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INSIDE

Changing Magma Conditions and Ascent Rates during the Soufriere Hills Eruption on Montserrat

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ABSTRACT

The Soufriere Hills volcano on the resort island of Montserrat caught the world's attention when phreatomagmatic explosions began in July of 1995. In late 1995, andesitic lava appeared as a dome in the central crater. Lava dome formation continues today, although sectors of the dome have periodically collapsed, generating pyroclastic flows. By integrating data from phenocryst analyses from the andesite (60 wt% SiO_2) with experiments, we have determined the temperature and depth at which the pre-eruption magma equilibrated, identified a pre-eruption heating event, and documented order-of-magnitude changes in the rate of magma ascent. Phenocryst-melt equilibria indicate that the andesitic magma was equilibrated in a storage zone at ~840 °C and 130 MPa (~5 km depth) prior to heating. Heating took place several weeks before the eruption and has continued. As the water-rich Soufriere Hills andesite magma ascends, the rate of magma rise is reflected by the thickness of reaction rims developed on hornblende phenocrysts in contact with melt, and by the extent of groundmass crystallization. These reactions, which have been experimentally calibrated, are variably observed in Soufriere Hills samples. The magma ascent rate at Soufriere Hills increased by a factor of 10 during the first four months of 1996, culminating in a large dome collapse and a large explosive eruption in September 1996. Most magma erupted in 1996 ascended from 5 km depth to the surface in <4 days. After slowing during the fall of 1996, the magma ascent rate increased again in spring 1997. This period of high ascent rate was followed by explosive eruptions throughout the fall of 1997. Both periods of high magma ascent rates correlate with times of high dome-volume growth rate.

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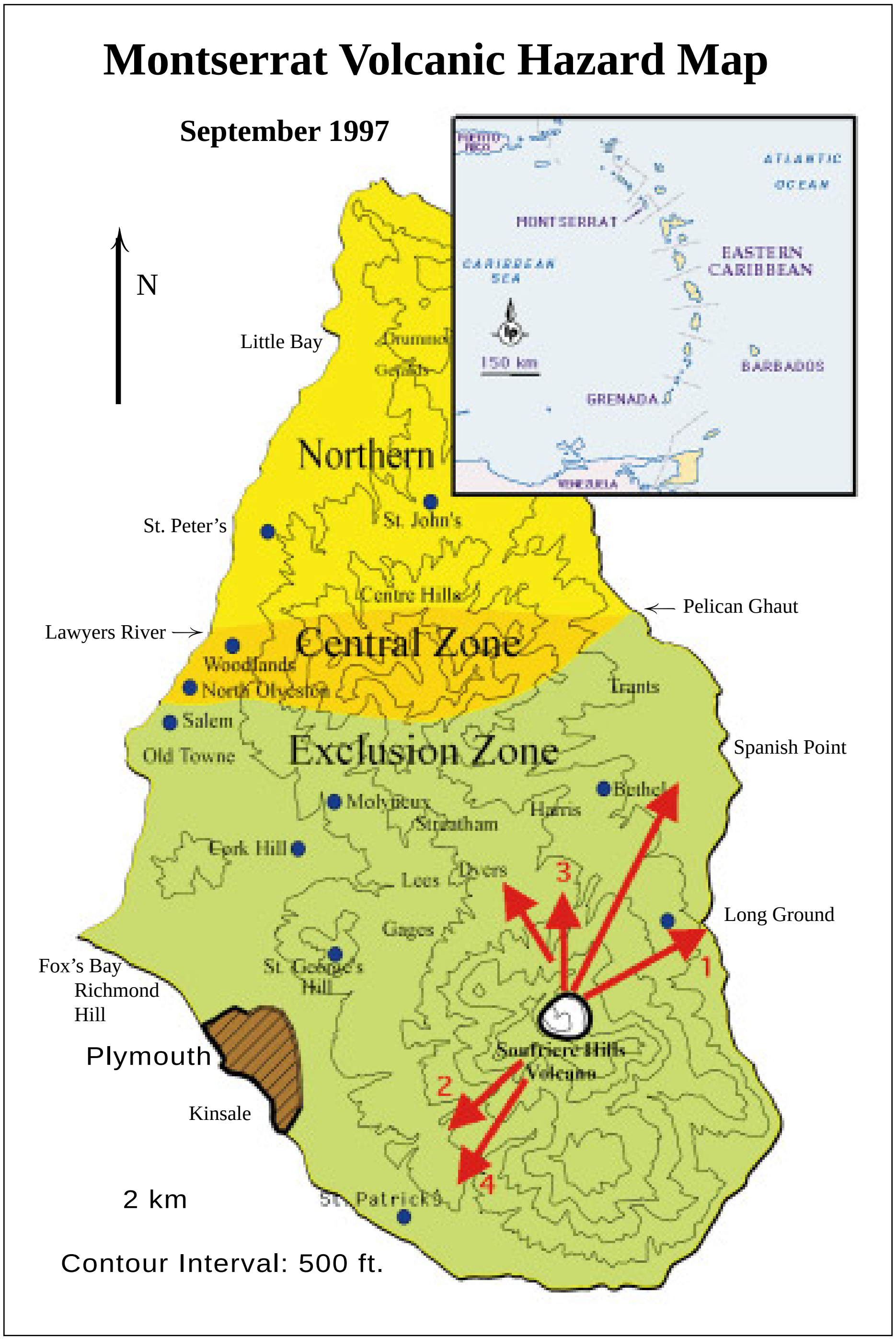

