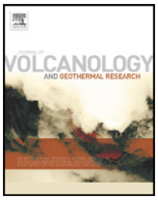
Journal of Volcanology and Geothermal Research 260 (2013) 117–126

Contents lists available at SciVerse ScienceDirect

Journal of Volcanology and Geothermal Research

journal homepage: www.elsevier.com/locate/jvolgeores



Tracking the permeable porous network during strain-dependent magmatic flow ☆

J.E. Kendrick [a,b,*], Y. Lavallée [a,b], K.-U. Hess [a], M.J. Heap [c], H.E. Gaunt [d], P.G. Meredith [d], D.B. Dingwell [a]

[a] Department of Earth and Environmental Sciences, Ludwig-Maximilians-Universität, Theresienstr. 41, 80333 Munich, Germany
[b] Department of Earth, Ocean and Ecological Sciences, School of Environmental Sciences, University of Liverpool, Liverpool L69 3BX, United Kingdom
[c] Laboratoire de Déformation des Roches, Équipe de Géophysique Expérimentale, Institut de Physique de Globe de Strasbourg (UMR 7516 CNRS, Université de Strasbourg/EOST), 5 rue René Descartes, 67084 Strasbourg cedex, France
[d] Rock & Ice Physics Laboratory, Department of Earth Sciences, University College London, Gower Street, London, United Kingdom

ARTICLE INFO

Article history:
Received 13 November 2012
Accepted 23 May 2013
Available online 28 May 2013

Keywords:
Magma
Deformation
Rheology
Viscosity
Strain localization
Damage

ABSTRACT

Rheological variations have been postulated as the cause of transitions from effusive to explosive volcanic eruption style. Rheology is integrally linked to the composition and textural state (porosity, crystallinity) of magma as well as the stress, temperature and strain rate operative during flow. This study characterises the rheological behaviour and, importantly, the evolution of physical properties of two magmas (with different crystallinity and porosity) from Volcán de Colima (Mexico) — a volcanic system known for its rapid fluctuations in eruption style.

Magma samples deformed in a uniaxial press at a constant stress of 2.8, 12 or 24 MPa, a constant temperature of 940–945 °C (comparable to upper conduit or lava dome conditions) to strains of 20 or 30% displayed different mechanical behaviour and significant differences in measured strain rates (10^{-2}–10^{-5} s^{-1}). The evolution of porosity, permeability, dynamic Young's modulus and dynamic Poisson's ratio illustrate a complex evolution of the samples manifested as strain-hardening, visco-elastic, constant-rate and strain-weakening deformation. Both magmas behave as shear-thinning non-Newtonian liquids and viscosity decreases as a function of strain. We find that strain localisation during deformation leads to the rearrangement and closure of void space (a combination of pores and cracks) followed by preferentially aligned fracturing (in the direction of the maximum principal stress) to form damage zones as well as densification of other areas. In a dome setting, highly viscous, low permeability magmas carry the potential to block volcanic conduits with a magma plug, resulting in the build-up of pressures in the conduit. Above a certain threshold of strain (dependent upon stress/strain rate), the initiation, propagation and coalescence of fractures leads to mechanical degradation of the magma samples, which then supersedes magmatic flow and crystal rearrangement as the dominant form of deformation. This results in lower apparent viscosities than those anticipated for magma of such crystallinity, especially at high strain rates. In a lava dome, this could result in dome collapse and the concomitant depressurisation could trigger an explosive eruption.

