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Mafic enclaves record syn-eruptive basalt intrusion and mixing

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ABSTRACT

Mafic enclaves hosted by andesite erupted at the Soufrière Hills Volcano between 1995 and 2010 yield insights into syn-eruptive mafic underplating of an andesite magma reservoir, magma mixing and its role in sustaining eruptions that may be widely applicable in volcanic arc settings. The mafic enclaves range in composition from basalt to andesite and are generated from a hybrid thermal boundary layer at the interface between the two magmas, where the basalt quenches against the cooler andesite, and the two magmas mix. We show, using an analytical model, that the enclaves are generated when the hybrid layer, just a few tens of centimetres thick, becomes buoyant and forms plumes which rise up into the andesite. Mafic enclave geochemistry suggests that vapour-saturated basalt was underplated quasi-continuously throughout the first three eruptive phases of the eruption (the end member basalt became more Mg and V-rich over time). The andesite erupted during the final phases of the eruption contained more abundant and larger enclaves, and the enclaves were more extensively hybridised with the andesite, suggesting that at some time during the final few years of the eruption, the intrusion of mafic magma at depth ceased, allowing the hybrid layer to reach a greater thickness, generating larger mafic enclaves. The temporal trends in mafic enclave composition and abundance suggests that basalt recharge and underplating sustained the eruption by the transfer of heat and volatiles across the interface and when the recharge ceased, the eruption waned. Our study has important implications for the petrological monitoring of long-lived arc eruptions.

1. Introduction

Andesites are the most common volcanic rock type erupted at convergent margins and are fundamental to the formation and evolution of continental crust (Rudnick, 1995). It is increasingly clear that many intermediate magmas in arcs are hybrids, formed during long residence periods in the crust (Cooper and Kent, 2014) and recharged frequently by mafic magmas (Eichelberger et al., 2000; Reubi and Blundy, 2009). Many intermediate composition magmas erupted in arcs preserve evidence of mingling and mixing with mafic magma shortly prior to eruption in the form of disequilibrium (Nakagawa et al., 2002; Singer et al., 1995; Tepley et al., 1999) or heating textures, diverse isotopic compositions (Davidson and Tepley, 1997; White et al., 2017), the presence of cryptic mafic components (Humphreys et al., 2009b) or macroscopic mafic enclaves (Bacon, 1986; Browne et al., 2006; Clynne, 1999; Martin et al., 2006). It remains unclear, however, whether mafic recharge of reservoirs is in itself a trigger for eruption (Murphy et al., 2000; Tepley et al., 1999; Victoria et al., 2008), or an outcome of unrest and impending eruption (Christopher et al., 2015). Such mingled magmas have been erupted at Mount Unzen, Japan (1991–1995) (Browne et al., 2006), Lassen Peak (Clynne, 1999; Tepley et al., 1999), Augustine volcano, Alaska (2006) (De Angelis et al., 2013; Nakamura, 1995), Arenal, Costa Rica (Reagan et al., 1987) and Soufrière Hills Volcano, Montserrat (Murphy et al., 2000).

Mafic enclaves typically comprise a complex hybrid assemblage of groundmass crystals, residual melt and host magma-derived components, such as "inherited" crystals and melt derived from the host magma (Bacon, 1986; Clynne, 1999; Humphreys et al., 2013, 2009b; Plail et al., 2014). Further, host magmas often contain crystals that preserve evidence of their admixture and subsequent ejection from the mafic magma. Thus, suites of cognate

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enclaves display a range of compositions and textures that reflect variable extents of differentiation of the mafic magma, or the degree of mixing with the host magma and/or changes in end-member magma composition (Bacon, 1986; Browne et al., 2006; Clynne, 1999). While we are making progress in understanding the role of mafic underplating in heating and mobilising magma bodies (Bachmann and Bergantz, 2006; Bergantz et al., 2015; Huber et al., 2011), we lack an overarching understanding of the controls on the nature of mixing with overlying host magmas. It is not known, for example, whether the enclaves reflect quasi-continuous, syn-eruptive mafic underplating, or whether episodes of mafic intrusion are decoupled from eruptions. Host and mafic enclave compositions may evolve during eruptions; these trends might allow understanding of how magmas mingle and on what timescales and what implications this may have for eruption triggering and sustenance.

