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Magma fracturing and degassing associated with obsidian formation: The explosive–effusive transition

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A B S T R A C T

This paper explores the role of melt fracturing in degassing rhyolitic volcanic systems. The Monte Pilato-Rocche Rosse eruptions in Italy evolved from explosive to effusive in style, and H_2O content in quenched glasses changed over time from relatively H_2O-rich (~0.90 wt.%) to H_2O-poor dense obsidian (~0.10–0.20 wt.%). In addition, healed fractures have been recorded in all different eruptive materials, from the glass of early-erupted tube pumice and rinds of breadcrusted obsidian pyroclasts, to the glass of late-erupted dense obsidian pyroclasts, and throughout the final effusive Rocche Rosse lava flow. These rocks show multiple fault sets, some with crenulated fault planes indicating resumption of viscous flow after faulting, complex obsidian breccias with evidence for post-brecciation folding and stretching, and centimetre- to metre-thick tuffisite preserved in pyroclasts and lava, representing collapsed foam due to fracturing of vesicle walls. These microstructural observations indicate that multiple fracturing and healing events occurred during both explosive and effusive eruptions. H_2O content in glass decreases by as much as 0.14 wt.% towards healed fractures/faults and decreases in stretched obsidian breccias towards regions of intense brecciation. A drop in pressure and/or increase in temperature along fractures caused diffusive H_2O migration through melt towards fracture surfaces. Repetitive and pervasive fracturing and healing thereby create conditions for diffusive H_2O loss into fractures and subsequent escape through permeable paths. This type of progressive magma degassing provides a potential mechanism to explain the formation of dense obsidian and the evolution from explosive to effusive eruption style.

1. Introduction

Deposits from rhyolite volcanoes worldwide indicate that many eruptions evolve from explosive to effusive (e.g., Eichelberger and Westrich, 1981; Cortese et al., 1986; Dellino and La Volpe, 1995; Barclay et al., 1996; Lara, 2009; Watt et al., 2013). Recent observations of rhyolite eruptions at El Chaitén, and Puyehue–Cordón Caulle, Chile, follow the explosive–effusive pattern for rhyolite volcanoes, where Plinian explosive activity transitioned to lava effusion within a week (Castro and Dingwell, 2009; Castro et al., 2012b; Schipper et al., 2013).

The whole-rock major element composition of rhyolites extruded during explosive–effusive rhyolite eruptions is generally constant within the eruptive cycle (e.g., Gioncada et al., 2003; Pallister et al., 2013; Watt et al., 2013). Although there can be a relative increase in crystal content in the products of effusive compared to explosive eruptions (cf. Castro and Dingwell, 2009; Watt et al., 2013), commonly the main change is a decrease in volatile contents (H_2O, CO_2, F, Cl, Li, Be and S) that is recorded in matrix glasses (Newman et al., 1988; Westrich et al., 1988; Dunbar and Kyle, 1992; Barclay et al., 1996; Lowenstern et al., 2012).

H_2O is the dominant volatile phase in volcanic melts, and dissolved H_2O contents in erupted rhyolite glasses vary from ~2.2 wt.% in explosive products, to between 0.5 and 0.1 wt.% in effusive deposits (e.g., Eichelberger and Westrich, 1981; Westrich et al., 1988; Castro and Dingwell, 2009). Generally, the juvenile components of explosive rhyolite deposits are dominantly pumice, whereas obsidian (vesicle-poor glass) forms a small proportion of the deposits (e.g., Eichelberger and Westrich, 1981; Schipper et al., 2013). However, H_2O-poor obsidian dominates amongst effusive deposits (Fink, 1980; Manley and Fink, 1987; Stevenson et al., 1994; Tuffen and Castro, 2009; Furukawa et al., 2010). Primary magmatic H_2O dissolved in glass from pyroclastic obsidian and feeder dikes can vary widely from 2.2 wt.% down to values in equilibrium with atmospheric pressure (0.10 wt.%; e.g., Eichelberger and Westrich, 1981; Westrich et al., 1988; Castro and Dingwell, 2009; Watkins et al., 2012). In contrast, glasses from obsidian lava record a narrower range at low values (0.1–0.5 wt.%; Westrich et al., 1988; Castro et al., 2005; Clay et al., 2012; von Aulock et al., 2013).

