$^{40}$Ar/$^{39}$Ar geochronology of the Silver Hills andesite, Montserrat, West Indies

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Abstract

Using $^{40}\text{Ar}/^{39}\text{Ar}$ furnace step heating on groundmass separates, volcanic flow ages are determined for six andesite flows from the Silver Hills region of Montserrat, West Indies. The measured dates suggest two major eruptive events around 1390 ka and 1500 ka. These dates fit within previous studies that suggest the Silver Hills are the oldest of the four major volcanic centers that make up the island. Major and minor element geochemistry shows all samples are andesites (~60 wt.% SiO$_2$) that represent a small range of fractional crystallization in the magma chamber. The samples collected for this study are composed of 30-60 percent phenocrysts of plagioclase, orthopyroxene, and clinopyroxene in a variably devitrified glassy matrix. Differences in groundmass characteristics support irradiation-induced recoil for sample SH07A that failed to produce a reliable age.

Keywords

$^{40}\text{Ar}/^{39}\text{Ar}$ geochronology, Montserrat, Silver Hills, Lesser Antilles
Introduction

Montserrat, one of the many volcanic arc islands associated with the Lesser Antilles arc (Fig. 1), is currently in an eruptive phase (Kokelaar, 2002; Luckett et al., 2007). The history of volcanic activity in Montserrat and the region is important to understanding and contextualizing the magmatic evolution of the Lesser Antilles as well as the hazards associated with the ongoing eruption (Zellmer et al., 2003; Roman et al., 2006). The dominantly andesitic composition of Montserrat (total eruptive volume less than 3% basalt) is consistent with the composition of neighboring islands to the north (Macdonald et al., 1999). To the south, in Guadalupe, Dominica, and Martinique, alkalic suites are more common (Brown et al., 1977).

MacGregor (1938) completed the first systematic study of Montserrat including basic geologic and petrologic work. K-Ar dating by Rea (1970; 1974) and Briden et al. (1979) yielded an age of 1.59 Ma for the Silver Hills massif in the north part of Montserrat. Additional work by Briden et al. (1979) concluded that Montserrat began forming approximately four million years ago at the Harris-Bugby complex in the east-central part of the island. Carlut et al. (2000) suggest that some of the conclusions by Briden et al. (1979) regarding remnant magnetization in Guadeloupe were inaccurate and thus there is skepticism involving other conclusions drawn by Briden et al. (1979) about other Lesser Antilles islands (Harford et al., 2002). Many researchers agree that historical volcanic activity in Montserrat has occurred from at least 6 volcanic centers and has resulted in 3 large masses - the Silver Hills, Centre Hills, and Soufrière Hills-South Soufrière Hills, the later of which is currently active. Harford et al. (2002) also suggest the K-Ar age determined for the Harris-Bugby complex by Briden et al. (1979) is
Figure 1. (A) Tectonic map of the Lesser Antilles with Montserrat inset (modified from Le Frient et al. 2004). (B) 4 volcanic centers that comprise Montserrat. (C) Sample locations in the Silver Hills, see corresponding sample location coordinates in Table 1.
incorrect, rather that the history of Montserrat volcanism began in the north at the Silver Hills and has steadily migrated south. While interest in Montserrat has heightened due to the eruptions over the last 12 years, only Harford et al. (2002) have used $^{40}$Ar/$^{39}$Ar geochronology to date the two dormant volcanoes to the north - the Centre Hills and Silver Hills. In this previous study, $^{40}$Ar/$^{39}$Ar dating for two samples from the Silver Hills yielded two distinct dates, 1160 ± 46 ka and 2580 ± 60 ka (Harford et al., 2002).

With little information known about the Silver Hills, this project was designed to confirm the age and composition of the eruptive phases using more precise $^{40}$Ar/$^{39}$Ar dates, whole rock geochemistry, and petrographic analysis.

Tectonic Setting

Montserrat (16°45’N, 62°10’W) is a 160 km$^2$ island located in the north-central section of the inner arc (Leeward Islands) of the Lesser Antilles islands (Fig. 1A). The Lesser Antilles arc formed by the subduction of the North American plate beneath the Caribbean plate at a rate between two and four cm/yr (Macdonald et al., 1999). In the Leeward Islands, the subduction zone trends 330° and dips 50-60° (Macdonald et al., 1999).