Figure 1. Map of Montserrat Island showing the Soufriere Hills volcano and the September 1997 volcanic hazard zones (after Montserrat Volcano Observatory Web site map, January 1998). The arrows show the directions taken by pyroclastic flows: (1) before January 1997, (2) in early spring, 1997, (3) following the large dome collapse of June 25, 1997, and (4) on December 26, 1997. The inset shows the position of Montserrat in the northern Lesser Antilles Volcanic Arc.

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Palm Harbor, Florida
September 16, 1997

Thomas E. Bolton
Ottawa, Ontario
November 21, 1997

Louis DeGoes
Bellevue, Washington
November 23, 1997

Valerie M. Ewing
Flower Mound, Texas
March 9, 1996

Ross R. Heinrich
St. Louis, Missouri
December 18, 1997

Henno Martin
Göttingen, Germany
January 7, 1998

CORRECTION

The correct dates for the Penrose Conference "Ophiolites and Oceanic Crust" are September 13–17, 1998. The announcement in the January 1998 issue of *GSA Today* contained incorrect dates. We apologize for the inconvenience.

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INTRODUCTION

Montserrat Island lies in the northern section of the Lesser Antilles volcanic arc (Fig. 1). Although the island has undergone several seismic crises in this century (Wadge and Isaacs, 1988), no historic eruptions had been known before the Soufriere Hills volcano began erupting in November 1995. The volcano, which is in the southern part of this popular resort island, has a central crater about 1 km in diameter that opens to the northeast (Fig. 1). Prior to the present eruption, this crater was partially filled by a dome that formed at about 350 yr B.P. (Young et al., 1997). Older volcanic deposits record earlier eruptions, at about 3950 yr B.P. The Soufriere Hills volcano itself contains many deposits produced by dome collapse from 26 to 16 ka (Wadge and Isaacs, 1988).

The present eruption began with precursor seismic activity, which increased in intensity from 1992 to late 1994, and a phreatomagmatic event in the Soufriere Hills crater on July 18, 1995. One of us (Devine) was in the Caribbean in July 1995 to study the dynamics of dome-forming events in Montserrat and Nevis; that project was quickly modified to include study of the modern Soufriere Hills eruption. The first dome-forming magma reached the surface between November 14 and 16, 1995. Since that time there has been nearly continuous extrusion of a hornblende-rich andesite, regular collapse of gravitationally unstable new dome segments producing pyroclastic flows like those shown in Figure 2, and occasional periods of explosive pressure release.

Several events stand out in the history of this eruption. On September 17, 1996, a collapse involving approximately one-third of the preexisting dome produced huge pyroclastic flows, and was followed by an explosive eruption of magma from depth which lasted several tens of minutes. The ash column rose to 14,000 m, and a pumice was deposited over the island. In late 1996 and early 1997, rapid dome growth on the south side of the new dome gradually filled the preexisting crater and weakened the crater wall. The first sizable pyroclastic flows to go to the south (flow 2 in Fig. 1) went over the wall in the following months, devastating a heavily settled (although evacuated) part of the island. New dome growth moved to the north side of the edifice in May 1997, and six weeks later a major collapse sent pyroclastic flows over the north wall of

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the crater (flow 3 in Fig. 1), essentially completing the circle of pyroclastic flow devastation around the volcano. One of these flows closed the Montserrat airport. Very active dome growth punctuated by numerous explosions continued throughout the summer and fall of 1997. In late December, the dome was still growing without explosive eruptions. A large collapse of the wall and adjacent dome on December 26, 1997, produced a flow that reached the ocean (flow 4 in Fig. 1).

