Changes in the style of dome growth at Soufrière Hills Volcano, Montserrat

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Abstract

Soufrière Hills Volcano (SHV) on the Caribbean island of Montserrat has now been in eruption for nearly 8 years. Within this time period there have been two main phases of andesitic lava dome growth: from November 1995 to March 1998, and then from November 1999 to the present time. The first phase of dome-building was regularly punctuated by dome collapses and, from 1995 to late 1997, the background extrusion rate gradually increased, leading to more explosive activity. Growth of the dome stopped in March 1998, just 3 months after the most voluminous dome collapse. From March 1998 to November 1999, there appeared to be no extrusion of new lava. This period of "residual" activity, however, was not quiet, but was characterised by dome collapses and small Vulcanian explosions.

Dome extrusion was renewed in mid-November 1999, and the early growth of the new lava dome was characterised by cyclical behaviour, evidenced by observational, seismic and gas emission data, similar to periods seen during the first phase of dome growth. By mid February 2000 the cyclicity in seismic activity had disappeared completely, and had been replaced by an even distribution of hybrid earthquakes and rockfall activity. Two major collapses of the new dome on 20 March 2000 and 29 July 2001 were probably initiated by intense rainfall. Dome growth re-started immediately after the collapses, and was again accompanied by cyclicity for up to a few months duration.

The two phases of dome growth from SHV have been somewhat different in style. Perhaps the most striking difference is that the second phase of dome growth has been characterised by a fairly constant extrusion rate over a long period, and that collapses have been infrequent and widely spaced over time. As a result, during the second phase the dome has grown considerably larger than in the first phase. In contrast, during the first phase, the dome was smaller and much more dynamic, with the rate of growth fluctuating rapidly, the direction of extrusion switching frequently and collapses occurring more often. Explosive activity was also common during the first phase of dome growth, and tended to coincide with high extrusion rates and to follow collapses. The virtual absence of explosive activity during the second phase may therefore be a reflection of the constant and relatively low rate of extrusion, and the infrequency of collapses.

Understanding the differences between the two phases of dome growth using an integrated strategy of multidisciplinary monitoring could be the key to forecasting the long-term behaviour of SHV.

Introduction

The eruption of Soufrière Hills Volcano (SHV) on Montserrat, West Indies, began on 18 July 1995, with phreatic explosions from Castle Peak, a prehistoric andesite dome, sited within the horseshoe-shaped English's Crater (Fig. 1). After an initial phreatic phase, most of the following 32-month period involved activity related to the growth and collapse of a viscous andesitic lava dome (Young *et al.* 1998). Growth of the dome ceased on about 10 March 1998, at which time the total amount of magma erupted since 1995 was 300 x 10^6 m^3 (dense rock equivalent; DRE). The volume of the dome at this time was 113 x 10^6 m^3 (DRE). After the cessation of magma extrusion in March 1998, seismic activity decreased markedly, and the dome appeared to be stable. Little or no lava was extruded for the next 20 months, although some significant gravitational dome collapses and small Vulcanian explosions did occur (Norton *et al.* 2002). In November 1999, a second phase of lava extrusion commenced. This paper outlines the events that have been observed at SHV in this second phase of lava extrusion from November 1999 to the present, and compares the behaviour of the volcano in the two phases of dome growth, by examining the whole range of monitoring data collected at the Montserrat Volcano Observatory (MVO).

Figure 1. Map of Montserrat, West Indies showing locations mentioned in the text.

Event chronology

October to November 1999: Earthquake swarms and small explosions signal the re-start of extrusion

- At the end of October 1999, following about 20 months of virtually no lava extrusion, a series of phreatic explosions occurred.
- An intense hybrid swarm from 3-8 November 1999 followed.
- Magmatic explosions on 8 and 9 November 1999 produced steamy ash clouds which rose up to 6-8 km.
- The fall-out material contained small (<0.5 cm) pumice clasts.
- These explosions were followed by periods of low-frequency tremor, but there was no associated pyroclastic flow activity.
- On 27 November 1999 new dome growth was observed in the gorge in the centre of the 1995-98 dome, marking the start of the second phase of magma extrusion (Fig. 2). Until February 2000, the dome growth was accompanied by banded tremor.

Figure 2. View of the dome complex in December 1999 from the east showing the new dome growth in the gorge formed during the dome collapses and explosions from July 1998 to October 1999.

Major dome collapse of 20 March 2000

- There was a sudden increase in activity on 20 March 2000 with a major dome collapse to the east. No precursory seismic activity was recognised.
- The collapse started with a gradual build-up of pyroclastic flow activity, peaking nearly 4 hours after the start of the event.
- The collapse followed a period of intense rainfall.
- About 95% (ca. 22 x 10^6 m^3) of the new lava dome was removed, leaving a canyon-like feature extending deep into the southeast flank of the dome.
- Within 24 hours of the collapse, a new lava dome was seen in the canyon.
- The initial rapid growth of the new dome was accompanied by banded tremor which lasted for several weeks.

Continued growth of the lava dome

- Dome growth continued within the canyon for the next 16 months.
- The dome growth was steady at an average rate of about 3 m^3 s^{-1}.
- In mid March 2001, the dome growth slowed significantly, and actually stopped for several weeks to mid May 2001, but then resumed at a similar rate to previously measured.

