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Editorial: Volumes, Timescales, and Frequency of Magmatic Processes in the Earth's Lithosphere

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Editorial on the Research Topic

Volumes, Timescales, and Frequency of Magmatic Processes in the Earth's Lithosphere

Heat, mass, and fluid transfer processes related to the formation and growth of the continental crust along convergent and divergent plate boundaries, and the formation, modification, and recycling of the continental crust are key research themes in the solid Earth Science community. Establishing the link between magma generation, transport, emplacement, and eruption can therefore significantly improve our understanding of crust-forming processes associated with plate tectonics, and, particularly, help determining the architecture, and composition of the Earth's lithosphere.

One of the Earth's characteristic processes is chemical differentiation, forming a SiO_2-rich continental crust that is continuously shaped and reworked throughout Wilson cycles. The continental crust covers 41% of Earth's surface (Cogley, 1984) and sits at higher elevation compared to the oceanic crust that tends to be largely subducted. The SiO_2-rich rocks that dominate the upper portions of Earth's crust are unique in the Solar System (e.g., Taylor, 1989) and are ultimately linked to the presence of liquid water on Earth (Bowen, 1928; Campbell and Taylor, 1985). But when, where and for how long magmas are stored within the Earth's lithosphere and how they contribute to its chemical, physical, and thermal architecture remain important challenges in geosciences.

The presence of magmatic bodies in the crust have been confirmed through a wide range of geophysical investigations; however, the volume, geometry, mechanics, chemical signatures, and evolution of these bodies remain poorly constrained. Establishing the link between magma generation, transport, emplacement, and eruption is therefore essential to significantly improve our understanding of crust-forming processes associated with plate tectonics, and help determine the Earth's lithosphere architecture, composition, and dynamics. In this cross-disciplinary Research Topic, contributions aim to answer such fundamental questions.

HOW DO WE DETECT VOLUMES AND GEOMETRY OF MAGMATIC BODIES AT DEPTH AND THEIR ERUPTIVE PRODUCTS?

In recent decades, advances in geophysical techniques that image the structure of magma plumbing systems have allowed identification of zones of melt accumulation, crystal mush development, and magma transport (e.g., Magee et al., 2018). Combining these geophysical observations with petrological and geochemical data allows the development of entire magma plumbing systems to be

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understood. Reuber et al. (2018) employ lithospheric-scale three-dimensional visco-elasto-plastic geodynamic models and a joint modeling gravity inversion approach to test the influence of chamber connectivity, rheology of the lithosphere, and the effective density of the magma chambers on the dynamics of the system and amplitude of surface uplift. By application of their numerical approach to Yellowstone's magmatic system, one of the largest magmatic systems on Earth, they validate their approach against processes that are observable using the present-day geophysical spatial resolution (Vasco et al., 2007; Smith et al., 2009).

The structure of upper crustal magma plumbing systems controls the distribution of volcanism and influences tectonic processes. Specifically, space for shallow-level sills and laccoliths is commonly generated by bending and uplift of overlying rock and sediment ("roof-uplift" mechanics). The surface expression of forced folds captured by seismic reflection images can be used to constrain both elastic and inelastic mechanics and related geometries of the intruding magma bodies in the shallow Earth's crust. Magee et al. use seismic-based observations to evaluate the elastic and inelastic deformations that accommodated magmatic intrusions. Using geological and geophysical information from the Resolution-1 borehole offshore eastern New Zealand, the authors show that post-emplacement, burial-related compaction processes can modify initial fold amplitude and intrusion thickness. Magee et al. thereby provide a methodology that can account for post-emplacement, burial-related compaction signature, and enable more accurate estimation of the intrusive magma body thickness in two-dimensional seismic reflection profiles.

HOW CAN WE QUANTIFY CHEMICAL, MECHANICAL, AND THERMAL PROCESSES THAT INFLUENCE MAGMA TRANSPORT AND ERUPTION EVENTS?

