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Fracture of magma containing overpressurised pores

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ABSTRACT

Fragmentation is inherent in explosive eruptions. Fragmentation is usually credited to either a critical overpressure during rapid decompression (the fragmentation threshold) or a critical strain achieved during magma ascent. Here, we explore—using an elastic damage mechanics model—a scenario in which magma containing overpressurised pores (as a result of a decompression event, crystallisation-induced pore overpressure, amongst others) experiences a differential stress that can be accommodated elastically. This scenario has previously been overlooked, primarily due to the limitations of the available experimental apparatus: Fragmentation experiments cannot apply a differential stress and deformation experiments require that the applied pore fluid pressure does not exceed the confining pressure. Unaffected by these limitations, our numerical modelling has highlighted that the brittle strength, and the strain required for failure, can be reduced by almost an order of magnitude when the pores within the magma contain an overpressure of just 0.5 MPa. Macroscopic failure of the numerical samples is manifest as a throughgoing fracture and the generation of few fine particles (when compared with experimental rapid decompression fragmentation). In certain scenarios, small differential stresses may therefore act as a trigger for sustained explosive activity if the resultant fracture can penetrate magmas containing high pore pressures or if the fracture encourages flank/dome collapse, thus decompressing magma so that the pores contain overpressures above the fragmentation threshold. Alternatively, the resultant fracture could assist outgassing and thus reduce the explosivity of subsequent eruptions during a particular period of unrest. External stresses, previously unconsidered but invariably present in a dynamic volcanic system, may therefore play a large role in the development and cessation of explosive activity.

1. Introduction

Magma fragmentation is often assigned to one of two mechanisms: (1) Strain- or ascent-driven fragmentation, or (2) rapid decompression fragmentation. The first mechanism, strain- or ascent-driven fragmentation (e.g., Woods and Koyaguchi, 1994; Martí et al., 1999; Papale, 1999; Gonnermann and Manga, 2003; Melnik et al., 2005), occurs due to an increase in strain rate and the structural relaxation time of the magma close to the conduit walls, a consequence of the variation in pressure and gas volume fraction across the conduit (Papale, 1999). The melt phase of the magma will react as a solid if the strain rate is higher than the inverse of the relaxation timescale (Dingwell and Webb, 1990; Dingwell, 1996), leading to magma fragmentation (e.g., Papale, 1999; Gonnermann and Manga, 2003). Strain-induced fragmentation of ascending magma has been associated with sustained explosive eruptions (Papale, 1999) and fracturing/healing cycles during lava extrusion (Tuffen et al., 2003; Kendrick et al., 2014). Indeed, experimental studies have also shown that magmas cross the viscous–brittle transition as strain and strain rate are increased (e.g., Lavallée et al., 2008; Cordonnier et al., 2012; Kendrick et al., 2013; Lavallée et al., 2013; Shields et al., 2014). In the second mechanism, fragmentation is induced when the rapid decompression of pressurised magma results in a decompression wave capable of generating a tensile stress that exceeds the strength of the magma (e.g., Alidibirov and Dingwell, 1996; Zhang, 1999; Koyaguchi et al., 2008). Bubbles of exsolved gases form in magmas as the magma depressurises on its ascent to the surface (Sparks, 1978; Toramaru, 1989; Mangan and Cashman, 1993; Navon and Lyakhovsky, 1998; Gonnermann and Manga, 2012). If the ascent rate is slow compared to the relaxation timescale of the melt phase, the increasing volume of volatiles is accommodated by the growth of bubbles (e.g., Proussevitch and Sahagian, 2005 and references therein). In this scenario, the pressure inside the bubbles (the pore pressure, Pp) will likely equilibrate with the overburden pressure provided by the overlying magma column. However, a pore overpressure (i.e., when the pore pressure is higher than the overburden pressure) can develop if the decompression rate exceeds the rate at which the bubble walls can grow (which is invariably tied to numerous factors, including the volatile content, ascent rate, and viscosity; e.g., Massol and Jaupart, 1999; Proussevitch and Sahagian, 2005; Nguyen et al., 2014). For example,

