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Petrologic evidence for pre-eruptive pressure-temperature conditions, and recent reheating, of andesitic magma erupting at the Soufriere Hills Volcano, Montserrat, W.I.

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Abstract. The recent eruption of the Soufriere Hills Volcano in Montserrat (July, 1995, to present; September, 1997) has produced an andesitic dome (SiO_2 ~59-61 wt.%). The eruption has been caused by invasion of mafic magma into a preexisting andesitic magma storage region (P ~130 MPa; ≥5 km depth). The composition of the andesite has remained essentially constant throughout the eruption, but heating by the mafic magma increased the andesite temperature from ≤830°C to ≤880°C. Prior to being heated, the stable mineral assemblage in the andesite was plagioclase + amphibole + orthopyroxene + titanomagnetite + ilmenite + quartz. The rise in temperature from ≤830°C to ≤880°C (fO_2 ~ 1 log unit above NNO) has caused quartz to become unstable, and has also caused changes in silicate and Fe-Ti oxide mineral compositions. The andesitic magma is likely saturated with an H_2O-rich vapor phase in the upper part of the magma storage region. Melt H_2O content is ~4.7 wt.%.

Introduction

The most recent eruption of the Soufriere Hills Volcano in Montserrat, Lesser Antilles volcanic arc, has produced an andesitic dome, numerous pyroclastic flows and tephra fall. Near real-time petrologic studies of these eruptive products have revealed conditions in the magma storage region, and variations in magma ascent rate, which control eruptive style [*Devine et al.*, this volume]. This paper summarizes much of the bulk chemistry, mineralogical, and textural data, and provides an estimate the pre-eruptive pressure, temperature, and fO_2 conditions in the magma storage region prior to the present eruption. This work complements companion studies of the phase equilibria of the new dome andesite [*Barclay et al.*, this volume], the use of hornblende reactions as indicators of magma heating/mixing and magma ascent rate [*Devine et al.*, this volume], and studies of mafic inclusions [*Murphy et al.*, this volume].

Analytical Methods

Samples were collected approximately every two months (December, 1995, to present). Most samples are gray, relatively poorly-vesicular andesite blocks from pyroclastic flow deposits. More pumiceous samples include a sample from the 17-18 September, 1996, explosive eruption [*Robertson et al.*, this volume] and a sample erupted in September, 1997. Three to six polished thin sections were made of each sample for petrographic and textural examination, and for electron microprobe analysis of glasses and minerals using methods described elsewhere [*Devine*, 1995; *Devine et al.*, 1995].

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Results

The new andesite (~59-61 wt.% SiO_2) falls within the range of compositions of older Soufriere Hills andesites and dacites [*Rea*, 1974; *Wadge and Isaacs*, 1988; *Devine*, 1987]. There have been no major temporal variations in major-element or trace-element composition throughout the eruption (Table 1). The andesite is porphyritic (~40 vol. % crystals), with phenocrysts of plagioclase (~30 vol. %), hornblende (<6.5 vol. %), orthopyroxene (<5 vol. %), titanomagnetite (<2 vol. %), and minor ilmenite and apatite. Rare embayed quartz grains, which in some cases are rimmed with fine-grained clinopyroxene, are found in all samples. Orthopyroxene phenocrysts are, in some cases, also overgrown by clinopyroxene. Titanomagnetites are generally subhedral and free of exsolution lamellae, but in a few samples, the titanomagnetite was converted to lattice-like intergrowths of more Ti-rich titanomagnetite and hematite, probably because of slow, near-surface cooling. The groundmass is composed of the same mineral assemblage as the phenocrysts, except that hornblende is replaced by clinopyroxene. The degree of crystallization of the poorly vesicular groundmass varies with eruptive style and magma ascent rate. The matrix glass is high-silica rhyolite. In general, new dome samples appear to be modally uniform, except for <1-2 vol.% basalt or basaltic andesite inclusions with fine-grained, diktytaxitic textures [*Murphy et al.*, this volume].

