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Overview of the eruption of Soufriere Hills volcano, Montserrat, 18 July 1995 to December 1997

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Abstract. The onset of phreatic volcanic activity at the Soufriere Hills volcano, Montserrat on 18 July 1995 followed a three-year period of heightened volcano-seismic activity beneath the island. Phreatic explosions gave way to continuous eruption of juvenile andesitic magma in the form of a lava dome on or around 15 November 1995. Magma production rate has varied, leading to changes in eruptive style. An explosive eruption on 17 September 1996 followed a period of enhanced dome growth and large-scale gravitational collapses from its eastern flank. Increasing dome volume led to stressing and overtopping of the confining crater walls to the southwest, north and west during early 1997. Sustained high magma production rate since June 1997 has led to three periods of major gravitational dome collapses followed by vulcanian explosive eruptions. Dome growth re-started immediately after the cessation of the latest of these explosive phases in October 1997 and continues as of December 1997.

Volcanic History, Precursor Activity and Monitoring

The Soufriere Hills volcano (SHV) lies in the south-central part of the British overseas territorial island of Montserrat, near the northern end of the Lesser Antilles volcanic arc (Figure 1). The island comprises a number of volcanic centres up to c. 4.3 Ma old [*MacGregor*, 1938; *Rea*, 1974], with the younger centres lying in the southern third of the island. The SHV superstructure comprises four andesite lava domes and a fan of associated pyroclastic flow deposits. Radiocarbon dates from these pyroclastic flow deposits [*Wadge and Isaacs*, 1988] suggest that SHV was most active between 24 and 16 Ka, although recent work has shown that the summit crater was likely formed c. 4,000 years ago [*A. Smith*, personal communication, 1997]. Castle Peak Dome, a small andesitic lava dome (estimated total erupted volume 45 ± 15 x10^6 m^3) partially filled the crater c. 323 ± 50 years BP [*Young et al.*, 1996; *S. Young*, unpublished data].

Significant increases in seismicity and in hot spring activity occurred on Montserrat in 1897-98, 1933-37 [*MacGregor*, 1938; *Perret*, 1939] and 1966-67 [*Shepherd et al.*, 1971]. Reported felt intensities suggest that earthquakes occurred at shallow depths (<5 km) beneath the volcano and elsewhere (most notably St George's Hill, Figure 1) in 1933-37. Earthquake epicentres for the 1966-67 swarm were scattered along an ESE-trending zone centred on SHV at estimated depths of 3 to 10 km. There was an increase in each case of heat flow and some changes in gas compositions at some or all of the soufrières (hot springs) located on the flanks of the volcano. Water-tube tiltmeters in place during the 1966-67 crisis recorded minor changes on the lower flanks of the volcano, peaking at c. 0.3 μrad/day [*Shepherd et al.*, 1971].

A short-lived increase in volcano-related seismicity occurred in mid-1985 following a magnitude 6.2 earthquake 30 km from SHV; both the 1933-37 and 1966-67 volcano seismic crises also followed probable magnitude 6 or more earthquakes within 50 km of Montserrat [*Shepherd*, 1989].

Some increase in seismicity was noted in the Montserrat area in 1992 and this activity increased markedly in November 1994, with a large number of relatively deep (? 10 to 20 km) earthquakes being recorded by the regional seismic monitoring network on Montserrat and surrounding islands. However, no direct precursor seismic activity was noted in the days or weeks prior to the onset of phreatic activity on 18 July 1995. The hydrothermal system showed few changes during this period [*Hammouya et al.*, 1998].

Monitoring of the current Soufriere Hills eruption has included a wide range of geophysical and geological tools, most importantly short period and broad-band seismology, a variety of ground deformation surveying techniques and electronic tiltmeters, volcanological monitoring including petrology and geochemistry, dome and deposit mapping and volume assessment, gas monitoring through direct sampling and remote sensing, and a wide variety of environmental monitoring including ground and rain water geochemistry and ash chemistry and concentrations in the atmosphere.