Montserrat lies along the youngest of three recognizable island arcs, with the current one active since the Pleistocene (Baker, 1984; Macdonald et al., 1999). The older arcs to the east are dated to Eo-Oligocene and Pliocene times and are commonly referred to as the Limestone Caribees as they are composed of carbonate platforms built on subsiding volcanic bases (Baker, 1984). The westward shift of the volcanic arc, from Antigua (Limestone Caribees) to Montserrat (Volcanic Caribees), occurred
approximately nine million years ago and is attributed to changes in spreading direction and rate of the Mid-Atlantic Ridge (Briden et al., 1979). South of Martinique the arcs converge, but to the north the western Volcanic Caribees are distinct from the Limestone Caribees (Fig. 1).

**Geologic Setting**

The three major volcanic massifs that comprise Montserrat; the Silver Hills, Centre Hills, and Soufrière Hills, along with the smaller South Soufrière Hills are identified in Figure 1B. Most of the exposed Silver Hills are highly eroded andesitic pyroclastic flow deposits and remnants of lava domes (Fig. 2). The eastern cliffs, near Yellow Hole, show significant hydrothermal alteration. A previous study, using $^{40}$Ar/$^{39}$Ar geochronology, determined ages of 1160 ± 46 ka and 2580 ± 60 ka for two samples from the southern and western Silver Hills, respectively (Harford et al., 2002).

The densely vegetated Centre Hills are significantly eroded, more completely on the west coast than on the east coast, potentially as a result of the strong easterly prevailing winds and ocean currents (Harford et al., 2002). Deep valleys have been scored into the sides of the Centre Hills and have thus altered the original volcanic deposits. The Centre Hills are mostly composed of eroded lava domes, block-and-ash flow deposits and lahar deposits (Harford et al., 2002). The dormant Centre Hills, based on five $^{40}$Ar/$^{39}$Ar dates, range in age from 550 ± 23 ka to 954 ± 12 ka (Harford et al., 2002).

The younger and still active Soufrière and South Soufrière Hills have been significantly less affected by erosion compared to the mountains to the north. The basaltic
Figure 2. Field photos of (A) block-and-ash flow, SH07D, marker for scale; (B) meter-scale lava deposit, SH07E.
to basaltic andesite composition of the South Soufrière Hills volcaniclastic beds have been interpreted as the result of Strombolian to Vulcanian eruptions (Harford et al., 2002). Based on dates determined by Harford et al. (2002), the Soufrière and South Soufrière Hills may be considered the result of one volcanic center, despite geochemical differences that suggest slightly different magma sources. The active Soufrière hills nucleus is marked by four domes which each have identifiable andesite fan deposits from their respective eruptions. Roobol and Smith (1998), Harford (2002), and Smith et al. (2007) mapped the stratigraphy in detail of the Soufrière and South Soufrière Hills.

**Petrography**

Six rock samples were collected from various altitudes in the Silver Hills (Fig. 1C). Fresh samples were gathered from large outcrops along the radio transmitter access road with sample SH07A at the peak of the Silver Hills (400 meters above sea level) and SH07E at an altitude of 206 meters above sea level. Sample SH07F was taken from the eastern cliff of the Silver Hills above Yellow Hole at an elevation of 105 meters. Samples SH07B and SH07D are from fresh faces of block-and-ash flows (Fig. 2A) whereas SH07C and SH07E are from the centers of meter-scale lava flows (Fig. 2B). Sample SH07A is most likely from a block-and-ash flow while SH07F is certainly from a lava flow.

Photomicrographs of each of the six samples are shown in Figure 3. Each of the samples is composed of a glass-, oxide-, plagioclase-rich matrix, and between 30-60% phenocrysts - plagioclase, orthopyroxene, clinopyroxene (in decreasing order). The
Figure 3. Photomicrographs (ppl + xpl) at magnification 10X. (A) SH07A in plane-polarized and cross-polarized light. Cumulate in upper left portion of photomicrograph. (B) SH07B, interpenetration twinning in orthopyroxene (OPX). Plagioclase is commonly characterized by concentric compositional zoning (PL). (C) SH07C, orthopyroxene and plagioclase cumulate in upper portion of image. Groundmass has larger, lath shaped plagioclase crystals.
Figure 3 continued. Magnification 10X. (D) SH07D. Large orthopyroxene (OPX) with secondary replacement. Anhedral plagioclase in groundmass. Higher concentration of phenocrysts than A, B, and C. Interpenetration twinned pyroxene (PX). (E) SH07E. Higher abundance of phenocrysts than A, B, C, and D. Twinned clinopyroxenes (CPX) and concentric zoning in plagioclase (PL). (F) SH07F. Large plagioclase phenocrysts (PL). Groundmass plagioclases are thin but long and similarly oriented.
abundance of phenocrysts ranges from 30-40% in SH07 - A, B, and C to 50-60% in SH07 - D, E, and F (Fig. 3).

