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Effects of crystals on the rheology and convection of magma

A.C. Rust (1), N.J. Balmforth (2), A.M. Jellinek (2)

(1) University of Bristol, U.K., (2) University of British Columbia, Canada
(Alison.Rust@bristol.ac.uk)

This study explores the sensitivity of the dynamics of magma convection to rheological models for crystal-rich magmas. We present theoretical and experimental stability results on Rayleigh-Bénard convection of fluids with a yield strength. For Newtonian fluids, motion should spontaneously grow from ambient noise once the temperature gradient exceeds a critical value. In contrast, for a Bingham fluid that is treated as rigid at stresses below the yield strength, an order one stress perturbation is required to initiate motion for any temperature difference. However, magmas may not be totally rigid at small stresses. We find that if the fluid is viscoelastic or very viscous at low stresses then there are critical Rayleigh numbers for instability.

In the laboratory we examine the convection of a fluid with a Herschel-Bulkley rheology. By varying rheology and temperature gradients we evaluate how convective instability is modified by yield stress. We also examine the effects of localized perturbations (e.g., bubble rise) on the onset and subsequent pattern of convection. We find that yield strength drastically inhibits the onset of convection and if convection does occur, flow is much more localized than for a Newtonian fluid under the same conditions. Where an extrinsic perturbation motivates convection, it is the magnitude rather than the frequency of the perturbation that matters.

Our results highlight the importance of understanding the details of the nature of yield strength for predicting the onset and pattern of convection. Furthermore, the effect of yield strength on convection may depend on whether the magma is initially stagnant (e.g., the heating of a locked mush) or whether it develops a yield strength due to crystallization as it convects.