Phreatic Activity, July to November 1995

Eruptive activity began on 18 July 1995 from several steam vents forming a NNW line across the NW side of Castle Peak Dome. These vents later coalesced to form a single, large vent and a second major vent opened on the SE side of the crater floor on 28 July. Phreatic explosions with associated steam and ash columns to 3 km height continued for four months, with cold base surge ash clouds from the largest explosions on 21 August, 31 October, 4 and 9 November engulfing the is-

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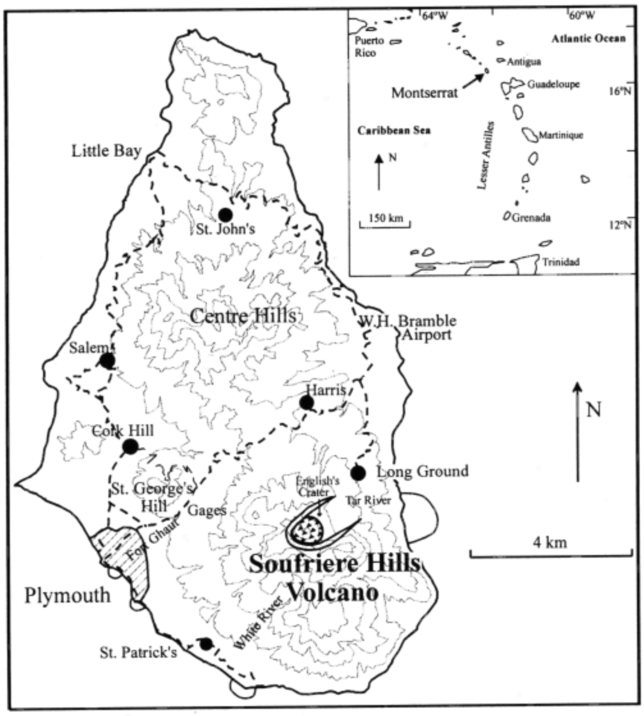

Figure 1. The island of Montserrat, with locations mentioned in text. Contours are at intervals of 500 ft. Area with symbols in English's Crater is the new lava dome, which has overgrown Castle Peak Dome. Outline of new pyroclastic flow fans also shown.

land's capital, Plymouth, causing darkness for up to 30 minutes on each occasion and producing ashfalls of a few millimetres 5 km downwind. The erupted ash was andesitic in composition, interpreted as finely comminuted fragments of Castle Peak and older domes; no evidence for juvenile material was found at this time. Further small vents opened within the crater through the course of the phreatic phase. SO_2 production averaged 300 tonnes per day, with maxima associated with vigorous steam emission events.

Seismicity during the phreatic phase of the eruption was dominated by volcano-tectonic earthquakes located both beneath the crater area and scattered beneath other parts of southern Montserrat, especially St George's Hill [*Aspinall et al.*, 1998]. Some long-period earthquakes and tremor episodes were also recorded by the local seismic network. An intense swarm of shallow hybrid earthquakes immediately preceded development of a small (c. 40,000 m^3) dome-like mass with central spine on the W side of Castle Peak Dome in late September 1995. Any deformation associated with this event was not recorded by the electronic tiltmeters then in place on the lower flanks of the volcano.

Early Dome Growth, November 1995 to September 1996

The onset of continuous dome extrusion in mid-November 1995 was preceded by localised deformation in the crater area measured by Electronic Distance Meter (EDM) [*Jackson et al.*, 1998] and is thought to have directly followed a period of intense earthquake activity on 14/15 November. Poor visibility prevented sighting of the new dome until 30 November, when it was seen to be a blocky mass partially filling the enlarged initial phreatic vent.

Dome growth continued at c. 0.5 m^3/s until late January 1996, when a swarm of repetitive hybrid events lasting around two weeks accompanied a significant increase in extrusion rate, which then continued at c. 2 m^3/s until late July 1996 (Figure 2). The dome comprised highly viscous andesitic (c. 59% SiO_2) lava with plagioclase, hornblende and orthopyroxene as the main phenocryst phases and a high groundmass crystal content. Fine to coarsely crystalline mafic inclusions comprise a small amount of the dome rock, whose bulk composition has remained very uniform [*Devine et al.*, 1998a]. Rock falls from the dome produced small amounts of ash which were entrained in the gas plume blown consistently westwards by the easterly trade winds. Numerous spines where extruded vertically from the blocky dome surface at up to 30 m/day, most collapsing after a few days. One surface of each spine was often smooth and curved, with a breccia coating and striations indicative of movement upwards through a conduit in a semi-solid state. Horizontal spines were also extruded, two early in 1996 being co-linear and oriented NNW.

Throughout this period of dome growth, deformation as measured by EDM and electronic tiltmeters was at a very low level [*Jackson et al.*, 1998], and no significant changes in hydrothermal geochemistry or heat production [*Hammouya et al.*, 1998] or wide-field ground deformation [*Mattioli et al.*, 1998] were measured from pre-eruptive conditions. SO_2 monitoring by correlation spectrometer (COSPEC), re-established in April 1996, gave low to moderate gas production (c. 200 t/day; *Young et al.* [1998]), with low SO_2 to HCl ratios (average < 1) as measured by open-path Fourier Transform Infra-Red spectroscopy [*Oppenheimer et al.*, 1998].