Plagioclase phenocrysts are variably zoned (Fig. 1). Many have relatively homogeneous, low-An cores (An_{50-60}) surrounded by high-An-content (>An_{75}), sieve-textured zones containing abundant small (1-30 μm) melt inclusions. These high-An-content zones may be mantled by lower-An-content overgrowths up to 100 μm thick, and, in some cases, thin calcic rims. The high-An zones in the interiors of some large phenocrysts range in composition from ~ An_{50-60} to >An_{80} near the melt inclusion zone, and back to ~ An_{50-60} at, or near, the rims of the crystal. Other plagioclase phenocrysts lack the sieve-textured zones, being normally zoned with high-An (An_{75-80}) cores and ~An_{50-60} rims. These are, in general, smaller than the sieve-textured phenocrysts, but can reach >1 mm in length. About 30-50% of plagioclase phenocrysts and microphenocrysts have thin (<15 μm), reversely zoned, high-An-content (>An_{60}) rims.

Table 1. Whole rock and melt inclusion analyses

Sample ID Date erupted	MONT128 Dec. 1995 whole rock	MONT140 May 1996 whole rock	MONT153 Sept. 1996 whole rock	Ave. comp. 12/95 to 10/97	MONT153 Sept.1996 MI's in plag	MONT153 Sept 1996 MI in quartz
SiO_2 (wt.%)	59.72	59.46	60.11	60.02(38)	71.34(101)	77 10(10)
TiO_2	0.58	0.66	0.67	0.60(6)	0.21(5)	0.18(4)
Al_2O_3	18.26	17.90	17.53	17.86(26)	12.77(25)	9.83(6)
FeO*	6.61	6.89	7.10	6.57(42)	1.70(31)	1.17(14)
MgO	2.80	2.77	2.89	2.72(18)	0.34(14)	0.22(1)
CaO	7.43	7.53	7.44	7.57(14)	2.35(18)	1.52(5)
Na_2O	3.33	3.64	3.49	3.50(17)	4.29(19)	4.14(11)
K_2O	0.92	0.81	0.78	0.82(6)	1.92(12)	1.72(9)
MnO	0.13	0.23	0.18	0.18(4)	0.09(3)	0.10(8)
P_2O_5	0.14	0.15	0.11	0.14(2)	-	-
Total	99.92	99.82	100.32	99.98	95.01	95.99
V.B.D.	-	-	-	-	4.99	4.01
# of anals.	-	-	-	6	26	3
Cl (ppm)	-	-	-	-	3372(430)	2634(112)
Rb	16	14	15	15(1)	-	-
Sr	276	273	277	275(3)	-	-
Y	23	22	24	23(2)	-	-
Zr	104	105	100	103(3)	-	-
Ba	211	231	224	223(10)	-	-

Numbers in parentheses represent estimated standard deviations (e.s.d.) in terms of least units cited to their immediate left; hence, 60.02(38) indicates an e.s.d. of 0.38 wt.%. All Fe calculated as FeO. V.B.D. indicates volatiles estimated by difference (see text). Analytical methods of *Devine* [1995] and *Devine et al.* [1995].

Hornblende phenocrysts are large (≤1 cm), euhedral-subhedral, green to brown, and typically have 0-120 µm-thick reaction rims of fine-grained pyroxenes, plagioclase, magnetite and glass. The rims are interpreted to result from decompression of the magma during its ascent (Devine et al., this volume). A small but ubiquitous sub-population of hornblendes are surrounded by thick (>200 µm), coarse-grained rims. Hornblende phenocrysts are high in SiO_2 (46-48 wt.%), low in Al_2O_3 (~8 wt.% in the cores to ~6.4 wt.% at the rims), with Mg#'s ~63-65. Amphibole crystals in tephra fall deposits from the 17-18 September, 1996, explosive eruption lack decompression breakdown rims, but have scalloped or slightly rounded outlines, suggesting that they were resorbed to some extent within the amphibole stability field (see below).

Orthopyroxene phenocrysts (<3 mm) are euhedral and relatively homogeneous ($En_{60}Fs_{38}Wo_2$; Mg# 58-62). Some grains, however, are mantled by thin overgrowths (5-25 µm thick) of more magnesian orthopyroxene ($En_{66}Fs_{31}Wo_3$; Mg# ~68), and some have clinopyroxene overgrowths ranging up to several tens of µm's thick.