The staff of the Montserrat Volcano Observatory (MVO) is continuously monitoring the eruption seismically, by helicopter flights, and by measuring dome volume changes using a combination of techniques (Sparks et al., 1998). Members of the observatory staff and visiting scientists also regularly measure gas release and deformation around the mountain, and collect samples (Young et al., 1997). Samples have not been easy to collect because the eruption is occurring in the crater, but accelerated dome growth is often closely followed by collapse and pyroclastic flows that allow new magma to be sampled. We have studied these samples under a microscope, have done chemical analyses by electron microprobe, and have performed hydrothermal experiments on a sample of the andesite to determine the depth, water content, and temperature of the magma storage region, and have deduced changes in magma ascent rate over time.

PRE-ERUPTION MAGMA

The dome-forming magma erupting at Soufriere Hills is an andesite (~60 wt% SiO_2) consisting of phenocrysts of variably zoned plagioclase, hornblende, orthopyroxene, embayed quartz, magnetite, ilmenite, and apatite in a microcrystalline groundmass (Fig. 3). The mineralogy of the groundmass is the same except that clinopyroxene, an anhydrous mineral, is present instead of hornblende, which is hydrous. There has been no change in the magma composition since the eruption began. Interestingly, it is also essentially identical to the magma that formed the Castle Peak dome 400 yr B.P. (Devine et al., 1998). Inclusions of a more mafic basaltic andesite are common in the erupted magma. Many of these inclusions are glass-bearing, and some contain hornblende, indicating crystallization at depth in a water-rich magma. This more mafic material appears to have been added to the andesitic magma over time at a range of *P-T* conditions (Murphy et al., 1998).

MAGMA STORAGE ZONE

The temperature, pressure, and water content of the magma storage region

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In cooperation with the Association of American State Geologists (AASG), GSA makes an annual award for the best paper on environmental geology published either by GSA or by one of the state geological surveys. The award is a $1000 cash prize from the endowment income of the GSA Foundation's John C. Frye Memorial Fund. The 1998 award will be presented at the autumn AASG meeting to be held during the GSA Annual Meeting in Toronto, Canada.

Nominations can be made by anyone, based on the following criteria: (1) paper must be selected from GSA or state geological survey publications, (2) paper must be selected from those published during the preceding three full calendar years, (3) nomination must include a paragraph stating the pertinence of the paper.

Nominated papers must establish an environmental problem or need, provide substantive information on the basic geology or geologic process pertinent to the problem, relate the geology to the problem or need, suggest solutions or provide appropriate land-use recommendations based on the geology, present the information in a manner that is understandable and directly usable by geologists, and address the environmental need or resolve the problem. It is preferred that the paper be directly applicable by informed laypersons (e.g., planners, engineers). Deadline for nominations for 1998 is **MARCH 30, 1998.**

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The deadline is **April 30, 1998,** for submitting nominations for these four awards: William T. Pecora Award, National Medal of Science, Vannevar Bush Award, Alan T. Waterman Award.

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Figure 2. View from the northeast of the Soufriere Hills lava dome in March 1997. A partial dome collapse has just occurred, and a pyroclastic flow is moving to the east down the steep slope of the volcano.

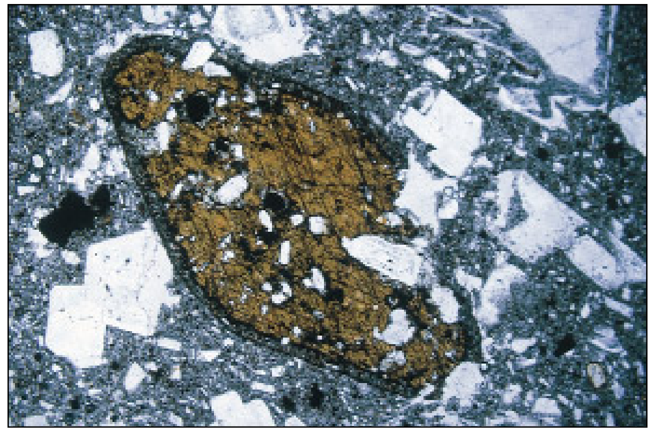

Figure 3. Photomicrograph under crossed polarizers of the December 1995 Soufriere Hills andesite. Mineral phenocrysts include a 2-cm-long, inclusion-filled hornblende grain (brown), complexly zoned plagioclase crystals (white), and a euhedral magnetite phenocryst (black). These phenocrysts occur in a largely crystalline matrix. The dark reaction rim on the hornblende crystal is 120 µm thick.

