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The role of magma mixing in triggering the current eruption at the Soufriere Hills volcano, Montserrat, West Indies.

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Abstract. The andesite lava currently erupting at the Soufriere Hills volcano, Montserrat, contains ubiquitous mafic inclusions which show evidence of having been molten when incorporated into the andesite. The andesite phenocrysts have a range of textures and zonation patterns which suggest that non-uniform reheating of the magma occurred shortly before the current eruption. Reheating resulted in remobilisation of the resident magma and may have induced eruption.

Introduction

The role of magma mixing as a mechanism for triggering volcanic eruptions has become widely recognised (e.g. *Sparks et al. 1977, Eichelberger, 1995*). Influx of fresh magma into a reservoir containing cooler magma can cause remobilisation by addition of heat and/or volatiles to the resident magma. Both processes can lead to pressurisation in the magma chamber which can trigger eruption. The dome lava currently erupting at the Soufriere Hills volcano, Montserrat, is a phenocryst-rich (35–45 vol%) andesite (58.5–60.5 wt% SiO_2) containing ubiquitous fine-grained mafic inclusions (51–55 wt% SiO_2). The textures and mineral chemistry provide evidence for reheating of the andesite magma due to influx of mafic magma. This paper discusses the origin of the mafic inclusions and the petrological evidence for magma mixing, using data from samples erupted between Dec. 1995 and Aug. 1997. The current eruption is interpreted to result from injection of mafic magma into a long-lived highly crystalline magma body, which was remobilised to form the crystal-rich andesite.

Andesite Petrology

The phenocryst assemblage (vol%) consists of plagioclase (28–30%), including 2-3% microphenocrysts (80–250 μm), amphibole (3–10%), orthopyroxene (2–5%), titanomagnetite (1.5–2%), quartz (<0.5%), clinopyroxene microphenocrysts (<1%) and accessory apatite and ilmenite. The groundmass (<80 μm) consists of plagioclase, ortho- and clinopyroxene, titanomagnetite, high-Si rhyolite glass (75–80 wt% SiO_2, Table 1). Cristobalite occurs as vapor-phase crystals and devitrification products in the groundmass of some samples.

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Plagioclase textures and compositions vary widely (Figure 1). The predominant plagioclase is coarse-grained with oscillatory zoned sodic cores (An_{48-58}). Rims can be unzoned but between 30-50% of plagioclase phenocrysts are strongly reverse zoned, with or without dusty sieve-textures (c.f. *Kawamoto, 1992*). Reverse zoned rims (~30–150 μm) typically range between An_{60-80} but where dusty sieve-textures are present, the rims range up to about An_{85}. Most reverse zoned crystals remain calcic to the outer rim. The sieve zones consist of a micron-scale intergrowth of calcic plagioclase and glass which truncate original oscillatory zonation, implying an origin by resorption and rapid re-growth. Rare highly calcic crystals (An_{80-94}), interpreted as mafic xenocrysts, also occur. Plagioclase microphenocrysts typically have cores between An_{60-75}, more calcic than phenocryst cores. These may be normal (An_{50-60}) or reverse (An_{70-80}) zoned. Plagioclase microlites (<80 μm) range between about An_{50-75} with a much narrower intra-grain range.

Hornblende occurs as large phenocrysts (up to 1 cm) but does not occur as microphenocrysts or in the groundmass. Al_2O_3 contents range between 6–8% (see Figure 2). Orthopyroxene phenocryst cores have Mg# (molar Mg/Mg+Fe_{total}) between 58–62 and Wo (molar Ca/Ca+Mg+Fe_{total}) between 1.8–2.3 (Figure 3). Three phenocryst populations can be defined: (i) unzoned with no rim reaction textures; (ii) reverse zoned with narrow rims (1–25 μm) of more magnesian (Mg# of 63–68) and calcic (Wo 2.5–3.6) orthopyroxene; (iii) overgrowths of very fine-grained clinopyroxene. The width of the reverse zoned rims has increased during the present eruption from <5μm in the early dome lava to 10–25 μm in later-erupted material, suggesting that the rims have grown recently. Groundmass orthopyroxene has Mg# between 60–66 and Wo between 1.8–4.5. Orthopyroxene in amphibole reaction textures has Mg# between 63–70 and Wo from 3–5, ranging into the pigeonite field. Clinopyroxene microphenocrysts and microlites have high Mg# (66–74).