Titanomagnetite phenocrysts (<1 mm; cores $Mt_{78}Usp_{22}$) are subhedral. The rarity of ilmenite crystals (cores $Ilm_{77}Hem_{23}$) makes it difficult to find coarse-grained magnetites and ilmenites that are in contact. Titanomagnetite is, in some cases, observed to form thin (<30 µm) reaction rims on larger ilmenite grains. Similar textures are observed in 1991-1992 Mount Pinatubo mixed magma samples [*Pallister et al*, 1996]. Diffusion gradients exist in titanomagnetite crystals that are in contact with ilmenite crystals (see below).

Glass inclusions trapped in plagioclase and quartz phenocrysts have been analyzed (Table 1). Most inclusions in plagioclase were trapped when the sieve-textured zones formed. The volatile contents of the melt inclusions in plagioclase and quartz crystals from 17-18 September, 1996, tephra fall samples were estimated using the "difference method" (100 wt.% minus analytical total equals volatile content; *Devine et al.*, 1995). Inclusions in plagioclase phenocrysts from the 17-18 September, 1996, explosive tephra contain ~5.0 wt.% total volatiles. Subtracting a measured average Cl content of ~3,400 ppm, the inferred H_2O content of the trapped melt is ~4.7 wt.%. Melt inclusions in earlier erupted magmas (December, 1995, to March, 1996) are anhydrous, most likely a result of cracking and leakage during magma ascent [e.g., *Tait*, 1992].

Recent heating of the magma storage region due to magma mixing

There are several lines of evidence that suggest that the Soufriere Hills andesite magma storage region was heated just prior to, and during, the July 1995-to-present eruption. This evidence is (1) the large compositional variability of magnetite crystals, even in the most recent eruptive products, as discussed below; (2) the thin, high-Mg# rims on some orthopyroxene phenocrysts; (3) the thin, An-rich rims on plagioclase phenocrysts; (4) the scalloped textures of breakdown-rim-free hornblende phenocrysts; (5) the embayment and/or clinopyroxene mantling of quartz phenocrysts; and (6) the clinopyroxene mantling of some orthopyroxene phenocrysts.

Fe-Ti oxide geothermometry and oxygen geobarometry are complicated by a wide diversity of oxide mineral compositions. Analytical transects across grain boundary interfaces between in-contact titanomagnetite/ilmenite pairs (from September, 1996, and September, 1997, tephra fall samples), however, reveal the presence of strong titanium diffusion gradients in the titanomagnetite grains. The TiO_2 contents of titanomagnetite grains that are close to the interfaces typically range up to >12 wt.%. In addition, about half of the large titanomagnetite grains are reversely zoned, having low-TiO_2 cores (~7.8 wt.%) and higher-TiO_2 (~8.4 wt.%), near-rim compositions (<30 µm thick; see also *Nakamura*, 1995). Finally, titanomagnetite reaction rims on ilmenite phenocrysts, and small (<30 µm) titanomagnetite grains in the groundmass, have relatively high TiO_2 contents (~12.6 wt.%; $Mt_{63}Usp_{37}$).