1. Introduction

1.1. Motivation

The frequent and as yet unpredictable transition from effusive to explosive volcanic behaviour is common to active composite volcanoes, yet our understanding of the processes which control this evolution is poor. The rheology of magma, dictated by its composition, porosity and crystal content, is integral to eruption behaviour (McBirney and Murase, 1984; Lejeune and Richet, 1995; Petford, 2003; Caricchi et al., 2007; Lavallée et al., 2007; Cordonnier et al., 2009). Indeed, rheological variations have previously been cited as the cause of effusive–explosive transitions on multiple timescales (Dingwell, 1996; D'Oriano et al., 2005; Lavallée et al., 2008; Cordonnier et al., 2009; Divoux et al., 2011). Fragmentation and explosive eruptions result from the brittle failure of magma at high temperature (Lavallée et al., 2008; Tuffen et al., 2008; Smith et al., 2011) and for a given material, the transition into the brittle regime is initiated by a decrease in temperature or increase in shear stress or strain rate (Dingwell and Webb, 1989; Webb and Dingwell, 1990; Lavallée et al., 2007).

Laboratory experiments which aim to simulate realistic volcanic conditions permit the controlled study of volcanic processes (Pallister et al., 1992; Kennedy et al., 2005; Smith et al., 2009; Hess et al., 2007;

☆ This is an open-access article distributed under the terms of the Creative Commons Attribution-NonCommercial-No Derivative Works License, which permits non-commercial use, distribution, and reproduction in any medium, provided the original author and source are credited.

* Corresponding author at: Department of Earth and Environmental Sciences, Ludwig-Maximilians-Universität, Theresienstr. 41, 80333 Munich, Germany.
E-mail address: jackie.kendrick@liverpool.ac.uk (J.E. Kendrick).

0377-0273/$ – see front matter © 2013 The Authors. Published by Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.jvolgeores.2013.05.012

Lavallée et al., 2008; Tuffen et al., 2008; Cordonnier et al., 2009; Heap et al., 2009; Heap et al., 2011; Smith et al., 2011) and aid the development of models to describe the behaviour of magmas in conduit and dome settings (Melnik and Sparks, 1999; Melnik, 2001; Caricchi et al., 2007; Lavallée et al., 2007; Costa et al., 2009; Deubelbeiss et al., 2011). Experiments on magma show that the addition of crystals to a melt increases viscosity at low strain rates. At low crystallinity (<40%), this non-linear increase has been described by the Einstein–Roscoe equation (Roscoe, 1952), as parameterised by Marsh (1981). Above a threshold of crystallinity (defined by the maximum packing fraction, which in itself is dependent upon the size, shape and distribution of the suspended crystals; Cimarelli et al., 2011; Picard et al., 2011) particle–particle interaction permits the transmission of stress via the solid fraction (Petford, 2003) resulting in non-Newtonian rheological behaviour (Lejeune and Richet, 1995; Carreau et al., 1999; Caricchi et al., 2007; Lavallée et al., 2007; Cordonnier et al., 2009; Deubelbeiss et al., 2011). Lavallée et al. (2007) present a rheological law for this non-Newtonian behaviour based on experiments on a wide range of natural magmas which contain a fully connected crystal structure.

In this study we track the damage evolution in experimentally deformed natural magmas for the first time. A magma's ability to degas through the permeable porous network and its propensity for fragmentation are integrally linked to the physical state of the magma, which must be better understood to predict volcanic behaviour. The samples chosen are from Volcán de Colima (Mexico), a volcano which experiences regular transitions in eruption style. The initial rock-physical, chemical and microstructural properties of the samples were characterised using porosity and permeability measurements, ultrasonic wave velocity measurements (that were also used to determine dynamic Young's modulus and Poisson's ratio), X-ray fluorescence, scanning electron and optical microscopy, X-ray computed tomography and differential scanning calorimetry. Then, following episodes of high-temperature deformation (at different stresses), the evolution of the physical properties and the microstructural state of the samples were tracked by systematically re-measuring porosity, permeability, ultrasonic wave velocities, and by re-imaging the samples through X-ray computed tomography.

