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Time-and temperature-dependent conduit wall porosity: A key control on degassing and explosivity at Tarawera volcano, New Zealand

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ABSTRACT

The permeability of volcanic conduit walls and overlying plug can govern the degassing and explosivity of eruptions. At volcanoes characterized by a protracted history of episodic volcanism, conduit walls are commonly constructed of quenched magma. During each successive eruptive phase, reheating by ascending magma can modify the porosity, permeability and H_2O content of the conduit wall rocks and overlying plug. We investigate whether the unusual explosivity of the 1886 basaltic eruption at Tarawera volcano is related to the heating and degassing of the AD1314 Kaharoa rhyolitic rocks, through which it erupted. We heat cores of perlitic Tarawera dome rhyolite to 300 °C–1200 °C for 30 min to 3 days at atmospheric pressure. We characterize time (t)- and temperature (T)-dependent variations in porosity, volatile content and texture through SEM image analyses. We also directly measure pre- and post-experimental connected and isolated porosity and water content. We identify four textural/outgassing regimes: Regime 1 ($T \leq 800$ °C, $t \leq 2$ h), with negligible textural changes and a significant loss of meteoric water (1.4–0.72 wt.% H_2O); Regime 2 ($800 \leq T \leq 1100$ °C, $t \leq 6$ h), with cracking and vesicle growth and a 5–10% increase in connected porosity; Regime 3 ($800 \leq T \leq 1200$ °C, $t \geq 30$ min), with healed cracks, coalesced and collapsed vesicles, and overall reduced porosity; and Regime 4 ($T \geq 1200$ °C, $t > 30$ min), with a collapse of all connected porosity. These regimes are governed by the temperature of the event (T) relative to the glass transition temperature (T_g) and the time scale of the event (t) relative to a critical relaxation time for structural failure of the melt (τ_r). We identify a quantitative transition from predominantly brittle behavior such as cracking, which enhances connected porosity and permeability, to viscous processes including crack healing and vesicle collapse, which act to reduce connected porosity. Applied to the 1886 basalt eruption at Tarawera, we show that progressive heat transfer ultimately reduced the open porosity and permeability of the conduit walls, thereby partially sealing the conduit and reducing volatile loss. We argue that this mechanism was an underlying reason for the exceptional explosivity of the 1886 eruption. We further suggest that textural changes associated with reheating could explain some of the cyclic deformation and degassing observed at many lava domes preceding explosive eruptions.

1. Introduction

Individual volcanic eruptions can shift rapidly in style from relatively quiescent lava dome extrusion to explosive eruptions (e.g. Sparks, 2003; Voight et al., 1999). These shifts are generally attributed to variations in physical properties such as gas content, viscosity, vesicularity, wall rock permeability, and crystallinity (e.g. Gonnermann and Manga, 2007; Jaupart, 1998; Melnik and Sparks, 2002). To date experimental and theoretical studies have focussed on variation of these properties as magma rises and decompresses (e.g. Baker et al., 2006; Gardner, 2007; Hammer and Rutherford, 2002; Larsen et al., 2004; Proussevitch et al., 1993; Takeuchi et al., 2009; Yoshimura and Nakamura, 2008) or is sheared (Gonnerman and Manga, 2003; Lavallee et al., 2007, 2008; Okamura et al., 2010; Smith et al., 2009; Tuffen et al., 2003, 2008). Natural pumice, dome rocks and experimentally decompressed glasses show huge textural variations in their permeable vesicle and crack networks (Jaupart, 1998; Michaut and Sparks, 2009; Mueller et al., 2008; Rust and Cashman, 2004; Saar and Manga, 1999; Takeuchi et al., 2008; Westrich and Eichelberger, 1994; Wright et al., 2009; Yoshimura and Nakamura, in press). Other experimental studies investigate the effects of temperature on water speciation, solubility, and magma viscosity (Stolper, 1989; Yamashita, 1999; Zhang et al., 2007). Rocks from conduit walls also exhibit variation in porosity (Kennedy et al., 2005; Rust et al., 2004; Stasiuk et

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al., 1996). Yet, no studies have addressed the isobaric time-dependent textural changes of conduit walls in response to reheating. Here we address two key questions: 1. How is degassing of the ascending magma affected by changes in permeability of the conduit walls during reheating? 2. To what extent can the release of volatiles from the reheated wall rock contribute towards the eruption?