Geophysical, petrological, and geochemical methods are generally applied across a range of different spatial and temporal scales, and to different tectonic settings to evaluate the chemical, mechanical, and thermal processes that govern magma transport and eruption at active volcanoes. Zellmer et al. show the possibilities provided by better integration between these methodologies, when constraining the role of the crustal thermo-mechanical properties on magma transport. By studying the long debated processes controlling the relative proportion of intrusive to extrusive volumes of arc magmas along subduction zones (Crisp, 1984; White et al., 2006), Zellmer et al. use published ambient noise tomography data from the NE sector of the Japanese arc system, to propose that plutons/magma reservoirs (bodies characterized by low shear velocities) are found beneath most of the active volcanoes exhibiting caldera-forming eruptions, and represent a hotter and more ductile crustal response to intrusive activity that hinders magma transport to the surface along most of the arc. The approach also identifies mechanisms to explain the behavior of Zao volcano, which has erupted more frequently and produced greater tephra volume than any other volcano along the Japanese arc in the last 2,000 years. At Zao volcano, Zellmer et al. propose that frequent low-volume volcanism is fed by dikes that traverse the relatively cool and brittle arc crust. This dichotomy of volcanic activity highlights how physical and thermal heterogeneity of the arc crustal system influences volcanic style, frequency, and volumetric output at the surface.

Linking seismicity to magma dynamics at depth preceding volcanic eruption events is the target of Lanza and Waite. By stacking of thousands of repetitive explosion-related long-period (LP) events at Pacaya volcano, Guatemala (October-November 2013), and using non-linear waveform inversion, Lanza and Waite re-construct the associated non-linear moment-tensor, to characterize seismicity along a tensile crack, dipping $\sim 40^\circ$ to the east. This allows them to infer that the N-S elongate geometry of the volcano conduit remains consistent throughout most of the edifice. The authors show how decoding seismic signals produced by volcanoes is crucial windows to magmatic systems and the complex interactions between gas, liquid, and solid along magma pathways.

The extent to which the physical properties of magma (e.g., density and viscosity) exert a fundamental control on their transport and eruptibility is the focus of Hartley and Maclennan (2018). Studying exposed lava flows of known age and volume from Iceland's Northern Volcanic Zone, the authors directly relate erupted volumes to magmatic physical properties. They identify that over 85% of the total volume of erupted magma was close to a density and viscosity minimum coincident with the nucleation of plagioclase in the basalt. This petrological window favors a high buoyancy of the magmas with respect to the upper crustal rocks. While primitive basalts and olivine-phyric picrites with densities higher than upper crustal rocks demonstrate that any density filter must be leaky, Hartley and Maclennan (2018) show that this is facilitated by the generation of overpressure in magma chambers in the lower crust and uppermost mantle.

Moving to shallowest levels of the magmatic system, understanding shallow magma transfer, volcanic edifice growth, and interaction between edifice stress state and magma transfer remains challenging from routine seismology and geodesy monitoring techniques. Derrien and Taisne show laboratory-based analog experiments that reproduced the mechanics of volcanic edifice birth and growth in an analog elasticity-dominated material. By monitoring the evolution of the stress field within and around the volcano edifice, the authors show that cyclic eruptive patterns alternating between eruptive and intrusive phases contribute to the formation of the initial volcanic edifice and to the subsequent edifice growth radial compressive stress build-up and release that act to localize the stress field to shallow level. Derrien and Taisne demonstrate these experiments can be used as a proxy for long-term stress perturbations in volcanic edifices and can provide understanding of edifice morphology during successive eruptive activity stages.

Finally, Eyles et al. present seismic data from Eritrea, Yemen, and Saudi Arabia which, when integrated with interferometric synthetic aperture radar data (Xu et al., 2015), identifies the propagation and inflation of a ~ 12 km-long dike, emplaced parallel to the overall strike of the Red Sea as the earthquake focal mechanisms observed on 12th and 13th December 2011, which were then followed by the subaerial eruption witnessed by Yemeni fishermen on 18th December 2011, and the formation of a new volcano in mid-ocean ridge system at Sholan Island, Read Sea.

HOW DO WE DECIPHER THE RECORD PRESERVED IN MINERALS, GLASSES, AND ROCK TEXTURES TO CONSTRAIN THE TIMESCALES AND DYNAMICS OF MAGMATIC PROCESSES AT DEPTH?

Textural, petrological and chemical forensic approaches are critical in the interrogation of igneous rocks, and in determining the processes through which they formed. As elsewhere in this volume, we highlight the additional insight that can be gained by combining approaches, or linking traditional and more novel methods.

Seitz et al. (2018) use nanoscale secondary ion mass spectrometry, coupled to compared quartz zonation, Ti-in-quartz thermometry, and diffusion chronometry to assess eruption timescales for coeval rhyolitic crystal-rich and crystal-poor magmas from the Jurassic Chon Aike Province in Patagonia (Argentina). The data support rapid melt extraction and eruption in < 10 years in the crystal-poor systems. It also supports rapid (< 3 years) and violent eruption within the crystal mushes, but only after long storage in a reservoir affected by continuous thermal fluctuation. Critically, the authors show that the mobilization and eruption of both crystal-rich and crystal-poor magmas can occur over the same short timescales.

