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Caught in the act: Implications for the increasing abundance of mafic enclaves during the recent eruptive episodes of the Soufrière Hills Volcano, Montserrat

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[1] An exceptional opportunity to sample several large blocks sourced from the same region of the growing Soufrière Hills lava dome has documented a significant increase in the presence of mafic enclaves in the host andesite during the course of a long-lived eruptive episode with several phases. In 1997 (Phase I) mafic inclusions comprised ~1 volume percent of erupted material; in 2007 (Phase III) deposits their volumetric abundance increased to 5–7 percent. A broader range of geochemically distinctive types occurs amongst the 2007 enclaves. Crystal-poor enclaves generally have the least evolved (basaltic) compositions; porphyritic enclaves represent compositions intermediate between basaltic and andesitic compositions. The absence of porphyritic enclaves prior to Phase III magmatism at Soufrière Hills Volcano suggests that a mixing event occurred during the course of the current eruptive episode, providing direct evidence consistent with geophysical observations that the system is continuously re-invigorated from depth. **Citation:** Barclay, J., R. A. Herd, B. R. Edwards, T. Christopher, E. J. Kiddle, M. Plail, and A. Donovan (2010), Caught in the act: Implications for the increasing abundance of mafic enclaves during the recent eruptive episodes of the Soufrière Hills Volcano, Montserrat, *Geophys. Res. Lett.*, *37*, L00E09, doi:10.1029/2010GL042509.

1. Introduction

[2] Magma mixing is a ubiquitous process in many arc-related volcanic systems; it brings together compositionally and physically dissimilar magmas whose interaction can provide a trigger for eruption [*Sparks et al.*, 1977; *Eichelberger*, 1980]. Evidence for mixing or mingling processes immediately prior to eruption has been described at many recently active volcanoes and is implicated in sustaining long-lived eruptive episodes (e.g., Stromboli [*Pichavant et al.*, 2009]; Popocatepetl [*Roberge and Wallace*, 2009]). Most studies of magma mixing focus on detailed geochemical, petrological and microtextural analysis of the erupted products. Such studies provide important evidence for pre-eruptive thermal and chemical perturbation of the magmatic system. Yet, many of the detailed mechanical models for mixing-induced volcanic eruptions focus on larger-scale processes within the storage region and conduit [*Snyder et al.*, 1997; *Phillips and Woods*, 2002]. Thus, macroscopic, field-based observations can also be important for differentiating between competing hypotheses for the mechanisms controlling mixing-driven eruptions. The large-scale record of mixing processes is frequently obliterated during fragmentation and so obtaining field-based observations during eruptions is difficult and dangerous.

[3] This paper presents the first results from a unique opportunity to observe mixing processes during the course of a long-lived volcanic eruption: the ongoing eruption of the Soufrière Hills Volcano (SHV), Montserrat. Field-based, petrographic and geochemical descriptions are used to evaluate the processes that produced the mingling features, their relation to changes in eruptive behaviour at the SHV and implications for interpreting and recognising changes in the storage system during the course of the eruption. It is inferred that the increase in abundance of mafic enclaves is consistent with a pulse of new, less evolved material into the storage system from depth with evidence that this has involved the exchange of mass as well as heat between the resident andesite and the incoming more mafic magma.

2. Soufrière Hills Volcano

[4] The SHV on the Caribbean island of Montserrat (16.7°N, 62.2°W) has been active since July 1995. Its andesitic dome-forming eruption is one of the best monitored and highly instrumented eruptive episodes in recent times; observations and inferences relating to its behaviour have been extremely well documented [e.g., see *Christopher et al.*, 2010; *Wadge et al.*, 2010]. The eruption to date has involved five prolonged phases comprising dome growth (referred to as Phases I to V) pyroclastic flows and surges, Vulcanian explosions, and, in 1997, a debris avalanche that triggered a lateral blast. These phases are punctuated by periods of 'residual' activity, where no new material is seen at the surface but dome collapse, ash venting and occasional explosions do occur.