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beneath the volcano have been determined using the compositions of phenocrysts and glasses in the Soufriere Hills andesite (Devine et al., 1998). Particular emphasis has been placed on explosively erupted, rapidly quenched pumiceous samples that have not been affected by reactions occurring in more slowly cooled dome samples.

Pressure information can be derived from the aluminum content of hornblende in multiphase, quartz-bearing assemblages as discussed by Hammarstrom and Zen (1986). Use of Al-in-hornblende geobarometry is justified in estimating the storage depth for the Soufriere Hills magma, because quartz phenocrysts are present in all samples, and these phenocrysts appear to have been in equilibrium with hornblende before any changes took place in the magma storage region. The Soufriere Hills hornblende phenocrysts are generally uniform in composition, and contain 6.2 wt% Al_2O_3. Putting their composition in the Johnson and Rutherford (1989) geobarometer yields a pressure of 130 ± 25 MPa (~5–6 km depth).

Temperature estimates can be obtained from coexisting Fe-Ti oxide phases. Adjacent magnetite and ilmenite phenocrysts in the Soufriere Hills samples have homogeneous cores and zoned 15–25-µm-thick rims where they are in contact with each other. Calculations using the core compositions yield an equilibration temperature of 840 °C at relatively oxidized conditions (f_{O_2} equal to 1 log unit above the NNO oxygen buffer); rim compositions yield higher temperatures (830 to 930 °C). These observations suggest that the magma storage zone was at ~830 °C and ~5–6 km depth at some time just before the eruption.

Analyses of melt (now glass) trapped as inclusions in plagioclase and pyroxene phenocrysts indicate that the pre-eruption Soufriere Hills melt contained 4.7 wt% dissolved water. This is exactly the amount expected if the pre-eruption magma were saturated with a water-rich vapor phase at 130 MPa. It is possible that the water content of the melt in the andesitic magma decreased somewhat after the heating (mixing) event, but it clearly remained above ~4.0 wt% because hornblende remained stable in the heated magma.

The final evidence pertaining to conditions in the pre-eruption magma comes from phase equilibrium experiments carried out on a sample of the Soufriere Hills andesite. Samples of the powdered andesite were sealed in noble metal tubes along with excess water and held at a given *P*, *T*, and f_{O_2} for times up to 10 days. Most of the experiments were run using a sample previously held at either a higher or lower temperature (Fig. 4; see caption). These experiments show that both quartz and Al-poor (6.2 wt%) hornblende would be stable along with plagioclase, orthopyroxene, magnetite, and ilmenite at 830 °C and 130 MPa when the magma was saturated with a water-rich vapor (Barclay et al., 1998). These experimental data also show that if the temperature in this magma is increased above 830 °C at constant pressure and water content, melting occurs at the expense of the phenocrysts,

