

Time constraints on magma ascent from volatile element diffusion in apatite

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Diffusion theories and models in crystals have been widely used for constraining the timescale of magmatic processes. A remaining challenge is to determine the timescale of relatively short magmatic processes that occur within hours to weeks, such as the ascent of magma towards the Earth's surface, which can play a key role in controlling eruptive style. Our recent study has shown that chemical zoning of volatile elements, such as chlorine (Cl), in volcanic apatite is a promising new indicator of the times and rates of magma ascent. However, application of this new tool requires knowledge of the diffusion mechanism and rates of volatile elements/molecules in apatite. We have performed experiments at magmatic temperature (800–1100 °C), 1-atm to determine the diffusivities of F-Cl-OH in apatite. We used gem-quality natural crystals with distinct compositions of F-Cl-OH, and made two types of diffusion couples by either embedding a single crystal into fine powders, or depositing nanoscale thin film over single crystal. Compositional profiles were obtained from the experimental products using multiple techniques, including secondary ion mass spectrometer (SIMS), electron microprobe (EPMA), and nuclear reaction analyses (NRA). A striking feature of the chemical profiles is the presence of uphill diffusion of Cl, which reflects a multi-component diffusion process of F, Cl and OH, whose anions are present at the same crystallographic site of apatite. Compositional profiles measured from the run products using SIMS and EPMA were fitted with those computed using a three-component diffusion model (based on a finite-difference algorithm) to extract the diffusivities of F, Cl and OH. We find that parallel to the c-axis, F diffuses faster than Cl which in turn diffuses faster than OH, and the difference in diffusivities between F and OH is more than one order of magnitude. The diffusion of Cl and OH is anisotropic, i.e. one to two orders of magnitude faster parallel to the c-axis than perpendicular to it. We have applied the new diffusion data and to natural apatite from two eruptions with distinct explosivities at Merapi volcano (Indonesia). We find that the Cl zoning in apatite from the dome-forming eruption in 2006 requires magma ascent to occur at least 12 to 14 days before eruption, whereas the absence of Cl zoning in apatite from the more explosive eruption in 2010 reflects a maximum time of magma ascent of about 5 days. The calculated timescales match with the duration of volcanic unrest before the two eruptions, and reflect more rapid magma ascent in 2010 than 2006. Our diffusion data and model based on apatite provide new constraints on the times and rates of magma ascent, which would contribute to a better understanding of the cause of different eruption activities, and to potentially more accurate eruption forecasting.

Keywords: Apatite, Multicomponent diffusion, Magma ascent, Timescale, Eruptive style