Origin of Basalts by Hybridization in Andesite-dominated Arcs

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ABSTRACT

Mafic magmas are common in subduction zone settings, yet their high density restricts their ascent to the surface. Once stalled in the crust, these magmas may differentiate, and assimilate crust and other melts and crystal mushes to produce hybridized intermediate magmas. The Soufrière Hills Volcano on Montserrat is a ‘type locality’ for such hybridization processes and yet, just 3 km south of the crater, voluminous basalts have erupted from the South Soufrière Hills volcano within the same time period as the Soufrière Hills Volcano was erupting hybrid andesites (131–128 ka). Basaltic South Soufrière Hills magmas have 48–53 wt % SiO₂ and 4–6 wt % MgO. They were hot (970–1160°C), volatile-rich (melt inclusions contain up to 6 wt % H₂O) and were stored at 8–13 km depth prior to eruption (based on olivine- and pyroxene-hosted melt inclusion volatile geochemistry). Melt inclusions do not preserve basaltic liquids: they are andesitic to rhyolitic in composition, related to one another by a line of descent controlled by simple closed-system fractionation. Whole-rock compositions, however, are best described by a hybridization model involving ‘back-mixing’ of andesitic to rhyolitic melts with mafic crystal phases such as magnetite, olivine, orthopyroxene and clinopyroxene. Phenocryst zoning illustrates repeated mixing events between evolved melts and mafic phenocrysts; this feature, when coupled with the heterogeneity of crystal compositions, strongly suggests that although the bulk compositions are basaltic (containing Fo₈₀ olivine), they were assembled from disparate ingredients, probably derived from mafic crystal mushes and more evolved melt lenses of variable composition. The mixing events occur days to weeks prior to eruption. We propose that the South Soufrière Hills basaltic magmas, with their higher bulk density relative to andesites from neighbouring volcanoes, ultimately may have been eruptible owing to both the transtensional tectonics imposed by offshore grabens (related to oblique subduction in the Lesser Antilles arc) and surface unloading caused by large-scale edifice collapse. Our observations support the idea that compositional changes in arcs might reflect not only changes in source compositions, but also effects caused by variations in crustal strain and tectonics.

Key words: crystal zoning; magma mixing; melt inclusions; tectonics; mineral chemistry, olivine, magma chamber

INTRODUCTION

Intermediate magmas are generated by intensive crustal magmatic processing involving crystallization, assimilation and mixing (Anderson, 1976; Eichelberger, 1978; Rudnick, 1995; Eichelberger et al., 2006; Reubi & Blundy, 2009; Kent et al., 2010; Melekhova et al., 2013). Mafic magmas are implicated in these processes through recharging of magma bodies by mingling at the interface and by large-scale overturn in magma reservoirs (Pallister et al., 1992; Bateman, 1995).
These processes are well illustrated by volcanoes in the Lesser Antilles arc, where andesitic lavas containing mafic enclaves are commonly erupted. Andesites may erupt preferentially owing to their relatively low density compared with denser mafic lavas that are ‘trapped’ at depth by a density filter mechanism (Plank & Langmuir, 1988). Rheological and lithological barriers may also inhibit the upward migration of a basaltic melt (Eichelberger, 1978; Dufek & Bergantz, 2005; Karlstrom et al., 2009; Kent et al., 2010). Indeed, intermediate to rhyolitic magma reservoirs can obstruct the passage of mafic magma, explaining why basaltic eruptions often only reach the surface on the periphery of silicic volcanoes (Hildreth, 1981). An interesting variant on this process is illustrated on Montserrat, where basalts were erupted from the South Soufrière Hills (SSH) volcano over the same broad time interval as crystal-rich andesites (with rhyolitic melts) were being erupted from the Soufrière Hills Volcano (SHV) located less than 3 km away. This raises the question as to what mechanisms allow eruption of felsic and mafic magmas in such close proximity.

More detailed study of the SSH is also of interest because, although there is strong evidence that andesites are generated largely by mixing of repeated injections of mafic magma into high-level silicic magma chambers (Anderson, 1976; Eichelberger, 1978; Eichelberger et al., 2006; Reubi & Blundy, 2009; Kent et al., 2010), the petrogenesis and history of the mafic magmas is not well understood and may itself be complex. The density filter trap (Plank & Langmuir, 1988) means that mafic enclaves from the SHV are the only evidence of deeper, mafic magmas that are available for petrological analysis; in many cases these mafic inclusions have experienced varying degrees of mingling, quenching and degassing that obscure their original characteristics. Thus, a study of closely related (in distance and time) andesitic and basaltic volcanism at the SHV and SSH has the potential to reveal more detail regarding the nature of basaltic magmas resident in the mid- to upper crust, and can provide insights into the relative importance of magma mixing and crystal fractionation in controlling the composition of all arc volcanic rocks, and how this relates to processes of magma storage, hybridization, eruption triggering and growth of the arc crust.

We present new whole-rock and melt inclusion analyses of basaltic to andesitic lavas erupted from the SHV. We compare their geochemical characteristics with those of the andesites erupted from the SHV and examine the geochemistry of single phenocryst phases to characterize compositional gradients related to normal crystal growth during cooling and also owing to magma mixing. We assess whether their compositions could have been generated by simple processes of fractional crystallization alone or whether mixing between disparate liquid and mush components is necessary. Mineral–melt thermometry (based on two-pyroxene and plagioclase–glass pairs) and barometry (using the H$_2$O–CO$_2$ systematics of melt inclusions) have been used to estimate pre-eruptive storage conditions. We use the relaxed compositional steps across olivine crystals to infer pre-eruptive mixing timescales between felsic liquids and mafic crystals. Using all of the available petrological and geochemical data we develop a model for the generation of hybrid basalts on Montserrat and how they are assembled, and speculate as to the possible reasons for extraction and eruption of higher density hybrid magmas relating to local tectonics and unloading.