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pore overpressure can develop due to crystallisation of magma driving local volatile oversaturation and the exsolution of volatiles into isolated pores (e.g., Tait et al., 1989; Sparks, 1996; Stix et al., 1997). Local pore overpressures can be generated if a low permeability magma plug (Michaut et al., 2009; Yokoo et al., 2009) or low permeability country rock (Jaupart, 1998; Kennedy et al., 2010) impedes gas movement and ultimate escape. Larger overpressures can exist following rapid decompression triggered by dome/sector collapse or fracture propagation (i.e., the magma is suddenly exposed to atmospheric pressure; e.g., Alidibirov and Dingwell, 1996). For a given porosity, if the pore overpressure exceeds a critical pressure—coined the fragmentation threshold (e.g., Alidibirov and Dingwell, 1996)—the resultant decompression wave results in an expansion of gas sufficient to break the bubble walls and fragment the magma. Magma overpressure driven fragmentation has been associated with a wide variety of volcanic activity (Massol and Jaupart, 1999 and references therein), from Vulcanian explosions (e.g., Druitt et al., 2002; Kennedy et al., 2005; Burgisser et al., 2010; Cole et al., 2014) to Plinian eruptions (e.g., Walker and Croasdale, 1970). As a result, considerable attention has been devoted to understanding and quantifying the fragmentation threshold of magma. Experimental studies, for example, have shown that the fragmentation threshold is inversely and nonlinearly dependent on connected porosity (e.g., Alidibirov and Dingwell, 1996; Martel et al., 2000, 2001; Spieler et al., 2004; Kueppers et al., 2006; Scheu et al., 2008).

In this study we envisage a scenario where external differential stresses are acting on the magma within a conduit. Such external stresses are likely ubiquitous in a highly stressed volcanic system on the verge of an explosive eruption (e.g., Gerst and Savage, 2004; Roman et al., 2004). If the strain rate is sufficiently high, or the magma is sufficiently viscous, these stresses may be accommodated elastically by the magma. In our scenario, the magma contains a pore overpressure that is insufficient to fragment the magma (i.e., the resultant pore overpressure is lower than the fragmentation threshold). This pore overpressure could exist due to a number of reasons, for example: Crystallisation, decompression fracture, and sector/dome collapse, amongst others. The motivation of this study is to assess whether elastically accommodated external differential stresses can fragment magma containing a pore overpressure (below the fragmentation threshold) and, if so, to evaluate the magnitudes of stresses and strains required and the style and characteristics of brittle failure. Until now, the influence of external differential stresses and strains on the fragmentation or failure of magmas containing a pore overpressure has not been explored specifically: Experimental studies of overpressure-driven fragmentation have been performed in the absence of an imposed differential stress (e.g., Spieler et al., 2004) and triaxial deformation experiments (e.g., Cordonnier et al., 2012) require that the confining pressure is greater than the applied pore pressure. To explore this concept, we employ an elastic damage mechanics model—the two-dimensional flow-coupled Rock Failure and Process Analysis code model (e.g., Tang et al., 2002)—to deform numerical samples containing overpressurised pores. A similar model has recently shown that, in the absence of a pore overpressure, porosity and pore size play crucial roles in dictating the brittle strength of volcanic rocks and magmas (Heap et al., 2014). We briefly describe the model before presenting the influence of porosity and pore size on the failure of magmas containing pore overpressures (at overpressures below the classically defined fragmentation threshold). Finally, we demonstrate the implications of the model output using simple conceptual volcanic scenarios.

