Refining timescales of magmatic processes and volatile transfer in subvolcanic systems with 3D diffusion modeling of complex crystals

Adrien Mourey[1], *Euan Mutch[1,2]

1. Earth Observatory of Singapore, Nanyang Technological University, 2. Asian School of the Environment, Nanyang Technological University

Constraining the timescales of magma processes and volatile loss is essential for understanding how fast magmas ascend and release volatiles to the surface, directly influencing eruption dynamics and volcanic hazards. These timescales can be retrieved through diffusion chronometry, which models the compositional zoning in crystals and melt inclusions generated by diffusion during magma storage, ascent, and eruption. However, current diffusion chronometry approaches primarily rely on 1D models that neglect the complex 3D structures of crystals and melt inclusions, leading to potentially inaccurate reconstructions of subsurface magmatic timescales and degassing pathways. Here, we present the first 3D diffusion model for natural olivine crystals containing melt inclusions, using X-ray micro-tomography and finite element numerical modeling. By applying our approach to a suite of olivine crystals from Kīlauea (Hawai ʻi) that display complex morphologies from skeletal to polyhedral, we estimate decadal magma storage times linked to olivine core Fe-Mg re-equilibration and pre-eruptive mixing of days to weeks from rim zoning, quantify maximum cooling rates of 7.5–15 °C/s from Mg diffusion in melt inclusions, and calculate decompression rates of 1×10^{-4} to 6.3×10^{-3} MPa/s from water contents in olivine-hosted melt inclusions using an analytical solution for diffusive equilibration of water in an anisotropic host. Given the ubiquitous presence of complex mineral textures in volcanic systems worldwide, our approach offers a transferable framework to constrain the timescales of volatile degassing and magmatic processes across diverse tectonic settings on Earth and beyond, thereby enhancing forecasts of magma evolution and volcanic hazards.

Keywords: Diffusion chronometry, X-ray micro-tomography, Melt inclusions, Numerical Modelling