**Geological background**

The Lesser Antilles, like many arcs, comprises predominantly andesitic volcanic islands with relatively few basaltic centres. For example, in the northern and central islands (Saba to St. Lucia) <10% of the erupted volcanic rocks are basaltic. Where basaltic rocks are present, they generally occur as small-volume centres adjacent to much larger andesitic volcanoes (Westercamp & Mervoyer, 1976; Rea & Baker, 1980; MacDonald et al., 2000). This is exemplified on Montserrat (Fig. 1), where andesite lavas are predominant (Rea, 1974), with a single isolated basaltic centre (SSH) in the southernmost part of the island. Apart from the SSH, basalt occurrences are restricted to mafic inclusions (enclaves) within andesites. There is abundant petrological evidence (particularly from the currently active SHV) to show that the erupted andesites are hybrids formed over long timescales ($10^5$–$10^6$ years) by multiple recharges of deeply sourced mafic magmas into large reservoirs of crystal-rich andesite magmas prior to ascent to the surface (Murphy et al., 2000; Humphreys et al., 2009; Plail et al., 2014).

The SSH basalts are, however, sufficiently geochemically distinct from the SHV basaltic enclaves to suggest that they reflect different magma sources and processes, such as increased contribution from slab fluids relative to subducted sediments (Zellmer et al., 2003; Cassidy et al., 2012, 2014), and thus provide information regarding magmas forming within the arc that are not generally observed, at least in an identifiable form, at the surface. Indeed, the SSH volcanic rocks represent some of the most mafic lavas in the northern Lesser Antilles arc (47 wt % SiO$_2$; 6 wt % MgO), with the exception of high-Mg basalts in Martinique (Westercamp & Mervoyer, 1976). These geochemical differences are not simply related to the temporal evolution of the volcanism on Montserrat, because Ar–Ar dating and stratigraphic relationships clearly indicate that the SSH and the SHV were both active in the interval 130 ± 5 ka (with SHV-type rocks forming the basal unit to the main SSH lithologies), and the predominant andesitic volcanic rocks of the island were emplaced before and after eruption of the SSH (Harford et al., 2002; Cassidy et al., 2012).

The island of Montserrat is located in the northern part of the Lesser Antilles, a 750 km long chain of volcanic islands formed as a result of the slow (2 cm a$^{-1}$)
subduction of the North American plate beneath the Caribbean plate (Fig. 1; Wadge, 1984; DeMets et al., 2000). The oblique nature of this subduction means that the northern part of the arc is influenced by transtensional forces that have led to intra-plate deformation (Feuillet, 2000; Feuillet et al., 2010). Montserrat lies on crust ~30 km thick that sits on an asthenospheric mantle wedge that extends to ~130 km
depth (Wadge & Shepherd, 1984). The island comprises four volcanic centres: Silver Hills (2600–1200 ka), Centre Hills (950–550 ka), the SHV (282 ka to present) and the SSH (131–128 ka) (Harford et al., 2002). All these volcanic centres (except for the mafic-dominated SSH) are andesitic in composition, but their erupted products all contain abundant mafic inclusions (Rea, 1974; Murphy et al., 2000; Zellmer et al., 2010; Plail et al., 2014).

The SHV centre has been studied in most detail and its products are composed of phenocrysts of orthopyroxene, plagioclase and amphibole in a rhyolitic glass, with clear evidence for magma mixing and mingling (Murphy et al., 2000; Humphreys et al., 2009, 2013). Underplating of crystal-rich andesite within the crust by hydrous mafic magma causes instabilities to form at the interface, creating mafic enclaves (Edmonds et al., 2014; Plail et al., 2014), interspersed with sporadic magma overturn events that thoroughly mix the magmas (Woods & Cowan, 2009), distributing mafic components (Fe-rich plagioclase microlites, K-rich glass; Humphreys et al., 2010) into the andesite magma body. The petrography and geochemistry of the mafic enclaves of the SHV is also best explained by a mixing process between a mafic end-member (which varies in composition with time owing to lower crustal cryptic process) and variable amounts of rhyolitic melt hosting up to 20 vol. % phenocrysts of plagioclase, amphibole and magnetite, although not in bulk-rock proportions.

Whereas there have been a large number of studies on the andesites of Montserrat, petrological work on the SSH basalt is more limited. Murphy et al. (2000) reported that the mineral assemblage consists of plagioclase, olivine, clinopyroxene and titanomagnetite. The SSH exposures comprise a range of rock types from lava flows, to scoria, to reworked volcaniclastic material (Cassidy et al., 2014), with some more mafic enclaves and some lava flows containing cumulate xenoliths of orthopyroxene and plagioclase, similar to those described by Kiddle et al. (2010). The SSH exposures can be divided into two units on the basis of their distinct trace element and isotopic compositions: SSH Suite A has lower Sr/La and Sm/Zr ratios, but higher Zr/Er ratios and more radiogenic Pb isotope compositions than Suite B (Cassidy et al., 2014).

**METHODS**

**Samples**

Samples of SSH rocks were collected along the south coast of Montserrat (Fig. 1; Table 1). Splits were crushed using an agate mortar and powdered for whole-rock analysis; thin sections were also cut for electron microprobe analysis (EMP) and scanning electron microscope (SEM) analysis. Fractions of samples were crushed coarsely and crystals of enstatite, augite and olivine were picked from the 125–250 μm grain size fraction. The crystals were ground and polished to expose melt inclusions and mounted in indium for secondary ion mass spectrometry (SIMS) analysis. All the inclusions analysed were naturally quenched, 40–200 μm in size, and were not necked or breached by cracks.

**Whole-rock analysis**

Major elements were analysed by X-ray fluorescence (XRF) analysis of glass beads prepared by fusion of a mixture of 0.5 g subsamples and lithium tetraborate in a ratio of 1:10. Analyses were undertaken using a Philips Magix Pro WD-XRF system at the National Oceanography Centre (NOC), Southampton, UK. Error and external accuracy were generally <2%.

**Microanalysis (EMP, SEM and SIMS)**

Concentrations of H2O and CO2 in glass were obtained by SIMS on a Cameca IM 4f ion microprobe at the NERC microanalytical facility at the University of Edinburgh, using a 15 kV primary beam of O– ions (Hauri et al., 2002; Blundy & Cashman, 2008). Positive secondary ions were accelerated to 4500 eV, with an offset of ~75 eV (for 1H and trace elements) and ~50 eV (for 12C) (~20 eV) to reduce transfer of molecular ions. A 50 μm raster was performed for 3 min prior to the start of each analysis, and a primary beam current of 5–6 nA was used with a non-rastered, oval-shaped beam covering a 15–20 μm area on single spots within the boundaries of the melt inclusions. Peak positions were verified before each analysis. The following elements were analysed by counting for 3 s in each of a 10 cycle run: 1H, 23Mg, 30Si. These counts were then normalized to 30Si and converted to concentrations using a calibration curve populated by glass standards. The relative ion yield for H correlates with SiO2 content, such that plotting 1H/30Si versus H2O yields a single working curve for glasses of variable SiO2 content. CO2 concentrations, however, require a correction for SiO2 content.

