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From rock to magma and back again: The evolution of temperature and deformation mechanism in conduit margin zones

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ABSTRACT

Explosive silicic volcanism is driven by gas overpressure in systems that are inefficient at outgassing. The zone at the margin of a volcanic conduit—thought to play an important role in the outgassing of magma and therefore pore pressure changes and explosivity—is the boundary through which heat is exchanged from the hot magma to the colder country rock. Using a simple heat transfer model, we first show that the isotherm for the glass transition temperature (whereat the glass within the groundmass transitions from a glass to an undercooled liquid) moves into the country rock when the magma within the conduit can stay hot, or into the conduit when the magma is quasi-stagnant and cools (on the centimetric scale over days to months). We then explore the influence of a migrating viscous boundary on compactive deformation micromechanisms in the conduit margin zone using high-pressure (effective pressure of 40 MPa), high-temperature (up to 800 °C) triaxial deformation experiments on porous andesite. Our experiments show that the micromechanism facilitating compaction in andesite is localised cataclastic pore collapse at all temperatures below the glass transition of the amorphous groundmass glass T_g (i.e., rock). In this regime, porosity is only reduced within the bands of crushed pores; the porosity outside the bands remains unchanged. Further, the strength of andesite is a positive function of temperature below the threshold T_g due to thermal expansion driven microcrack closure. The micromechanism driving compaction above T_g (i.e., magma) is the distributed viscous flow of the melt phase. In this regime, porosity loss is distributed and is accommodated by the widespread flattening and closure of pores. We find that viscous flow is much more efficient at reducing porosity than cataclastic pore collapse, and that it requires stresses much lower than those required to form bands of crushed pores. Our study therefore highlights that temperature excursions can result in a change in deformation micromechanism that drastically alters the mechanical and hydraulic properties of the material within the conduit margin zone, with possible implications for pore pressure augmentation and explosive behaviour.

1. Introduction

Magma vesiculation is the consequence of volatile oversaturation during decompression (Gonnermann and Manga, 2012) or heating (Lavallée et al., 2015). Once exsolved, the ease with which these volatiles can escape, governed by the permeability of the system, is thought to impact volcanic explosivity (Eichelberger et al., 1986; Woods and Koyaguchi, 1994; Melnik et al., 2005; Mueller et al., 2008). The conduit margin zone (comprising the magma at the conduit margin and the adjacent wall rock) is thought to be the annulus through which degassed volatiles dominantly escape, a result of its highly fractured, brecciated, and banded nature (Rust et al., 2004; Tuffen and Dingwell, 2005; Lavallée et al., 2013; Gaunt et al., 2014).

The fractured physical state of the conduit margin zone is a consequence of the shear stresses in the magma-filled conduit (e.g., Tuffen and Dingwell, 2005). In the shallow edifice, a brittle response to an applied stress can be expected from (1) country rock adjacent to the conduit (Heap et al., 2015a), (2) volcanic material at the conduit margin without a substantial melt phase (i.e., high-crystallinity; Smith et al., 2011; Violay et al., 2012), and (3) magma with a substantial melt phase at the conduit margin deforming at a strain rate that exceeds the structural re-

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laxation timescale of its melt phase (Ichihara and Rubin, 2010; Lavallée et al., 2013). Brittle deformation (i.e., fracture formation) increases the porosity and permeability of volcanic materials (Nara et al., 2011; Lavallée et al., 2013; Violay et al., 2015; Heap and Kennedy, 2016; Farquharson et al., 2016a), thus locally increasing the efficiency of outgassing and potentially decreasing the likelihood or intensity of an explosive eruption (Mueller et al., 2008; Lavallée et al., 2013; Castro et al., 2014).

Deeper in the edifice (≥1 km), the country rock adjacent to the conduit will accommodate stresses in a dominantly ductile manner (Shimada, 1986; Loaiza et al., 2012; Adelinet et al., 2013; Heap et al., 2015a). Ductile deformation in both the solid and liquid regimes can decrease the porosity, and therefore permeability, of the materials within the conduit margin zone, thus potentially increasing the likelihood or intensity of an explosive eruption (Kennedy et al., 2010; Kendrick et al., 2013; Heap et al., 2015a, 2015b; Schauroth et al., 2016). The micromechanical mechanism responsible for ductile deformation in volcanic rocks (or magmas without a substantial melt phase) is distributed (Shimada, 1986; Zhu et al., 2011) or localised (Loaiza et al., 2012; Adelinet et al., 2013; Heap et al., 2015a) cataclastic pore collapse. Viscous flow of the amorphous melt phase is the mechanism responsible for ductile deformation in magma containing a substantial melt phase residing at a temperature above its glass transition temperature T_g (Quane et al., 2009; Lavallée et al., 2013; Kendrick et al., 2013; Vasseur et al., 2013; Heap et al., 2015b). We note that high strain rates can shift the transition from ductile to brittle deformation to greater depths (Webb and Dingwell, 1990; Cordonnier et al., 2012; Lavallée et al., 2013; Kushnir et al., 2017).