A switch in focus of dome growth in early March prompted build-up of an unstable flank on the NE side of the dome which produced the first pyroclastic flows [*Cole et al.*, 1998] of the crisis into the Tar River valley during late March 1996

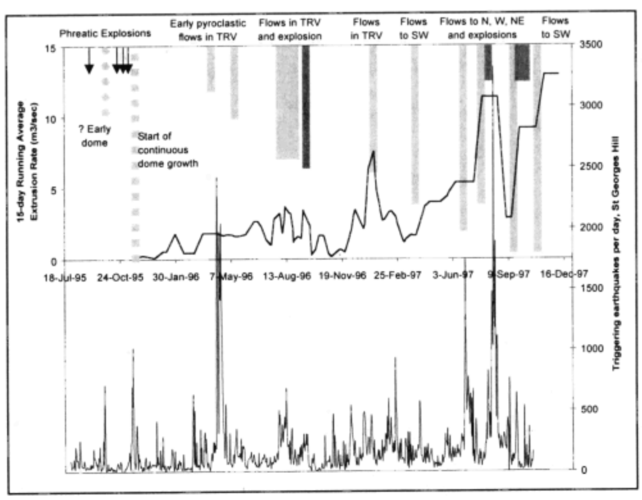

Figure 2. Plot showing magma extrusion rate as deduced from dome and deposit volume calculations, smoothed and shown as a 15-day running average; the number of triggering earthquakes on the St George's Hill seismic station per day, which is a measure of the seismic activity; and at the top, significant events during the eruption. Lighter bars are dome collapses, darker bars are explosions; length of bars gives relative magnitude of events. TRV is Tar River Valley.

by gravitational collapse from the dome flanks. High internal dome pressures at this time were evidenced by gas jetting and vigorous steam venting. A series of flows on 12 May were the first to reach the coastline, 2.5 km from the dome, and a delta of pyroclastic flow material has gradually built out since that time.

A rapid increase in extrusion rate (to >4 m^3/s) was preceded and accompanied by an enhanced level of seismic activity towards the end of July 1996. This led to a series of partial dome collapses during the following 7 weeks (29 and 31 July, 11 and 21 August, 2/3 and 17 September), all of which produced pyroclastic flows which travelled as far as the sea within the Tar River valley. These flows deposited several million cubic metres of material within the valley and on the delta as well as producing ash which fell over much of the island. Increased magma ascent rate at this time is evidenced by the unaltered nature of hornblende phenocrysts [*Devine et al.*, 1998b] and the vesicular nature of some of the extruded material. SO_2 flux also increased along with extrusion rate at this time [*Young et al.*, 1998], and high gas pressures were again indicated by vigorous ash and gas venting. Long-period earthquakes and banded tremor were both evident during this period [*Miller et al.*, 1998].

The loss of c. 12 $\times 10^6$ m^3 of material (c. 40 % of the dome) during gravitational collapses on 17 September 1996 [*Sparks et al.*, 1998] led to depressurisation of the dome interior and conduit and a short-lived explosive eruption was initiated late on 17 September [*Robertson et al.*, 1998]. Deposits from the c. 14 km high eruption column were distributed over the southern half of the island, although pyroclastic flow deposits were confined to the Tar River valley, where the Tar River Estate House was destroyed by an ash cloud surge. Ballistic clasts, preferentially emplaced into a sector up to 2.1 km to the NE of the dome and containing the village of Long Ground, caused the destruction of more than 10 homes. The resulting ash cloud was tracked across the Caribbean by weather satellites and caused damage to one aircraft and the island of Guadeloupe, c. 60 km away, was covered by 1 to 2 mm of ash [*Observatoire Volcanologique de la Soufrière de Guadeloupe – IPGP*, personal communication, 1996]. An estimated 3 $\times 10^6$ m^3 of material was erupted during this phase of activity.

Intrusive Activity After 17 September Explosion

Dome growth resumed on 1 October 1996 within the scar left by the explosive activity two weeks earlier. After initial moderate growth, accompanied by relatively high gas production, dome activity declined through November and, in conjunction with high levels of cyclic hybrid earthquake activity, intrusion occurred adjacent to the SW crater wall, causing its instability and slow collapse. Measurement of surface cracks and rate of landsliding were used to qualitatively monitor the rate of deformation of the wall. Heavy rain in late November induced mudflows in streams draining the SW, E and W flanks of the volcano, with material derived from crater wall landslides, pyroclastic flow deposits and ash deposits respectively.