Carbon was measured independently of 1H, using the same beam conditions, but with a 50 μm image field to improve transmission at moderate mass resolution, which was sufficient to resolve 24Mg2+: at the 12C peak position for background olivine measurements and inclusion analyses. 12C was analysed for 3 s in each of 20 cycle runs in which 24Mg2+, 28Si2+ and 30Si were also measured. During data processing the first five cycles of the 1H analyses and the first 10 cycles of the 12C data were discarded to avoid the effects of surface contamination on the samples that may have survived the cleaning process. Instrumental backgrounds were minimized by allowing samples held in epoxy to outgas in a separate vacuum for at least 10 h prior to use in the SIMS instrument. The full list of glass standards used is given in Supplementary Data Table 1 (supplementary data are available for downloading at http://www.petrology.oxfordjournals.org). The accuracy and precision were monitored throughout the sessions by repeat analysis of the standards as unknowns: for H2O analyses these were <9% and <6%, respectively; and for CO2 <11% and <8%, respectively. The average CO2 and H2O
backgrounds over seven sessions were 56 ppm and 0.03 wt % respectively. The lack of co-variation between Al₂O₃ and MgO in melt inclusion analyses suggests that they do not follow the vectors anticipated for post-entrainment crystallization of the host mineral.

The major element and volatile (S, Cl and F) compositions of the glasses, inclusions and phenocrysts were determined using a Cameca SX100 electron microprobe at the University of Cambridge. Quantitative determinations of elements were made using the wavelength-dispersive system with TAP, PET and LIF crystals. A range of metal, oxide and silicate (e.g. jadeite, wollastonite) standards was used for calibration of the spectrometers. All analyses used an accelerating voltage of 15 kV. For olivine, pyroxene and plagioclase a spot size of 4 μm and a 100 nA beam current were used. For glasses, a 10 μm spot was used with a beam current of 60 nA for Cl, F, S, P, Cr and Ni, and 4 nA for all other elements, with counting times of 50–200 s per analysis. During glass measurements, Na peaks were counted first to avoid significant migration during the run. In addition to calibration of each X-ray line, a series of secondary reference standards (olivines, pyroxenes, feldspars and glasses) were measured daily to check accuracy, precision and totals. Standards used were periclase for Mg, jadeite for Na, fused Si for Si, rutile for Ti, fayalite for Fe, K-feldspar for K, corundum for Al, apatite for P, and pure metals for Cr and Mn. Repeat analyses of standards were used to estimate the precision of An, Mg# and Fo determinations. The forsterite content of the St. John’s Island Olivine standard was determined with a precision of 2σ = 0.46 mol % (n = 33). Precision of Mg# in clinopyroxene was similar to the precision of forsterite content in olivine. Anorthite content in the Anorthite55 standard was determined with a precision of 2σ = 1.01 mol % (n = 46).

Accuracy was generally better than 5% for most elements, based on repeat analyses of EMPA secondary standard 2390-5 and by comparison with reference concentrations for the standard, with the exception of TiO₂, K₂O, P₂O₅ and Cl, for which accuracy was better than 20–35%. Detection limits for S, Cl and F were 40, 38 and 170 ppm, respectively, and precision was typically <5% for all oxides, with the exception of MnO, P₂O₅ and F, for which precision was better than 20%.

Backscattered SEM images were obtained at the NOC, using a LEO 1450VP (variable pressure) SEM. Carbon-coated samples were imaged at 15 kV, a working distance of 10 mm and a nominal beam current of 50–500 pA, using both secondary electron (SE) and backscattered electron (BSE) detectors.

**RESULTS**

The whole-rock samples are black to grey in colour and poorly to moderately vesicular (6–38%, average 20%). The SSH samples have bulk-composition ranging from basalt to andesite (47–58% SiO₂) (Table 1; Fig. 2). Also shown in Fig. 2 are the compositions of andesites and mafic enclaves erupted from the SHV during the period 1995–2010, together with previously published data from the SSH (Murphy et al., 1998, 2000; Horwell et al., 2001; Zellmer et al., 2003; Humphreys et al., 2009, 2010; Cassidy et al., 2012). Relative to the SSH, the SHV volcanic rocks are more silica, ranging from basaltic andesite to dacite (53–68% SiO₂), although the SHV volcanic rocks contain mafic enclaves that range from basalt to basaltic andesite (48–55% SiO₂).

The SSH lavas are highly crystalline, with 31–53 vol. % phenocrysts and microphenocrysts (>100 μm) and 47–69% microlites. Plagioclase is the most abundant mineral phase (up to 61 vol. % of the crystal assemblage), followed by orthopyroxene (15 vol. %), olivine (11 vol. %) and clinopyroxene (10 vol. %), with titanomagnetite and rare amphibole in the basaltic andesite samples (SSH5B) forming the remaining 3 vol. % (Fig. 3). The microlite crystal size fraction comprises a similar assemblage, although with less olivine present.
On average, olivines form the largest crystals (mean size 390 μm; range 61-100 μm) and are often euhedral to subhedral. They are commonly fractured and slightly altered (slightly reddened along cracks, visible in plane-polarized light). The forsterite contents [molar Fo% = 100Mg/(Mg+Fe)] range from 56 to 80 mol % (Figs 4 and 5), with two main peaks in olivine core compositions (Fo 72–80 in Group 1; Fo 56–68 in Group 2) and two peaks in olivine rim compositions that are slightly less forsteritic than the cores. Most of the olivines are normally zoned or unzoned, but some exhibit reverse zoning (Figs 6 and 7), suggesting multiple magma batches that have experienced mixing. The reverse-zoned olivines have core compositions of Fo71–80, compared with Fo 56–80 in the normally zoned olivines (Figs 5 and 6). There is a negative correlation between olivine forsterite content and CaO and MnO concentrations, with generally higher Fo% and lower Ca and Mn contents in the cores (Fig. 5). These correlations are significant at >95% confidence, with P values <0.05. This correlation is especially strong between MnO and Fo%, with an $R^2$ value of 0.9; it is less apparent between CaO and Fo% ($R^2$ of 0.36). The normally zoned olivine crystals show a trend of increasing Fo% from rim to core, mirrored by decreasing CaO and MnO profiles (Fig. 6a and b). Figure 6b illustrates an olivine with reverse zoning towards the outer edge of the crystal.
with a thin (<20 μm) band of normal zoning at the rim and no visible overgrowth. The core of this crystal has a constant forsterite content of Fo72, except for the outer 50 μm. The increase in forsterite content in the reverse zone is positively correlated with CaO, but negatively correlated with MnO content.