[5] Rock samples from SHV have been well characterized and are continuously sampled as part of the monitoring program of the Montserrat Volcano Observatory (www.mvo.ms). The crystal-rich andesite contains minor (~1 vol%) but ubiquitous quench-textured mafic inclusions [*Murphy et al.*, 1998, 2000]. The resident andesitic magma is inferred to have been variably reheated from its pre-existing storage condi-

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Table 1. Estimates of Proportions of Mafic Inclusions in Dome Blocks Deposited in the Lower Belham Valley

	Phase I	1997	1	2	3	4	0[a]
Total inclusions			124	91	162	60	23
Total points			1598	1600	1281	1120	352
% inclusions	1–2[b]	1.39[c]	7.76	5.69	12.65	5.36	6.53
		% Type[d]					
Diktytaxitic			67.74	40.66	96.91	65.00	-
Andesite			0.81	0.00	0.00	0.00	-
Waxy			29.84	56.04	0.00	26.67	-
Mixed			0.00	0.00	3.09	8.33	-
Undifferentiated			1.61	3.30	0.00	0.00	-

[a]Boulder 0 was analysed while developing the technique and notes on inclusion type were not taken.
[b]*Murphy et al.* [1998, 2000]. These were derived via point counting from multiple thin-sections of the andesite, and from field data (S. Sparks, personal communication, 2009).
[c]S. C. Loughlin (personal communication, 2007). Average surface area occupied by mafic enclaves in 39 pumice sections measured from the vulcanian eruption of 10th August 1997.
[d]Diktyaxitic: Some quenched margins, small interlocking groundmass crystals, randomly orientated around vesicles (+/− included larger crystals). Andesite: Zone of rock with distinct margin but crystallinity and appearance very similar to SHV andesite. Waxy: Groundmass not apparent, greasy dark grey appearance. Included crystals. Mixed: Distinct enclave with both diktyaxitic and waxy components, contact between these is two often irregular.

tions by the intrusion of mafic magma, possibly represented by the mafic enclaves [*Murphy et al.*, 1998, 2000]. The magmatic system shows strong petrological and geochemical evidence for being open with far more mafic magma present at depth than has been sampled by the current eruptive episode [*Murphy et al.*, 2000; *Edmonds et al.*, 2001]. Recent geophysical evidence is consistent with two magma reservoir regions: a shallow storage region (~5 km) that is periodically recharged from depth by a deeper region at around 12 km [*Elsworth et al.*, 2008].

[6] The third phase (Phase III) of dome growth at SHV started in August 2005; despite initially low rates of extrusion, dome growth was generally rapid (>10 m^3/s at times) and in May 2006 the rapid growth culminated in the second largest collapse during the current eruption [*Wadge et al.*, 2010]. Dome growth continued until January 2007 with notable episodes of dome growth in the NW sector during September and October 2006. On the 24th December 2006 a vigorous episode of growth in this sector culminated in the collapse of an estimated 3–4 million m^3 of material into the Belham river valley, previously untouched by this eruptive episode [*Wadge et al.*, 2010]. This collapse only sampled lava from Phase III dome growth, with the majority of the material extruded in the few weeks prior to collapse.

3. Deposit Description and Analysis

[7] Pumice and five blocks were sampled from the snout of the flow in January 2007. Fifty to 100 m of the flow front had been eroded back up valley, but further upstream substantial deposits of pyroclastic flow material were still intact. The deposits largely comprised dense blocks (up to 2 m in diameter) set in a beige-pink sandy matrix. The dense blocks were generally dark grey to red-brown in colour, with a granular appearance, quite distinct from the usually dark grey boulders in typical Belham lahar deposits. Blocks from the pyroclastic flow were also identified by the presence of percussion marks, and the presence of localised superficial hydrothermal material (associated with the cooling of the pyroclastic flow). The most striking feature of these blocks was the presence of abundant mafic inclusions (Figure S1a of the auxiliary material).[1] Five blocks were selected to quantify the abundance of the inclusions (Table 1). Blocks with comparatively flat faces were used ($\gg$0.5 m by 0.5 m) and measurements were made on a 2 cm grid on the flat face from each block. This size interval was chosen after experimentation to ensure sampling of the full range of inclusions with the typical number of points in a survey. Enclaves to around 0.5 cm maximum diameter were included; below this size it was difficult in the field to differentiate between crystal glomerocrysts in the host rock and the mafic enclaves. Maximum and minimum enclave diameters were measured and notes made on the general shape of the inclusions.

4. Geochemistry and Microscopic Methods

[8] Representative samples of the most abundant inclusion types were collected for petrographic and bulk rock analysis from each sampled block. Major and trace elements were determined using the XRF at UEA (Table S1). Large blocks were crushed to ensure a sample size greater than any potential heterogeneities. Several different types of inclusion were sampled and examined using transmitted light and SEM microscopy.