The zone at the margin of a volcanic conduit is the boundary through which heat is exchanged from the hot magma to the colder country rock. Temperature excursions, resulting from the injection of hot magma batches or the cooling of the magma within the conduit, will move the T_g isotherm thus modifying the operative micromechanism of deformation, with attendant implications for the mechanical response and the physical property evolution (e.g., porosity and permeability) of the materials within the margin zone. At a depth ≥1 km, where ductile deformation will dominate, the materials within the margin zone may repeatedly transition between the micromechanisms of cataclastic pore collapse and viscous flow. The transition between these compaction micromechanisms, and the accompanying changes in mechanical and hydraulic behaviour, has never been explicitly studied. Experimental studies of compaction in magmas have largely been limited to uniaxial experiments (Quane et al., 2009; Kendrick et al., 2013; Heap et al., 2014a) or isobaric conditions in which other forces, such as surface tension, dominate (Vasseur et al., 2013; Kennedy et al., 2015), while deformation experiments designed to study compaction in volcanic rocks have all been performed at ambient-temperature (Loaiza et al., 2012; Adelinet et al., 2013; Heap et al., 2015a). High-pressure and high-temperature studies of magma deformation have focussed on magma viscosity determination (e.g., Champallier et al., 2008) or the onset of fracturing (e.g., Kushnir et al., 2017) and, so far, have not provided *in-situ* measurements of porosity during deformation. A recent study however has shown, by means of a pore fluid volumometer, that compactive behaviour is encountered in low-porosity basalt at a confining pressure of 100 MPa and a temperature of 950 °C (Violay et al., 2015).

Our aim here is to investigate compaction processes in the conduit margin zone of a typical andesitic stratovolcano as the materials are heated or cooled. To achieve this goal we performed a series of high-pressure (at a pressure analogous to ∼1 km depth) triaxial experiments on porous andesite at temperatures from ambient to 800 °C in which we monitored sample porosity during deformation. A detailed understanding of the micromechanical processes responsible for compaction in the conduit margin zone, and how they influence mechanical behaviour and hydraulic properties, is paramount to our comprehension of pore pressure changes and the likelihood of explosive behaviour at active volcanoes worldwide.

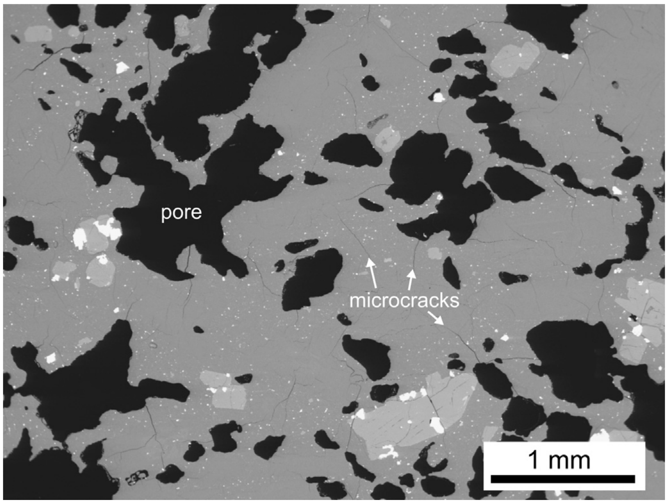

Fig. 1. Backscattered scanning electron microscope (BSEM) image of the as-collected andesite studied herein. Porosity is black. A pore and microcracks are labelled on the image.

2. Experimental material

We use an andesite block collected from the La Lumbre debris-flow track at Volcán de Colima, an active stratovolcano located in the Trans-Mexican Volcanic Belt (Mexico) (Varley and Komorowski, 2017). Although our block was sourced from Volcán de Colima, we consider the implications presented in this study to be applicable to active and frequently collapsing andesitic stratovolcanoes worldwide. Cylindrical core samples used for this study were all drilled from this block in the same orientation.

The andesite collected has a porphyritic texture consisting of a glassy groundmass (with abundant microlites) that hosts pores and a phenocryst cargo (long axis <1.5 mm; Fig. 1). The phenocrysts and groundmass contain many randomly orientated microcracks up to a few mm in length (Fig. 1). The average connected and total porosity is 0.265 and 0.268 (isolated porosity ∼0.03), respectively (determined by helium pycnometry; the connected porosity of each sample is given in Table 1). The phenocryst volume fraction is ∼0.4 and the groundmass consists of glass (volume fraction ∼0.135) containing ∼0.2 volume fraction of microlites (of mainly plagioclase with subordinate high-density Fe–Ti oxides), estimated from 2D scanning electron microscope (SEM) images using ImageJ. The bulk composition of the here-studied andesite includes 61.5 wt.% SiO_2, measured using X-ray fluorescence (XRF; complete XRF analysis is presented in the Supplementary Information), and is very similar to that of the products erupted over the last two decades (Heap et al., 2014b).

The temperature at which the glass within the groundmass transitions from a glass to an undercooled liquid—the glass transition temperature (T_g)—was determined using a Netzsch Pegasus 404 simultaneous thermal analysis device at a heating rate of $20\,°\mathrm{C\,min}^{-1}$. The glass transition is manifest as a non-linear endothermic peak in heat flow relative to the smoothly changing baseline value. During heating from the unknown natural cooling path during which the rock was formed, this peak occurred at ∼750.2 ± 3.5 °C (see Supplementary Information for further details).