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The explosivity and style of volcanic eruptions are controlled by the ability of magmatic gas to escape as magma ascends and decompresses. Magma overpressure driving eruption is a function of the balance between gas exsolution and gas loss (e.g., Sparks, 2003). Permeable networks of connected bubbles and shear-induced brittle fractures are thought to allow gas migration and outgassing of the system (Eichelberger et al., 1986; Jaupart and Allègre, 1991; Stasiuk et al., 1996; Gonnermann and Manga, 2003; Cabrera et al., 2011; Holland et al., 2011; Lavallée et al., 2013; Schipper et al., 2013). The critical vesicularity at which significant gas loss occurs varies due to complex relationships between porosity and permeability (Rust and Cashman, 2004), partly controlled by shear flow (Wright and Weinberg, 2009). Measurements of the permeability of natural, vesicular volcanic samples and laboratory analogs indicate that bubbles form a percolating network at porosities between 30 and 80 vol.%, depending on melt viscosity, crystallinity, magnitude of shear, and bubble expansion rate (e.g., Klug and Cashman, 1996; Saar and Manga, 1999; Mueller et al., 2005).

For the expected range of permeabilities in vesicular magmas (10^{-15} to 10^{-12} m^2; cf. Rust and Cashman, 2011), calculated degassing times are longer than the estimated timescale of magma ascent through shallow conduits (Gonnermann and Manga, 2003; Takeuchi et al., 2008; Okumura et al., 2009). Slow degassing implies that another mechanism must explain the gas loss required to defuse explosive volcanic systems and give rise to effusive lava flows. Shearing experiments and measurements of natural vesicular rhyolite samples indicate that deformation of foams can greatly enhance sample permeability (Okumura et al., 2009; Wright and Weinberg, 2009; Okumura et al., 2010; Caricchi et al., 2011) and give rise to oriented, tube-like, bubble–bubble open paths, thought more typical of the relatively deep parts of conduit based on their presence in highly vesicular pumiceous pyroclasts (Blower, 2001; Wright et al., 2006; Okumura et al., 2009).

Torsional shear deformation experiments on vesicular samples have also shown that foams can sustain brittle fracture and degas (Okumura et al., 2010). However, these experiments also indicate that slip in the fractured interface prevents further brittle failure and shear-induced bubble coalescence. Healing of fractures results in resumption of viscous deformation (Tuffen et al., 2003), thus fracturing will only be a significant degassing mechanism if magma fracturing and healing events are common and pervasive (Okumura et al., 2010).

Different mechanisms have been proposed to explain the lack of preserved open permeable pathways in obsidian and the change from explosive to effusive behaviour in silicic volcanic systems. Vesicle collapse as well as fracturing and healing of melt, both induced by magma shearing in the conduit, can potentially explain: a) degassing, b) low porosity in eruptive products, and c) change in eruptive behaviour from explosive to effusive (Eichelberger et al., 1986; Gonnermann and Manga, 2003; Castro et al., 2012a; Okumura et al., 2013; Schipper et al., 2013). Cabrera et al. (2011) measured H_2O content across a healed fault in pyroclastic obsidian glass and demonstrated that fractures are directly related to degassing by providing low pressure and/or high temperature sites, which lead to diffusion of volatiles from the melt into the fracture, and provide a permeable path for gas escape.

In order to account for considerable degassing of melt and explain explosive to effusive transitions, fracturing and healing must be a pervasive and repetitive process (e.g., Gonnermann and Manga, 2003; Rust and Cashman, 2007; Cabrera et al., 2011; Castro et al., 2012b). Repeated fracturing and healing of melt during eruptions have been demonstrated in several volcanoes, both in the conduit during ascent and in lavas (Stasiuk et al., 1996; Tuffen et al., 2003; Rust et al., 2004; Tuffen and Dingwell, 2005; Rust and Cashman, 2007; Tuffen and Castro, 2009; Tuffen et al., 2010; Castro et al., 2012b; Schipper et al., 2013). Estimated fracturing and healing times of obsidian glass are compatible with the time between earthquakes recorded during silicic lava eruptions (e.g., Tuffen et al., 2003; Yoshimura and Nakamura, 2010; Cabrera et al., 2011; Castro et al., 2012b).