**Plagioclase petrography**

Plagioclase crystals range in size from microlites (<15 μm) to phenocrysts (>500 μm), with the latter commonly showing both normal and oscillatory zoning, as well as sieve textures (Fig. 3). Anorthite contents [An mol % = 100Ca/(Ca + Na)] range from 49–97% (Fig. 4). The feldspars are commonly normally zoned, but rare reverse-zoned phenocrysts are also present (Fig. 7), suggesting that a complex set of magmatic processes has occurred. The plagioclase crystals can be separated into two main groups based on their anorthite contents. The cores and reverse-zoned rims are anorthitic (An79–97), whereas the rims of the normally zoned plagioclase are more albite (An82–70) and are generally richer in MgO, FeO and TiO₂ than the more anorthitic cores and rims (Fig. 8). Complex dissolution and resorption textures are also seen in some crystals (Fig. 8b).

**Pyroxene petrography**

The average size of the orthopyroxene crystals is 142 μm ± 100 μm. They are commonly zoned and often occur as overgrowths on olivine (e.g. Fig. 6a). Magnesium number [Mg# = 100Mg/(Mg + Fe)] ranges from 60 to 74 (Figs. 4 and 9), and all crystals are enstatite in composition. TiO₂ and Al₂O₃ contents generally decrease with decreasing Mg# (Fig. 9), but Mg# does not correlate significantly with Al/Ti ratio. Orthopyroxene shows common reverse zoning and some normal zoning, but rare unzoned crystals are also present (Fig. 7).

Clinopyroxenes have an average crystal size of 176 μm ± 100 μm, with Mg# ranging from 58 to 80. The majority of the clinopyroxenes are augite, but some cores are diopside. The augites are commonly zoned, but rare unzoned crystals also exist. Some Ca-poor clinopyroxene occurs as pigeonite overgrowths on olivine (Fig. 6a). Plots of Mg# versus minor elements (Fig. 9) show that the clinopyroxenes have higher...
Fig. 4. Histograms to show the main crystal chemical ranges, including Kernel Density Estimation (KDE) curves, which correspond to the probability density function axis. (a) Distribution of forsterite content in olivines. (b) Anorthite distribution of cores and rims in plagioclase crystals. (c) Mg-number distribution of cores and rims in ortho- and clinopyroxene. The key for (a) and (b) is provided at the bottom of (b).
concentrations of TiO$_2$ and Al$_2$O$_3$ with lower Al/Ti ratios than the enstatites. A traverse of a normally zoned clinopyroxene crystal shows complex saw-tooth zoning (Fig. 10b) that is particularly oscillatory in the last 70 μm toward the rim, which occurs along with a sharp increase in Al$_2$O$_3$ and TiO$_2$ and a decrease in both Mg# and Al/Ti ratios.

**Melt inclusion geochemistry**

The melt inclusions are pristine, up to 90 μm in diameter, with no vapour bubbles and no daughter crystal phases. They span a range in compositions from andesitic to rhyolitic, with 58.2–72.6 wt % SiO$_2$, 0.45–2.6 wt % K$_2$O and 0.01–2.8 wt % MgO (Fig. 2; Table 2). Their H$_2$O contents range from 1-50 to 6-19 wt %, with CO$_2$ contents of 20–313 ppm (Fig. 11). CO$_2$ and S concentrations decrease with increasing melt SiO$_2$ content, ranging from 395 ppm S and 313 ppm CO$_2$ at 58.2 wt % SiO$_2$, to 18 ppm S and 20 ppm CO$_2$ at 72.6 wt % SiO$_2$. Cl shows a positive relationship with SiO$_2$, ranging from 2500 ppm at 58.2 wt % SiO$_2$ to 3610 ppm at 72.6 wt % SiO$_2$.

**DISCUSSION**

The range of textures and mineral, whole-rock and melt inclusion compositions suggests that the SSH mafic magma petrogenesis was just as complex as that observed for the SHV andesitic volcanic system on Montserrat and involved the assembly of multiple components. Here we discuss the origin of these components by considering the pressure–temperature conditions of magma storage, fractional crystallization and magma mixing that are reflected in the crystal and melt phases in the SSH erupted products, as well as the conditions required for the eruption of these products at the surface.

**Pre-eruptive temperature, pressure and volatile content**

Temperature estimates for the magma reservoir conditions are derived from two-pyroxene thermometry and plagioclase–whole-rock equilibria after applying the equilibrium test (where K$_D$ is 1.09 ± 0.14 for pyroxene and 0.1 ± 0.11 for plagioclase) (Table 3) (Putirka, 2008). The calculated temperature range of 970–1170 °C is hotter than the estimates of the temperature for the neighbouring SHV magma reservoir, which is thought to reside at 840 ± 40 °C based on experimental studies and pyroxene thermometry, and be heated by mafic magmas with temperatures of 900 ± 100 °C (Devine et al., 1998, 2003; Barclay et al., 1998; Murphy et al., 2000; Humphreys et al., 2009) (Table 3). The SSH temperatures reported here were calculated for different samples and give a wide temperature range; this supports our argument that the erupted magma comprises components assembled from multiple magma batches with differing storage conditions.

The melt inclusion data were used to estimate equilibration pressures using VOLATILECALC (Newman & Lowenstern, 2002; Table 4). Most of the calculated pressures (using a temperature of 1000 °C) range from 194 to 267 MPa, which equates to depths of 8.4–11.6 km (using an upper crustal density of 2300 kg m$^{-3}$; Hautmann et al., 2013), with one sample yielding a pressure of 25 MPa and a depth of 1.2 km. By comparison the magma stored beneath the SHV is thought to reside in a dual reservoir system, one at 5–6 km depth and the
other at 10–12 km depth (Barclay et al., 1998; Devine et al., 1998; Murphy et al., 1998; Elsworth et al., 2008; Paulatto et al., 2010). With the exception of the low H₂O measurement (1.5 wt %), which probably represents a melt inclusion that either equilibrated at shallow depth (1.2 km) or has lost H⁺ by diffusive equilibration (Gaetani et al., 2012), the H₂O contents in the SSH melt inclusions lie at the upper range of H₂O contents (1.0–6.3 wt %) measured in SHV melt inclusions (Humphreys et al., 2009; Mann et al., 2013; Edmonds et al., 2014). Thus, the high anorthite contents in the cores of the SSH plagioclase crystals (up to An₉₇) are most probably due to the high dissolved H₂O contents (water contents exert a first-order control on anorthite content and can elevate the anorthite contents to >An₉₀; figure 4 in Lange et al., 2009).

