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Is magma modeled as a hard-sphere suspension or soft-sphere suspension?

Aika Kurokawa[1*], Kei Kurita[1]

[1]Earthquake Research Institute, University of Tokyo

Magma is known as a complex fluid composed of three phases; silicate-melt, crystals and gases. Generally the rheology of suspension changes drastically depending on the mutual volume fraction from gaseous behavior to solid one. The rheology of magmatic system consisting of crystals and silicate melt has been modeled via hard-sphere suspensions such as a mixture of glass beads and viscous fluid. With respect to such solid-liquid system, [A. A. Arzi, 1978] introduced an important concept, Rheological Critical Melt Percentage (RCMP) 20%, which separates solid behavior and liquid behavior. RCMP is understood as a kind of jamming transition and important value since it predicts freezing rheologically above the thermodynamic freezing point. But even at larger melt percentage than RCMP, another type of significant change in the magmatic rheology has been clarified experimentally. That is the emergence of yield strength at the crystal volume fraction of around 20%. From this critical value to (100% - RCMP), magma behaves as a yield stress fluid. On the other hand, models for simple hard-sphere suspension predict this behavior at much higher volume fraction of approximately 60% e.g. [M. Otsuki et al., 2010]. Thus the range in which hard-sphere suspension behaves as a yield stress fluid is quite limited compared to laboratory-determined magmatic rheology. This is because the shape of silicate crystals in magma is generally elongated, which should be modeled as prolate or oblate ellipsoids with high aspect ratio and crystals in magma can easily form networked structures known as crystal clots, crystal cluster, synneusis, crystal chain and so on even if the particle volume fraction is small. Therefore to estimate effective volume fraction, the excluded volume should be considered [A. P. Philipse, 1996].

In this presentation we discuss whether the hard-sphere suspension is an adequate model for the magma and what are needed for proper modeling. Although individual silicate crystals are hard enough in the time scale of magma dynamics, the networked structure of crystals is quite weak and it easily breaks upon flowing stress. Yield stress emerges during breakage of the network. To look at this behavior, we consider the system should be composed of soft-sphere instead of hard-sphere, where widespread repulsive potential as well as a kind of attractive potential are needed.

We utilized an analog material, a polymer, p-NIPAM to conduct rheology characterization of suspension to see complex behaviors of magma by the deformability associated with the networked structures. In a series of our model experiments, firstly it was revealed that p-NIPAM aqueous suspension has the critical volume fraction, which is almost equivalent to that of magma. This indicates p-NIPAM aqueous suspension can be an analogue of magma to see complicated behaviors in magma caused by networked structures of crystals. At the same time it was found that this suspension has a multiplicity relationship between shear stress and shear rate and this multiplicity and the yield stress are inextricably linked together via aging effect. We consider this should be a universal characteristic for two-phase mixture system such as suspension, which has networked structures. Since magma suspension is known to have the yield stress and the networked structures of crystals empirically, this result indicates that magma can possesses the multiplicity, which can trigger self-induced oscillation phenomena.