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# Flow and fracturing of viscoelastic media under diffusion-driven bubble growth: An analogue experiment for eruptive volcanic conduits

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**Abstract**

To visualize the behavior of erupting magma in volcanic conduits, we performed shock tube experiments on the ductile–brittle response of a viscoelastic medium to diffusion-driven bubble expansion. A sample of shear-thinning magma analogue is saturated by gas Ar under high pressure. On rapid decompression, Ar supersaturation causes bubbles to nucleate, grow, and coalesce in the sample, forcing it to expand, flow, and fracture. Experimental variables include saturation pressure and duration, and shape and lubrication of the flow path. Bubble growth in the experiments controls both flow and fracturing, and is consistent with physical models of magma vesiculation. Two types of fractures are observed: i) sharp fractures along the uppermost rim of the sample, and ii) fractures pervasively diffused throughout the sample. Rim fractures open when shear stress accumulates and strain rate is highest at the margin of the flow (a process already inferred from observations and models to occur in magma). Pervasive fractures originate when wall-friction retards expansion of the sample, causing pressure to build-up in the bubbles. When bubble pressure overcomes wall-friction and the tensile strength of the porous sample, fractures open with a range of morphologies. Both types of fracture open normally to flow direction, and both may heal as the flow proceeds. These experiments also illustrate how the development of pervasive fractures allows exsolving gas to escape from the sample before the generation of a permeable network via other processes, e.g., bubble coalescence. This is an observation that potentially impact the degassing of magma and the transition between explosive and effusive eruptions.


*Keywords:* volcanic conduit; analogue experiment; vesiculation; fragmentation; degassing

## 1. Introduction

During volcanic eruptions, the liberation of volatiles through vesiculation can generate contrasting physico-chemical behaviors of the enclosing magma. Amongst the physical changes, fast volume increase is in most decompressive cases the most relevant, generating a dramatic increase in the rate of deformation of the magma and an acceleration of the processes that often lead to an explosive eruption. Here we investigate the expansion, flow and fragmentation of magma using an analogue material which undergoes rapid vesiculation. In particular, we use a viscoelastic magma analogue to simulate the rate-dependent viscosity of magma, and we

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investigate the specific case of bubble growth driven by strong supersaturation.

Despite the long-standing acknowledgement of its central role in explosive volcanism, the investigation of nucleation, growth, and coalescence of gas bubbles in magma (magma vesiculation) is still providing new insights into eruptive phenomena. Recent examples come from three aspects of magma dynamics in volcanic conduits: flow, fragmentation, and degassing. Firstly, complex rheology controls how magma flows in volcanic conduits: the abundance, and size and shape distribution of bubbles strongly affect the rheology of magma [1–6] and its resulting flow profile in volcanic conduits [7]. Secondly, bubble growth in magma forces the liquid phase to deform differentially at small- and large-scales (i.e., around each bubble vs. up the volcanic conduit). At present it is still unclear if, during explosive eruptions, viscoelastic magma fragments in response to the small- or large-scale deformation and stress accumulation [8–10]. Moreover, total porosity, thickness of bubble walls and bubble pressure likely control magma fragmentation during both steady and unsteady fast decompression events [11–15]. Thirdly, bubble coalescence can eventually cause magma to become permeable and, via degassing, to erupt effusively instead of explosively [16–18] or less explosively [19]; coalescence and permeability also affect the final texture and emplacement mode of pyroclasts [e.g., 20].

Published experimental investigations on magma vesiculation used either silicate melts (remelted rock or synthetic) at magmatic temperature or analogues (including water, gum–rosin solutions, and silicon and other polymers) at ambient or lower temperature. The former are best suited for nucleation, growth, and coalescence experiments that involve relatively small strain and strain rates of the sample [e.g., 18,21,22] and the latter are best suited for highly non-equilibrium bubble expansion/fragmentation experiments at higher strain and strain rates [e.g., 23–26]. In particular, this last group of experiments does not aim at rigorous scaling of natural processes, but, as noted by [27], represents "a tool to identify and investigate the fundamental processes and interactions operating within the flows". Within this frame we present a new type of analogue experiment on magma vesiculation and fragmentation that can be used to investigate many of the vesiculation-related processes mentioned above. A novel point of the experiment is the combination of a viscoelastic magma analogue, which has a rate-dependent rheological behavior more similar to magma [28], with the diffusion-driven nucleation, growth, and coalescence of bubbles.

## 2. Experimental techniques

### 2.1. Rheology of the magma analogue

Our magma analogue is a silicon polymer named "Changeable Silly Putty® ". It is viscoelastic and solvent of Ar gas depending on pressure. We used a forced oscillation rheometer to measure sample rheology within the linear viscoelastic region of response (stress range from 150.7 to 3037.9 Pa, peak strain of 20%) at 25 °C. The polymer is shear-thinning, its viscosity $\eta$ decreasing from $5\times10^4$ to $1\times10^3$ Pa s on the strain timescale $10^3$–$10^{-2}$ s, and its relaxation time $\tau$ is 0.2 s (Fig. 1). To evaluate the effect of dissolved Ar on the viscosity of the sample we measured the rate of sinking of a steel rod into the sample under high (10 MPa) and atmospheric pressure. Although we did not model the results to quantify the viscosity, only a minor increase in apparent viscosity under high pressure appeared (sinking velocity being 20% higher under atmospheric pressure than under high pressure), probably as a consequence of sample compaction. No other effect of dissolved gas on viscosity emerged.

### 2.2. Apparatus set-up

The experiments took place inside the Plexiglas® high-pressure chamber (volume $10^{-4}$ m$^3$, pressure up to 20 MPa) of a shock-tube apparatus (modified from [29]) (Fig. 2). Gas Ar entered in the chamber from the top so that the upper part of the sample saturated uniformly. The sample was left at room temperature under a given saturation pressure $P_s$ for a given saturation time $t_s$.

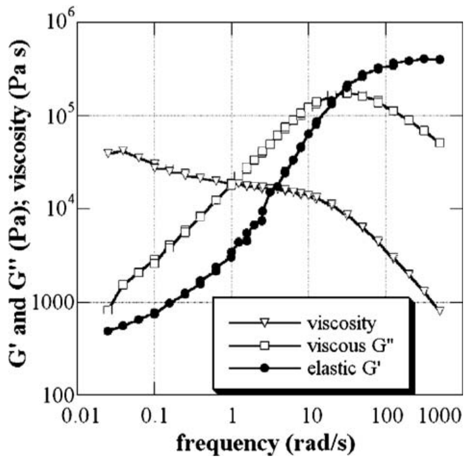


Fig. 1. The results of forced oscillation rheometry of the magma analogue at 25 °C show a shear thinning viscosity. A relaxation time of 0.2 s comes from the frequency where the elastic ($G'$) and viscous ($G''$) modulus cross each other.