2. Description of the model and simulations

Owing to their flexibility, elastic damage mechanics models have been used to investigate damage accumulation and failure in a number of scientific disciplines, including, and not limited to: Geophysics (e.g., Tang et al., 2003), geology (e.g., Lacroix and Amitrano, 2013), engineering (e.g., Xu et al., 2006), and volcanology (e.g., Heap et al., 2014). Recently, Heap et al. (2014) demonstrated that output from the Rock Failure and Process Analysis code model (Tang, 1997) is qualitatively similar to model predictions from the micromechanical model of Sammis and Ashby (1986).

The two-dimensional flow-coupled Rock Failure and Process Analysis code (F-RFPA^{2D}) model (e.g., Tang et al., 2002, 2004; Wang et al., 2013), used in this study, assumes that the melt within the magma reacts in an elastic (i.e., the stress is not dissipated viscously) and brittle manner (i.e., the melt acts as a solid and, as a result, the pores are stationary) to an external stress. As a result, the start of our model (time and strain equal zero) corresponds to the time when magmas containing a pore overpressure first experience a differential stress that can be accommodated elastically. Although a time-dependent RFPA model exists (Xu et al., 2012), we have chosen to use a time-independent model because, under the high strain rates implicated by a brittle response, there is insufficient time for time-dependent subcritical processes (such as stress corrosion cracking, see Heap et al., 2011) to influence the mechanical behaviour of the deforming magma. In this study we adopt the convention that compressive stresses and strains are positive.

The two-dimensional numerical samples of this study—40 mm in length and 20 mm in width—consist of 80,000 square elements with sides of 0.1 mm. The elements within the sample were assigned the same mean physical and mechanical properties (Table 1) used in Heap et al. (2014). To reflect material heterogeneity on the microscale (variations in glass strength, microlite number density, amongst others), each 0.1 mm square element is assigned a value of residual uniaxial strength (compressive σ_{cr} and tensile σ_{tr}) and Young's modulus E_0 using a Weibull probability density function (Weibull, 1951; Wong et al., 2006):

$$x(u) = \frac{m}{u_0}\left(\frac{u}{u_0}\right)^{m-1}\exp\left[-\left(\frac{u}{u_0}\right)^{m}\right] \quad (1)$$

where $x(u)$ is either $\sigma_{cr}(u)$, $\sigma_{tr}(u)$ or $E_0(u)$, where u is the scale parameter of an individual element and u_0 is the scale parameter of the average element (both of which depend on the parameter in question). We have chosen to let the Weibull shape parameter be $m = 3$ (the homogeneity index) for in all of our numerical simulations, the same value used in Heap et al. (2014). Low values of m ($m < 3$) result in heterogeneous samples and high values of m ($m > 3$) result in homogeneous samples. An example of the distribution of Young's modulus and uniaxial compressive strength using $m = 3$, for a sample with the mean element physical and mechanical properties given in Table 1 (containing 80,000 elements), is presented as Fig. 1. The modelled uniaxial compressive strength of a numerical sample containing 0% porosity and a homogeneity index $m = 3$ was found to be 553 MPa (Heap et al., 2014). The strength of porosity-free borosilicate glass is about 600 MPa at a temperature of 535 °C and a strain rate of 10^{-3} s^{-1} (Vasseur et al., 2013), serving to validate our approach and choice of mean physical and mechanical properties (Table 1) and Weibull shape parameter m.

We introduced porosity (5 or 25%) into our numerical samples in the form of circular pores (diameter of either 0.5 or 1.0 mm). The pores were placed in the samples at random and without overlap (i.e., all of the porosity is isolated). Examples of the numerical samples are given

Table 1
The physical and mechanical properties of the groundmass used in the Rock Failure and Process Analysis code ($RFPA_{2D}$) stochastic modelling. The same input values were used in Heap et al. (2014).

Homogeneity index	3
Mean uniaxial compressive strength [MPa]	2300
Mean Young's modulus [GPa]	100
Poisson's ratio	0.25
Ratio of compressive to tensile strength	10
Frictional angle [degrees]	30