Also, working in silica-rich volcanism, Bindeman et al. use a combination of Ar-Ar dating, isotopic analysis, petrological, and thermomechanical modeling to investigate the genesis of voluminous eruptible rhyolites leading to caldera-forming eruptions. By exploring the diversity of compositional flavors found at the Karymshina caldera, which is the largest silicic system of the Kamchatka Peninsula (eastern Russia), the authors capture the magmatic diversity arising from fractional differentiation of mantle-derived basalts and assimilation of mafic crust produced during basalt magmatism. The time-integrated isotopic analysis reveal that the generation of these "super-rhyolites" required increasing magma differentiation and that the spikes of rhyolitic magmatism were likely driven by delamination of cumulates and lithospheric mantle after 4 million years of crustal thickening.

Similar insight can be achieved by applying multiple methods to mafic magmatism. Ubide et al. provide a very detailed textural and geochemical analysis using laser ablation time-of-flight mass spectrometry and clinopyroxene-melt thermobarometric and hygrometric calibrations to accurately track the depth, temperature, and water content of the shoshonite magmas from Stromboli volcano (Italy). They found that the volcanic system of Stromboli was originally dominated by protracted periods of magma replenishment and convection, punctuated by rapid megacryst evacuation and eruption upon arrival of more mafic magma (days to weeks). Since the inception of current steady-state activity, the melts from injections triggering eruptions have become appreciably more mafic, suggesting that intrusion of primitive magma may be a key driver of the modern eruption's dynamics at Stromboli.

Karlstrom et al. tackle a very different challenge, and use thermochronological methods to probe the mechanics of flood basalt emplacement and the tempo of individual eruptions, targeting two exhumed dikes from the Columbia River Flood Basalt province in northeast Oregon, USA (e.g., Ho and Cashman, 1997; Camp et al., 2017). Using apatite and zircon (U-Th)/He thermochronology, thermal modeling of melt-fraction temperature relationships for the intruding magma and a Bayesian Markov-Chain Monte Carlo inverse modeling framework, Karlstrom et al. interrogate partly and un-reset ages (i.e., crystallization age of host pluton) and reset ages (i.e., exact timing of dike emplacement), to define distinct emplacement histories for the two magma bodies. The inverse modeling shows that while one dyke was fed continuously over 1–6 years, the other had a shorter thermal lifespan with an unsteady heating rate suggestive of low magma flows. The authors highlight the power of Bayesian inversion methods to quantify magmatic processes that have hitherto been challenging to constrain.

Finally, Potter et al. (2018) showcase a time-integrated petrological and geochemical investigation of basalts from the Kimama borehole in the Snake River Plain of central Idaho, USA (Shervais et al., 2011, 2012, 2013). This rock core links eruptive processes to the construction of mafic intrusions and highlights the cyclic variations in basalt composition caused by temporal chemical heterogeneity related to fractional crystallization and assimilation of previously-intruded mafic sills over 5.5-million-year history. Through detailed logging of distinct lava flows representing single eruptive episodes and flow groups, the time-integrated chemical variation can be constrained. Potter et al. (2018) propose that this evolution is related to source heterogeneity, magma processing during physical, and chemical evolution of the layered intrusions, and varying degrees of assimilation of gabbroic to ferrodioritic sills at shallow to intermediate depths over short periods of time.

CONCLUDING REMARKS

Understanding the volume and timescales of magmatic processes, and the controls on the evolution of magmatic systems have become key challenges in twenty-first century geoscience. In this introduction, we have highlighted how cross-disciplinary approach that fosters the collaboration of scientists of different expertise can constrain new insight into the physical and chemical properties of magmatic systems, from both single to repetitive events, and across a wide range of both spatial and temporal scales.

The original multidisciplinary research presented here has been driven by the need to correlate magmatic processes across the storage system, with volcanic eruptions at surface, and the associated geological hazards. The papers presented in this Research Topic all address the complexities necessitated by a three-dimensional and time-integrated (4D) view of magmatic systems. These contributions indeed offer new perspectives on how magmas evolve, how they feed active volcanoes, and how to link volcanism and plutonism within this "top-to-bottom" approach of observing and decoding surface processes to monitor deep processes in the Earth's interior.

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MP drafted the first version of the manuscript. All authors contributed to the final version of the manuscript.

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