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The nature of yield strength and effects on Rayleigh-Bernard convection

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We present experimental and theoretical stability results on Rayleigh-Bénard convection of viscoplastic (e.g., Bingham) fluids. These flows are relevant to the convection and mixing of magmas and muds as well as planet-scale convection. For Newtonian fluids where there is no yield strength, 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 (i.e., linearly stable at all Rayleigh numbers). However, real fluids including magmas and muds will not be perfectly rigid solids at small stresses and we find that stability is sensitive to the rheology below the yield stress. If the fluid is viscoelastic or very viscous at low stresses then there are critical Rayleigh numbers for instability, which in the viscoelastic case is an oscillatory instability.

These theoretical results highlight the importance of understanding the details of the nature of yield strength for predicting the onset of convection. In the laboratory we examine the rheology and convection of carbopol, a homogeneous viscoplastic fluid typically described with a Herschel-Bulkley constitutive law but is dominantly elastic below its yield stress. 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 through fluid) on the onset and subsequent pattern of convection. Preliminary results indicate that even very small yield strengths drastically inhibit the onset of convection and if convection does occur, flow is much more localized than for a Newtonian fluid under the same conditions. In particular, carbopol with an apparent viscosity (above the yield stress) such that the convection should be turbulent exhibits cellular convection. It seems that yield stress prevents turbulence and confines upwelling to the pathway set up at the start.