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The rheology of crystal-rich magmas (Kuno Award Lecture)

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The rheology of magmas controls not only eruption dynamics but also the rate of transport of magmas through the crust and to a large extent the rate of magma differentiation and degassing. Magma bodies stalled in the upper crust are known to spend most of their lifespan above the solidus at a high crystal content (Cooper and Kent, 2014; Huber et al., 2009), where the probability of melt extraction (crystal fractionation) is the greatest (Dufek and Bachmann, 2010). In this study, we explore a new theoretical framework to study the viscosity of crystal bearing magmas. Since the seminal work of A. Einstein and W. Sutherland in the early 20th century, it has been shown theoretically and tested experimentally that a simple self-similar behavior exist between the relative viscosity of dilute (low crystal content) suspensions and the particle volume fraction. The self-similar nature of that relationship is quickly lost as we consider crystal fractions beyond a few volume percent.
We propose that the relative viscosity of crystal-bearing magmas can be fully described by two state variables, the intrinsic viscosity and the crowding factor (a measure of the packing threshold in the suspension). These two state variables can be measured experimentally under different conditions, which allows us to develop closure relationships in terms of the applied shear stress and the crystal shape and size distributions. We build these closure equations from the extensive literature on the rheology of synthetic suspensions, where the nature of the particle shape and size distributions is better constrained and apply the newly developed model to published experiments on crystal-bearing magmas. We find that we recover a self-similar behavior (unique rheology curve) up to the packing threshold and show that the commonly reported break in slope between the relative viscosity and crystal volume fraction around the expected packing threshold is most likely caused by a sudden change in the state of dispersion of the magma (change in the state variables caused by either shear localization or crystal breakage). We argue that the model we propose is a first step to go beyond fitting experimental data and towards building a predictive rheology model for crystal-bearing magmas.

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