Crystal shape exerts a first order control on magma rheology

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Suspended crystals have a strong impact on the rheology of magma. It is well known that magma viscosity increases non-linearly as crystal fraction increases, and that shear thinning, yield stress and other non-Newtonian phenomena emerge at moderate-to-high crystal fractions. It is less widely recognized that the shape of the crystals also plays a crucial role in determining suspension rheology. We present a simple model for the rheology of suspensions of crystals, which accounts for crystal shape.

Our model is based on the results of laboratory analogue experiments which quantify the rheology of suspensions of particles in a Newtonian liquid. The aspect ratio of the particles is systematically varied in the range 0.04 to 22 (i.e. from strongly oblate to strongly prolate). For each aspect ratio, we quantify the suspension viscosity η_r as a function of particle fraction ϕ_m from close to the dilute limit to close to the maximum packing fraction ϕ_m. We find that viscosity increases as a power law function of particle fraction for all aspect ratios, and that the increase is more dramatic the more oblate or prolate the particles are. The data are well described by the Maron Pierce model: $\eta_r = (1 - \phi/\phi_m)^{-2}$ when ϕ_m treated as a fitting parameter. Another way of saying this is that the curves of viscosity against particle fraction collapse to a single curve when particle fraction is normalized by the maximum packing fraction. We use this fitting approach to determine ϕ_m for each particle aspect ratio dataset and find a systematic relationship between particle aspect ratio and maximum packing fraction, which is well captured by a (purely empirical) log-Gaussian function. This relationship allows maximum packing fraction to be calculated for particles of known aspect ratio.

Application of the model to determine the viscosity of a crystal bearing magma is straightforward when crystal fraction and aspect ratio are known. We demonstrate this by incorporating our viscosity model into a test bed conduit flow model. The results show that crystal shape has a profound influence on model predictions and that ignoring crystal shape introduces serious errors into models of magma flow. We adopt a benchmark case of the explosive eruption of magma with 30% fraction of crystals with aspect ratio of 10 (a reasonable value for prolate microlites). If we ignore particle shape and treat crystals as equant, the crystal fraction has to be increased from 30% to greater than 50% to obtain the same results.