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Segregation processes in vesiculating crystallizing magmas

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Abstract

Vesiculation of crystallising magma can produce either a mobile vesicular magma or a rigid network of crystals containing vesicular liquid. Where partially crystallized rigid mush underlies less-crystallized magma, such as near the base of a lava flow or in the cumulus pile of a magma chamber, evolved interstitial melt and/or gas may escape into the main body of magma. The consequences of this may include contamination of the overlying liquid with gas and interstitial melt, or intrusion of diapirs of vesicular evolved liquids to form vertical vesicle cylinders and other segregation features found in many basaltic lava flows and sills. Analog experiments were used to investigate some of the phenomena that can arise during vesiculation within a crystal mush, which was simulated by pumping air through a porous plate that formed the floor of a container filled with a viscous liquid floored with a layer of glass beads. Experiments used either a single liquid or two stably stratified liquids with a liquid interface either coincident with the top of the porous layer of beads or slightly above the porous layer. For a range of liquid viscosities and air flow rates (vesiculation rates), individual bubbles emerged from the top of the porous layer of beads and carried a thin trail of interstitial liquid into the overlying liquid. The number of bubble trains leaving the surface of the porous bed increased with decreasing liquid viscosity and flow rate, and with increasing bead size (and, hence, with increasing permeability). Analog vesicle cylinders, composed of diapirs of bubbly interstitial liquid, were produced only when a layer of buoyant bubbly liquid lay above the surface of the porous layer. The relative size of the bubbles and constrictions within the porous layer are argued to control whether individual bubbles (leading to bubble trains) or vesicular liquid (leading to vesicle cylinders) leaves the porous layer and hence whether vesicle cylinders can form.

Keywords: magma; lava; vesicles; segregations; porous medium

1. Introduction

Evolved magmas and igneous rocks are often formed during the crystallization and vesiculation of magma but, although the dynamical processes accompanying crystallization in volatile-undersaturated magma chambers have been studied extensively (e.g., Sparks et al., 1984; McBirney et al., 1985; Huppert et al., 1986; Tait and Jaupart, 1992; Jaupart and Tait, 1995), the role of vesiculation in igneous processes (as distinct from volcanic eruption processes) has received comparatively little attention. In lava flows, lava lakes, and shallow intrusions, the magma is typically vesicular and this can potentially introduce additional dynamical factors to the behaviour of the magma or lava. For example, three situations in which vesiculation and crystallization may

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play important roles are in driving evolved interstitial melt out of plutonic mushes to form highly evolved magmas (Sisson and Bacon, 1999; Bachmann and Bergantz, 2003); in the formation of vesicular segregations of evolved liquid within basaltic lava flows, lava lakes and sills (Anderson et al., 1984; Rogan et al., 1996; Goff, 1996); and in generating magmatic fluids capable of escaping into ore-forming environments (Candela, 1991). In these instances, crystallization drives the compositional evolution of the melt whereas vesiculation drives physical segregation of that evolved melt and/or gas. The interplay between vesiculation and crystallization, and the factors that influence that interplay, are therefore relevant in several igneous environments.

The general problem can be considered in terms of the progressive crystallization of a hydrous magma (melt plus crystals plus gas). The crystal assemblage will be anhydrous or nearly so, so the water fraction in the residual melt (±gas) increases. At high pressure, and low water content, the water remains dissolved and a point is reached when the magma becomes a porous rigid crystal framework containing interstitial residual melt. The transition from a mobile magma to a rigid crystal framework containing melt occurs at solid fractions between 0.2 and 0.5 depending on the shape and size of the crystals (Philpotts and Carroll, 1996; Philpotts et al., 1998; Hoover et al., 2001; Saar et al., 2001). At low pressures or high water contents, the residual melt becomes water-saturated and gas bubbles exsolve. The behaviour of the crystallizing magma now depends on the relative rates of vesiculation and crystallization, and also on the volumetric fraction of crystals. If vesiculation starts before crystallization has formed a rigid network, one of two behaviours is possible (Fig. 1). First, if the increase in gas volume occurs faster than the increase in crystal volume, crystals will be pushed apart by the rapidly expanding gas phase (Fig. 1(b)) such that the magma properties become less and less influenced by the presence of the crystals. Secondly, in contrast, if vesiculation is slow relative to crystallization, the magma can become a rigid crystal network containing vesicular melt (Fig. 1(c)). The latter situation can also arise if vesiculation does not start until after a rigid crystal framework has formed.

Whether a vesiculating magma evolves to a rigid or a mobile state obviously has implications for the subsequent behaviour of the magma and its constituent phases. In this paper we investigate the general properties of crystallizing vesiculating magma and use the results of analog

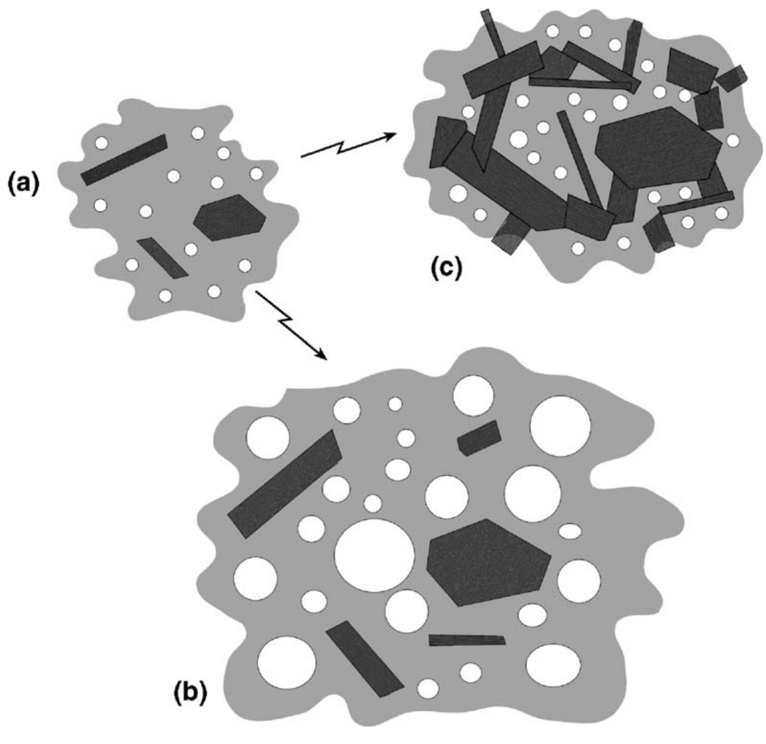

Fig. 1. Cartoon showing how a crystallizing hydrous magma may evolve from an initial stage shown in (a) into (b) an inflated mobile vesicular magma, or (c) a rigid porous crystalline matrix containing vesicular melt. In (b) crystal volume has increased at the expense of liquid volume, but the increase in gas volume has been much larger. In (c), gas volume has increased less than the crystal volume.