



Review

The rheology of two-phase magmas: A review and analysis

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ABSTRACT

We consider the current state of our understanding of the rheology of two-phase magmas, that is suspensions of either bubbles or crystals in a viscous silicate melt. The discussion is restricted to strain-rates at which the suspending melt can be considered Newtonian. We start by considering the range of textures found in magmas and the bubble deformation and particle motions caused by shearing. We then review proposed models for suspensions, focussing on those functions of the form $\eta_r = f(\phi)$ or $\tau = f(\dot{\gamma})$ that have been most widely used to describe magmatic systems (η_r is the relative apparent viscosity of the suspension, ϕ is the volume fraction of the suspended phase, τ is the driving stress, and $\dot{\gamma}$ is the strain-rate). Both theoretical and empirical methods are presented and then compared against the available analogue (i.e. non-magmatic) and magmatic data. The paper contains new data and significant re-analysis of previously published data. We present a new semi-empirical constitutive model for bubble-bearing magmas that is valid for steady and unsteady flow and large strains and strain-rates. This equation utilises a new parameter, the capillarity C_x , that encapsulates the combined effect of shearing and unsteadiness on bubble suspensions. We also present a new scheme for dealing with polydispersity of bubble suspensions. New data on the rheology of particle suspensions undergoing forced-oscillations are presented. These data show that the Cox–Merz rule only holds for dilute particle suspensions $\phi \lesssim 0.25$. A re-analysis of all available experimental data that relate rheology to particle aspect ratio provides distinct curves of maximum packing as a function of aspect ratio for smooth and rough particles with magmatic data lying on the curve appropriate for rough particles. We analyse several rheological datasets of crystal-bearing basaltic magmas and find that they are in good agreement with the constitutive equations derived from analogue data. By contrast, the same equations do not agree well with data for high-viscosity, haplogranitic melts. This may be an effect of fracturing or viscous dissipation within these samples. The paper concludes with a practical 'rheological recipes' section giving a step-by-step method for calculating a constitutive equation for a two-phase magmatic suspension and assessing its likely accuracy.

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Contents

1.	Introduction	136
2.	Melts and magmas	137
3.	Bubbles and particles in flow	137
3.1.	Bubble deformation, unsteadiness and viscoelasticity	137
3.2.	Particle motions	140
4.	Models	140
4.1.	Constitutive equations for particle suspensions	141
4.2.	Constitutive models for bubble suspensions	143
4.3.	Constitutive models for polydisperse suspensions	144
5.	Methods	146
5.1.	Relating observables to stress and strain-rate	146
5.2.	Oscillatory rheometry and the Cox–Merz rule	147
5.3.	Analogue versus magmatic methods	147

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6.	Data	147
6.1.	Bubble suspension rheology	148
6.2.	Particle suspension rheology	149
7.	Rheological recipes	152
7.1.	Melt phase rheology	152
7.2.	Crystal-bearing magma	152
7.2.1.	Worked example	153
7.3.	Bubble-bearing magma	154
7.3.1.	Worked example	154
8.	Concluding remarks	155
	Acknowledgements	156
	Appendix A. Supplementary information	156
	References	156

1. Introduction

It is difficult to overstate the importance of an accurate, quantitative description of the *rheology* of magmas for volcanological research. This knowledge is fundamental to determining the rate at which a magma will flow, the internal forces and structures that will be generated during the flow, and ultimately the distance attained before magma finally comes to rest (e.g. Lautze and Houghton, 2005; Llewellyn and Manga, 2005; Melnik and Sparks, 2005; Rowland et al., 2005; Carrichi et al., 2007; Gonnermann and Manga, 2007; Hale and Wadge, 2008; de Maissoneuve and Bachmann, 2009; Massol and Jaupart, 2009; Applegarth et al., 2010). Flow rates and internal forces or pressures are intimately linked to degassing and crystal growth and so magma rheology can also be a key determinant of magma geochemistry (e.g. Cashman and Blundy, 2000; Hale et al., 2007). Magma rheology is therefore a controlling input to all models of magmatic flow and hence our ability to predict volcanic hazards or interpret the volcanic record.

