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Dynamics of magma flow near the vent: Implications for dome eruptions

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ABSTRACT

Magma erupting out of a volcanic vent into a flow or a dome is subjected to a marked change of boundary conditions which strongly affects the distribution of gas pressure and stress within the flow. A numerical code is implemented to study the role of degassing-induced crystallization. The 2-D governing equations for a compressible viscous liquid are solved with a fully axially symmetric Finite Element Model for different crystal contents and vent geometrical shapes. The potential effects of gas pressure, deformation rates and elongational stresses on the stability of endogenous dome growth are studied for two shallow vent structures. For common eruption conditions, values of the internal gas pressure at the vent may be as large as 2 MPa. The magnitude of gas pressure at the vent is sensitive to the amount of crystallization and to the shape of the shallow conduit beneath the vent. High tensile stresses of ≈2 MPa are generated at the vent, which may account for ring fracturing of the dome and gas escape through shallow fissures. Such failure conditions may also lead to a change of exit conditions, from lateral spreading to the vertical protrusion of a lava spine.

1. Introduction

Lava dome explosions and collapses are major hazards (Nakada and Fujii, 1993; Watts et al., 2002) and have motivated a large number of studies on shallow conduit flow processes (Gonnermann and Manga, 2003; Melnik and Sparks, 2005; Costa et al., 2007) and lava dome behaviour (Newhall and Melson, 1983; Iverson, 1990; Voight and Elsworth, 2000). Few studies, however, have treated the coupling between conduit and dome flows, and specifically how eruption behaviour depends on local flow conditions at the vent, where lava exits the volcanic conduit and spreads horizontally (Hale and Wadge, 2003, 2008).

Dome carapaces can fail during growth episodes, leading to the formation of individual lava lobes (Watts et al., 2002), so-called whaleback structures growing perpendicular to the flow direction as well as lava spines (Nakada and Fujii, 1993; Nakada et al., 1999). In some cases, concentric ring fractures develop above the vent and allow the degassing of magma (e.g.: (Matthews et al., 1997; Bluth and Rose, 2004). The link between brittle behaviour and degassing is obvious but potentially involves a host of different processes. The fracturing of magma may occur in the eruption conduit or within the dome itself. Following Gonnermann and Manga (2003), Hale and Muhlhaus (2007); Collier and Neuberg (2006) have proposed shear failure at the conduit margins, which provides pathways for gas escape and hence may prevent explosive regimes. Dome explosion or collapse has been attributed to large gas pore pressures and a highly discontinuous and irregular outer skin (Newhall and Melson, 1983). Evidence for excess pore pressure within dome lavas has been provided by many authors (Blake, 1990; Sparks, 1997; Fink and Griffiths, 1998; Massol and Jaupart, 1999; Lensky et al., 2004). The volume fraction of gas within lava domes varies within a large range of 0 to 70% (Ramsey and Fink, 1999; Kueppers et al., 2005), indicating that complex controls are at play. For instance, the texture of the 1980–1989 Mount St Helens lava dome alternated between a scoriaceous interior beneath a smooth skin and a smooth interior beneath a scoriaceous skin (Anderson and Fink, 1990). Fink and Griffiths (1998) have used analog experiments on the spreading of crust-forming materials to establish a widely used classification of lava dome morphology. The main variables are flow rate, viscosity and the magnitude of heat lost to the atmosphere (or water for subaqueous flows). In some cases, however, it has been proposed that the main control on dome emplacement is not cooling but degassing-induced crystallisation (Sparks et al., 2000). Degassing-induced crystallization depends on pressure changes during ascent and spreading at the surface, which depend on flow rate, but it also affects the rheology of magma and lava, and hence the eruption rate. Thus, one cannot specify the two processes independently and a self-consistent model of dome-forming eruptions requires a full dynamical framework specifying how excess pore pressures, flow stresses, degassing and crystallization develop.

Much information on phenomena that occur during lava dome build-up may be obtained from the extensive literature on polymer

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extrusion. Extrusion out of a thin tube proceeds in an increasingly complex fashion as the flow rate grows larger (Migler et al., 2002). The polymer is smooth for small extrusion rates and develops a series of different instabilities with increasing rate. The so-called sharkskin instability comes first, characterized by quasi periodic surface roughness, followed by stick–slip behaviour at higher extrusion rates. As the flow rate is increased further, gross melt fracture occurs as the polymer gets extruded in an irregular fashion. Detailed laboratory experiments and numerical calculations demonstrate that the key process is elongational deformation as the material exits the tube (Venet and Vergnes, 2000; Arda and Mackley, 2005). Such flow processes are expected for most types of materials, independently of their rheological behaviour (Venet and Vergnes, 2000).

