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The flow-to-sliding transition in crystalline magma

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Magmatic flows are rarely, if ever, entirely free of crystals. If these crystals distribute in an approximately homogeneous way, their impact on flow can be captured by defining a suitable effective viscosity for the suspension. A spatially heterogeneous crystal distribution, however, can build up to the degree that the flow behavior of the crystal-bearing magma becomes substantially different from that of a pure melt. One example is the transition from flow to sliding, in which the deformation in the crystalline magma is concentrated almost entirely in a thin interfacial layer as opposed to being distributed in a typical flow profile throughout the domain. The transition is particularly consequential for the large-scale dynamics of the system, because it can be associated with transport rates increasing by orders of magnitudes.

Most conduit models associate the flow-to-sliding transition with a critical crystal fraction, often in the 60% range. Here, we hypothesize that the flow to sliding transition can occur at crystal fraction as low as a few percents under certain conditions. We test our hypothesis by numerically reproducing existing laboratory measurements of the effective viscosity of plagioclase-bearing basalt in a rotational viscometer. We utilize a direct numerical method to resolve the interactions between the crystals and the magmatic melt at the scale of individual interfaces in 2D. Our numerical approach only requires assumptions about the pure phase including the crystal fraction and crystal shape. All phase interactions and their aggregate effect on the flow emerge self-consistently from the simulation itself.

Our simulations suggest that the behavior of multiphase suspensions at low fluid Reynolds number is highly variable and depends sensitively on the characteristics of the immersed phases and the geometry of the flow domain. We show that there is no meaningful dilute limit in which the phase interactions can be neglected or captured by adjusting the effective rheology of the suspension in a way that removes dependencies on the properties of the immersed phase. Since our models operate at the scale of individual crystals, our model results are testable in both field and laboratory settings. In fact, they suggest that observations of microstructure provide valuable constraints on the large scale flow dynamics at the time. Particularly important is the degree of preferential crystal alignment and the existence of force chains or crystal clusters.

