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Quantifying dynamic rheology, phase interactions and strain localisation in deforming three phase magmas using high-speed x-ray tomography

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The crystal and bubble cargoes of magmas are critical to controlling magma mobility and rheology. These cargos vary in both time and space and the local, and bulk, rheological behaviour are correspondingly heterogeneous. Tracking how these heterogeneous cargoes evolve, and how crystals and bubbles interact with each other in deforming systems is a critical challenge in volcanology, as these processes control both the chemical and physical evolution of the magma, including phenomena such as melt-crystal segregation, strain localisation, and fragmentation. The only methodology available to track these processes in real time, and at the scale of individual melt-crystal-bubble interactions is high speed x-ray tomography. This non-destructive imaging technique allows the rapid acquisition of sequential 3D images that capture the physical, and to some degree chemical, microstructure of the sample during a deformation cycle.

We utilise in situ tomographic methods developed in materials science to perfume magmatic deformation experiments on synthesized three phase systems at magmatic temperatures. Through a novel combination of a high temperature laser heating system [1] in situ micro-precision deformation apparatus [2] and the temporal and spatial resolution available at the TOMCAT beam line at the Swiss Light Source synchrotron facility we performed in situ observations of the microstructural evolution of a synthesized anhydrous borosilicate melt seeded with a variable concentration of non-reactive rutile crystals and air bubbles (30-70 volume %). The experiments were conducted at 800-1000C, under constant deformation rates of 0.25-5.00 microns/second. Each 3D image has 2D and 3D spatial resolution of approximately 3 microns per pixel, and each 3D image took $\sim$3 seconds to acquire.

Here we present this innovative high speed, high temperature, syn-deformation tomographic data , and show how it can be used to trace the location and local distribution of each crystal and bubble within a small volume cylindrical experimental charge (3mm diameter, 5mm length) undergoing shear along a single vertical plane. By qualitative and quantitative analysis of the sequential images collected over 5-15 minute deformation cycles we track the local bubble, crystal and melt concentrations on a range of spatial scales. From this we calculate a spatially heterogeneous and dynamic local viscosity [3] and assess our results against recently developed 3-phase rheological models [4]. We will present how this real time 4D information can be used to quantify the dynamics of magma motion, discuss the implications of spatially and temporally variable rheological behaviours, and show how this novel technique can be integrated with other volcanology methods to improve our understanding of volcanic and magmatic processes.

[1] Fife et al. 2012. J. Synchrotron Rad. 19, 352-358
[2] Kareh et al. 2014 Nature Comm. 5 4464.
[3] Giordano, et al. 2008 EPSL 271 123-134.
[4] Truby et al. 2015 P.Roy.Soc.A. 2015471 20140557