Earth and Planetary Science Letters 429 (2015) 223–233

Contents lists available at ScienceDirect

Earth and Planetary Science Letters

www.elsevier.com/locate/epsl

Timescales for permeability reduction and strength recovery in densifying magma

M.J. Heap [a,*], J.I. Farquharson [a], F.B. Wadsworth [b], S. Kolzenburg [c], J.K. Russell [d]

[a] *Géophysique Expérimentale, Institut de Physique de Globe de Strasbourg (UMR 7516 CNRS, Université de Strasbourg/EOST), 5 rue René Descartes, 67084 Strasbourg cedex, France*
[b] *Department for Earth and Environmental Sciences, Ludwig-Maximilians-Universität, Munich, Theresienstr. 41/III, 80333 Munich, Germany*
[c] *Dipartimento di Scienze della Terra, Università degli Studi di Torino, 35 Via Valperga Caluso, 10125, Torino, Italy*
[d] *Volcanology and Petrology Laboratory, Department of Earth and Ocean Sciences, University of British Columbia, Vancouver, V6T 1Z4, Canada*

ARTICLE INFO

Article history:
Received 6 April 2015
Received in revised form 21 July 2015
Accepted 24 July 2015
Available online 18 August 2015
Editor: T.A. Mather

Keywords:
welding
changepoint
P-wave velocity
uniaxial compressive strength
fracture healing
outgassing

ABSTRACT

Transitions between effusive and explosive behaviour are routine for many active volcanoes. The permeability of the system, thought to help regulate eruption style, is likely therefore in a state of constant change. Viscous densification of conduit magma during effusive periods, resulting in physical and textural property modifications, may reduce permeability to that preparatory for an explosive eruption. We present here a study designed to estimate timescales of permeability reduction and strength recovery during viscous magma densification by coupling measurements of permeability and strength (using samples from a suite of variably welded, yet compositionally identical, volcanic deposits) with a rheological model for viscous compaction and a micromechanical model, respectively. Bayesian Information Criterion analysis confirms that our porosity–permeability data are best described by two power laws that intersect at a porosity of 0.155 (the "changepoint" porosity). Above and below this changepoint, the permeability–porosity relationship has a power law exponent of 8.8 and 1.0, respectively. Quantitative pore size analysis and micromechanical modelling highlight that the high exponent above the changepoint is due to the closure of wide (∼200–300 μm) inter-granular flow channels during viscous densification and that, below the changepoint, the fluid pathway is restricted to narrow (∼50 μm) channels. The large number of such narrow channels allows porosity loss without considerable permeability reduction, explaining the switch to a lower exponent. Using these data, our modelling predicts a permeability reduction of four orders of magnitude (for volcanically relevant temperatures and depths) and a strength increase of a factor of six on the order of days to weeks. This discrepancy suggests that, while the viscous densification of conduit magma will inhibit outgassing efficiency over time, the regions of the conduit prone to fracturing, such as the margins, will likely persistently re-fracture and keep the conduit margin permeable. The modelling therefore supports the notion that repeated fracture-healing cycles are responsible for the successive low-magnitude earthquakes associated with silicic dome extrusion. Taken together, our results indicate that the transition from effusive to explosive behaviour may rest on the competition between permeability reduction within the conduit and outgassing through fractures at the conduit margin. If the conditions for explosive behaviour are satisfied, the magma densification clock will be reset and the process will start again. The timescales of permeability reduction and strength recovery presented in this study may aid our understanding of the permeability evolution of conduit margin fractures, magma fracture-healing cycles, surface outgassing cycles, and the timescales required for pore pressure augmentation and the initiation of explosive eruptions.

1. Introduction

Welding of volcanic materials occurs through the viscous sintering, compaction, and agglutination of melt particles above their glass transition temperature (e.g., Grunder and Russell, 2005). Welding can occur in the absence of an external load through surface relaxation (Vasseur et al., 2013), but can be assisted by the additional stress provided by the mass of any overlying material (e.g., Quane et al., 2009) or by shear strain (e.g., Tuffen et al., 2003; Kolzenburg and Russell, 2014). The prevalence of welding examples in volcanic environments highlights the importance for thor-

---

[*] Corresponding author.
E-mail address: heap@unistra.fr (M.J. Heap).

http://dx.doi.org/10.1016/j.epsl.2015.07.053
0012-821X/© 2015 Elsevier B.V. All rights reserved.