5. Textures and Abundance of Mafic Enclaves

[9] Our most important observation is the almost five-fold increase in inclusion abundance in the blocks from the January 2007 flow compared to all other reported abundances of mafic enclaves at SHV (Table 1).

[10] In the field mafic inclusions were subdivided into four recognisable types (summarised in Table 1). The diktytaxitic type was volumetrically dominant; however, in some instances enclaves appeared to be a mixture of the diktyaxitic and the waxy type, with a distinct border between enclaves and the andesitic matrix ('mixed enclaves' in Table 1). The degree of mixing between these two types approximated magma mingling in places with a highly irregular border (see Figure S1b). These textures were generally restricted to larger enclaves (>5 cm), and were not present in every block but where present were locally abundant. Overall, inclusion margins were usually rounded but varied to crenulate, wispy, pillow-shaped and highly irregular fingers. The apparent major-axis of inclusions is not normally distributed and shows a bi-modal population with peaks at 2–3 cm and 5–6 cm. The largest inclusions observed were 70–80 cm long; the largest measured in the surveyed boulders was 12.3 cm.

[11] Detailed petrographic analysis for this study focused on the two most abundant enclave types: diktyaxitic and mixed. Macroscopically diktyaxitic enclaves were divided into two groups based on visual inspection (Table 1): phenocryst-rich (porphyritic) and phenocryst-poor. The porphyritic group contained proportions of phenocrysts similar to Phase I enclaves; *Murphy et al.* [2000] suggested that larger crystals in Phase I enclaves are xenocrysts de-

[1]Auxiliary materials are available in the HTML. doi:10.1029/2010GL042509.

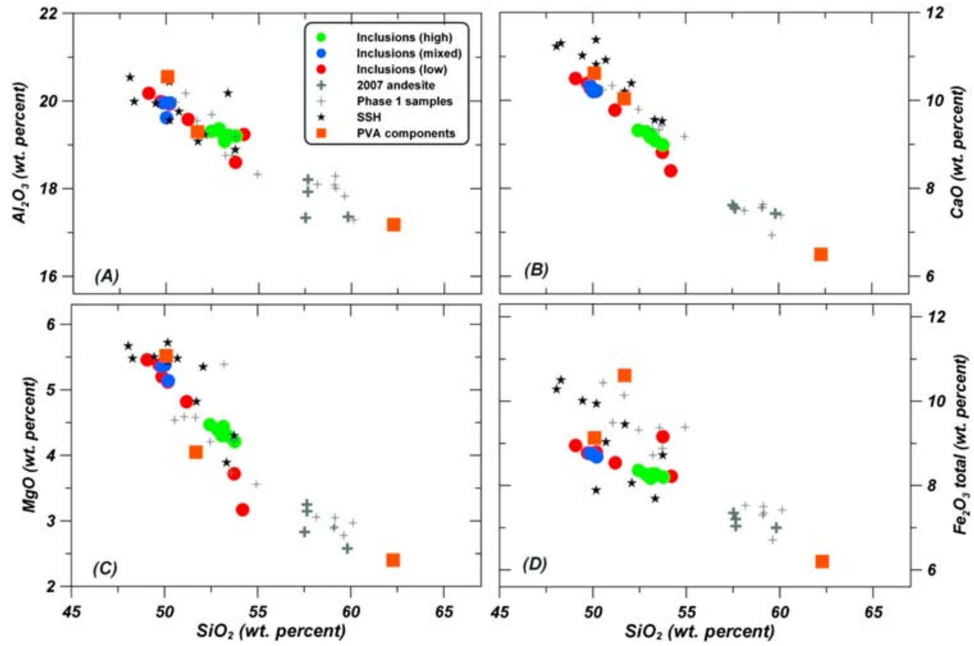

Figure 1. (a–d) Harker variation diagrams of selected XRF major element compositions of the mafic inclusions and andesites. Phase I and South Soufrière Hills data from *Murphy et al*. [1998, 2000] and *Zellmer et al.* [2003]. Symbols here refer to both enclaves and andesite data. "High" refers to phenocryst-rich bearing enclaves referred to as porphyritic in the text, "low" refers to phenocryst-poor enclaves, for full explanation of "mixed" refer to Table 1 and text.

rived from the andesite. Crystal proportions in the porphyritic enclaves are 19–27% (Table 1), but individual crystals are texturally similar to those found in the phenocryst-poor group. Included plagioclase crystals have ubiquitous overgrowth rims (Figure S1c) that are not always present in similar size crystals within the andesite. Plagioclase crystals are also frequently observed transecting the boundary between enclave and host andesite (Figure S1d), suggesting that these crystals have been inherited from the andesite. The majority of the large amphibole phenocrysts in the enclaves have been opaticised (opaque in transmitted light), which is consistent with destabilisation via either heating, melt degassing or oxidation of the melt [*Murphy et al.*, 2000; *Rutherford and Devine*, 2003]. In the groundmass, diktyaxitic crystal size is highly variable and qualitatively does not seem to bear a relationship to the size of inclusions. Some enclaves have groundmass crystals consistent with two stages of growth (Figure S1e).

