



Rheology of porous volcanic materials: High-temperature experimentation under controlled water pressure

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ABSTRACT

We present a suite of 21 high-temperature, uniaxial deformation experiments performed on 25 by 50 mm unjacketed cores of porous ($\Phi \sim 0.8$) sintered rhyolitic ash. The experiments were performed at, both, atmospheric (dry) and elevated water pressure conditions (wet). Experiments used a constant displacement rate of $2.5 \times 10^{-6} \text{ m s}^{-1}$ corresponding to a strain rate ($\dot{\epsilon}^0$) of $\sim 5 \times 10^{-5} \text{ s}^{-1}$; a single experiment was run at $2.5 \times 10^{-5} \text{ m s}^{-1}$ ($\dot{\epsilon}^0 \sim 5 \times 10^{-4} \text{ s}^{-1}$). Dry experiments were conducted mainly at 900 °C, but also included a suite of lower temperature experiments at 850, 800 and 750 °C. Wet experiments were performed at ~ 650 °C under water pressures of 1, 2.5, and 5 MPa, and at a fixed $P_{\text{H}_2\text{O}}$ of ~ 2.5 MPa for temperatures of ~ 385 , 450, and 550 °C. During deformation, strain is manifest by shortening of the cores, reduction of porosity, flattening of ash particles, and radial increase of the cores. The continuous reduction of porosity leads to a dynamic transient strain-dependent rheology and requires strain to be partitioned between a volume (porosity loss) and a shear (radial increase) component. These data demonstrate the effect of porosity on the rheology of dry and hydrous melts. The effect of increasing porosity is to expand the window for ductile deformation for dry melts by delaying the onset of brittle deformation by ~ 50 °C (875 °C to 825 °C). The effect is more pronounced in hydrous melts (~ 0.67 – 0.78 wt.% H_2O) where the ductile to brittle transition is depressed by ~ 140 to 150 °C. Increasing water pressure also delays the onset of strain hardening due to compaction-driven porosity reduction. These rheological data are pertinent to any volcanic processes involving high-temperature porous magmas (e.g., magma flow in conduits, welding of pyroclastic materials).

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1. Introduction

Many volcanic processes involve the production and growth of gas-filled bubbles, the connection of bubbles to create permeability, and the subsequent collapse of the bubbles. These cycles of bubble growth and collapse are important elements in processes that govern magma ascent, fragmentation processes, dome growth and collapse, and the inflation, collapse, welding of pyroclastic density currents (Ohnaka, 1995; Sparks et al., 1999; Llewellyn et al., 2002; Rocchi et al., 2004; Quane and Russell, 2005).

Despite its obvious importance for understanding and modelling volcanic processes, our knowledge of the rheological properties of porous magmas is incomplete. Compaction and sintering of particulate materials in the ceramics industry has shown some of the effects of porosity on the viscosity of multi-phase systems (Rahaman et al., 1987; Ducamp and Raj, 1989; Sura and Panda, 1990). More

importantly, these studies have inspired experimentation on materials pertinent to volcanology. There are now a number of high-temperature experimental studies on synthetic melt systems that elucidate the rheological behaviour of porous melts (i.e., Stein and Spera, 1992; Lejeune et al., 1999; Quane et al., 2004). There are also a smaller number of parallel experimental studies on natural volcanic materials (i.e. Friedman et al., 1963; Bierwirth, 1982; Bagdassarov and Dingwell, 1992; Quane, 2004; Quane and Russell, 2005) and these studies report a wide range of rheological behaviours (see Quane and Russell, 2005; Grunder and Russell, 2005 for reviews).

Only one of the aforementioned studies involved high-temperature deformation of natural volcanic material in the presence of water (Friedman et al., 1963). Ultimately all natural magmas vesiculate at or near the Earth's surface to produce bubble-rich melts, which can continue to foam to the point (and beyond) of fragmentation. The vesiculation process produces both connected and isolated porosity and the amount and nature of the porosity govern fluid permeability. Events that create permeability (i.e., increase in connected porosity) increase the efficacy of fluid escape and suppress explosivity; conversely, processes that destroy permeability (i.e., increase in isolated porosity

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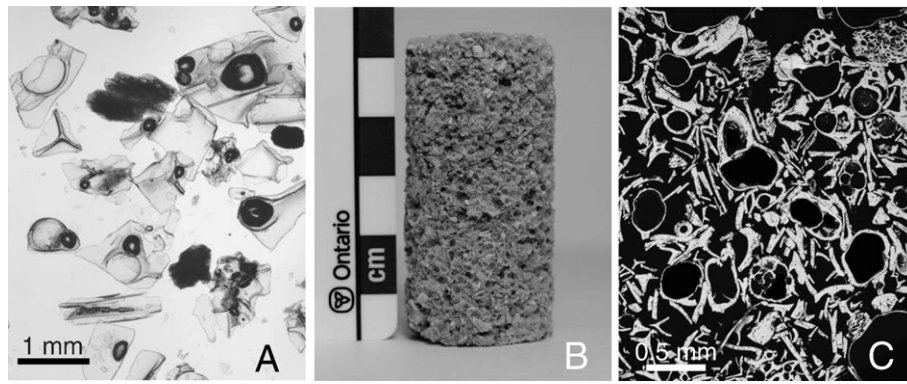