An average composition of the current andesite and some older Soufriere Hills andesites are given in Table 1. Older andesites erupted since 18 ka have a narrow range in composition (58–63.5 wt% SiO_2). The older andesites have very similar phenocryst core compositions to the current andesite (Figures 1–3).

Mafic Inclusion Petrology

Fine-grained mafic inclusions (1 mm to 40 cm in size) form a ubiquitous but minor (~1-2%) component of the andesite. Similar mafic inclusions occur in Soufriere Hills andesites, dating back to at least 24 ka (*Wadge and Isaacs, 1988*). The inclusions have basaltic to basaltic andesite bulk compositions, resembling older (~100 ka) mafic lavas of the South Soufriere Hills centre (Table 1).

The inclusions are typically ellipsoidal, although angular inclusions also occur. They have sharply defined smooth or

Table 1. Representative Major Element Analyses

Samp No.	Average andesite	MVO 57	MVO 36	MVO 62	MVO 49	MVO 26	MON 32	MO 67	MO 69	MVO 25	MVO 37	MON 18
Date	1995-97	1996	1996	1996	1996	350	SSH	SSH	SSH	350	3,750	18,000
Type	Lava, pum	Glass	Inc	Inc	Inc	Inc	Scoria	Scoria	Lava	Lava	Pum	Lava
SiO_2	59.48 (.58)	76.21	52.45	51.05	53.72	53.20	50.69	52.07	53.33	59.05	63.00	63.05
TiO_2	0.64 (.03)	0.33	0.82	0.85	0.81	0.85	0.89	0.91	0.86	0.63	0.55	0.57
Al_2O_3	18.02 (.36)	12.9	19.69	20.18	19.19	18.76	19.76	19.23	20.18	17.92	17.38	16.91
FeO^T	6.72 (.27)	2.1	9.32	9.49	8.88	8.72	9.03	8.06	7.69	7.32	5.55	5.79
MnO	0.18 (.01)	0.06	0.21	0.21	0.20	0.17	0.18	0.17	0.16	0.16	0.16	0.16
MgO	3.00 (.15)	0.17	4.21	4.59	4.22	5.39	5.48	5.35	3.89	2.99	2.38	2.50
CaO	7.61 (.22)	2.5	9.80	10.34	9.43	9.36	10.92	10.39	9.56	7.83	6.57	6.47
Na_2O	3.49 (.15)	3.68	2.78	2.77	2.86	2.87	2.37	3.05	3.30	3.33	3.47	3.51
K_2O	0.73 (.05)	2.05	0.53	0.36	0.54	0.46	0.57	0.60	0.86	0.64	0.80	0.89
P_2O_5	0.15 (.01)		0.18	0.16	0.15	0.22	0.10	0.18	0.16	0.13	0.14	0.14

All Fe is recalculated as FeO and analyses are normalised volatile free. The first column gives an average, with standard deviations in brackets, of 22 recent lava and pumice (pum) samples,. The second column gives an andesite groundmass glass composition, analysed by electron microprobe. The Na_2O content is probably too low by about 15-20% due to volatilisation. The analyses of MO67 and MO69 were supplied by Prof. P. Baker, analysed at Nottingham University. The remaining samples were analysed at Leicester University. Differences in Fe and Na between the datasets are due to interlaboratory variation. However, the compositions of the mafic South Soufriere Hills (SSH) rocks are similar to the Soufriere Hills mafic inclusions (Inc). The andesite analyses demonstrate the narrow range in bulk composition over the last 24 ka.

crenulate contacts with the host and some have chilled margins defined by a decrease in groundmass grainsize at the inclusion-host contact. They are generally phenocryst-poor (typically 1–5%), with phenocrysts of plagioclase only. They have diktytaxitic quench-textured groundmass (c.f. *Bacon, 1986*) consisting of randomly oriented interlocking elongate or acicular crystals, predominantly plagioclase with lesser amounts of mafic minerals, patches of rhyolitic glass and abundant interstitial voids. Pargasitic amphibole and titanomagnetite occur in most inclusions, ± orthopyroxene, ± clinopyroxene. Most inclusions are amphibole-bearing but amphibole is absent in some small inclusions. There is a general positive correlation between inclusion size and groundmass crystal size.