6. Geochemistry of Mafic Enclaves

[12] The compositional range of sampled enclaves is similar to that of Phase I inclusions reported by *Murphy et al*. [2000] and *Zellmer et al*. [2003], with some subtle differences (Figures 1a–1d and see Table S1 for analyses and brief sample descriptions). Overall the abundances of $Fe_2O_3^T$ and CaO are slightly lower with concurrent increases in K_2O and MgO, consistent with a closer affinity to South Soufrière Hills basalt. Generally the porphyritic samples have more evolved compositions (Figures 1a–1d).

[13] Our preliminary geochemical data (Figures 1a–1d) show that the majority of the 2007 enclaves are somewhat different from previously published enclave data. To investigate further the relationship of these enclaves to the andesite and Phase I enclaves Polytopic Vector Analysis (PVA) was performed on new and existing analyses. PVA has been successful in identifying end-member compositions and processes responsible for generating compositional arrays observed in rocks from the same volcano [*Vogel et al.*, 2008]. PVA can use all of the chemical element data simultaneously and evaluates each sample with respect to differing components of the identified end members. Following the method of *Vogel et al*. [2008], the initial analysis was applied to determine the number of end members necessary to describe the system (andesite and mafic enclaves, Figure 2). For each number of end-members (or eigenvectors) in the initial analysis, the agreement between each variable and the value calculated using the end-members is determined (Kloven Miesch Coefficient of Determination, KMCD). In the case of the SHV major element data, three end-members provide a very good fit to the data with KMCD > 0.90 (1 indicates perfect agreement) for all elements with the exception of Na and K (KMCD > 0.80). The relationship of the three end-member compositions to the whole-rock data are shown in Figure 2. The three end-members are: an andesite composition that is close to the most evolved andesite analysed; a mafic component that represents a less evolved magma and a mafic component that more closely represents an average composition for the enclaves reported for Phase I of the eruption. When the analyses are expressed in terms of these end-members (Figure 2), a clear distinction emerges between the Phase I and the 2007 (Phase III) enclaves. The 2007 enclaves have a closer affinity with the least evolved end member and a mixing or fractionation relationship with the end-member andesite. The less evolved mafic composition is somewhat similar to the South Soufrière Hills basalts with the notable exception of K_2O and Sr (Table S1). Variation in these particular elements in parental magmas was ascribed to variable fluid content by *Zellmer et al*. [2003]. The porphyritic enclaves are best described as a mixture of the less

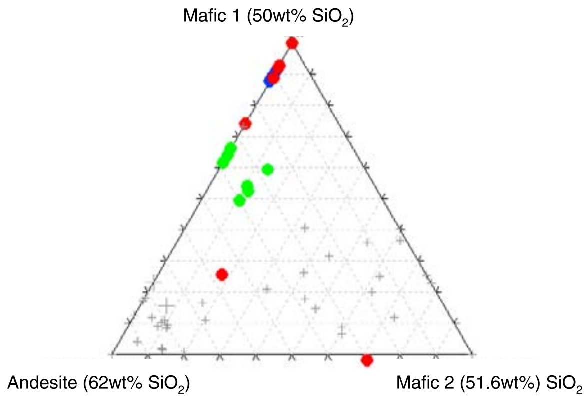

Figure 2. Polytopic vector analysis of the differing types of enclaves and andesite data. Red circles are phenocryst-poor enclaves from Phase III; green circles are phenocryst-rich (porphyritic) enclaves and blue circled are from "mixed" enclaves (as above). Larger grey crosses are andesite analyses from this study and smaller crosses are Phase I enclave and andesite data from *Murphy et al*. [1998, 2000] and *Zellmer et al.* [2003].

evolved mafic end-member and the andesite, consistent with the suggestion that the included crystals have been derived from the host andesite.