Fig. 1. Starting experimental materials. (A) Photomicrograph of loose Rattlesnake Tuff ash in immersion oil. (B) Photograph of fabricated core (~2.5 cm by 5 cm) of Rattlesnake Tuff ash used in high- T deformation experiments. (C) SEM microphotograph of pre-experiment core of sintered ash showing proportions of ash (light grey) to pore space (black) and the diversity of ash particles, including: bubble walls, glass shards, and pumiceous fragments. Large, round, thin-walled bubble shards are likely a product of vesiculation of hydrous shards during the sintering process. Smaller, thick-walled bubble shards are a direct product of the original fragmentation. Modified from Robert et al., 2008.

or decrease in total porosity) create the potential for developing overpressures that cause explosive behaviour (Kennedy et al., 2005). How porosity affects the viscosity of the magma remains unclear (Sparks et al., 1999; Llewellyn et al., 2002; Quane and Russell, 2005).

Here, we investigate the rheology of natural porous volcanic materials at high-temperatures (T) and under a controlled fluid pressure ($P_{\text{H}_2\text{O}}$). Our program uses uniaxial compression experiments to deform cores of sintered volcanic ash having initial porosities of ~80%. The rheological behaviour of the system varies with experimental condition (e.g., T and $P_{\text{H}_2\text{O}}$). These compaction experiments cause deformation of the sintered cores of ash and a reduction in porosity with the consequence that the rheological properties of the samples are transient during the experiment. Most strain can be ascribed to volume loss by pore destruction (volume strain), however, we also show that radial expansion of the sample cores (shear strain) becomes increasingly important at high values of strain. Our results also demonstrate that, at the timescales of these experiments, the window of ductile (viscous) deformation is expanded substantially by increasing porosity under both dry and wet conditions. These results have implications for the processes governing the welding of ignimbrites (Sparks et al., 1999), fragmentation cycles in volcanic conduits (Tuffen et al., 2003; Kennedy et al., 2005) and the formation and flow of clastogenic lavas (Manley, 1996; Wolff and Sumner, 2000).

2. Experimental methods

2.1. Experimental apparatus

All experiments presented are performed using the Volcanology-Deformation-Rig (VDR) at the University of British Columbia in conjunction with a water cell specifically designed for high-temperature experimentation at volcanic conditions in the presence of water (Quane et al., 2004; Robert et al., 2008). The cell can operate at temperatures up to 1100 °C and fluid pressures of 0–150 MPa; sample sizes can be up to 30 mm in diameter and 100 mm in length. Deformation experiments on sample cores can be performed under a constant load (<1136 kg) or at constant displacement rate ($5 \cdot 10^{-6}$ to $2.5 \cdot 10^{-2}$ cm/s). The load cell has a resolution of 0.086 kg and the displacement transducer a resolution of 0.00013 cm. The VDR's computer system records time, load, and displacement; the water cell is equipped with a transducer that records water pressure continuously.

A detailed description of the experimental apparatus and its calibration for recovering melt viscosity can be found in Robert et al. (2008). The original design for the bottom of the cell has been modified slightly to prevent leaks. Specifically, the bottom seal remains metal-on-metal, but we have developed a more efficient tightening mechanism that provides an even pressure distribution around the entire lower seal.

Table 1
Chemical composition of the Rattlesnake Tuff ash

Oxide	Literature ^a	SQ-00-00 ^b	SQ-00-01 ^c	GRRS30 ^d	SQ-08-21b ^e	RS_melt ^f	RS_melt ^g
		Sieved	Sintered	Sintered	Post-experiment	XRF	EMP
SiO ₂	77.11	73.99	76.79	76.12	76.11	76.27	76.29
TiO ₂	0.12	0.15	0.17	0.14	0.16	0.20	0.14
Al ₂ O ₃	11.77	12.12	12.34	13.16	12.63	12.86	12.04
FeO(T)	1.45	1.11	1.16	1.00	1.14	1.36	1.37
MnO	0.09	0.07	0.07	0.08	0.07	0.08	0.08
MgO	0.00	0.04	0.00	0.07	0.00	0.06	0.04
CaO	0.35	0.29	0.31	0.29	0.30	0.31	0.30
Na ₂ O	3.70	3.26	3.34	3.83	3.39	3.60	3.39
K ₂ O	5.23	4.42	4.57	4.59	4.59	4.74	4.89
P ₂ O ₅	0.01	0.02	0.01	0.01	0.00	0.01	0.01
H ₂ O	0.00	3.30	0.15	0.14	0.24	0.07	0.00
Total	99.83	98.77	98.91	98.43	98.63	99.56	98.54

^a Analysis from Streck and Gruner (1997).

^b Natural Rattlesnake Tuff ash sieved to coarse ash from Quane (2004).

^c Rattlesnake Tuff ash after sintering from Quane (2004).

^d Rattlesnake Tuff ash after sintering (this study).

^e Rattlesnake Tuff ash from post-experimental core (dry) from Quane (2004).

^f XRF analysis of Rattlesnake Tuff melt (cf. Robert et al., 2008).

^g EMP analysis of Rattlesnake Tuff melt (cf. Robert et al., 2008).

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