There is evidence from a wide range of volcanic systems of magma mixing and mingling between a "host" evolved magma with intruding mafic magma, suggesting this is a common process and integral to the petrogenesis of complex, hybrid andesites. As well as the macroscopic evidence in the form of decimetre-scale mafic enclaves, there is abundant textural and petrological evidence for mixing and mingling. In Soufrière Hills lavas, the presence of plagioclase, pyroxene and oxide microlites, crystal clots, plagioclase phenocrysts with high Fe rims and high K_2O glass derived from the disaggregation of mafic enclaves (Humphreys et al., 2013, 2009b), shows that the bulk andesite contains up to 6% vol. of a 'cryptic' mafic component (Humphreys et al., 2013) as well as the 1–12% vol. in the form of mafic enclaves (Barclay et al., 2010; Komorowski et al., 2010; Mann et al., 2013; Murphy et al., 2000; Plail et al., 2014). In Kanga Island in the Aleutian arc, decreasing andesite bulk SiO_2 concentrations have been correlated with increasing mafic cumulate crystal clots proportions (Brophy, 1990). The 1953–1974 eruption of Trident volcano in Katmai National Park Alaska also shows a decrease in the host dacite bulk SiO_2 over the course of the eruption as the storage region homogenises with mafic magma (Coombs et al., 2000). The host magma erupted at Unzen, Japan during the 1991–95 eruption is calculated to contain between 10 and 25% mafic magma (Browne et al., 2006), which is a result of multiple mixing events (Vogel et al., 2008). The mixing efficiency may change over the course of an eruption caused by gradual changes in bulk viscosity and temperature of the overlying magma, as demonstrated in the 1915 eruption products of Lassen Peak, USA (Clynne, 1999; Klemetti and Clynne, 2014; Sparks and Marshall, 1986). The degree and style of magma mixing can strongly influence eruptive style, as demonstrated by eruptions at Quizapu, Chile (Ruprecht and Bachmann, 2010). The 1846–47 effusive eruption with geochemical and petrological evidence for magma mixing resulted significant reheating of host magma from 830 to 1000 °C; this mixing enhanced magma degassing, but reduced rapid magma expansion and explosive behaviour. Changing mafic enclave compositions over the lifetime of an eruption, where magma mingling is prevalent, have also been observed during many eruptions, but the significance of this is unclear. At Unzen, Japan, the repeated intrusion of two mafic magmas was inferred from differences in REE and trace elements between two distinct mafic enclave types (Vogel et al., 2008). At Shirataka volcano Japan, two mafic enclave types are identified on the basis of high and low K_2O over a 200 kyr period (Hirotani and Ban, 2006).

In this paper we present whole rock major and trace element data and glass major element data for andesites and their mafic enclaves erupted during the 1995–2010 eruption of the Soufrière Hills Volcano (Montserrat, West Indies) (Wadge et al., 2014). This well-studied eruption produced magma mixing and mingling features that are common to many intermediate arc magmas globally. The data are used to infer the petrogenesis of the enclaves and to develop an analytical model to describe the formation of the enclaves from a mixed boundary layer at the interface between mafic magma and overlying andesite. The temporal trends in composition are used to assess whether basalt was intruded in a discrete event at the beginning of the eruption, or quasi-continuously throughout, and whether enclave compositions might be useful for evaluating whether long-lived eruptions may be waning.

1.1. Geological setting

Most of the volcanic centres on Montserrat (West Indies; Fig. 1) are andesitic, with mafic enclaves ubiquitous in the lava domes and block and ash deposits. South Soufrière Hills Volcano, which abuts Soufrière Hills at the south of the island (Fig. 1) has erupted magmas of basaltic to basaltic andesite composition (Cassidy et al., 2015; Zellmer et al., 2003a). The recent eruptions of Soufrière Hills included five phases of andesitic dome-forming activity, separated by pauses in lava extrusion (Table 1) (Wadge et al., 2014), allowing examination of temporal trends in magma composition. Samples of andesite and mafic enclaves emplaced during phases III, IV and V were collected at locations shown in Supplementary Table 1. Data for phases I and II are compiled from the literature (Mann et al., 2013; Murphy et al., 2000; Zellmer et al., 2003a).

Previous work has characterised the andesite and its mafic inclusions. The complex zoning patterns and disparate age histories of plagioclase phenocrysts indicate that the andesite is a hybrid that has undergone multiple cooling and reheating events in the shallow crust for 10^3–10^4 years prior to the current eruption (Zellmer et al., 2003a, 2003b). Excess sulphur emissions, mafic enclaves and phenocryst disequilibria textures (Barclay et al., 1998; Edmonds et al., 2001; Humphreys et al., 2009b; Murphy et al., 2000, 1998; Sparks et al., 1998) are interpreted as evidence of an intrusion of a hotter, volatile-saturated mafic magma at depth underplating the andesite (Christopher et al., 2010). Remobilisation and reheating of the crystal-rich andesite has been proposed to have been initialised via 'convective self-mixing', 'gas sparging' or 'a defrosting front' (Bachmann and Bergantz, 2006; Burgisser and Bergantz, 2011; Couch et al., 2001). Diffusion profiles across Fe–Ti oxides in the andesite constrain the timing of the interaction between mafic and andesitic magmas to be days to weeks before eruption (Devine et al., 2003). Seismic "crises" which occurred prior to the onset of the 1995–2011 eruption and in 1933–37 and 1966–67 (Shepherd et al., 1971)have been proposed to have been caused by magma intrusion at depth (Aspinall et al., 1998).

The volume fraction of mafic enclaves in the erupted andesite has increased from ∼1% in phase I to ∼8–12% in phase V (Barclay et al., 2010; Komorowski et al., 2010; Murphy et al., 2000; Plail et al., 2014), but the causes for this are enigmatic. Substantial quantities of mafic-derived material are also found disaggregated at the crystal-scale within the andesite (Humphreys et al., 2013). Mafic enclaves have become larger with time: 87% of 158 phase I hybrid enclaves observed in the field were under 6 cm in longest dimension (Plail et al., 2014). In phase III, the maximum size for an enclave measured was 14 cm (Barclay et al., 2010). The largest phase V enclave measured to date is 26 cm.

2. Samples and methods

Samples of lava dome blocks containing mafic enclaves were acquired from block and ash deposits erupted during phases III to V (details of sampling locations and deposit types are given in Supplementary Material). Splits of samples were crushed and powdered and blocks were also made into 30 μm thick probe sections. Seventy-four powders from mafic enclave and andesite samples were analysed using X-ray fluorescence (XRF) (details of methods