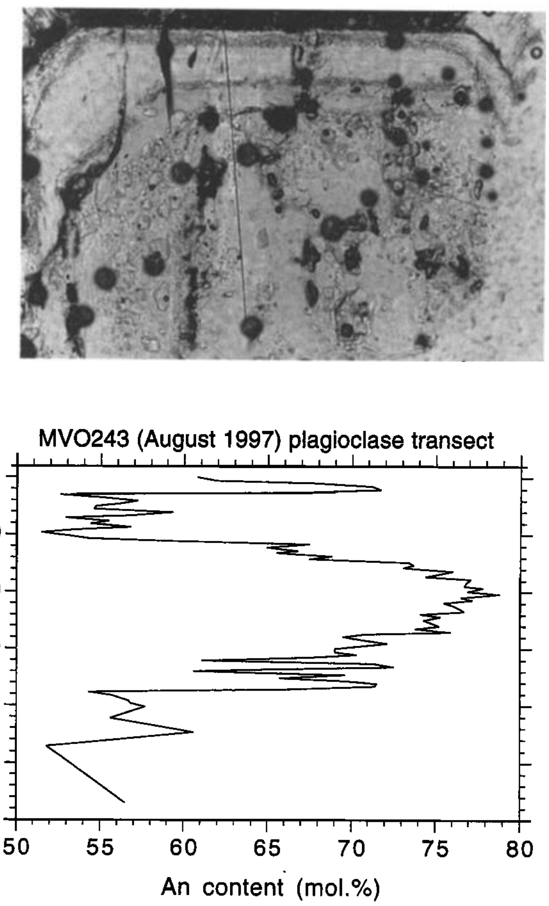

Fig. 1. (a). Photomicrograph of plagioclase phenocryst from new dome magma; width of field of view is 1335 μm; **(b)** analytical transect of above plagioclase along line in photo.

The program QUILF, which calculates equilibrium conditions for coexisting Fe-Mg-Ti oxides, as well as pyroxenes and quartz [*Andersen et al.*, 1993], suggests that the high-TiO_2 titanomagnetite crystals in the groundmass, and their coexisting ilmenite, high-Mg# orthopyroxene, and clinopyroxene crystals, could be near equilibrium at a temperature of ~865°C, at $\log fO_2$ = -11.4; i.e., about 1.2 log units above NNO. If those estimates are correct, the activity of silica is predicted by the program to be ~0.9; i.e., quartz should no longer be a stable phase, a prediction consistent with petrographic observation. This estimate of the temperature of the magma after the latest heating event (~865°C) is close to the estimated thermal stability limit of amphibole, as determined by experiment (<880°C; *Barclay et al.*, this volume).

Analyses of the cores of large (>100 μm) titanomagnetite and ilmenite phenocrysts give estimated temperatures of ~834-850°C and estimated oxygen fugacities about 1.1 log units above the nickel-nickel oxide (NNO) buffer at those temperatures ($\log fO_2$~-11.8; method of *Andersen and Lindsley*, 1988). These temperature estimates are similar to those deduced from experimental phase relations, which indicate that quartz and amphibole are stable together only at temperatures less than or equal to ~830°C [*Barclay et al.*, this volume].

The clinopyroxene rims on orthopyroxene and quartz grains are thought to develop at the same time. The presence of these rims, without any indication of them reacting to form hornblende, suggests that the latest heating event raised the temperature of the pre-eruptive magma to the reaction boundary at which hornblende reacts to form clinopyroxene plus melt [*Rutherford and Devine*, 1988; *Barclay et al.*, this volume]. Heating to the hornblende-clinopyroxene reaction boundary can also account for the slightly scalloped shape of the hornblende phenocrysts and precipitation of more anorthitic plagioclase rims. Temperatures must have been raised above the stability limit of quartz in this magma [*Barclay et al.*, this volume], accounting for their embayed texture. The heating event must not only be recent, but must also be ongoing (as of September, 1997), because the observed compositional heterogeneity in titanomagnetite phenocrysts would be lost in a few weeks to a few months [*Gardner et al.*, 1995; *Nakamura*, 1995; *Venezky and Rutherford*, 1998]. The observation that quartz grains that lack clinopyroxene reaction rims have not been completely dissolved, and the presence of An-rich rims on some plagioclase phenocrysts, also lend support to the idea of a recent heating event.

Titanomagnetite crystals in tephra explosively erupted in September, 1997, more than two years after the onset of the present crisis, are characterized by Ti diffusion gradients where they are in contact with ilmenite. Such gradients would be smoothed out in a few weeks to months, so the heating that caused the gradients must have been within a few months of the September, 1997, explosive eruption. The existence of the gradients suggests that mafic magma has continued to invade the andesitic magma storage region throughout the eruption. The evidence of continued heating also suggests that parts of the andesitic magma have not yet been heated to ~880°C by the invading mafic magma. It seems likely that the ongoing eruption is being driven by mafic magma supply rate into the base of the andesitic magma storage region [*Sparks et al.*, this volume].

