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Geochemical evidence for relict degassing pathways preserved in andesite

Melissa Plail[a,*], Marie Edmonds[b], Madeleine C.S. Humphreys[c], Jenni Barclay[a], Richard A. Herd[a]

[a] School of Environmental Sciences, University of East Anglia, Norwich, NR4 7TJ, UK
[b] Department of Earth Sciences, University of Cambridge, Downing Street, Cambridge, CB2 3EQ, UK
[c] Department of Earth Sciences, University of Oxford, South Parks Road, Oxford, OX1 3AN, UK

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ABSTRACT

Andesitic arc volcanoes degas large quantities of volatiles; evidence for vapour transport in the erupted lavas is rarely preserved and poorly understood, but is crucial for understanding eruption style. We present geochemical evidence for the transport of metal-bearing vapour in shear zones preserved in lavas erupted from Soufrière Hills Volcano, Montserrat. Textural evidence suggests that shear-induced brittle failure occurred in a narrow zone (at the conduit wall or in the lava dome). Elevated metal concentrations (Cu, Au, Ag, Pb, Zn) within the zones indicate that the fractures acted as a transient pathway for metal-bearing magmatic gases. During slip, frictional heating to temperatures of >1000 °C caused partial melting at the slip surface. Resorption of volatiles and metals into the partial melt preserved the geochemical signature of magmatic vapour in the shear zone. Cordierite, which is highly unusual in volcanic rocks, crystallised from the peraluminous partial melt, with metal-bearing sulphides and oxides. The shear zones provide the first geochemical evidence for vapour segregation and transport through viscous andesite magmas and provide an insight into controls on eruption style.

1. Introduction

Effective outgassing during andesitic eruptions moderates explosivity and controls eruption style (Sparks, 2003). In andesites, shallow segregation and escape of gas in the volcanic system may take place through a permeable bubble network (Eichelberger et al., 1986), through the conduit walls (Jaupart, 1998; Jaupart and Allegre, 1991; Stasiuk et al., 1996), or through networks of brittle fractures created by shear deformation of ascending magma at low pressures (Gonnermann and Manga, 2003; Edmonds and Herd, 2007; Castro et al., 2012; Cabrera et al., 2011). Observations, experiments and theory show that while magma behaves in a ductile way at low strain rates, it can fail in a brittle manner at high strain rates (Walker, 1969; Neuberg et al., 2006; Dingwell, 1996; Lavallée et al., 2012). Repeated brittle failure at the conduit walls during the 2004–2008 eruption of Mount St Helens produced a layer of cataclasite on the surfaces of lava spines, which channelled gases (Iverson et al., 2006; Cashman et al., 2008; Pallister et al., 2012) and this process may lead to frictional melting (Grunewald et al., 2000; Schwarzkopf et al., 2002; Tuffen and Dingwell, 2005; Kendrick et al., 2012). Evidence for repeated episodes of fracture and healing in rhyolite magma have been identified in an eroded conduit in Iceland (Tuffen et al., 2003). At Soufrière Hills Volcano, Montserrat (SHV), swarms of low frequency earthquakes have been attributed to the generation of shear fractures at the conduit walls (Neuberg et al., 2006), and cyclic activity during lava dome growth at SHV may be linked to stick-slip motion of magma in the conduit controlled by pressure accumulation and relaxation at the conduit walls (Lensky et al., 2008). Recent experimental work indicates that shear localisation and development of permeable fracture zones at the conduit edges may induce the rapid ascent of the less-sheared and non-degassed magma toward the conduit centre thus causing explosive volcanism (Okumura et al., 2013). Closure and healing of permeable pathways for gas transport can occur via foam collapse, or welding of particulate matter in fractures perhaps assisted by frictional heating (Tuffen and Dingwell, 2005). The development (and closure) of permeable pathways for gas transport may therefore have important implications for eruption style.

