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Gas accumulation in particle-rich suspensions and implications for bubble populations in crystal-rich magma

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A B S T R A C T

Gas mobility plays an important role in driving volcanic eruptions and controlling eruption style. The explosivity of an eruption depends, among other factors, on how easily gas can escape from the magma. Many magmatic systems have high concentrations of suspended crystals that inhibit gas migration through the melt. We use suspensions of plastic beads in corn syrup to investigate interactions between rising bubbles and particles. We observe different interaction styles as the ratio ψ of bubble to particle size is varied. Large bubbles ($\psi>1$) deform and sometimes break up as they move around particles. Small bubbles ($\psi<1$) are frequently trapped within the suspension, increasing the concentration of gas held within the system. We compare our experiments to bubble populations in tephra from Stromboli volcano, Italy. We show that these samples typically have bubbles and crystals of similar sizes and suggest that crystals might play a role in controlling bubble size in this natural system as well as in our experiments. Because small bubbles ($\psi<1$) get trapped within the suspension, and can be formed by breakup of larger bubbles, we expect that an increase in gas flux will result in an increase in the population of small bubbles. Changes in bubble number density and vesicularity in tephra erupted during periods of different eruptive intensity may thus provide a way of tracking changes in gas flux through the magma prior to eruption.

1. Introduction

Mafic eruptions are commonly interpreted using results of two-phase flow experiments (e.g. Vergniolle and Mangan, 2000). However, many volcanic systems include three phases (solid, liquid, gas), where the crystals present in suspension may influence the rise of gas bubbles. If the crystal concentration is low, the crystal-liquid mixture can be treated as a fluid with higher effective density and viscosity than the liquid phase alone, slowing bubble rise. If the crystal concentration is high, however, crystals might not be able to move freely, and the effect of solids on gas bubbles could be more complicated. In this study, we use analogue experiments to investigate the influence of particles on bubble populations in low Reynolds number (viscous) systems with high particle concentrations (~50% by volume). We focus on the dynamics of small bubbles in viscous suspensions, and examine what this can tell us about gas flux. We apply our results to Stromboli volcano, Italy, where the crystallinity is similar to the particle concentrations in our experiments, and gas rises through a mostly stagnant magma.

Experiments similar to ours have been done in high Reynolds number systems in chemical engineering. In these systems, the local percentage of gas in the system (termed gas holdup) generally decreases with increasing solids concentration because of an increase in particle-aided bubble coalescence. However, these studies demonstrate that the effect of particles on gas holdup is complicated and depends on both particle size and concentration (see Mena et al., 2005, for an overview). Here, we focus on the low Reynolds number equivalent, where inertia is negligible.

We compare the results of our experiments to bubble and crystal populations observed in tephra from Stromboli volcano. At Stromboli, gas migration through a shallow crystal-rich magma produces ~13 megatons of gas per day, of which only 10% is accompanied by eruption of volcanic rocks (Harris and Ripepe, 2007). These Strombolian eruptions occur every 10–15 min and eject tephra and ash to heights of a few hundred meters. Non-eruptive active degassing episodes (puffing) account for another 45% of the gas (Harris and Ripepe, 2007). These events are frequent (~ every 2 s) and produce pressure pulses of ~10^3 Pa at the vent (Ripepe et al., 2007). The remaining ~45% of degassing is completely passive. This shows that the overall gas flux at Stromboli far outstrips the magma flux.

At Stromboli, two magmas are inferred to exist at depth. They have similar, high potassium–basaltic compositions but differ in crystal content. Tephra erupted during normal Strombolian activity derives

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from magma with a crystallinity of approximately 50%. This (shallow) magma resides above a more volatile-rich and crystal-poor magma that is erupted as pumice during infrequent paroxysms (e.g. Bertagnini et al., 2003; Landi et al., 2004).

To investigate the mechanisms of small bubble migration through a crystal-rich, essentially stagnant magma such as at Stromboli, we perform analogue experiments using solid particles (plastic beads), gas (air bubbles) and a viscous fluid (corn syrup). We use different experimental setups to study 1) the influence of solid particles on the rise of a single bubble and 2) the influence of solid particles on bubble populations. In what follows, we first discuss our analogue experiments. We then use our experimental results to interpret bubble populations in crystal-rich tephra from Stromboli. We discuss the applicability of our experiments to Stromboli through a comparison of dimensionless parameters in both systems. We then combine our experimental results with data from the literature to speculate on the effect of gas flux on bubble populations at Stromboli.

2. Experiments and observations

We examine the rise of small bubbles through a viscous suspension using analogue experiments. The physical properties of the materials used in these experiments are listed in Table 1. Below, we first describe the setup and then the observations for three different sets of experiments. The first two examine how a single rising bubble interacts with particles. The third experiment examines the interactions of a stream of bubbles with particles.