1.2. Volcán de Colima, history and erupted products

Volcán de Colima is an active volcano which, together with the extinct Nevado de Colima, forms the Colima Volcanic Complex, located in the Trans-Mexican Volcanic Belt. The current eruptive period is part of an ~100-year cycle of explosive to effusive events which culminate in Plinian eruptions (Luhr and Carmichael, 1980; Breton et al., 2002; Luhr, 2002). The current period of activity was marked at its onset by an increase in volcano-tectonic (VT) seismicity which began in November 1997 (Dominguez et al., 2001; Navarro-Ochoa et al., 2002; Zobin et al., 2002), and which was swiftly followed by a dome-building episode and multiple lava flows (in November 1998). This transitioned into periodic explosive behaviour in 1999 and early 2001, and formed a summit crater. Subsequently, effusive behaviour recommenced forming a lava dome, which eventually overflowed the crater in February 2002 and flowed down the northern flanks (Varley et al., 2010). In March 2003 the eruption once again transitioned to explosive behaviour, whereby repeated Vulcanian explosions occurred over 18 months. These subsided as a new phase of block-lava extrusion occurred during late 2004 (Zobin et al., 2008), but resumed in December 2004. During May and June 2005, following numerous swarms of long period (LP) events which indicated ascending magma (Varley et al., 2010; Arámbula-Mendoza et al., 2011), a number of dome-building eruptions and larger Vulcanian events occurred, with associated column collapses and pyroclastic flows (Gavilanes-Ruiz et al., 2009). A new dome began to form in early 2007, and in early 2010 the dome was growing by approximately 2000 m^3/day (James and Varley, 2012) before eventually overflowing the crater rim (Lavallée et al., 2012). During late 2010 multiple incandescent landslides travelled down the North, South and Western flanks of the volcano. In January 2011 “dust plumes” from landslides were sighted over the 2.6 million m^3 lava dome (Fig. 1), which stopped growing between June 2011- December 2012, but has since reawakened.

Fig. 1. Lava dome. Arial photograph of the lava dome at Volcán de Colima, pictured here in November 2012.

Despite the frequent fluctuations in eruptive style at Volcán de Colima, there is little variation in the erupted products, which tend to be highly crystalline, intermediate, andesitic lavas (Mora et al., 2002; Valdez-Moreno et al., 2006). Lavallée et al. (2012) found that recent dome lavas contain approximately 30 vol.% phenocrysts, 25–50 vol.% microlites and 14–45 vol.% glass. Porosity is highly variable between 1 and 30% (Kolzenburg et al., 2012; Lavallée et al., 2012), with a bimodal distribution showing peaks at 12 and 26%. Plagioclase, diopside and hypersthene dominate the crystal assemblage, forming a porphyritic texture. Hornblende phenocrysts occur sporadically and olivine and iron-titanium oxides occur as xenocrysts, all of which reside in a peraluminous, rhyolitic interstitial glass. Exceptions are the more mafic (Luhr and Carmichael, 1990; Luhr, 2002; Savov et al., 2008) culminating explosive eruptions of the 100-year cycles (González et al., 2002), which are attributed to the influx of mafic magma into the magma chamber from a deeper reservoir. Magma is largely degassed by the time it reaches the surface (Reubi et al., 2013), and Atlas et al. (2006) suggest vapour-saturated crystallisation during ascent at depths of less than 12 km. Melt inclusions measure H_2O concentrations of 0.1 to 2.5 wt.% and CO_2 concentrations of up to 800 ppm (Reubi et al., 2013), indicating trapping conditions of 10–150 MPa and 959–1015 °C. Correspondingly, Savov et al. (2008) suggest storage temperatures of 960–1020 °C based on geothermometry of pyroxenes.

2. Method

2.1. Sample selection

The two sample materials chosen for this study are the andesites COL-B2 and COL-LAH4 (Table 1, Fig. 2A and E) from the dome-building eruptions and explosions that occurred during 2004. The two sample materials were selected on the basis of their contrasting initial porosities and crystal contents. The two lavas contain 9.5 and 27.2% porosity (a combination of cracks and pores), 34 and 20% phenocrysts, 31 and 23% microlites, and 26 and 30% interstitial melt for B2 and LAH4, respectively. The andesites from this particular eruptive period are isotropic, evidenced both seismically (by use of ultrasonic wave velocity measurements) and optically (by thin section and tomographic