Vigorous exogenous growth recommenced on 11 December culminating in an intense dome collapse and the production of the first pumiceous pyroclastic flows. This was accompanied by a slowing of crater wall deformation. High growth rates accompanied by cyclic inflation and deflation of the dome then led to a further period of partial dome collapses through mid to late January 1997. Fast-moving, voluminous pyroclastic flows were produced at this time from the E and SE flanks of the dome; these were again confined to the Tar River Valley.

Rapid Dome Growth and Explosions, Mid to Late 1997

The dome remained relatively stable despite continued growth until late March 1997, when collapses from the active SW flank prompted pyroclastic flow activity in the White River valley, with runout lengths for flows approaching 4 km. These flows overtopped the by now highly weakened and eroded SW crater wall. Increased rate of deformation of the crater area and upper flanks of the volcano was recorded by GPS and EDM techniques from March 1997. The total volume of magma erupted by late March was c. 77 $\times 10^6$ m^3.

In mid-May, activity switched to the N and NE flanks of the dome and pyroclastic flows in early June eroded and overtopped the northern crater wall flowing up to 4 km down ghauts leading to the central E coast. The first pyroclastic flows into Fort Ghaut, which drains through Plymouth to the central W coast, occurred in mid-June, reaching a distance of c. 1 km. These sourced from a dome now c. 70 $\times 10^6$ m^3 in volume and growing at sustained rates of >4 m^3/s. SO_2 production at this time was enhanced in line with increased magma production rate.

A collapse of c. 5 $\times 10^6$ m^3 lava from the dome on 25 June produced voluminous pyroclastic flows with associated ash-cloud surges which devastated villages in the central and eastern parts of Montserrat. Strongly cyclic hybrid earthquake swarms and inflation/deflation of the dome (as measured by electronic tiltmeter) preceded this collapse [*Neuberg et al.*, 1998; *Voight et al.*, 1998], and minor vulcanian explosions occurred at the peak of cycles for a week or so afterwards. Continued rapid increase in volume (at 5 to 10 m^3/s) and height of the dome led to further large collapses, shedding material to the N and especially to the W throughout July, building a large fan of debris in the Gages area and filling ghauts on the N flank. A sequence of 13 vulcanian explosions occurred in early August with ash columns to 15 km and associated column collapse and generation of radial pumiceous pyroclastic flows. Explosions generally occurred immediately following the peak in cyclic hybrid earthquake activity accompanied by dome inflation/deflation.

Explosive activity recommenced in late September following the biggest single collapse to date; the dome volume was in excess of 85 $\times 10^6$ m^3 prior to the collapse, which included c. 9 $\times 10^6$ m^3 of lava. This collapse produced pyroclastic flows which caused further devastation to eastern Montserrat. Within a day, the first of 75 vulcanian explosions had occurred. All but one of these explosions was accompanied by column collapse pyroclastic flows with runout distances of up to 5 km. Vertical eruption columns typically reached 6 to 10 km height, and ballistic blocks reached a km or so from the vent. Ash from these explosion clouds was distributed over much of the northeastern Caribbean. Volume of emitted products was typically an order of magnitude less than that of the 17 September 1996 explosion. A large (c. 300 m diameter) crater was reamed out adjacent to the back wall of a northfacing scar, centred over the initial phreatic vent and presumably the central feeder conduit.

Dome growth rapidly filled the October explosion crater and then switched to the southwest side of the dome, where a new lobe was extruded at up to 11 m^3/sec through November and December 1997, associated in early November with swarms of large hybrid events recorded on neighbouring islands and two large dome collapses. The dome volume as at 25 December 1997 was c. 110 $x10^6$ m^3 and the total erupted volume was over 240 $x10^6$ m^3.

Conclusions

The 1995-present eruption of the Soufriere Hills volcano has provided an opportunity for modern technology and volcanological thinking to be fully utilised in the thorough documentation of an andesitic dome-forming eruption as well as to provide timely and accurate disaster mitigation advice. This paper provides an overview of eruptive events and other papers in this volume highlight many of the areas of progress. Key highlights which have advanced volcanology significantly through this eruption include the better understanding of the role of microlite crystallisation, degassing and magma viscosity on ascent rate and changes from passive extrusion to violent explosion, the association of seismicity with changes in sub-surface and surface processes, the accurate tracing of dome growth and magma extrusion rate which has generally increased through the eruption and also shown great variety on short time-scales, and the near-source deformation and crater-wall instability induced by dome growth. Perhaps most importantly, these papers highlight the great complexity of volcanic systems and the continued general lack of precursor signals which can be used as precise predictive tools for future activity.

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