Two samples (SH07 - A and C) have cumulate textures composed of plagioclase and orthopyroxene with no clinopyroxene. The phenocrysts composing the cumulate in SH07A are approximately 40% larger than those in SH07C (Fig. 3 A, C). SH07 - B and D show interpenetration twinning in orthopyroxene (Fig. 3 B, D), and SH07D exhibits a large orthopyroxene with alteration (Fig. 3D).

The groundmass of SH07A is composed of plagioclase microlites, glass, and oxides (Fig. 3A). SH07B has an intergranular groundmass with relatively equal sizes and numbers of plagioclase to oxide and glass (Fig. 3B). The groundmass of both SH07 - C and E have thin, elongated, subhedral to euhedral plagioclase crystals that lack a preferred orientation (Fig. 3 C, E). Alternatively, SH07F also contains elongated euhedral plagioclase crystals but their subparallel orientations preserve a flow fabric best viewed in plane-polarized light (Fig. 3F). Plagioclase crystals in the groundmass of SH07D are distinct from the other samples as they are anhedral and show some preferred orientation (Fig. 3D).

**Whole-Rock Geochemistry**

*Methods*

X-ray fluorescence whole-rock geochemistry analyses were performed at Macalester College (Jeff Thole, analyst). Samples were prepared by crushing the rock into a fine powder in a SPEX 8510 shatterbox. Use of pre-contaminated bowls, (iron for trace elements, and tungsten carbide for major elements) lessened the possibility of cross-
contamination. Ten grams of rock and 18 drops of Polyvinyl Alcohol were mixed and pressed into pellets for trace element analyses on the stainless steel mold with a pressure of 6 tons (Craddock et al., 2007). One gram of rock (dried for two hours at 140°C) and five grams of lithium metaborate/tetraborate flux was used to prepare fused glass beads for major element measurements (Craddock et al., 2007). Samples were analyzed on a Phillips PW-2400 X-Ray Fluorescence spectrometer.

Results

All six samples from the Silver Hills are andesites ranging from 59 to 62 wt.% SiO₂ (Table 1, Fig. 4). Five of the analyses are very similar, and the greatest variation shown is in sample SH07F, from the eastern cliffs, which yielded the highest values for MnO, MgO, CaO, Ba, Co, Cr, Ni, and V (Table 2).

Figure 4 shows the plots for vanadium versus SiO₂ and K₂O versus SiO₂. The inverse relationship plot demonstrates that vanadium varies by a factor of three between basalts and andesites, as is expected for the mafic rock. The reported value for nickel for SH07F was the only sample that has a high enough concentration to be above detection limits within 95.4% confidence. In aggregate, the high vanadium, nickel, and chrome values for SH07F are different from the other five samples trace element concentrations and perhaps contain information about the magma’s source region and fractional crystallization pattern.
<table>
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<tr>
<th>Sample</th>
<th>SH07A</th>
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<th>SH07C</th>
<th>SH07D</th>
<th>SH07E</th>
<th>SH07F</th>
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<td>101</td>
<td>94</td>
<td>99</td>
<td>99</td>
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</tbody>
</table>

Values reported are average of 2 analyses; Fe analyzed at total Fe2O3.
All samples dried >2 hours at 110 deg. Celsius prior to LOI.
Loss on Ignition (LOI) reported as percent weight change of pre-dried samples after sintering for one hour at 1000 deg. C.
*LDM = Limit of Determination of a Method = the minimum concentration that can be determined at the
95.4% level of confidence; calculated as recommended by Rousseau (2001); LMD = 2 x Standard Deviation
(equation 12 in Rousseau, 2001); n = 10.

Red italicized values below LDM.
Figure 4. SiO₂ versus (A) K₂O and (B) vanadium from Silver Hills samples SH07-A,B,C,D,E,F (SvH07) plotted with data collected by Harford et al. (2002). Lines represent classifications determined by Gill (1981).
$^{40}\text{Ar}/^{39}\text{Ar}$ Geochronology

Methods

The six samples from the Silver Hills (Fig. 1) were prepared for $^{40}\text{Ar}/^{39}\text{Ar}$ dating at the University of Wisconsin-Madison Rare Gas Geochronology Laboratory. Holocrystalline groundmass was separated by crushing, sieving, and sorting using magnets and heavy liquids to remove pyroxene and plagioclase phenocrysts. Groundmass samples were weighed and packaged in copper foil packets along with the 1.194 Ma Alder Creek rhyolite sanidine standard (Renne, 1998). Samples were irradiated for three hours at the Oregon State University reactor in the Cadmium-Lined In-Core Irradiation-Tube with fast neutron doses of $15 \times 10^{15}$ n/cm$^2$. Analytical procedures and data reduction methods are given in Singer and Brown (2002).