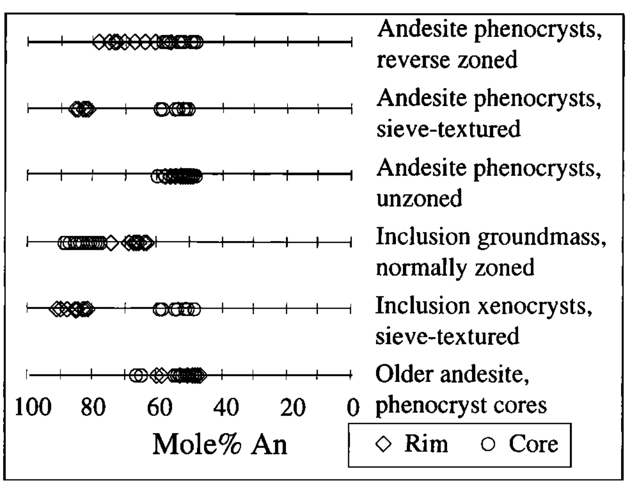

Figure 1. Plagioclase compositions as mole% anorthite to illustrate differences between the various plagioclase populations. Core compositions of phenocrysts in older (≈18,000 ka) andesites are similar to those in the current andesite.

Plagioclase phenocrysts are highly calcic, An_{85-93}, and are often normally zoned to rims An_{75-85}. The diktytaxitic groundmass plagioclase is An_{75-85}. Plagioclase xenocrysts with sodic cores and reverse-zoned sieve-textured rims, compositionally identical to phenocrysts in the andesite (Figure 1), are common in the mafic inclusions. Sieve-textures are invariably well-developed on the xenocrysts.

Amphibole in the mafic inclusions occurs as elongate or acicular crystals which form the diktytaxitic framework of the inclusions. The mafic inclusion amphibole has higher Al_2O_3 (12–14.5%) than amphibole in the andesite (6–8% Al_2O_3) (see Figure 2). Xenocrysts of low-Al amphibole, derived from the andesite, are common in the mafic inclusions. The xenocrysts typically show reaction textures at the rims and along cleavages, forming a very fine-grained intergrowth of pyroxene, titanomagnetite, plagioclase and minor olivine (Fo_{60-62}).

Pyroxene also occurs as acicular or elongate crystals forming the diktytaxitic framework of the mafic inclusions. Orthopyroxene overlaps in composition with the reverse zoned rims of the andesite phenocrysts and with the more magnesian andesite groundmass orthopyroxene (Figure 3). Large orthopyroxene xenocrysts, with core compositions identical to phenocrysts in the andesite, are common.

The quench textures and interstitial voids, the presence of host-derived xenocrysts in the inclusions, the chilled margins and the crenulate contacts are characteristic of magmatic mafic inclusions which have been quenched in a cooler silicic liquid (*Bacon, 1986, Blundy and Sparks, 1992*). Elliptical inclusions

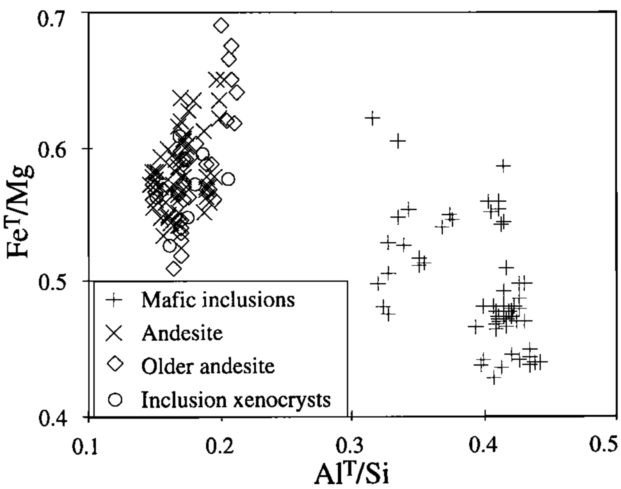

Figure 2. Fe/Mg plotted against Al/Si to illustrate the differences in composition between amphiboles in the mafic inclusions and the andesite. Amphibole in the older andesite (3,750 and 18,000 ka) is similar to that in the current andesite.

