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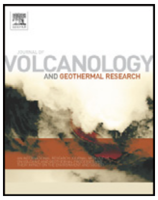

Unravelling textural heterogeneity in obsidian: Shear-induced outgassing in the Rocche Rosse flow

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ABSTRACT

Obsidian flow emplacement is a complex and understudied aspect of silicic volcanism. Of particular importance is the question of how highly viscous magma can lose sufficient gas in order to erupt effusively as a lava flow. Using an array of methods we study the extreme textural heterogeneity of the Rocche Rosse obsidian flow in Lipari, a 2 km long, 100 m thick, ~800 year old lava flow, with respect to outgassing and emplacement mechanisms. 2D and 3D vesicle analyses and density measurements are used to classify the lava into four textural types: 'glassy' obsidian (<15% vesicles), 'pumiceous' lava (>40% vesicles), high aspect ratio, 'shear banded' lava (20–40% vesicles) and low aspect ratio, 'frothy' obsidian with 30–60% vesicles. Textural heterogeneity is observed on all scales (m to μm) and occurs as the result of strongly localised strain. Magnetic fabric, described by oblate and prolate susceptibility ellipsoids, records high and variable degrees of shearing throughout the flow. Total water contents are derived using both thermogravimetry and infrared spectroscopy to quantify primary (magmatic) and secondary (meteoric) water. Glass water contents are between 0.08–0.25 wt.%. Water analysis also reveals an increase in water content from glassy obsidian bands towards 'frothy' bands of 0.06–0.08 wt.%, reflecting preferential vesiculation of higher water bands and an extreme sensitivity of obsidian degassing to water content. We present an outgassing model that reconciles textural, volatile and magnetic data to indicate that obsidian is generated from multiple shear-induced outgassing cycles, whereby vesicular magma outgasses and densifies through bubble collapse and fracture healing to form obsidian, which then re-vesiculates to produce 'dry' vesicular magma. Repetition of this cycle throughout magma ascent results in the low water contents of the Rocche Rosse lavas and the final stage in the degassing cycle determines final lava porosity. Heterogeneities in lava rheology (vesicularity, water content, microlite content, viscosity) play a vital role in the structural evolution of an obsidian flow and overprint flow-scale morphology. Post-emplacement hydration also depends heavily on local strain, whereby connectivity of vesicles as a result of shear deformation governs sample rehydration by meteoric water, a process previously correlated to lava vesicularity alone.

1. Introduction

1.1. Effusive silicic volcanism

The generation and emplacement of effusive silicic lava provides an ongoing conundrum for volcanologists. Magma viscosities on the order of 10^8 to 10^{12} Pas (e.g., Farquharson et al., 2015) inhibit bubble growth and contribute to volatile oversaturation in the melt as rhyolitic magma ascends to lower pressures and depths in the conduit (e.g., Sparks, 1978). Solubility calculations show that if magma contained dissolved water in concentrations typical of obsidian lava (0.1–0.4 wt.%) decompression during ascent would result in vesicularities far beyond those inferred for fragmentation (Gonnermann, 2015). Therefore to avoid explosive fragmentation of ascending magma there must be significant volatile removal from the melt i.e., open-system degassing (outgassing) in order to reduce gas overpressure (e.g., Taylor et al., 1983; Eichelberger et al., 1986; Gonnerman & Manga, 2003) and result in effusion of degassed obsidian lava.