Results

Table 2 shows complete results for each of the six samples; only five samples gave reliable inverse isochron ages. Age plateau spectra and inverse isochron diagrams for all six samples are shown in Figure 5. Samples SH07 - B, C, E produced relatively flat age plateaus over the seven steps measured (Fig. 5 a, b, c). Inverse isochron analysis supports the determined ages of $1383.6 \pm 20.1$ ka, $1416.0 \pm 18.8$ ka, and $1381.1 \pm 16.2$ ka respectively (Fig. 5 a, b, c). The age plateau for SH07D shows a weighted mean plateau similar to SH07 - B, C, and E, disregarding the initial step-determined age (analysis includes steps 2-8 of 8 total steps measured) (Fig. 5D). The inverse isochron for SH07D shows a similar age of $1398.8 \pm 20.2$ ka. SH07F also has a relatively flat plateau but the calculated date ($1505 \pm 49.5$ ka) is over 100 ka older than the other 4 samples (Fig. 5E).
Table 2. Summary of $^{40}$Ar/$^{39}$Ar Furnace Incremental Heating Results

<table>
<thead>
<tr>
<th>Sample</th>
<th>Experiment #</th>
<th>Latitude (N)</th>
<th>Longitude (W)</th>
<th>K/Ca Total</th>
<th>Age Spectrum</th>
<th>Isochron Analysis</th>
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<td>SH07-A</td>
<td>UW67A2</td>
<td>$16^\circ 48'38.6&quot;$</td>
<td>$62^\circ 11'35.1&quot;$</td>
<td>No plateau; likely due to $^{39}$Ar recoil</td>
<td></td>
<td></td>
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<td>SH07-B</td>
<td>UW67A4</td>
<td>$16^\circ 48'29.7&quot;$</td>
<td>$62^\circ 11'35.5&quot;$</td>
<td>0.366</td>
<td>1384.8 ± 15.9</td>
<td>295.8 ± 6.7</td>
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<tr>
<td>SH07-C</td>
<td>UW67A6</td>
<td>$16^\circ 48'14.1&quot;$</td>
<td>$62^\circ 11'37.2&quot;$</td>
<td>0.184</td>
<td>1406.7 ± 20.6</td>
<td>294.7 ± 3.3</td>
</tr>
<tr>
<td>SH07-D</td>
<td>UW67A8</td>
<td>$16^\circ 48'8.3&quot;$</td>
<td>$62^\circ 11'42.6&quot;$</td>
<td>0.234</td>
<td>1407.4 ± 27.9</td>
<td>295.8 ± 2.1</td>
</tr>
<tr>
<td>SH07-E</td>
<td>UW67A10</td>
<td>$16^\circ 48'4.5&quot;$</td>
<td>$62^\circ 11'43.2&quot;$</td>
<td>0.177</td>
<td>1389.8 ± 18.2</td>
<td>295.8 ± 2.1</td>
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<td>SH07-F</td>
<td>UW67A12</td>
<td>$16^\circ 48'24.9&quot;$</td>
<td>$62^\circ 10'50.7&quot;$</td>
<td>0.196</td>
<td>1534.5 ± 42.8</td>
<td>296.6 ± 3.3</td>
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All ages calculated using the decay constants and isotope abundances of Steiger and Jäger [1977] ($\lambda^{40}$K = $5.543 \times 10^{-10}$ yr$^{-1}$)
J-values calculated relative to the 1.194 Ma Alder Creek rhyolite sanidine [Renne et al., 1998]
See Hora et al., 2007 or Jicha and Singer 2006 for $^{40}$Ar/$^{39}$Ar methods of the Rare Gas Geochronology Laboratory at UW-Madison
Ages in **bold** are preferred
Figure 5. Age Spectra and inverse isochron diagrams for 6 Silver Hills samples. A-D) Samples SH07-B, C,D, and E show relatively flat age spectra with similar weighted mean plateaus. F) The inverse isochron for SH07A suggests Ar loss during irradiation induced recoil. Analytical procedures and data reductions described in Singer and Brown (2002).
Figure 5 continued.
Sample SH07A has a downward stepping age spectrum and a high MSWD value (9.07) suggesting possible $^{39}$Ar recoil during irradiation (Singer, 2007) (Fig. 5F).