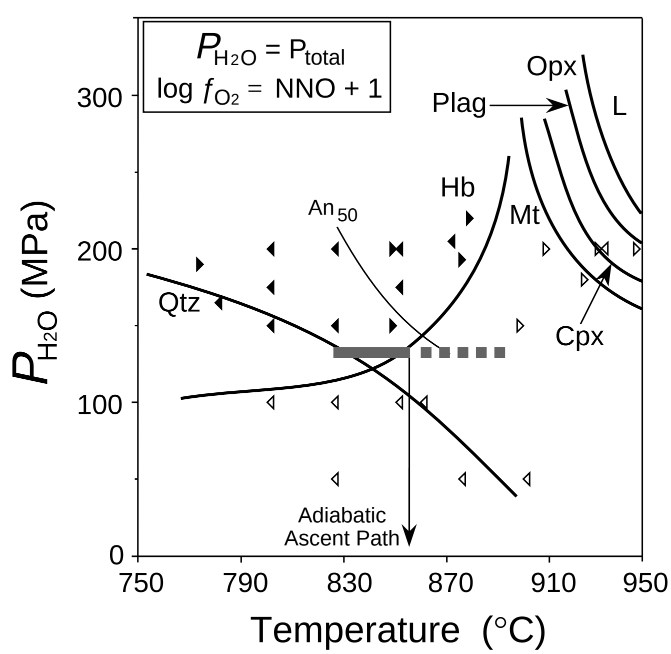

Figure 4. Experimentally determined phase equilibria of the Soufriere Hills andesite modified after Barclay et al. (1998). Curves show the onset of crystallization of individual phenocryst phases as temperatures drop. Phenocrysts are: Hb—hornblende; Opx—orthopyroxene; Cpx—clinopyroxene; Plag—plagioclase; Fe-Ti oxides—magnetite; Qtz—quartz; An_{50}, plagioclase composition in equilibrium with melt. The Hb curve represents a reaction of melt with clinopyroxene to form hornblende. The horizontal bar indicates *P* and *T* of pre-eruption magma; the pressure estimate is from Al-in-hornblende geobarometry. Pre- and postheating temperature estimates are from Fe-Ti oxide geothermometry discussed in the text. Arrowheads indicate individual experiments and direction of approach to final temperature. At 130 MPa, heating of a magma to >860 °C, or ascent of magma, results in hornblende breakdown.

plagioclase becomes more Ca-rich (anorthitic), and the hornblende coexisting with the melt becomes more Al-rich. Phenocrysts in the Soufriere Hills samples indicate that these compositional changes were taking place just prior to eruption.

PRE-ERUPTION HEATING EVENT

All samples studied display characteristics of a pre-eruption heating event in the Soufriere Hills magma storage region. The most direct evidence of this event is compositional zonation in the magnetite and ilmenite phenocrysts; the core compositions yield temperatures of 840 °C, whereas rims of some adjacent crystals last equilibrated at ~900 °C. What caused this heating? Was it an influx of new hot magma? How hot did it get? Did the heating occur as one event or has it been continuous throughout the eruption?

These questions are still being investigated, but it appears that the phenocryst-rich andesitic magma residing in the 130 MPa (~5 km deep) magma storage region was intruded by a higher temperature, more mafic magma just prior to the eruption. Evidence for a higher temperature magma comes from the basaltic andesite inclusions containing rhyolitic glass that are scattered throughout the Soufriere Hills magma. When hornblende is present in these inclusions, it is more Al-rich (8–15 wt% Al_2O_3) than that in the andesite, indicating crystallization under higher temperature conditions. Another indicator of heating is the presence of clinopyroxene overgrowths on orthopyroxene and quartz crystals. The fact that hornblende remains stable at the same time that Ca-pyroxene overgrowths show no sign of reaction with the surrounding melt to form hornblende suggests that conditions just prior to the eruption (after heating) were essentially at the phase boundary where hornblende reacts to form clinopyroxene + melt (see Fig. 4). An observation that neither supports nor rules out magma mixing in the storage region is the constancy of the bulk composition of the magma that erupted from 1995 to 1997.

Evidence on when heating caused by magma mixing could have occurred comes from arrested mineralogical reactions. Particularly important is the compositional zonation observed on rims of magnetite and ilmenite phenocrysts in contact with each other. The thickness of such diffusional zones on magnetite phenocrysts depends primarily on temperature and the interdiffusion coefficient of Fe and Ti in the crystal. Both existing diffusion data and recent experiments suggest that it takes two to four weeks to develop a 20–25-µm-thick diffusion profile on magnetite if the temperature of the andesite storage zone is at 850 °C. Less time (5–10 days) is required if the temperature is at 880 °C (Venezky and Rutherford, 1998). The presence of similar diffusional zonation profiles in samples from both the September 1996 and June 1997 eruptions suggests that heating has been ongoing. If heating had occurred only in late 1995, the thickness of the diffusional zones in crystals from samples erupted in 1997 would be much thicker than those in the earlier erupted magmas.

Amazingly, evidence of an earlier magma chamber heating event appears to have survived in all of the Soufriere Hills andesitic lavas erupted from 1995 to 1997. This evidence comes from a small relict population of hornblende phenocrysts with very thick breakdown rims (300–400 µm). The hornblende surrounded by these thick rims has a higher aluminum content than the main population of hornblende phenocrysts, which are characterized by very thin or no reaction rims at all. Crystals with intermediate thickness reaction rims are generally not present. These observations are interpreted to mean that the phenocrysts with thick rims are the only hornblende crystals that survived an earlier heating event. The interiors of these crystals underwent little or no change in composition during ascent because they had limited or no contact with the melt. Subsequent cooling and crystallization of the magma with temperatures reaching 830 °C produced most of the hornblende phenocrysts present in the erupted lavas.