Previous authors have recognised that gas escape through permeability development in the conduit is vital for the generation of obsidian, and several mechanisms have been proposed. Early work by (Eichelberger et al., 1986) suggested that silicic magma rises as a highly permeable foam which, upon extrusion, loses gas via development of

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bubble connectivity, enabling outgassing to the conduit walls (Jaupart & Allegre, 1991). Another body of work describes shear-induced fracturing of magma, leading to permeable pathways through which volatiles can escape (Stasiuk et al., 1996; Gonnerman & Manga, 2003; Okumura et al., 2009; Cabrera et al., 2010; Castro et al., 2012). There is widespread evidence for this non-explosive magma fragmentation, in the form of brittle fracture and healing. Observations of transient pyroclastic channels, or tuffisites, have been made at numerous volcanoes: Mule Creek Vent, USA (Stasiuk et al., 1996), Torfajökull, Iceland (Tuffen et al., 2003), Chaitén, Chile (Castro et al., 2012) as well as explosive products from the Monte Pilato-Rocche Rosse eruption, Lipari (Cabrera et al., n.d.). These veins of welded fragmental material describe shear fracture and healing of silicic magma (Tuffen et al., 2003) and may result in dense bubble-free obsidian bands (Castro et al., 2005a; Tuffen & Dingwell, 2005; Gonnerman & Manga, 2005; Cabrera et al., n.d.).

(Shields et al., 2014) experimentally show the effect of shear on outgassing of viscous magmas, highlighting significant localisation of shear strain during deformation. Some authors postulate that localised shear-induced fracture alone is not an effective large-scale outgassing mechanism and that a combination of permeability via bubble connectivity and fracture development is required to fully outgas ascending magma (Castro et al., 2012; Okumura et al., 2013; Sano et al., 2015) and result in volatile-poor obsidian lava. Most recently (Castro et al., 2014) suggest a combined explosive-effusive eruption style is responsible for obsidian generation, where tuffisite veins act as long-reaching pathways for gas removal from closed-system magma batches, resulting in lava effusion accompanied by pyroclastic fountaining and explosions (Schipper et al., 2013; Tuffen et al., 2012a).

Extreme textural heterogeneity of obsidian lava suggests that outgassing is a complex process and may continue during surface flow. When erupted, obsidian lava flows display a range of magmatic water contents, vesicularities and structural features that raise questions about mechanisms of obsidian emplacement and post-emplacement processes. (Eichelberger et al., 1986), as part of the permeable foam model, suggests that dense obsidian is formed from collapse of foamy magma upon extrusion, and that any heterogeneities in vesicularity are the result of incomplete bubble collapse. This idea was refuted by (Fink et al., 1992), who also recognised evidence for secondary exsolution of volatiles during surface flow. They suggest that a degree of volatile stratification exists in the conduit that contributes to the different water contents observed in eruptive products. (Fink, 1983) and (Manley & Fink, 1987) suggest a layered structural model for obsidian flows, composed of glassy obsidian, crystalline rhyolite, pumiceous and brecciated zones. We build on this model by investigating textures and volatile contents in the surface of an obsidian flow.

A particular difficulty when analysing lava flows is determining the degree of strain undergone by the rock, a parameter shown to be fundamental for studies of lava outgassing. Strain is notoriously difficult to extract from natural lava samples. Strain markers, such as microlites, magmatic enclaves and deformed bubbles have been used (Castro et al., 2002; Rust et al., 2003; Ventura, 2004), however these techniques can be complex, time consuming and require extensive sample preparation. In this study we use a simple, precise and extremely rapid technique which requires minimal sample preparation: measurement of the Anisotropy of Magnetic Susceptibility *AMS*, to determine the shapes and degree of anisotropy of the ellipsoid of magnetic susceptibility in various samples (e.g., Cañón Tapia, 2001). This, in combination with a detailed petrographic study and 2D and 3D characterisation of the samples, reveals the relationships between AMS and the distribution of strain within the obsidian flow. Furthermore, we overcome issues surrounding the interpretation of deformed bubble textures in thin sections (stereology) by using 3D computed tomography analysis. We also analyse obsidian density, vesicularity, hydration by meteoric water and magmatic water contents.

By combining an array of methodologies we determine the importance of strain localisation on the outgassing and emplacement of obsidian. The focus of this study is the Rocche Rosse lava flow, Lipari. With this field example we quantify the distribution of obsidian flow physical properties and propose a gas loss model that can account for the textural heterogeneity observed in effusive silicic eruptions.

