g., can they help to predict the explosiveness of future eruptions)?

" That is indeed one of the goals of my research. Over the past decade, volcano monitoring has seen a rapid expansion such that the quantity and quality of volcano observations is now multiple times above where it was. My research group has since been working on a number of studies using models to learn about the dynamic processes immediately preceding volcanic eruptions and how these can be recognised in monitoring data. We still have some way to go before hazard monitoring and early warning will become a routine reality, but I believe we are moving in the right direction. "

Can the models be used in mineral exploitation (i.e., can they be used to predict the location and extent of an orebody?)

" It may come as a surprise to many that, despite mining them for centuries, we still understand little about the genesis of magmatic ore deposits. Perhaps that is because they involve extraordinarily complex mixtures of materials of highly exotic compositions. Multi-phase reactive transport models are indeed the right tool for deciphering these processes: ore genesis relies on a combination of reactive enrichment of metals in mobile fluids followed by focused transport along crustal fractures where resource minerals are deposited. Understanding what factors favour these rare and peculiar expressions of reactive transport will help to understand where we should look for undiscovered deposits. "