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Universal brittle-viscous transition in magmatic liquids

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All explosive eruptions involve the transition in magma behaviour between dominantly viscous and transiently brittle. This can happen by exceeding a critical velocity or by exceeding a critical vesiculation rate in the volcanic conduit. In both cases the local shear rate exceeds the structural relaxation rate of the liquid, causing the liquid phase to become unrelaxed such that it may support fracture propagation.

Here we collate a database of published observations in which natural, synthetic, and analogue magmas of a range of compositions were deformed by decompression-induced vesiculation or shear deformation under applied shear stresses. In all cases, a single characteristic structural relaxation timescale of the liquid is constrained and compared with the dominant timescale of deformation. We show that the ratio between these two timescales – a Deborah number (De) – can be used to scale the threshold between different behaviors. We find that irrespective of composition or experiment type, De = 0.01 defines the threshold between relaxed viscous flow and unrelaxed fracture propagation, and that De = 1 is a second threshold between fracture propagation and entirely brittle failure. These two thresholds are consistent with the onset of elasticity and peak elasticity, respectively, determined by rheological measurements in the frequency domain.

When De is < 0.01 – the regime in which liquids are purely viscous – the Brinkman number (Br) scales the threshold between deformation timescales that will result in a dominant viscous heating effect and those that won't. Unlike the Deborah number, Br is scale-dependent, and so it is specific to these studies investigated.

We posit that in a volcanic conduit, De is highest at the conduit margin, where the deformation timescale is lowest. Moving toward the conduit center De decreases, passing through the brittle threshold (De = 1), transitional behaviour (0.01 < De < 1) and to viscous behaviour (De < 0.01) until reaching the center where the deformation timescale is highest and relaxed viscous flow dominates. We use these insights to explore the ratio between the two timescales for liquids of different compositions at typical eruptive temperatures to construct a universal deformation and relaxation map for different eruption styles.