**Melt inclusion chemistry**

With one exception, H₂O contents are approximately constant over the entire range of K₂O, SiO₂ and MgO concentrations (Fig. 11). At depths of 8–12 km, the exsolved vapour is likely to be CO₂-rich (Blundy et al., 2010), and the invariant water contents may thus indicate that the magmas hosting the phenocrysts erupted at the SSH had similar primary H₂O contents (Tables 2 and 4). Cl concentrations are positively correlated with those of SiO₂, consistent with Cl behaving incompatibly, with little or no degassing. Both CO₂ and S contents decrease with increasing SiO₂, indicating that these volatiles were progressively partitioned into a vapour phase as the melts evolved. This is consistent with experimental data that suggest that oxidized arc rhyolites are associated with high vapour–melt partition coefficients for sulphur (Clemente et al., 2004; Zajacz et al., 2012). Similar melt inclusion trends have been observed in melt inclusion suites from Grenada that range from basalt to rhyolite and are thought to be related by fractional crystallization (Devine, 1995), as well as other examples from the Kermadec arc (Haase et al., 2006, 2011; Barker et al., 2013), South Sandwich Islands (Pearce et al., 1995), Mt Shasta (Grove et al., 2003) and from experimental studies (Sisson et al., 2005).

Figure 2 illustrates a comparison of melt inclusion and whole-rock data from the SSH and SHV with models of fractional crystallization at pressures of 100–200 MPa under moderately oxidizing conditions using the AlphaMelts/RhyoliteMELTS model (Ghiorso & Sack, 1995; Gualda et al., 2012). Two scenarios are considered: the first model involves fractional crystallization from a mafic bulk-rock starting composition, and the second model starts from the most mafic melt inclusion composition. In the first model, the starting composition is defined by the most mafic of the SSH whole-rocks (~47% SiO₂). The input parameters include a fixed pressure (100 or 200 MPa), a starting temperature of 1200°C (as defined by the two-pyroxene thermometer above, and close to the calculated liquidus temperature from RhyoliteMELTS) and an oxygen fugacity, fO₂, buffered at QFM + 2 (where QFM is quartz–fayalite–magnetite) or NNO (nickel–nickel oxide).
The melt was then cooled at 50°C intervals to simulate isobaric fractional crystallization involving olivine, plagioclase, magnetite, augite, enstatite and amphibole (Table 2, Fig. 2). Regardless of the pressure or fO2, simple isobaric fractional crystallization predicts non-linear liquid lines of descent that fail to reproduce the simple linear trends defined by the majority of the whole-rock data. Hence, the range in whole-rock data from both the SSH and SHV are best described by a hybridization model in which the rocks are mixtures between andesitic to rhyolitic melts and mafic crystal phases, as observed in many other arc volcanic settings (Davidson et al., 2005; Reubi & Blundy, 2009; Kent et al., 2010; Cashman & Blundy, 2013; Humphreys et al., 2013; Cooper & Kent, 2014).

In contrast, a fractional crystallization history can explain most of the melt inclusions from the SSH, and a significant proportion of those from the SHV. These melt inclusions do not lie on the linear trend defined by the whole-rock data. For the melt inclusions, the best fit to the AlphaMelts/RhyoliteMELTS model (Ghiorso & Sack, 1995; Gualda et al., 2012) is provided by a scenario in which the starting composition is defined by the most mafic of the SSH melt inclusions (58.7% SiO2). The input and cooling parameters are the same as for the first modelling scenario above and, again, the effects of pressure and fO2 do not yield major variation in the liquid line of descent (Fig. 2).

To summarize, the melts are related to one another by fractionation crystallization and probably evolve in closed systems in storage lenses in the crust. The bulk basaltic lavas are ‘assembled’ by mixing liquids along this line of descent with mafic crystal mushes containing mixtures of plagioclase, olivine and clinopyroxene. The whole-rocks therefore represent hybrids or mixtures between melts and mush components. In detail, it can be observed that most of the melt inclusion liquids are in equilibrium with their host crystals (Table 2), which means that at the time of melt entrapment the crystal and its carrier liquid were in equilibrium. The crystals are strongly zoned, however, and the melts are therefore not necessarily in equilibrium with other parts of the crystal, or with other crystals in the magma.

The melt inclusions were trapped over a pressure range corresponding to depths of between 8 and 12 km (Table 4). We speculate that the more mafic liquids are sourced from the deeper parts of the magma reservoir system. In contrast to the SHV, the crystal assemblage at the SSH is markedly more mafic, probably derived from deeper in the crust. For the basalts of the SSH, the depths recorded from volatile solubilities in melt inclusions suggest that melt entrapment occurs at the deeper end of the range estimated for the SHV system by Edmonds et al. (2014), thus preserving a greater range of melt inclusion compositions (from andesite to rhyolite), further suggesting that in general melts become more evolved upward through the crust. This is supported by a broad negative correlation in the melt inclusion data, between SiO2 and equilibration pressure ($R^2 = 0.45$), indicating that the least evolved compositions were generally formed at greater depths.

It is important to note that the record of pressures recorded by the melt inclusions is itself subject to bias. The depths of melt entrapment are probably governed not only by the physical dimensions of the reservoir but also, and perhaps more importantly, by the conditions under which melt inclusions form, which requires both high degrees of undercooling and a period of isothermal crystal growth (Kohut & Nielsen, 2004; Kent, 2008). Phenocrysts in the mafic magma may not have experienced sufficient undercooling until mixing with a more silicic magma, by which point eruption may have occurred before an isothermal period of crystal growth could trap mafic or intermediate melt inclusions (Koleszar et al., 2012).