ough investigation of the influence of viscous densification on magma physical properties. For example, evidence for welding has been observed in pyroclastic deposits (e.g., Wright and Cashman, 2013) including block-and-ash flow deposits (e.g., Michol et al., 2008; Andrews et al., 2014; Heap et al., 2014a), lava spatter (e.g., Mellors and Sparks, 1991), autobreccias in blocky-lavas and dome lavas (e.g., Sparks et al., 1993), autobreccias at the base of rheomorphic ignimbrites (e.g., Branney et al., 1992), conduit-filling pyroclastic deposits (e.g., Kano et al., 1997; Kolzenburg and Russell, 2014), and rhyolitic dykes and conduits (e.g., Tuffen et al., 2003; Tuffen and Dingwell, 2005; Okumura and Sasaki, 2014). Welding results in densification, modifying the physical and textural properties of the material. Indeed, welding has been shown to increase the density and strength and decrease the porosity and permeability of volcanic materials and analogues (e.g., Quane et al., 2009; Vasseur et al., 2013; Wright and Cashman, 2013; Okumura and Sasaki, 2014; Heap et al., 2014a). Ultimately, the evolution of physical properties can govern the timescales and extent of welding, the potential for rheomorphic flow, and volcanic explosivity. For example, the ease with which magma can outgas, controlled by the permeability of the system, can influence eruption style, magnitude, and frequency (e.g., Eichelberger et al., 1986; Woods and Koyaguchi, 1994). While the majority of laboratory studies considering the relationships between porosity and permeability for volcanic rocks have focussed on the consequence of ascent-driven vesiculation and bubble growth (porosity increase) for magma permeability (e.g., Eichelberger et al., 1986; Klug and Cashman, 1996; Saar and Manga, 1999; Blower, 2001; Rust and Cashman, 2004; Heap et al., 2014b; Farquharson et al., 2015, amongst others), there are comparatively few laboratory investigations that consider the impact of porosity destruction through magma densification (e.g., Wright and Cashman, 2013; Kendrick et al., 2013; Okumura and Sasaki, 2014; Heap et al., 2014a). Between individual explosive events, porous magma residing in a conduit spends a significant portion of time deforming under the mass of the overlying magmatic column at temperatures above the glass transition of the melt phase. During these intervals, a reduction in the magma permeability through viscous densification could lead to the build-up of pore pressure required for the development of an explosive eruption (e.g., Melnik et al., 2005; Diller et al., 2006). Here we report on a coupled experimental and modelling study that aims to better understand the timescales required to reduce permeability and increase strength during viscous magma densification.

2. Materials and methods

2.1. Materials and sample preparation

This study utilises a suite of natural blocks (about 30 × 30 × 30 cm) collected from the variably-welded block-and-ash flow (BAF) deposits that formed following the 2360 B.P. eruption of Mount Meager volcano (part of the Garibaldi Volcanic Belt, the northernmost segment of the Cascade Volcanic Arc of North America; see Michol et al., 2008; Andrews et al., 2014). The BAF deposits—initially >160 m thick—filled and dammed the Lillooet River valley. The densely-welded portions of the deposit are currently exposed in a 100 m rock wall that formed following the collapse of the pyroclastic dam and erosion from the concomitant flood. The clast sizes in the deposits are typically 5–15 cm in diameter, with rare large clasts up to 1 m. The matrix comprises vitric and crystal fragments (and occasional lithics) that are generally less than 1–2 mm in diameter (see Michol et al., 2008 and Andrews et al., 2014 for a full description of the deposit). The welding intensity of these compositionally similar BAF deposits (Stewart, 2002) ranges from incipient (>0.2 porosity) to dense (<0.1 porosity) (Michol et al., 2008; Heap et al., 2014a) and therefore provides the perfect opportunity to study the influence of viscous densification on material physical properties. Typical welding microtextures (e.g., clast elongation/flattening) found within the deposit are described in detail in Michol et al. (2008) and Heap et al. (2014a) (but also provided here as Figs. 3b and 3c). Using field texture maps, Michol et al. (2008) measured the average volumetric and pure shear strain recorded in these BAF deposits to be 42% (highest 92%) and 31% (highest 82%), respectively. We also sampled a fresh (non-oxidised), glassy block from the incipiently welded facies; we anticipate that this material best represents the source material for the BAF deposit. We analysed optical microscope photomicrographs of a sample of this lava using image processing software ImageJ to estimate the average crystal content of our welded materials. We estimated crystal content to be 0.25 (phenocrysts and minor microlites), the remainder of the sample comprising porosity (0.04–0.05) and a glassy groundmass (Fig. 3a). The dominant crystal size within the source material is between 100 and 400 μm, although we note the presence of occasional phenocrysts as large as a couple of mm and minor microlites (<100 μm) (Fig. 3a).

Table 1
Whole rock geochemistry (determined by X-ray fluorescence) and glass geochemistry (determined using an electron microprobe) for the materials of this study (data from Stewart, 2002).

Oxide	Whole rock (wt.%)	Glass (wt.%)
SiO_2	67.51	76.41
TiO_2	0.47	0.30
Al_2O_3	15.78	13.11
Fe_2O_3	3.40	1.20
MgO	1.48	0.26
CaO	3.44	1.18
Na_2O	4.60	4.41
K_2O	2.51	3.52
P_2O_5	0.16	–
LOI	0.70	–
Total	100.06	99.38

We prepared cylindrical samples, 20 mm in diameter and precision-ground to nominal lengths of 40 mm, from the blocks collected (the welded blocks and the lava block). Due to the size of our experimental samples, cores from the welded blocks were prepared so as to avoid any large (5–15 cm) clasts. Our welded BAF samples therefore contain vitric and crystal fragments (and occasional lithics) that are generally less than 1–2 mm in diameter (as shown in Figs. 3b and 3c; Michol et al., 2008). We further note that, in general, vitric fragments are larger than the crystal fragments (a consequence of the dominant crystal size, 100–400 μm, in the source material). The cores were then vacuum-dried at 40 °C for at least two days prior to measurement and experimentation.

The bulk composition of our materials is dacitic (SiO_2 = 68 wt.%) with a rhyolitic glass groundmass (SiO_2 = 76 wt.%); the wt.% of major oxides for both the bulk material and the glass are provided in Table 1 (data from Stewart, 2002).

2.2. Methods

Porosity and permeability were measured for each of the prepared cylindrical cores at the Université de Strasbourg (France). Connected porosity was measured using a helium pycnometer (for brevity, connected porosity will be simply referred to as "porosity" in the remainder of this manuscript). Steady-state gas (nitrogen) permeability was measured under a confining pressure of 1 MPa. Flow rate measurements were taken (using a gas flowmeter) under several pressure gradients (typically from 0.05 to 0.2 MPa) to determine the permeability using Darcy's law, and to assess the need for