with chilled margins must have been incorporated into the andesite as predominantly liquid blebs of mafic magma. Quenching is rapid because of the contrast in composition and temperature between the magmas (*Sparks and Marshall, 1986*). The rarer angular inclusions probably represent parts of dikes or sills which had already solidified. The correlation between grainsize and inclusion size is explicable in terms of cooling rate, where larger inclusions undergo slower cooling. The dependence of cooling rate on inclusion size can also account for the presence or absence of amphibole. Small inclusions quench rapidly at temperatures above the stability limit of amphibole, which is about 980°C in basaltic andesite at upper crustal pressures (e.g. *Sisson and Grove, 1993*). Larger inclusions had not fully quenched when cooling below 980°C and crystallize amphibole.

Geothermometry

Andesite magma temperatures are estimated using the QUILF program of Andersen et al. (1993) in single pyroxene mode, because the clinopyroxene microphenocrysts are not in equilibrium with the orthopyroxene phenocrysts. The QUILF thermometer has been tested on orthopyroxenes from clinopyroxene-absent experiments of Barclay et al. (1998) on Soufriere Hills andesite and of Gardner et al. (1995) on Mt. St. Helen's dacites, reproducing the experimental temperatures to within ±20°C or better. The current Soufriere Hills andesite gives a range of temperatures between 810–880°C, averaging 858 ± 20°C (180 analyses of 33 crystals). Similar estimates are obtained for andesites erupted over the last 24 ka. These core temperatures are very low for andesitic magma but are consistent with the occurrence of quartz which is stable in the experiments of Barclay et al. (1998) only below about 840°C. Temperature estimates for reverse zoned orthopyroxene rims are invariably higher than the crystal cores, ranging between 870–1030°C with a narrow intra-grain range.

The temperatures of the mafic inclusion magma, prior to interaction with the cooler andesite, are difficult to constrain because the mafic minerals have crystallized by quenching and may not record original magmatic temperatures. Furthermore, inclusion pyroxenes are heterogeneous and give inconsistent results. However, some relatively homogeneous orthopyroxene crystals give temperatures in the range 1020–1050°C, which may be close to the pre-mixing mafic magma temperature. Older South Soufriere Hills basalts, which have similar bulk compositions to the mafic inclusions, give clinopyroxene QUILF temperatures between 1050–1080°C. These temperature estimates may also be appropriate for the mafic inclusion magmas.

Discussion

The petrology of the Soufriere Hills magma is interpreted in terms of a substantial, long-lived, highly crystalline magma body, periodically invaded by mafic magma. The low temperatures of 858±20°C, about 200°C below the experimentally determined liquidus, suggest that the magma experienced a protracted cooling history with extensive crystallization, forming a highly crystalline body with a high-Si rhyolite residual melt (Table 1). Least squares calculations indicate that between 65-75% crystallization is required to generate the observed high-Si melt from the andesitic bulk magma. High crystallinity is also consistent with the presence of angular magmatic mafic inclusions, interpreted as dismembered dikes. In plutonic environments, mafic inclusions are formed where mafic magma is intruded into cooler, more silicic, crystal-rich magma, forming dikes and sills which subsequently disintegrate to form quenched inclusions, as the surrounding host is heated and remobilised (e.g. *Blundy and Sparks, 1991*). Crystal contents of 60-70% are required to give sufficient mechanical strength to allow intrusion of mafic magma as dikes (e.g. *Marsh, 1981, Furman and Spera, 1985*). The narrow range in mineral and bulk compositions and the evidence for a long cooling history suggest that all eruptions over the last 24 ka at least may be tapping the same magma body. This is supported by preliminary U-Th dating on mafic phenocrysts, which give ages of 25±8 ka