The formation of ring-fractures that develop in the axial region of a dome and the generation of spines that protrude out of a dome provide important clues on the mechanisms of magma failure. In this paper, we argue that the behaviour of gas-laden crystal-bearing magma as it exits a volcanic vent is a key to such phenomena. We pursue two goals: (1) detail the dynamics of magma extrusion from a vertical conduit, and (2) use the appropriate boundary conditions for determining failure conditions within the lava. As an alternative to studies that focus on the dome itself (e.g.: (Voight and Elsworth, 2000; Hale and Wadge, 2003)), we couple the physics of ascent through the volcanic conduit with mainly horizontal spreading immediately outside the vent. Existing models are either 1-D or 1.5-D (e.g. (Gonnermann and Manga, 2003; Melnik and Sparks, 2005; Woods et al., 2006)) or focus on processes occurring in the conduit below the vent (Collier and Neuberg, 2006). To our knowledge, the only model that tackles ascent in a conduit and lateral spreading in a dome deals with an incompressible liquid and hence cannot be used to investigate the coupling between vesicularity and crystallinity (Hale and Muhlhaus, 2007; Hale and Wadge, 2008). We have explored some basic features of vesicular viscous flows in a previous paper (Massol et al., 2001). Here, we take into account the pressure dependence of the two viscosity coefficients that are required to describe such flows as well as the equation of state for crystallising magma. We study two different boundary conditions: a) a condition of zero horizontal and vertical velocity at a wall of already solidified magma corresponding to endogenous growth, referred to as laterally-constrained (LC) and b) a free surface condition such that lava can develop horizontal velocities above the vent, corresponding to exogenous growth, referred to as laterally-unconstrained (LU). We focus on the role of degassing-induced crystallisation and on the effect of the conduit shape near the vent, and investigate the conditions for magma fracturing.

2. Magma flow conditions

In most cases, lava that accumulates in a dome has lost gas on its way to Earth's surface. Degassing during ascent at depth involves a large number of processes that are active over a large pressure range and that are currently debated (Stasiuk et al., 1996; Cashman and Blundy, 2000; Gonnermann and Manga, 2003; Melnik and Sparks, 2005; Taisne and Jaupart, 2008). These processes are outside the scope of the present paper which is focussed on the vicinity of the eruptive vent. Magma has already lost gas when it enters superficial conduit levels and we consider a low initial dissolved water content consistent with the small eruption rates of dome eruptions. Such dissolved water content corresponds to what is left at the pressures that prevail at shallow depth. We shall see that these small water contents are sufficient to achieve gas volume fractions in excess of 60% at the vent, which are relevant to dome lavas. We shall study the complex gas pressure distributions generated by the rapid changes of velocity that occur as lava exits the vent. Such changes induce large decompression rates leading to large gas overpressures. We investigate the effect of different exit boundary conditions and conduit geometry on flow parameters such as pressure and velocities and on parameters measurable in the field such as gas content.

We now discuss the model assumptions and framework. As magma flows, it loses heat to the conduit walls. For the large conduit apertures that are relevant to dome eruptions, the width of the thermal boundary layer is negligible compared to the conduit radius (Bruce and Huppert, 1990; Sparks et al., 2000; Collier and Neuberg, 2006). We thus neglect heat losses and assume that temperature changes are small (Mastin and Ghiorso, 2000).

2.1. Degassing and crystallisation kinetics

With small amounts of water, the extrusion of magma is a slow process and we may safely assume that dissolved water in the melt is everywhere in thermodynamic equilibrium with a gas phase. We use a solubility law of the form:

$$x = sp^n, \tag{1}$$

where x is the mass fraction of volatiles dissolved in the melt at pressure p and s a coefficient determined from experiment. For water in silicic melts, we take $s = 4.11 \times 10^{-6}$ Pa$^{-1/2}$ (Burnham, 1979). Due to non-linear form of this solubility law, large changes of dissolved water contents occur at small pressures which induce crystallisation of microlites (Cashman and Blundy, 2000; Sparks et al., 2000; Hammer and Rutherford, 2002; Szramek et al., 2006; Martel et al., 2006). The mass fraction of crystals in the magma may be kinetically controlled (Hammer and Rutherford, 2002; Melnik and Sparks, 2005), but we do not consider such effects here as we focus on the slow eruption rates. We use a simple crystallisation law compatible with experimental data and observations (Whitney, 1988; Moore and Carmichael, 1998; Hammer and Rutherford, 2002). Assuming equilibrium, the mass fraction of crystals, f_{cx}, depends on the amount of degassing according to:

$$f_{cx} = \alpha_{cx}\left(\frac{x_0 - x}{x_0}\right), \tag{2}$$

where x_0 the initial mass fraction of dissolved water, x the mass fraction of dissolved water and α_{cx} a coefficient that represents the maximum mass fraction of crystals. For example, in our calculations, $x_0 = 6\ 10^{-3}$ wt.% and at atmospheric pressure $f_{cx} = 0.6$ for $\alpha_{cx} = 0.75$. This linear equation for the crystal content may be thought of as the first term in a local expansion of a more complicated relationship, which is valid for the small variations of dissolved volatile content of interest here.

Microlite crystallization acts to increase the mass fraction of dissolved water in the residual melt, and hence affects the equation of state of the magma (Appendix A). The effect of crystal content on the amount of exsolved gas is largest at pressures between 0.5 MPa and 1 MPa, which approximately corresponds to a depth of 10 m to 40 m below the vent.

2.2. Viscosity

We use the function of Hess and Dingwell (1996) for the melt viscosity, μ_l. With microlites present, magma exhibits non-Newtonian behaviour above a certain crystal content threshold (Lavallée et al., 2007; Champallier et al., 2008) with a yield strength that depends on crystal shape (Walsh and Saar, 2008). We restrict our calculations to crystal volume fractions that are less than 60% for which non-Newtonian effects are small. Lejeune and Richet (1995) have shown that for crystal contents below the close packing limit a viscosity law such as that of Roscoe (1952) is appropriate:

$$\mu_c = \mu_l\left(1 - \frac{v_{cx}}{v_m}\right)^{-5/2}, \tag{3}$$