Mixing is well documented in other arc systems. A notable example of the mixing process described...
above is associated with the Mount St. Helens dacite, where temperature fluctuations of 20–40 °C were a consequence of incremental, or pulsed assembly of crustal magma bodies wherein each pulse interacts with ancestral, stored magmas, accounting for much of the plagioclase zoning and textural complexity seen in the erupted magmas (Cashman & Blundy, 2013). These authors suggested that magma storage systems under most arc volcanoes are dominated by similar processes, where crystal mushes are fed by hotter, slightly more mafic magma, coupled with episodes of magma ascent from one storage region to another. The presence of common enclaves of cumulate material, such as gabbro and pyroxenite, in the SSH lavas (Cassidy et al., 2014) is also consistent with the remobilization of plutonic material. The way in which the model we propose differs from this fundamental mixing scenario is that we propose ‘back-mixing’ to generate mafic bulk compositions by mixing more evolved melts with mafic mushes, illustrating the importance of not only mushes, but also regions of andesitic to rhyolitic liquids in magma reservoirs for generating bulk compositions.

### Textural evidence for mixing

The olivine, plagioclase and pyroxene phenocryst compositional profiles all record normal and reverse zoning, suggesting a combination of growth zoning and magma mixing (Figs 6, 7, 8 and 11). Major element mineral chemistry is modified during growth in response to cooling, melt compositional changes and magma reservoir conditions, including pressure, temperature, volatile content and $f_{O2}$ (Housh & Luhr, 1991; Nelson & Montana, 1992; Sisson & Grove, 1993; Couch et al., 2003a, 2003b; Streck, 2008; Cashman & Blundy, 2013). Minor element concentrations are particularly useful for discriminating between magma mixing and growth zoning, as they are almost entirely a function of melt composition and are largely unaffected by changes in magma storage conditions (Aigner-Torres et al., 2007; Ruprecht & Worner, 2007).

Zoning profiles in plagioclase crystals show that anorthite contents are negatively correlated with Fe, Mg and Ti (Fig. 8), with magma crystallization and differentiation yielding less An-rich compositions, and increases in magma temperature or water content raising An contents. Although Fe partitioning in plagioclase

![Fig. 8. Profiles of multi-element traverses showing plagioclase zoning: (a) s normal zoning of 9_SSH4Plag02; (b) demonstrates complex oscillatory zoning (15_SSH7BPlag02).](https://academic.oup.com/petrology/article-abstract/56/2/325/2380208)
strongly depends on crystal composition, and melt temperature and fO2 (Longhi et al., 1976; Sugawara, 2001; Aigner-Torres et al., 2007), melt composition has the greatest effect on plagioclase Fe content (Ginibre et al., 2002). By comparison, experimental data show a clear negative correlation between Ti and An% that is largely independent of temperature, and Mg partitioning depends weakly on An content (Bindeman et al., 1998) and temperature (Longhi et al., 1976; Aigner-Torres et al., 2007). Therefore, changes in An content, temperature and fO2 alone cannot fully replicate the increases in Fe, Mg and Ti observed at the rim of the crystals (Fig. 8). Rather, these observations suggest that the increases in these elements must be due, at least in part, to disequilibrium crystallization prior to eruption as a result of mixing with melts enriched in Fe, Mg and Ti. This interpretation is supported by the kernel density plots of anorthite content (Fig. 4), where two populations of cores are evident, as well as a large range of anorthite values at the rims. The population of cores with An76–95 probably represents deeper, more stable plagioclase crystallization, but the cores with lower anorthite contents (An90–95) may represent plagioclase crystals that evolved in a shallower (lower PH2O), more evolved, magma body. Zoning profiles (Fig. 8a) show cores with high anorthite contents (An90) and increasingly albitic rims (down to An50) with a corresponding increase in Fe, Mg and Ti contents. Such zoning profiles are consistent with plagioclase from a wet mafic mush being mixed into a more evolved melt at lower pressure.

A history of mixing is supported by the presence of two distinct groups in olivine core compositions (Figs 4 and 5): Group 1, Fo72–80; Group 2, Fo56–68. These groups suggest mixing between two distinct magma batches, or with the entrainment of more forsteritic olivines from a crystal mush into a more evolved crystal-rich magma. The olivine crystals (both Group 1 and Group 2) exhibit both normal (most common) and reverse zoning at the rim of the crystal (Figs 5c, 6 and 7). Many of the Group 1 olivines exhibit normal zoning at the rims, consistent with magma from a primitive mush entrained into a more evolved storage system. This hypothesis is illustrated by the zoning profile in Fig. 6b, which shows a Group 1 olivine with a lower forsterite, but higher Ca and Mn rim. Simple fractional crystallization would reduce the CaO content along with Fo content, but whereas Ca and Mn partitioning are not directly affected by melt fO2 and temperature (Dunn, 1987; Libourel, 1999), the Ca concentration of olivine is strongly dependent on the alkali content of the melt (Jurewicz & Watson, 1988; Libourel, 1999). Mixing of the Group 1 olivines into an evolved melt with a higher alkali content may therefore explain the observed increased Ca content with decreasing Fo. The reverse zoning observed in some of the Group 2 olivines is consistent with olivine from the partially crystalline andesite being exposed to the more mafic melt composition and higher temperature of the intruding magma.

Pyroxene Mg# can change in response to changes in melt composition or fO2 (Streck et al., 2002). Thus, the saw-tooth major element zoning in Fig. 10 is probably related to a combination of open-system fractionation and recharge (Ginibre et al., 2002; Ruprecht & Worner, 2007), whereas the relatively large increases in Mg# approaching the rims (the outer 40 μm of a fraction (~5%) of the pyroxenes are consistent with a change in the composition and/or temperature of the intruding mafic magma (Fig. 10). Indeed, similar orthopyroxenes have been present during SHV eruptions since May 1996, with well-developed reverse-zoned rims (10–25 μm) (Murphy et al., 2000).