2.1. Individual bubbles

The setup for the first set of experiments consists of a Plexiglas tank with a syringe and needle connected to the bottom (Fig. 1a). The tank is 15 cm wide, 25 cm tall and narrow (1.5 cm) in the third dimension (a Hele–Shaw cell) to ensure visibility through the particle layer. A randomly packed layer of plastic cubes with 7 mm sides was suspended on the interface between two types of corn syrup with different densities and viscosities (Table 1). The particle concentration in the suspension was approximately 50% by volume. The thickness of the particle layer was varied between 1 and 10 cm. Air injected into the system from below produced bubble sizes of 0.1 to 1 ml (bubble: particle width ratio ψ between 0.8 and 1.8). Measured wetting angles indicate that, in common with magmatic systems, the liquid phase preferentially wets the solid particles.

Increasing the bubble size relative to the particle size causes the interaction style to change (Fig. 2). When the bubble is much smaller than the pores in the suspension, it rises through the pores without displacing the particles and undergoes only minimal deformation (Fig. 2a). The speed of bubble rise varies along its contorted pathway around the particles. Very small bubbles sometimes stall completely beneath a particle, so that they are effectively trapped within the suspension. When the bubble is large and the particle layer is thin, the bubble can displace the particles in such a way that the bubble deformation remains small relative to the deformation of the suspension layer (Fig. 2d). When the particle layer is thick and the bubble is too large to move between particles without deforming, it can either elongate to move through the pores (Fig. 2b), or flatten underneath an individual particle. After a bubble flattens, it may either move around the particle or split into two or more parts (Fig. 2c) to create new bubbles that are sufficiently small to move through available pores in the network. The specific response depends on particle orientation (flat side down or edge down), position relative to the bubble (in the middle; towards the edge), and the bubble:particle size ratio ψ.

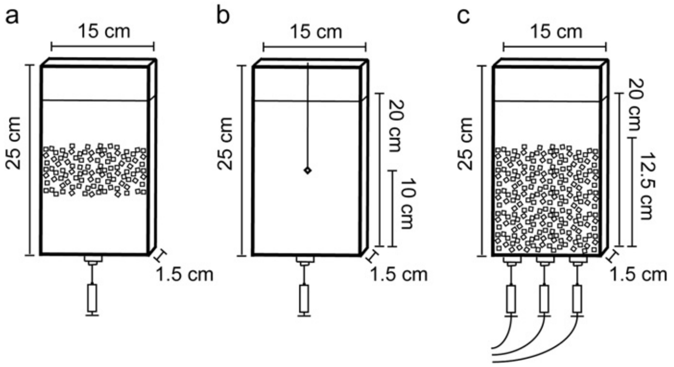

Fig. 1. Schematic of setups used to study a) styles of interaction between a single bubble and particles in suspension, b) occurrence frequency of different interaction styles between a single bubble and a single particle, and c) the effect of a particle suspension on bubble size distributions.

2.2. Splitting probabilities

We determined probabilities of different interaction styles between a single bubble and a single particle in a setup in which a particle was suspended from a metal rod into the low viscosity syrup (Fig. 1b). We injected a single bubble into the syrup approximately

Table 1

Properties of materials used in this study compared to natural systems. ρ: density, η: viscosity, V_b: bubble volume, d: bubble equivalent diameter, σ: surface tension, w: particle width, α: gas–solid wetting angle. Liquid properties for this study are measured at room temperature. [a] Value for the light syrup; the dense syrup was too sticky for the apparatus and its σ could not be measured. [b] Stromboli ρ: from Métrich et al. (2001) and Bertagnini et al. (2003) from glass in melt inclusions in pumice, η: calculated from compositional data for glassy matrices in crystal-rich scoria in Landi et al. (2004) using the method of Shaw (1972) with 0.1 weight% H_2O and T = 1115 °C (Landi et al., 2008) (not corrected for the influence of crystals), σ: based on Khitarov et al. (1979), d and w: dominant bubble and crystal sizes from Fig. 5a. Note that ρ and η are measured or calculated for glass and not corrected for the influence of crystals, and thus represent the density and viscosity of the melt phase alone and not the bulk magma. [c] Approximate volatile-free values at 1 bar, based on Spera (2000). [d] Basalt values from Khitarov et al. (1979). [e] Compositions ranging from dacite to synthetic haplogranite, from Bagdassarov et al. (2000) and Mangan and Sisson (2005). Wetting angles are measured on photos for experiments. SEM images for Stromboli show thin glass (melt) films between bubbles and crystals, indicating that the melt preferentially wets the crystals (0° wetting angle).

		This study	Mafic magma Stromboli[b]	Mafic magma	Silicic magma	Seawater
Liquid	ρ (kg/m^3)	Light syrup: 1320 Dense syrup: 1421	2690	2500–2700[c]	2350–2450[c]	1000
	η (Pa s)	Light syrup: 4.12 Dense syrup: 20	330	10^1–10^3[c]	10^5–10^{10}[c]	0.0018
Gas	V_b (ml)	0.1–1				
	d (mm)	5.8–12.4	0.1–0.3			
Liquid + gas	σ (N/m)	0.071[a]	0.1–0.4	0.09–0.4[d]	0.042–0.3[e]	0.072
Solid	w (mm)	7	0.1–0.3			
Liquid + gas + solid	α (°)	10–30	0			