The vents for many explosive eruptions are often plugged by fractured, vesicular lava domes or partially filled conduits (e.g. Johnson and Lees, 2000; Voight et al., 1999). Surprisingly, almost no attention has been given to the effects of the hot rising magma on the behaviour (i.e. evolution of texture and volatile content) of the lava that plugs the volcanic conduit. This is despite observations that show temperature rises in older lava domes prior to eruption (Wooster and Kaneko, 1997) that correlate with eruption style (Sahetapy-Engel and Harris, 2009). We propose that reheating can influence the degassing of both the older plug and the rising magma. Magmatic water and resorbed meteoric water dissolved in glass within the old plug may be available for degassing and vesiculation. This vesiculation in turn affects the porosity and the permeability of the plug and the ability of the rising hot magma to degas.

The 1886 Tarawera eruption (Cole, 1970; Nairn, 2002), is one of only a few examples of basaltic plinian eruptions (Houghton et al., 2004). At Tarawera, basalt erupts through a pre-existing dome complex and silicic conduit system (Carey et al., 2007). This may be a common occurrence at bimodal vents, however, descriptions of bimodal vent exposures are absent in volcanological literature. Detailed stratigraphic studies at Tarawera have tracked the shifting eruption centres and fragmentation level and documented interaction with groundwater and the pre-existing hydrothermal system (Carey et al., 2007; Houghton et al., 2004; Sable et al., 2006, 2009). The effect of rhyolitic conduit wall recycling during this eruption has also been discussed (Rosseel et al., 2006).

Conduit wall permeability is an important variable in explosive basaltic eruptions (Houghton and Gonnerman, 2008) but has not been investigated experimentally. We use laboratory experiments on the Tarawera rhyolitic lava to show that during an eruption the wall rock permeability is both time- and temperature-dependent, as is the release of volatiles from the wall rocks into the erupting magma. We argue that a reduction in the permeability of the conduit walls as a result of reheating hindered outgassing and increased the explosivity of the 1886 Tarawera eruption.

2. Methodolgy

2.1. Sampling

We collected samples that contained rhyolite and basalt from the proximal deposits of 1886 basaltic fissure eruption. The motivation for this sampling was to collect samples that show evidence for heat transfer between basalt and rhyolite. Enclave samples were collected from along the rim of the fissure on the summit of Tarawera lava dome (Fig. 1). We limited our samples to the crystal rich 1314 AD lava dome xenoliths/enclaves and excluded the older crystal-poor xenoliths (Carey et al., 2007). We chose a single large homogeneous glassy and perlitic sample of the lava dome to use for our experimental starting material. From this sample we drilled cylindrical cores 1 cm in diameter by 2 cm in length, which were then left in an oven overnight at 100 °C to remove surface water from the samples. The precise dimensions, density and porosity of samples were measured prior to, and following, heating experiments. The volume of these porous cylindrical cores was calculated from averages of replicate ($n=3$) measurements of diameter and length. This volume and the sample mass were used to calculate the bulk density (ρ_{bulk}) of the core. Skeletal (or framework) density ($\rho_{skeletal}$) is obtained by measuring sample volume via helium pycnometry. Connected porosity ($\Phi_{connected}$) (Table 1) was calculated from skeletal and bulk density from the relationship: $\Phi_{connected}=1-(\rho_{bulk}/\rho_{skeletal})$. We obtained values of dense rock equivalent (DRE) density for rock by crushing three cores and performing pycnometry on the resulting powders. All experimental cores have the same average DRE density ($2.34\ g/cm^3 \pm 0.10\ g/cm^3$). Using this average value for powder density we compute total and isolated porosity (Table 1) as: $\Phi_{total}=1-(\rho_{bulk}/\rho_{powder})$, and $\Phi_{isolated}=(\rho_{bulk}/\rho_{skeletal})-(\rho_{bulk}/\rho_{powder})$ (Michol et al., 2008). Porosity values have an uncertainty of up to 4% associated with the largest porosities measured by pycnometer (Michol et al., 2008).