Several intrusions of mafic magma may have occurred over the last 24 ka as magmatic mafic inclusions occur in all andesites erupted over this time. Each intrusive episode involves reheating of the magma which may subsequently return to steady low temperature state and continue to crystallize a low temperature mineral assemblage. The range in orthopyroxene rim

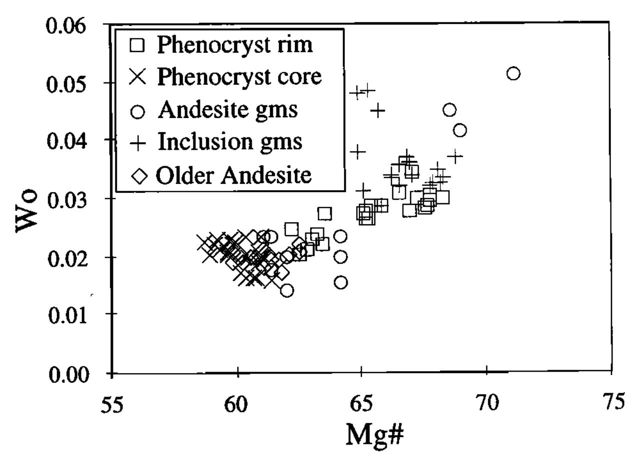

Figure 3. Phenocryst cores and rims of reverse zoned andesitic orthopyroxenes are plotted as mole fraction of Wo against Mg#. Andesite and mafic inclusion groundmass crystals and cores of crystals from the older andesite are also plotted.

temperatures and the variation in plagioclase textures and rim compositions imply that the effects of reheating are localised rather than uniform throughout the entire magma chamber. The variation in textures and rim compositions of the phenocrysts suggest that the magma represents a mixture of crystals which have experienced a wide range of thermal histories. Phenocrysts which come into close contact with or are incorporated into the intruding mafic magma show resorption and strong reverse zoning, other phenocrysts are reverse zoned but not resorbed, whereas others have been unaffected. The physical process can be described by a modified version of the model of Huppert and Sparks (1988), where intrusion of mafic magma induces convection in the host magma body. Temperatures are high during the early part of the intrusive process and adjacent to the mafic magma, but decline as the volume of remobilised magma increases. As heat is transferred to different parts of the remobilised magma, host minerals experience different thermal histories and are progressively mixed together due to convective stirring of the remobilised magma.

Several observations point towards a recent intrusive event. In particular, the reverse zoned rims on many orthopyroxene phenocrysts, which have increased in width since the beginning of the eruption, are strong evidence for recent reheating. Furthermore, plagioclase phenocrysts with reverse zoned rims typically have no sodic overgrowths, suggesting that the reverse zonation is recent. The predominance of calcic microphenocrysts in the size range between 80–250 μm also supports this argument. The resorption textures are characteristic of plagioclase which has been reheated and can develop on timescales of less than a few years in hydrous systems (*Nakamura and Shimakita, 1996*). The fact that resorption sieve-textures are most strongly developed on andesitic xenocrysts in the mafic inclusions supports reheating as a mechanism for their origin.

There are currently no definite constraints on whether there was a single reheating event at the beginning of the eruption or several such events during the course of the eruption. Although the exact timing of the most recent mixing event(s) is not constrained, the seismic episode beginning in 1992 may reflect the movement of magma through the crust from deeper levels. Preliminary interpretation of geophysical data from this period suggests that there was relatively deep (at least 14 km) seismicity (Young et al., 1998), suggesting movement of magma at deep levels within the crust. It is suggested therefore that intrusion of mafic magma may have occurred less than four years before the current eruption began, triggering the renewed activity.

Two mechanisms are considered to trigger and drive extrusive eruptions (Eichelberger, 1995). Firstly, crystallization alone can build up sufficient pressure in a closed system magma chamber. Secondly, replenishment with fresh magma can trigger eruptions by reheating and/or addition of volatiles to the resident magma. In a closed system, pressure and extrusion rate decrease with time (Stasiuk et al., 1993) whereas in an open replenished system, pressure and volume discharge may remain steady or even increase. Magma production rates have increased throughout the eruption (Sparks et al., 1998), which is much more consistent with an open system driven by influx of fresh mafic magma.

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