**Timing of mixing events**

The mixing of a phenocryst into a melt of a different composition would lead to a sharp step in the mineral composition crystallizing at the rim, assuming that conditions for crystal growth are maintained and that the mixing event results in an instantaneous, rather than gradual, change in the composition of the host melt. This sharp step then relaxes over time, via diffusion, as
the interior of the crystal begins to equilibrate with its new host melt composition. The resulting diffusion profiles may be used to estimate the timescales between magma mixing and eruption, by assuming a particular temperature (Costa & Chakraborty, 2004; Morgan et al., 2004; Costa & Dungan, 2005; Costa et al., 2008). This diffusion chronometric approach has been applied to reverse zoning profiles in our SSH samples (we cannot apply it to normal zoning profiles, because it is difficult to distinguish mixing-driven disequilibrium from fractionation-dependent growth zoning in this case). We use the DIPRA model (Girona & Costa, 2013) for both forsterite and Mn zoning, at 1000°C. The shapes of the compositional profiles in the reverse zones at the rims of two olivines (Fig. 5b) are consistent with relaxation of an initial compositional step over 10–60 days (Supplementary Figs 1 and 2). This timescale is similar to that estimated from compositional profiles in Fe–Ti oxides induced by heating in SHV lavas, where andesite remobilization by mafic intrusions occurred days to weeks prior to eruptions (Devine et al., 2003). A timescale of days to weeks between mixing and eruption is comparable with the short pre-eruptive mixing timescales calculated at Ceboruco, Quizapu, Nea Kamini and Mount Unzen volcanoes (days to months; Nakamura, 1995; Chertkoff & Gardner, 2004; Martin et al., 2008; Ruprecht & Cooper, 2012). Other mixed systems at Trident, Taupo and Volcan San Pedro give longer timescales (months to decades; Coombs et al., 2000; Costa & Chakraborty, 2004; Millet et al., 2014). Our results imply a relatively short period between the assembly of the SSH magmas and their ascent and eruption at the surface.

**Fig. 10.** Profiles of multi-element traverses showing pyroxene zoning: (a) reverse zoning of an orthopyroxene (12_SSH5Bopx09); (b) normal zoning of clinopyroxene (15_SSH7Bpx02).

**Formation of basaltic magmas at the SSH**
Basalts are often thought to represent relatively unmodified primary melts from the mantle. However, observations in this study from whole-rock trends, melt inclusions, fractional crystallization modelling and
Fig. 11. Melt inclusion plots, SiO₂ versus volatile contents.

Table 2: Major and volatile element compositions for melt inclusions analysed by electron microprobe and secondary ion mass spectrometry (SIMS) analysis

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<th>Sample</th>
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<th>MgO (wt%)</th>
<th>Al₂O₃ (wt%)</th>
<th>Na₂O (wt%)</th>
<th>K₂O (wt%)</th>
<th>CaO (wt%)</th>
<th>TiO₂ (wt%)</th>
<th>Cr₂O₃ (wt%)</th>
<th>FeO₁₀ (wt%)</th>
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<th>CO₂ (wt%)</th>
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All major element oxide concentrations are given in units of wt %; CO₂, S and Cl are given in ppm. FeO₁₀ denotes the FeO oxide concentration assuming that all Fe in the sample exists as Fe²⁺. Mg# MI is the magnesium-number of the melt inclusion [molar Mg/(Mg + Fe)]; Mg# host is the magnesium-number of the crystal host (olivine, pyroxene—augite or enstatite); K₀ is given by (X₉₀/X₉₀)host/(X₉₀/X₉₀)melt (in moles), which is equal to 0.3 ± 0.04. Values outside this range indicate disequilibrium between melt inclusion and host (Roeder & Emslie, 1970). b.d., below detection limit.
andesite lavas at the SSH and SHV at the closely spaced and near-coeval eruption of basaltic compositions have been well documented in arc mixing as a control over whole-rock and melt inclusion

Although many of the observations relating to magma mixing commonly occurs between mafic and felsic melts to phenocryst zoning attest to a hybridization model similar to that previously inferred for the formation of andesites at many intermediate systems. Magma mixing

In general, eruption of basaltic compositions in dominantly andesitic settings requires a favourable stress field (Hildreth, 1981). Indeed, density is not the only factor that limits the ascent of mafic magmas; structural controls imposed by lithology and rheological boundaries within the crust can also act to slow and sometimes stall magma ascent (Eichelberger, 1978; Dufek & Bergantz, 2005; Karlstrom et al., 2009; Kent et al., 2010). Faulting systems can promote the ascent of denser magmas, particularly within an extensional and therefore decompressional regime. Volcanoes are also commonly found along major strike-slip faults, such as the great Sumatran fault zone, the Sulawesi fault and the Liquiñe–Ofqui fault zone in Chile (Bellier & Sébrier, 1994; Lécuyer et al., 1997; Cembrano & Lara, 2009). In these areas, local extensional features are associated with single volcanoes, and it is suggested that a causal relationship exists between extension and intrusion (Moore, 1979; Aydin & Nur, 1982; Hutton & Reavey, 1992; Tibaldi, 1992; Milla & Torrente, 2003; Spinks et al., 2005; Brogi et al., 2010; Davis et al., 2010). In addition, there is evidence that tectonics can strongly control the composition of magmas. For instance, at the Taupo volcanic zone basaltic volcanism occurs at the intersection between major faults and caldera boundaries (Cole, 1990; Millet et al., 2014), whereas more intermediate magmatism occurs in areas that have experienced less crustal extension (Allan et al., 2013; Millet et al., 2014), following the recharge filtering process. Transtensional faults in the neighbouring island to Montserrat, Guadeloupe, which lies along the same en echelon fault system, are thought to control the location of volcanism and may be the cause for the frequent sector collapses on the island (Mathieu et al., 2011). Transtensional tectonics in this region may not only control the source of these magmas (Cassidy et al., 2012), but may also lead to localized faulting that thus provides a pathway for these higher density mafic magmas, which would otherwise be trapped within the crust (Fig. 12). Over time, however, the crust in these areas may impose lithostatic control as the eruption of the basalts thickens the crust. As a result, later magmas would be required to undergo differentiation by crystal segregation to become buoyant enough to erupt at the surface (Plank & Langmuir, 1988; Devine, 1995), thus increasing the likelihood of generating more evolved andesites. This is supported by numerical modelling by Pinel & Jaupart (2000), which predicts that as the edifice grows the ascent of lower density magma is favoured,

<table>
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<td>1166</td>
<td>94.0</td>
<td>Plag–melt</td>
</tr>
</tbody>
</table>

Depths are estimated using a lithostatic pressure gradient of 23 MPa km⁻¹ (Hautmann et al., 2013).