A few studies of tuffisite-bearing rhyolite (Cabrera et al., 2011; Castro et al., 2012; Berlo et al., 2013) have considered the implications of these high permeability zones for the channelling of magmatic volatiles. Sedimentary structures within tuffisite veins are consistent with transport of a fluidised gas–particle mixture (e.g. Heiken et al., 1988; Stasiuk et al., 1996; Tuffen et al., 2003; Tuffen and Dingwell, 2005). Decreases in H_2O concentrations towards

* Corresponding author. Tel: +44 (0) 1603 59 1338.
E-mail address: m.plail@uea.ac.uk (M. Plail).

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tuffisite veins in obsidian probably indicate degassing of magmatic water into the fractures (Castro et al., 2012; Cabrera et al., 2011). Changes in metal concentrations within and next to rhyolitic tuffisite veins have also been suggested to be linked to vapour transport (Berlo et al., 2013). Elevated carbon dioxide concentrations in pyroclastic obsidians from Mono craters (USA) may result from equilibration with high-CO_2 fluids concentrated via magma degassing at the conduit walls (Rust et al., 2004), although it remains unclear whether the degassing of the pyroclastic material was inhibited kinetically (Gonnermann and Manga, 2005). The paucity of geochemical and petrological evidence for gas pathways formed by brittle failure could be because gas transport zones are commonly being overprinted or destroyed during eruption, or perhaps because the transport zones themselves are not usually erupted.

We present here the results of a petrological and geochemical study of some narrow bands found in andesite lava blocks at Soufrière Hills Volcano, Montserrat (Fig. 1). We interpret the bands to represent the loci of shearing and brittle failure, and that they record clear evidence of relict pathways for magmatic gases in the highly viscous magma at low pressures in the volcanic system. We discuss the implications of our results for eruption style and mineralisation.

2. Background

Soufrière Hills Volcano (SHV), active since 1995, is characterised by phases of extrusive andesitic dome growth and pauses. SHV emits large fluxes of volcanic gases (dominantly H_2O, CO_2, SO_2, HCl). The gas is largely decoupled from the flux of magma to the surface, indicating efficient magma–vapour segregation (Edmonds et al., 2001). In this paper we examine rare samples from events during the two latest extrusive phases of activity; Phases IV (28 July 2008–3 January 2009) and V (9 October 2009–11 February 2010). Sample MVO1535 is a ballistic clast associated with pumice fallout ejected during a vulcanian explosion that occurred on 3rd January 2009 in Phase IV (Komorowski et al., 2010) (Fig. 1). Phase IV activity was characterised by increased average lava extrusion rates (6.8 $m^3\,s^{-1}$) in comparison to earlier extrusive phases (Wadge et al., in press) generating a total volume of 39×10^6 m^3 lava extrusion in Phase IV. A series of four vulcanian explosions on 3 January 2009, preceded by increased cyclic tremor amplitude indicating an increase in pressure (~25 MPa) (Chardot et al., 2010), marked the end of Phase IV. The largest explosion generated an 11 km-high plume, with an estimated conduit excavation depth of 1.9 km (Chardot et al., 2010). Large blocks of pumice and dome rock (20–40 cm in dimension) were ejected during the explosion. The deposits had a total volume of ~0.95 Mm^3 DRE (Komorowski et al., 2010).

Sample MVO1586 is from a large andesite block within pyroclastic density current deposits associated with the 11th February 2010 dome collapse marking the end of Phase V (Stinton et al., in press). High average extrusion rates in Phase IV were maintained during Phase V at 6.8 $m^3\,s^{-1}$, but dropped to an average of 0.1 ms^{-1} in the days preceding the dome collapse (Stinton et al., in press). However, it has been calculated that extrusion rates may have reached as high 35 $m^3\,s^{-1}$ for short periods of minutes to tens of minutes (Odbert et al., in press). A total of 38×10^6 m^3 of lava was added to the dome volume, resulting in a total dome volume of 245×10^6 m^3 before dome collapse on 11 February 2010. The dome collapse ($40–50 \times 10^6$ m^3) excavated material to a depth of 320 m (Stinton et al., in press), although vulcanian explosions during the collapse event may have sourced material from a greater depth. Extensive sampling of the dome collapse deposits and rockfalls from this eruptive phase yielded only this one sample displaying the shear textures described in this paper.