1.2. Rocche Rosse flow description

The Rocche Rosse (*RR*) lava flow in Lipari, Aeolian Islands (Fig. 1), represents the final, effusive stage of the most recent eruptive activity from the Monte Pilato pumice cone on Lipari Island, which ended in 1220 ± 30 AD (Tanguy et al., 2003) and produced a 2 km long, 100 m thick, almost aphyric rhyolitic pumice and obsidian flow (Davì et al., 2010). Approximately 400 years prior to lava effusion the Monte Pilato cone erupted explosively, producing over 200 m thick pumice deposits (Pichler, 1980). Whole rock chemistry is the same for explosive and effusive products (Gioncada et al., 2003; Cabrera et al., n.d.), except for a marked decrease in volatile content from maximum 0.9 wt.% H_2O measured in glassy rinds of obsidian pyroclasts to ~0.2 wt.% in obsidian lava (Gottsman & Dingwell, 2001; Davì et al., 2010; Cabrera et al., n.d.).

The *RR* extends NNW from the vent and appears to be formed of two major 'lobes'; one to the west and one to the east (Fig. 1, showing east lobe). The flow displays large and small scale folding, pervasive flow banding (sometimes enhanced by spherulite crystallisation) and a blocky, fractured upper surface, which often forms ramp structures. Only the uppermost several metres of the flow are accessible. Textures associated with flow emplacement are complex and reflect the large strains experienced during progressive lava extrusion. Glassy obsidian layers are found alongside more volatile-rich material. Compositionally the lava is calc-alkaline, and contains approximately 74 wt.% SiO_2, 5 wt.% K_2O and <1 wt.% H_2O (Pichler, 1980; Gottsman & Dingwell, 2001; Davì et al., 2010; Lanzo et al., 2010). A high alkali content and an eruptive temperature of >850 °C (Cas & Wright, n.d.; Davì, 2007) have been used to explain the anomalous length of the *RR*, as these factors lower magma viscosity and increase mobility of obsidian flows (Davì et al., 2011; Forni et al., 2013).

Previous work on the Rocche Rosse includes a petrological and geochemical study by (Davì et al., 2010) which interprets the *RR* as a superheated, initially water undersaturated magma that degassed in the upper conduit. It is thought that the lava is the result of fractional crystallisation of a latitic magma, with a degree of crustal assimilation (Davì et al., 2009; Davì et al., 2010; Davì et al., 2011). These authors infer that an injection of a more mafic melt was the trigger for the explosive phase of the eruption (Davì et al., 2011). Davì et al. (2010) see no noticeable variation in magmatic water content between pumice and obsidian samples and infer that the obsidian could be formed as a result of pumice collapse during flow.

Several studies exist on the devitrification textures found in the *RR*, which occur throughout in the form of spherulites, axiolites and lithophysae (Cole & Butler, 1892; Gimeno, 2003; Clay et al., 2012). Growth of these anhydrous crystalline aggregates, comprising alkali feldspars and cristobalite (Castro et al., 2008; Von Aulock et al., 2014) is controlled by H_2O diffusion through the melt and can occur throughout cooling, both above and below the glass transition interval (620–750 °C) (Castro et al., 2008; Clay et al., 2012; Watkins et al., 2009).

Gottsman & Dingwell (2001) use relaxation geospeedometry to model cooling rates of 0.2–0.3 °C/min and a glass transition temperature of 676–706 °C for the *RR* flow fronts, and postulate that the lava would be actively deforming during flow for days to weeks after the eruption had ceased at the vent, consistent with subsequent observations of obsidian flow advance at Cordón Caulle (Tuffen et al., 2012a). (Clay et al., 2012) suggests this would be important for spherulite growth and deformation as nucleation would have started in response to large undercoolings at temperatures above the glass transition (>800 °C) then continued with hydration at lower temperatures (<300 °C) on timescales of up to 400 years, with some spherulites forming prior to foliation textures and others nucleating long after flow ceased.