Although <1-2 vol.% mafic inclusions are present in the andesitic magma [*Murphy et al.*, this volume], their mineralogical and chemical diversity suggests that they may not all be samples of the mafic magma that has triggered the present eruption; they do, however, provide ample evidence of the potential for magma mingling and/or hybridization.

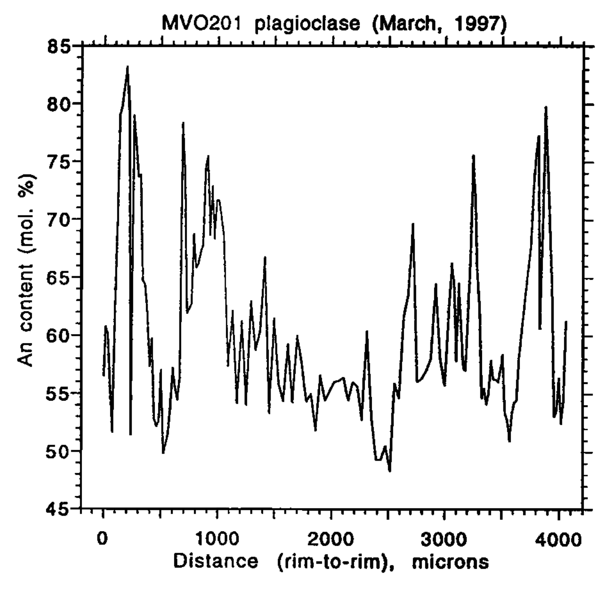

Fig. 2. Complex compositional zoning in plagioclase.

Similarly, the complex zoning of some large plagioclase phenocrysts (Fig. 2) suggests they they may have long residence times in the magma storage region, allowing them to have recorded multiple heating and/or mixing episodes.

History of the pre-eruptive magma

The temperature prior to the recent heating event is inferred to have been ≤830°C, and fO_2 is estimated to have been ~1 log unit above NNO. The heating event has subsequently raised the temperature of the magma to the reaction boundary at which hornblende reacts to form clinopyroxene plus melt, which is ~880°C [*Barclay et al.*, this volume], and fO_2 is estimated to be about 1 log unit above NNO.

If one assumes that the low-Al_2O_3 rims of hornblende phenocrysts grew in equilibrium with quartz, as well as the other phases, then the Al-in-hornblende geobarometer can be used to estimate the total pressure in the preeruption magma storage region [*Johnson and Rutherford*, 1989]. Hornblende with 6.4 wt.% Al_2O_3 yields a total pressure estimate of ~130 MPa (±25 MPa), which is consistent with experimentally constrained pressures required for quartz and hornblende coexistence in this magma [*Barclay et al.*, this volume]. Because all amphibole phenocrysts have rather low Al_2O_3 contents (6-8 wt.%), one may infer that all erupted magma has resided in the <200 MPa storage region (significantly higher pressures would result in higher Al_2O_3 contents in amphibole crystals). The 17-18 September, 1996, melt inclusions in plagioclase phenocrysts contain ~4.7 wt.% H_2O, which corresponds to the limit of water solubility in rhyolitic melts at pressures of ~135 MPa [*Silver et al.*, 1990; *Blank et al.*, 1993]. Although these melt inclusions were trapped well prior to the present eruption (there was significant crystallization of low-An plagioclase host since they were trapped; Fig. 1), it is reasonable to assume that the H_2O content of melt in the upper part of the magma storage region has remained about the same, because the close agreement between the estimates for total pressure (Al-in-hornblende) and water pressure (melt inclusions) suggests that the magma in the uppermost part of the storage region is saturated with an H_2O-rich vapor. A total pressure of 130 MPa corresponds to a depth of 5 to 6 km, assuming an andesite rock column. The hypocenters of most volcano-tectonic earthquakes that have occurred during the present crisis lie at depths shallower than ~6 km [*Aspinall et al.*, this volume], suggesting that the "top" of the magma storage region is approximately at that depth.

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