2.2. Experiments

We first heated the furnace to 300–1200 °C (±10 °C) at atmospheric pressure. This represents the expected temperature range of conduit rocks in contact with the erupting basalt (Rosseel et al., 2006). Cylindrical samples (described subsequently) in ceramic crucibles were placed in the centre of the furnace for a specified time

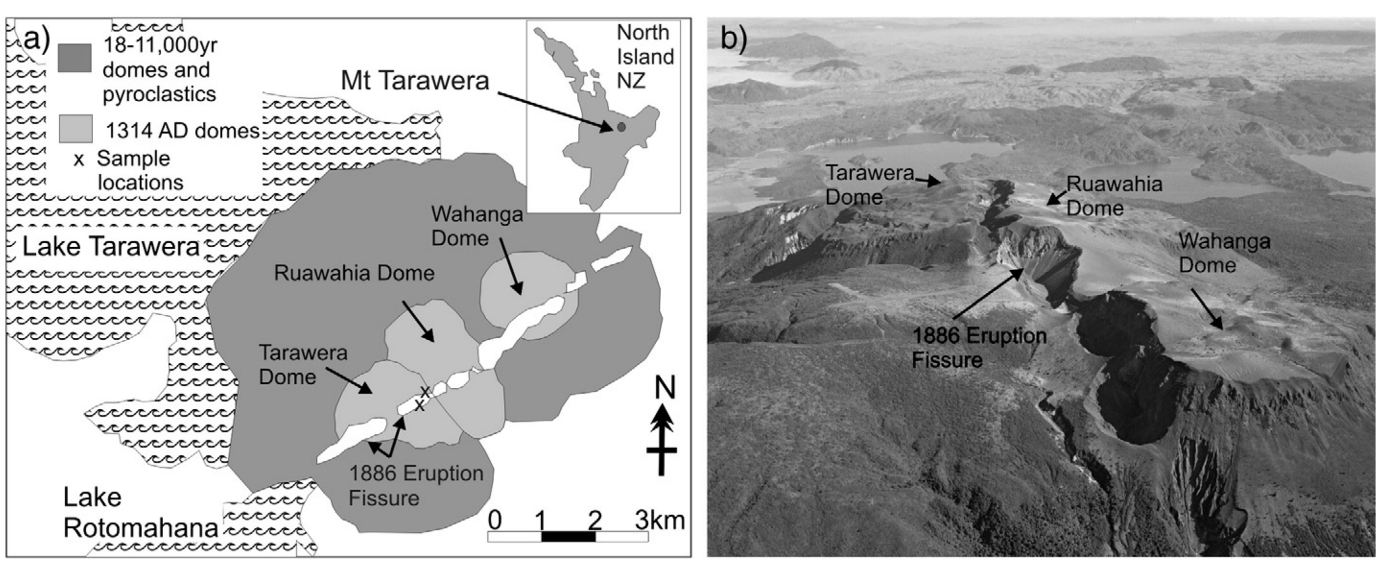

Fig. 1. Tarawera volcanic edifice shown as: a) geological map illustrating sampling locations on the rim of the 1886 eruption fissure (marked by X), and b) aerial photograph of the fissure and domes looking SW from NE of the Wahanga dome and taken by Lloyd Homer, GNS Science.