7. Discussion

[14] Our most fundamental observation is the large increase in the volumetric abundance of mafic enclaves in the host andesite between 1997 and 2007. Few other examples of ongoing mixing processes have been documented and even fewer reported in the midst of an active eruption. However, the instances that are described provide evidence that these changes reflect changing dynamic behaviour in the system. *Wada et al*. [2004] describe the distribution of inclusions in a granitic pluton and provide evidence for their emplacement via passive flotation towards the active zone (crystal mush) of the pluton. *Stout et al.* [2007] found that the distribution of mafic enclaves in the Chaos Crags dome complex at Lassen Park, California shows an increase in mafic enclaves in the final dome emplacement, in this instance synchronous with the cessation of dome growth. By contrast, mafic enclaves entrained in the Salina pyroclastic flow, Italy attest to increasingly turbulent conditions as the eruption progressed [*Perugini et al.*, 2004].

[15] For SHV the increase could represent (1) tapping of a different part of the magma storage region, which had 'seen' more mafic magma at some point in the past, (2) an increased input of mafic magma to the system since 1997 or (3) an increase in mixing efficiency. Discrimination between these possibilities is important for predicting the future eruptive behaviour of the SHV system. The first hypothesis would be consistent with a system in the waning stages, expelling the lower bowels of the eruptible storage region and possibly signalling the death of the magma system. The second and third hypotheses could signal reinvigoration of the system by a new thermal input. The extent and longevity of this reinvigoration depends upon whether the increase represents (1) a pervasive change in the abundance of mafic magma throughout the andesite storage region, or (2) a more localised injection of mafic magma. Again, discriminating between these possibilities has important implications for eruption dynamics and duration- for instance a localized perturbation would be consistent with a simple cyclic pattern of periodic dyke intrusion leading to short reactivation of the storage region and renewed dome growth consistent with earlier phases of activity at SHV. However, a pervasive change could be an indication that the entire system is being heated more rapidly which would imply a greater volumetric influx of mafic magma to the system or an increase of mixing efficiency. This might be expected to produce more significant changes in future eruption styles consistent with the behaviour of a hotter, more dynamic system.

[16] Based on the analysis of major and trace element geochemistry from Phase I, *Zellmer et al.* [2003] suggested that the mafic enclaves entrained within the andesite were related to one another via closed system fractionation of plagioclase and amphibole but that the enclaves were derived from a different source than the andesite. They suggested that the source for the andesite was similar in composition to the South Soufriere Hills basalt (Figures 1a–1d). The presence of the full range of enclave compositions throughout Phase I of the eruption suggests that the mafic magmas were all intruded prior to or synchronous with the onset of Phase I. Our Phase III geochemical data are most consistent with an input of new magmatic material derived from a source different to that of the earlier enclaves and one not previously observed in the andesite. This implies that the enclaves record an input of mafic magma subsequent to Phase I. The increased abundance of enclaves is therefore unlikely to represent a lower portion of the storage system or a waning stage of the eruption as in this instance enclave composition should remain similar. The petrographic and textural data suggest that the degree of interaction between the andesite and the new mafic magma was heterogeneous, with varying degrees of degassing and mixing between the two magmas; injection may also have occurred more than once. The porphyritic samples result from mass exchange with the andesite, which implies that in some instances degassing and interaction with the magma took place prior to quenching of the enclaves, consistent with the observations of *Humphreys et al.* [2010].

[17] At least three independent observations support the hypothesis of continued input of mafic magma at depth during the course of the SHV eruption. The excess emissions of sulphur that have continued throughout phase III dome growth and the subsequent pause in activity are consistent with the presence of an actively degassing mafic magma body [*Christopher et al.*, 2010]. *Humphreys et al.* [2009] used Cl/OH ratios in amphibole and melt inclusions as evidence for the continued input of heat and volatiles into the system from mafic magma below and suggested that portions of the andesite magma can be stored at depths > 5 km. *Voight et al*. [2010] use simple modelling to ascribe geodetic and seismic observations to the continuous throughput of magma from a deeper source to the shallow storage region throughout the ongoing eruptive episodes.

8. Conclusions

[18] The observation of increased abundances of mafic enclaves at Soufrière Hills Volcano provides evidence for

dynamic changes at depth during the course of the current eruptive episode. An increase in the overall abundance of the enclaves coupled with their distinctive composition record an injection of mafic magma subsequent to Phase I activity. Textural and petrographic differences between the host andesite and enclaves are consistent with the exchange of material during the course of the 1995-present eruptive episodes.

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