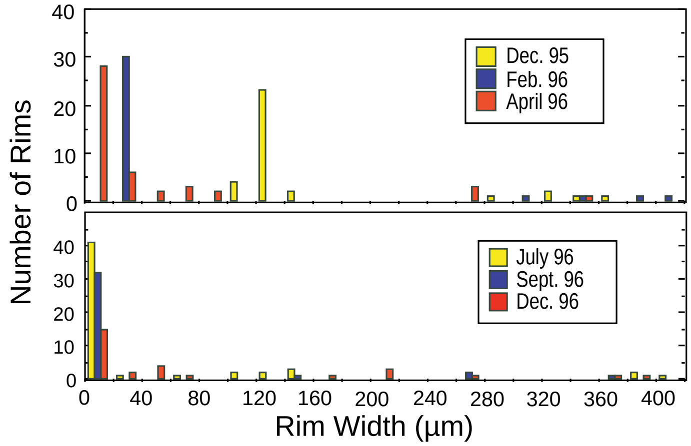

Figure 5. Histograms showing the number of hornblende phenocrysts vs. the thickness of the reaction rims in Soufriere Hills andesite samples erupted at various times from December 1995 through 1996. Rim thickness of the main hornblende population was used to calculate the ascent rates shown in Figure 6. The significance of the small thick-rimmed population is discussed in the text. The population with intermediate thickness rims erupted late in 1996 is thought to represent a mixing-in of some andesitic magma from earlier ascended material. The large populations of hornblende phenocrysts in the July to December 1996 samples plotting to the left of 10 µm all have near zero rim width.

MAGMA ASCENT RATE CHANGES: ERUPTION STYLE IMPLICATIONS

The rate of magma ascent from the ~5-km-deep storage region to the surface at Soufriere Hills has changed significantly over the two-year period of the eruption. This interpretation is based primarily on variations in the thicknesses of the reaction rims present on the main population of hornblende phenocrysts in magma extruded at different times. When a water-rich magma like the Soufriere Hills andesite ascends from depth, water in the melt is readily lost to gas bubbles. This decrease in the meltwater content causes hornblende in contact with the melt to become unstable, and after a short (~4 day) nucleation period, to develop a reaction rim. The rate at which rim growth occurs has been experimentally calibrated for dacitic composition magma (Rutherford

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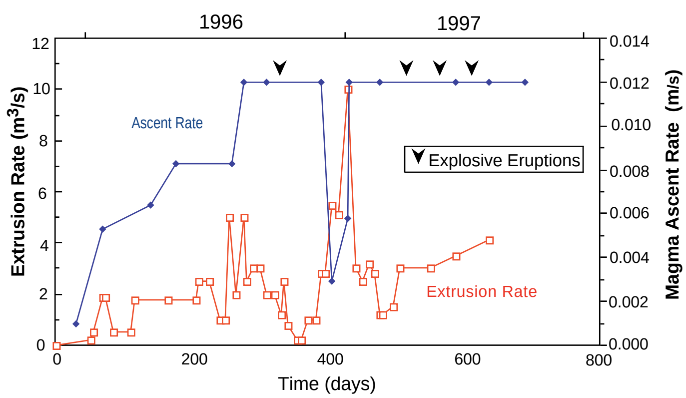

Figure 6. Average magma ascent rate and extrusion rate plotted against time during the ongoing Soufriere Hills eruption that began at the end of November 1995. The ascent rate estimates are based on hornblende reaction rim thicknesses (Devine et al., 1998), and an experimental calibration of thickness vs. time. The extrusion rate curve is from Sparks et al. (1997). See discussion in the text.

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and Hill, 1993), and this calibration has been used to estimate average ascent rates for the Soufriere Hills magmas.

As shown in Figure 5, a summary of the changes in reaction rim thicknesses in hornblende crystals for samples erupted over time, the December 1995 samples contain a main population of hornblende phenocrysts with 120 ± 20-μm-thick reaction rims formed where the crystals were in contact with melt (Fig. 3); the other 10% of the phenocrysts present have the very thick (300–400 μm) reaction rims discussed above. The same main hornblende population had only 18 μm rims in the February 1996 magma, and by April 1996, the rims on the main hornblende population had decreased to 10 ± 3 μm. Most hornblende crystals in samples from the July through September 1996 magmas had no reaction rims.