A quantitative description of the rheology of any fluid involves establishing how the deforming stress, the *shear stress* τ , is related to the rate of deformation, the *shear strain-rate* $\dot{\gamma}$. In general, a *constitutive equation* is given by $\tau_{ij} = f(\dot{\gamma}_{ij})$ where τ_{ij} and $\dot{\gamma}_{ij}$ are tensors that give a three-dimensional description of stress and strain-rate, respectively. For many flows of practical interest, including most flows which are used to measure rheology, the rectilinear nature of the flow and the symmetry of the tensors allows the equation to be reduced to the one-dimensional form $\tau = f(\dot{\gamma})$. Conventionally, stress is plotted against strain-rate to produce a *flow curve* (Fig. 1). The simplest constitutive equation is $\tau = \mu\dot{\gamma}$ which produces a flow curve that is a straight line through the origin with a slope of μ . Fluids with such a flow curve are called *Newtonian* and μ is the *viscosity* which is a parameter of the fluid that is independent of strain-rate, although it is usually strongly dependent on other variables such as temperature. (For a tensorial treatment of the main equations used in this review, refer to the Supplementary Information.)

Many fluids exhibit *non-Newtonian* rheology. A few examples of the non-linear flow curves associated with some typical non-Newtonian behaviours are also shown in Fig. 1. It is not possible to define a single, strain-rate-independent viscosity for such non-linear flow curves. However it is common practice to describe the rheology of non-Newtonian materials in terms of an *apparent viscosity* η which is simply the ratio of stress to strain-rate ($\eta = \tau/\dot{\gamma}$) and varies with strain-rate. Care must be taken in interpreting apparent viscosity for the following reasons. Graphically, η is the slope of the straight line to the point on the flow curve $(\dot{\gamma}, \tau)$. This slope gives the viscosity that a Newtonian fluid would have to have for its flow curve to go through that point. But the straight line to a point on a non-linear flow curve bears little relationship to the flow curve itself. Furthermore, whilst the ratio of stress

to strain-rate $\eta = \tau/\dot{\gamma}$ for a non-Newtonian fluid will of course have dimensions of viscosity, the constitutive equation $\tau = f(\dot{\gamma})$ for the non-Newtonian fluid need contain no parameter with dimensions of viscosity. Nevertheless, it is intuitive to think in terms of viscosity and so we will here also use the apparent viscosity, where this produces useful insights.

The source of the non-Newtonian rheology seen in many single phase fluids is associated with the arrangement of the molecules and the nature of the bonds between them; for example, polymers are usually non-Newtonian, as is the process of *creep*, which is the very slow flow of crystalline solids such as ice or rock. In magma, however, non-Newtonian rheology typically arises from the presence of a dispersed phase of either crystals or bubbles. In fact magma is rarely monophasic and is usually a suspension of solid particles (phenocrysts, microlites, lithics) and gaseous bubbles in a viscous carrying liquid (a silicate melt). Such multiphase suspensions are commonplace in nature and in industry and display all manner of non-Newtonian behaviour. As we shall see, suspended particles can cause the development of a yield stress. The surface tension of bubbles provides an internal restoring force which introduces a component of elasticity, so bubble

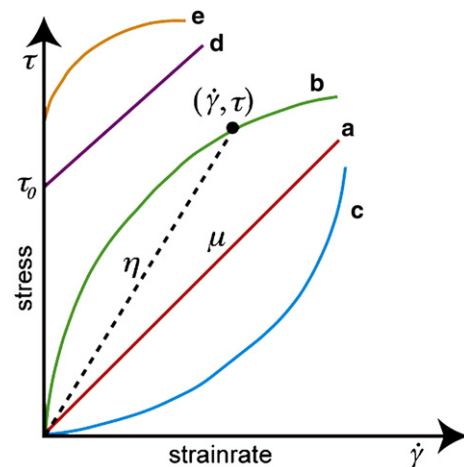


Fig. 1. Typical flow curves. (a) Newtonian (e.g. water, silicone oil, golden syrup, silicate melts), $\mu = \tau/\dot{\gamma}$. (b) Shear-thinning or *pseudoplastic* (e.g. ice, blood, paint). (c) Shear-thickening or *dilatant* (e.g. wet sand, wet starch). (d) Bingham (e.g. toothpaste, margarine) $\tau = \tau_0 + \eta_*\dot{\gamma}$. For these fluids, a minimum stress, the *yield stress* τ_0 , has to be overcome for flow to start. Note that whilst η_* does have dimensions of viscosity and is a constant, it is not the same as the apparent viscosity η , which varies with strain-rate, despite the linear relationship between stress and strain-rate. (e) Herschel-Bulkley, an example of a *plastic* fluid, $\tau = \tau_0 + K\dot{\gamma}^n$, shown here with $n < 1$, i.e. shear-thinning. The apparent viscosity η , which is the slope of the (dashed) line to a specific example point $(\dot{\gamma}, \tau)$, is also shown.

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