**Table 4**: Equilibration pressures for melt inclusions trapped in clinopyroxene and olivine phenocrysts using the saturation models of Dixon, 1997 in VOLATILECALC (Newman & Lowenstern, 2004)

<table>
<thead>
<tr>
<th>Sample</th>
<th>T (°C)</th>
<th>An% or Mg# value</th>
<th>Method</th>
</tr>
</thead>
<tbody>
<tr>
<td>11_SSH10_cpx04</td>
<td>1043</td>
<td>70.7</td>
<td>Two pyx</td>
</tr>
<tr>
<td>11_SSH10_cpx06</td>
<td>1024</td>
<td>70.4</td>
<td>Two pyx</td>
</tr>
<tr>
<td>6_SSH1F_cpx04</td>
<td>970</td>
<td>69.0</td>
<td>Two pyx</td>
</tr>
<tr>
<td>14_SSSH7G_plag01</td>
<td>1166</td>
<td>89.7</td>
<td>Plag–melt</td>
</tr>
<tr>
<td>14_SSSH7G_plag06</td>
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<td>94.0</td>
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</tr>
</tbody>
</table>

Tectonic control for the eruption of basalts

Although many of the observations relating to magma mixing as a control over whole-rock and melt inclusion compositions have been well documented in arc volcanic rocks (Reubi & Blundy, 2009), they do not explain the closely spaced and near-coeval eruption of basaltic and andesite lavas at the SSH and SHV at ~130 ka. In this context, it is noteworthy that the volatile contents of melt inclusions and geophysical investigations of the SHV support the existence of two upper crustal magma chambers; one at 10–12 km that feeds into a shallower chamber at 5–6 km depth that serves as the source of the erupted material (Barclay et al., 1998; Devine et al., 1998; Elsworth et al., 2008; Humphreys et al., 2009; Paulatto et al., 2010; Mann et al., 2013; Edmonds et al., 2014). We hypothesize that the eruption of more mafic rocks at the SSH was because these lavas were assembled directly from a magma chamber of similar depth (8–12 km) to the deeper of the two chambers below the SHV, but without passing through the shallower chamber. But what allows the SSH basalts to bypass this shallow density filter?

**Table 4**

<table>
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<td>14_SSSH7G_plag01</td>
<td>1166</td>
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</tr>
<tr>
<td>14_SSSH7G_plag06</td>
<td>1166</td>
<td>94.0</td>
<td>Plag–melt</td>
</tr>
</tbody>
</table>

Depths are estimated using a lithostatic pressure gradient of 23 MPa km⁻¹ (Hautmann et al., 2013).
thus promoting stalling in the crust and magma differentiation. Hence, the eruption of basaltic lavas may be characteristic of the early products of new eruption centres where extensional tectonics are operative in arc settings. This may be the case for many volcanic regions that have early phases of basaltic activity before evolving into mature andesitic systems, including northern Japan (Katsui et al., 1978, 1979), central south Chile (Lopez-Escobar et al., 1977), New Zealand (Price et al., 2005), the Aleutians and Alaska (Marsh, 1980; Myers & Marsh, 1981). The role of transtensional tectonics is strengthened by the observation that both Redonda and Kahouanne, two adjacent islands to Montserrat that lie on the same transtensional fault systems (Fig. 1), also produce mafic volcanism. These seamounts represent the emergence of new volcanism in the Lesser Antilles, and again suggest that early arc volcanism in this region may be controlled by tectonics, until further growth of the edifice inhibits the ascent of high-density mafic magmas, producing the commonly observed andesitic volcanoes. Although fault structures thus provide a possible mechanism for promoting the ascent of the SSH magmas, this alone does not explain the timing of SSH basaltic magmatism. Basaltic eruptions have not been identified at other periods in Montserrat’s history. The conditions favourable to

Fig. 12. Schematic figure showing how transtensional faulting can lead to the ascent of basaltic SSH magmas. The depths and processes involved in the generation of the SSH and SHV volcanism are shown. LCHZ, Lower Crustal Hot Zone of Annen et al. (2006).
basaltic eruptions at the SSH thus appear to have been transient, and are unique in the currently identified history of Montserrat. The SSH does not clearly correspond to an initial phase of volcanism, in the sense of the birth of a new volcanic centre, as the event is bracketed by andesite eruptions at the adjacent SHV, and there have been no subsequent eruptions (since 130 ka) at the SSH. We know of no reasons why fault activity at the time of SSH volcanism would have been enhanced relative to other periods in Montserrat’s history. Thus, although fault structures may have promoted ascent of dense mafic magmas at this location, this alone does not provide a satisfactory explanation for the timing of the SSH episode of basaltic volcanism. Other processes affecting crustal stress conditions, such as collapse of the volcanic edifice, may help explain the precise timing of SSH volcanism.

CONCLUSIONS

There is now abundant evidence that arc andesites are generated by hybridization processes, involving the mixing of felsic melts and abundant crystal phases; for instance, at the SHV on Montserrat, Mount St. Helens and Mount Hood (USA). Arc basalts, on the other hand, are commonly attributed to simple closed-system fractionation. Our study of the SSH shows that olivine-bearing basalt petrogenesis can be just as complex as the generation of andesites at the SHV, implying that, on account of the hybridization processes explored in this study, basalts in arcs may have a less simple history than is commonly assumed.

This study also shows how two volcanoes active at similar times and located very close to each other can erupt different bulk compositions. Basalts erupted from the SSH in Montserrat were stored under different magmatic conditions to the andesites of the SHV, yet underwent similar magmatic processes of mixing, recharge and cumulate entrainment prior to eruption. The range of magmatic temperature estimates (970–1160 °C) and reservoir depth estimates (8–12 km), coupled with crystal and whole-rock compositions, strongly indicates the presence of multiple magma bodies, which interact and feed basaltic eruptions. Melt inclusion data, phenocryst chemistry and fractional crystallization modelling suggest that mixing and crystal entrainment were involved in the petrogenesis of the SSH mafic magmas. The SSH magmatic system seems to match the deeper mafic-proposed SHV magma reservoir, but geophysical and petrological studies suggest that this deeper SHV system is much larger in volume than the shallow SHV reservoir. This is in contrast to the SSH, for which the results here show evidence for small, discrete pockets of crystal mushes with melt batches, which might appear in geophysical surveys as one large reservoir. We suggest that ascent of mafic magmas can be promoted by tectonics, so that they may ascend along faults or under specific stress conditions (i.e. post-collapse).

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SUPPLEMENTARY DATA

Supplementary data for this paper are available at Journal of Petrology online.

REFERENCES