Castro et al. (2012b) estimated the degree of melt fracture pervasiveness required to defuse El Chaitén's 2008 explosive eruption via diffusive water loss into fractures. They measured H_2O concentration profiles in the matrix glass of pyroclasts (with evidence of pervasive fracture and healing) and lava. They found that H_2O contents drop towards tuffisite veins and towards the edges of clasts within tuffisite veins. Modelled diffusion times that would account for these H_2O drops are ~10^2–10^5 s, similar to modelled times for diffusion of H_2O into healed faults in the rind of breadcrusted obsidian bombs on Lipari Island (Cabrera et al., 2011). The transition from explosive to effusive behaviour occurred within 10 days, therefore Castro et al. (2012b) argued that unless the magma at El Chaitén was fragmented into mm-size particles across the conduit, shear-induced fragmentation could only have accounted for enhanced degassing from magma near the conduit margins. However, the hybrid and concomitant explosive–effusive phases at Chaitén and Cordón Caulle rhyolite eruptions in Chile, indicate the occurrence of shear-induced degassing processes at the scale of the conduit (Schipper et al., 2013). Schipper et al. (2013) proposed that during the Cordón Caulle eruptions, areas of strain localisation and shear-induced magma-fragmentation were not restricted to conduit margins, but rather prevailed within the conduit through a network of branched shallow permeable zones that extended over more than 100 m depth and intersected highly sheared vesicular melt. These zones allowed degassing, where permeable gas escape from a foamed magma dominated over diffusive gas escape into fractures (Schipper et al., 2013). In this paper, we investigate the extent of fracturing and healing in eruptive products; the resultant effects on H_2O content of melt; and infer relationships between fracture, degassing, and eruption style during the explosive–effusive Monte Pilato-Rocche Rosse sequences on Lipari Island.

2. The Monte Pilato-Rocche Rosse sequences

Rhyolite magmas in the Aeolian Islands have been erupting for the last ~55 thousand years (Donato et al., 2006) and over the last ~42 thousand years on Lipari Island. On Lipari, rhyolite eruptive activity is typically cyclic, beginning with an explosive phase and ending with extrusion of obsidian lava flows without a major change in chemical composition (Cortese et al., 1986; Gioncada et al., 2003). The rhyolite explosive and effusive Monte Pilato-Rocche Rosse sequences at the northeastern corner of Lipari Island (Fig. 1) represent the most recent volcanic activity on the island (Cortese et al., 1986; Dellino and La Volpe, 1995) and took place during the sixth century AD (e.g., Dellino and La Volpe, 1995; Lucchi et al., 2010).

The Monte Pilato sequence began with explosive activity forming a large pumice cone (Monte Pilato itself) and the smaller, coeval, parasitic pumice Lami cone on its southern flank (Fig. 1b; Cortese et al., 1986). A small lava body was then erupted in the main crater of Monte Pilato (Tranne et al., 2002). Explosive activity then resumed within the ~1 km wide Monte Pilato crater forming a small tephra cone (Fig. 1b) that corresponds to the Rocche Rosse sequence (Cortese et al., 1986; Dellino and La Volpe, 1995). This later eruptive sequence ended with extrusion of the ~2 km long Rocche Rosse obsidian lava flow that covers the northern slope of the Monte Pilato pumice cone (Cortese et al., 1986) and extends into the sea (Gamberi and Marani, 1997). The small lava flow located below the Rocche Rosse tephra and above the Monte Pilato pumice, and an erosional surface located in the crater walls of the Monte Pilato pumice cone (Fig. 1b) separate the Monte Pilato and Rocche Rosse sequences (Dellino and La Volpe, 1995). Petrographic studies of the explosive and effusive products found that these are nearly aphyric containing only rare microlites of K-feldspar and pyroxene (Gimeno, 2003; Gioncada et al., 2003; Davì et al., 2009; Davì et al., 2010; Clay et al., 2012).

2.1. Eruptive products

Pyroclastic deposits from the Monte Pilato-Rocche Rosse sequences contain alternating layers of phreatomagmatic and purely magmatic