If we use the Rutherford and Hill (1993) experimental calibration of rim width vs. ascent time, the rim data for the hornblende phenocrysts from the various samples give average magma ascent rates that vary from 3.5 m/hr to > 42 m/hr (0.001 to >0.012 m/s in Fig. 6). The importance of the hornblende reaction rims is not so much to determine the absolute ascent rate estimates, but rather to determine the relative ascent rates over the duration of the eruption. The calculated rates plotted in Figure 6 indicate a sharp increase in the magma ascent rate in January 1996 following the initial extrusion of the dome lava in late 1995. This increase in magma ascent rate continued through the summer of 1996, culminating in the explosive eruption of September 17, 1996. The limit for the use of hornblende rims in estimating ascent rates was reached early in the summer of 1996, when the thickness of the hornblende rims went to zero. As a result, the magma ascent rates estimated for August and September 1996 (days 275–310) are minimum estimates.

Interestingly, there was a more or less steady increase in extrusion rate (see Fig. 6) over this initial eruption period, as indicated by dome volume growth (Young et al., 1997; Sparks et al., 1998). The correlation of increasing ascent rate with increases in the rate of dome growth (extrusion rate) over this period indicates that the change in extrusion rate resulted from accelerated magma ascent rate, and not from an increased conduit diameter.

Following the September 1996 eruption, dome growth quickly resumed. The hornblende reaction rim data indicate that there was some mixing of old conduit or dome magma with new magma from the storage region to form the samples obtained during the December 1996 events (see Fig. 5). However, early in 1997 the hornblende rim widths again became very thin and then the rims disappeared, indicating that the erupting magma was once again ascending rapidly (average rate >0.012 m/s) from the 5-km-deep storage zone. The rate of dome growth was also determined to be very high during this period. The rapid magma ascent through the early spring of 1997 was an indication that a period of occasional explosive activity was likely to occur, given the 1996 eruption history of this volatile-rich magma. As magma ascent rates increase, there is less opportunity for release of volatiles from the ascending magma. Periodic explosive eruptions such as were seen in the summer and fall of 1997 are the result.

PETROLOGICAL CHANGES VS. SURFACE OBSERVATIONS AND GEOPHYSICS

The petrological indications of magma storage zone conditions and magma ascent rate are generally consistent with results of other geological and geophysical studies of the Soufriere Hills Volcano. Seismic data appear to rule out magma storage at <5 km depth, but do not outline an aseismic magma storage zone. Much of the seismicity at the volcano is associated with shallow degassing or with dome collapses and rock falls (Montserrat Volcanic Observatory Web page, January 1998, http://www.geo.mtu.edu/volcanoes/west.indies/soufriere/govt/).

Mattioli et al. (1997) used surface deformation monitored by GPS measurements to model a shallow 1-m-wide feeder dike connecting to a deflating magma source region at 6 km depth. Spectroscopic measurements of the volcanic gas cloud indicate SO_2 emissions that are within the 50 to 500 tons/day range observed for other dome-forming eruptions (Young et al., 1997). Higher emissions (>1000 tons/day) are observed during periods of more rapid dome growth and pyroclastic flow emplacement. This observation supports our sample analyses, which show extensive degassing of dome magma samples, but relatively vesicular and undegassed samples erupted during explosive eruptions.

CONCLUSIONS

A combined petrographic, analytical, and experimental study of samples from the 1995 to 1997 Soufriere Hills eruptions on Montserrat Island has allowed us to determine that the pre-eruption andesitic magma was in a deep storage zone at a temperature of 830 ± 20 °C and a pressure of 130 ± 25 MPa (5–6 km depth), and was probably very close to being saturated with a water-rich fluid phase. While in this storage zone, the magma was variably heated for the 2–4 weeks prior to eruption. This heating almost certainly resulted from the intrusion of a more mafic magma, relicts of which are among the mafic inclusions in the dome andesite. Ascent rates for andesitic magma erupted from 1995 to 1997 at the Soufriere Hills Volcano have been determined by using the thickness of reaction rims developed on hornblende phenocrysts. The rim-thickness data show that the average ascent rate for magma erupted at different times has varied by a factor of 10, with high rates correlating with rapid rates of dome-volume growth.

ACKNOWLEDGMENTS

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