**Discussion**

Petrographic analyses suggest that while the samples are petrographically very similar, careful observations document subtle differences in phenocryst populations, and the nature of the groundmass. Cumulates serve as evidence that the order of crystallization begins with plagioclase and orthopyroxenes forming and later the creation of clinopyroxenes. The collection of phenocrysts (orthopyroxene, clinopyroxene, and plagioclase) and the SiO$_2$ content of the rock, if correlated with andesites from the actively erupting Soufrière Hills, suggests a crystallization temperature around 900°C (Barclay et al., 1998). Petrography shows variations in crystallization of the groundmass between samples from lava flows (SH07 - C and E) and the samples collected from block-and-ash flows (SH07 - B and D). The generally elongated subhedral to euhedral plagioclase crystals in the lava flow samples (SH07 - C and E) differ from the intergranular equal sized components of SH07B and the preferred orientation anhedral groundmass of SH07D (Fig. 3).

Plotting whole rock geochemistry data against previously determined values shows that the samples collected seem to fit within other work (Fig. 4) (Harford et al., 2002). The data collected by Harford et al. (2002) and the current samples show that the majority of rocks, when comparing the weight percent of K$_2$O and SiO$_2$, plot within the andesite boundaries as determined by Gill (1981) (Fig. 4A). Only one of the Silver Hills samples from Harford et al. (2002) plots within the dacite division for the SiO$_2$ vs. K$_2$O
relation (Fig. 4A). Results from this research complement the relation between vanadium and SiO₂ concentrations shown by Harford et al. (2002) on the scale from basalts to andesites (Fig. 4). Geochemistry shows the samples are similar with the exception of the geographically different sample (SH07F) that is marginally more mafic, suggesting slightly different fractional crystallization within the magma chamber.

⁴⁰Ar/³⁹Ar analysis shows four samples with similar dates (Fig. 5 - A, B, C, D), one sample with an age differing by nearly 100 ka (Fig. 5E), and one inconclusive sample (Fig. 5F). While samples SH07 - B, C, D, and E show similar ages, they exhibit different patterns of plagioclase crystallization within the groundmass, most obviously between the block-and-ash flow (sample SH07B) and the large lava flow (SH07 - C and E). SH07F gives an age approximately 100 ka before the four similar samples discussed above. Other evidence that supports this difference includes the uniquely oriented plagioclase matrix of SH07F, the high values of trace elements including nickel, chrome, and vanadium relative to the other five samples, and its physical distance from the other five samples.

Sample SH07A gives an unreliable date of 1450.2 ± 38.8 ka with a high MSWD value of 9.07. The downward stepping plateau, inverse isochron plot, and MSWD value suggest error in the results found for SH07A. Petrographic analysis of SH07A shows anhedral plagioclase microlites mixing with oxides and glass. Each of these factors suggest possible ³⁹Ar recoil caused by irradiation-induced redistribution in the reactor (Singer, 2007).
Conclusions

There were at least 2 major eruptive events at 1390 ka and 1500 ka that formed the Silver Hills. Petrographic analysis and geochemistry show all samples to be relatively similar in composition. The dates and geochemistry determined in this study support and expand on previous research done in Montserrat (Macgregor, 1938; Rea, 1974; Briden et al., 1979; Macdonald et al., 1999; Harford et al., 2002). The ages determined by $^{40}\text{Ar}/^{39}\text{Ar}$ geochronology are consistent with findings by Briden et al. (1979), Harford et al. (2002), and Rea (1974) that date the formation of the Silver Hills to at least two events around 1390 ka and 1500 ka. Future studies of Montserrat and the Lesser Antilles island arc should include more $^{40}\text{Ar}/^{39}\text{Ar}$ data for all volcanic massifs in order to improve the detailed volcanic history of the region. This region is unique because it has historical value but also the ongoing activity that allows researchers a view into the complexities of volcanism in island arcs.
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References Cited


Carlut, J., Quidelleur, X., Courtillot, V., and Boudon, G., 2000, Paleomagnetic directions and K/Ar dating of 0 to 1 Ma lava flows from La Guadeloupe Island (French West Indies): Implications for time averaged field models: Journal of Geophysical Research - Solid Earth, v. 105, p. 835-849.