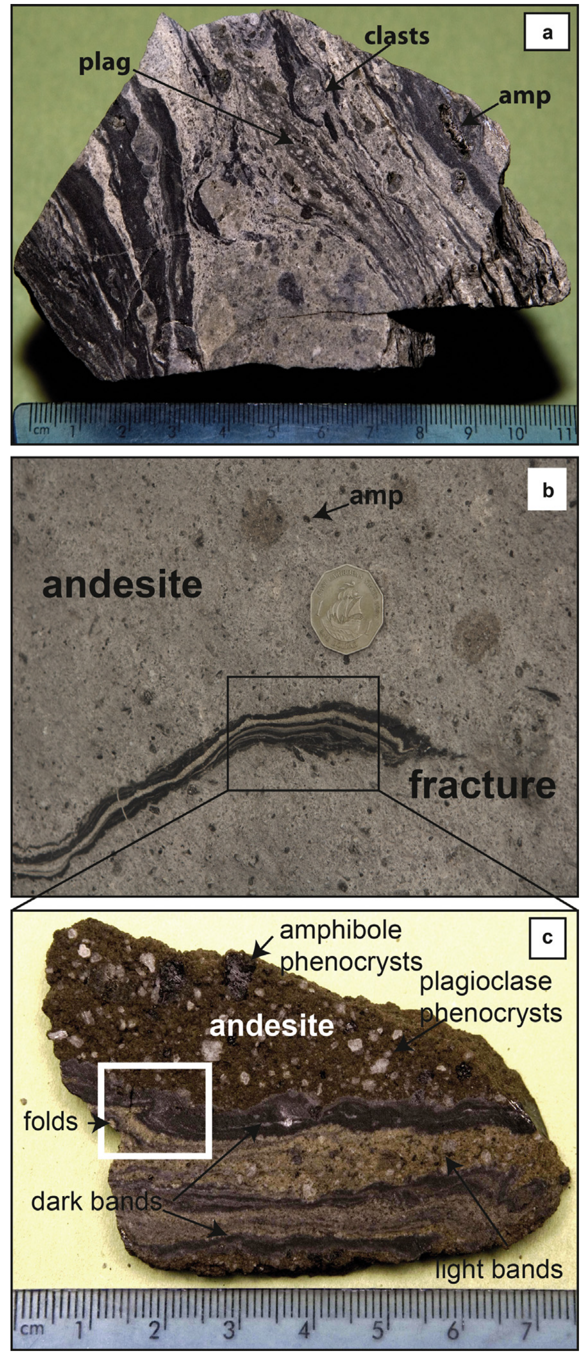

Fig. 1. Field and hand specimen images of samples used in this study. (a) MVO1535, collected from the vulcanian explosion of January 3rd 2009. Alternating dark and light bands entirely comprise the hand specimen. Visible plagioclase crystals are observed in the lighter bands. Darker bands are occasionally wrapped round clasts. (b) MVO1586, within andesitic block from February 11th 2010 dome collapse deposits, fracture is up to 2 m in length (coin scale: 2.7 cm). Amphibole phenocrysts are clearly visible in the host andesite (c) MVO1586 cut section with the host andesite with visible plagioclase and amphibole phenocrysts, note alternating dark fine-grained and lighter coarse-grained bands similar to (a). Subtle folding observed in the darker bands as highlighted in box.

3. Methods

Alternating dark and fine-grained, and light and coarse-grained bands from within both MVO1535 and MVO1586 were separated. In MVO1535, two dark bands (MVO1535b1 and MVO1535b2) were sampled and analysed. Andesite and mafic enclaves erupted in 2009 and 2010 were analysed for comparison. Samples were