Major dome collapse of 29 July 2001

- A second major dome collapse occurred on 29 July 2001.
- Again, the pyroclastic flow activity increased gradually over a period of several hours, and was associated with intense rainfall.
- A total volume of about 45 x 10^6 m^3 is estimated to have been removed from the dome. This was about 25 % of the total volume (including 1995-98 growth) at the time.
- Lithic clasts (to 6 cm diameter) were lofted in the plume and transported to about 8 km from the volcano.
- Heavy ashfall occurred on the island.

Continued growth of the lava dome

- The lava dome growth resumed immediately in the scar left by the collapse.
- Again, banded tremor followed the collapse, this time for 3 months, the longest period of cyclic activity during the eruption to date.
- The average rate of dome growth was estimated to be ca. 2 m^3 s^{-1}.
- The dome growth virtually ceased in June-July 2002.
- A change in dome growth direction in September 2002 resulted in the evacuation of about 300 citizens from an area close to the likely path of pyroclastic flows.
- At the time of writing this poster, the total volume of the dome had reached about 180 x 10^6 m^3 and a height in excess of 1150 m, the greatest volume and height ever reached since the eruption started in 1995.

Figure 3. View of the dome complex in March 2003 from the southeast showing the extent of the new dome growth. Nearly all the 1995-98 dome growth has been engulfed (cf. Fig. 2)

Integrated monitoring methods

Several methods have been used to monitor the activity of SHV. These comprise seismic, deformation, volcanological, and gas monitoring, and will be described briefly below. Together they comprise a fully integrated monitoring strategy at the MVO.

Seismic monitoring. The main monitoring method consists of seismic data collection and analysis (Miller *et al.* 1998). The seismic network consists of an array of short-period and broadband sensors stationed around the volcano (Fig. 4), transmitting data back to the MVO. Five main types of seismic signal have been recognized from SHV: volcanotectonic earthquakes, long period earthquakes, hybrid earthquakes, rockfall or pyroclastic flow signals, and explosion signals. The main types of seismicity recorded during the second phase of dome growth are rockfalls, hybrid earthquakes and long period earthquakes (Fig. 9).

Figure 4. Seismic station 6 km to northwest of volcano.

Deformation monitoring. Several different methods have been used to measure the deformation of the flanks of the volcano, the main methods being Global Positioning System (GPS - Fig. 5), Electronic Distance Measurement (EDM), and tilt measurements. In general, the majority of the deformation of SHV is confined to areas close to the crater.

Figure 5. GPS site 2 km to east of the volcano.

Figure 6. Sampling recent pyroclastic flow deposits, 3 km east of the volcano.

Volcanological monitoring. Observations of the volcanic activity have comprised a large proportion of the monitoring effort. Many different techniques have been used, but the main parameters that have been monitored include dome and deposit volumes (and consequently rates of extrusion), the geology and petrology of the new deposits (Fig. 6), and measurements of ash cloud heights.

Gas monitoring. Four methods of monitoring gas emissions have been used throughout the eruption. The first method used a Correlation Spectrometer (COSPEC) to measure the daily output of SO_2 from the volcano. This method was superceded in 2001 by the installation of a network of Differential Optical Absorption Spectrometers (DOAS). These are currently only monitoring SO_2 but it is hoped that they will be able to measure other gases in the future. SO_2 has also been measured at ground level using diffusion tubes that are left at sites around the volcano for about 2 weeks. Trends in these data have closely followed long term averages of COSPEC data so that, when COSPEC measurements were not possible, diffusion tube results provide a useful proxy for SO_2 output from the volcano. The fourth method is Fourier Transform Infrared Spectrometry (FTIR - Fig. 7), which has been used to measure the ratios of various gases in the plume, most notably SO_2/HCl.

Figure 7. FTIR monitoring, 5 km west of the volcano.

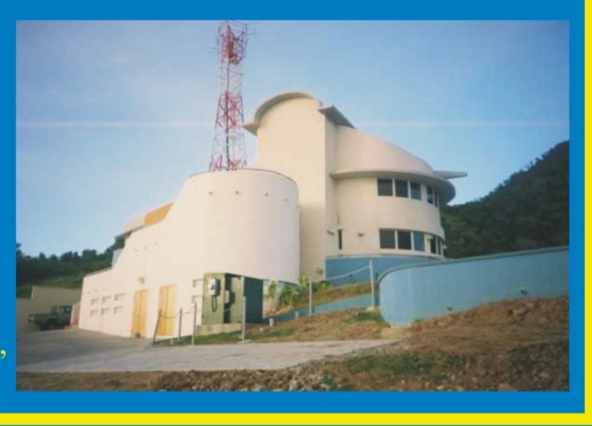

Figure 8. New MVO building at Flemings, Montserrat.

New developments. In March 2003, the MVO moved into new purpose-built premises, 5 km to the north-west of the volcano (Fig. 1). This is the fifth location for the MVO, previously being sited in rented accommodation in the north of the island. This new facility should enhance the capability of the MVO to make real-time observations of the volcanic activity and provide more timely information to the authorities and public at large. Collaborative projects with external groups, for example, the CALIPSO project with Carnegie Institute and universities at Penn State, Arkansas and Bristol, aim to enhance the quality and range of monitoring data.

Datasets

Seismic data (Figure 9). Periods of dome growth are characterised by rockfall and long-period seismicity, with occasional hybrid swarms (generally marking switches in dome growth). In contrast, the period of little or no dome growth from March 1998 to November 1999 was characterised by higher levels of volcano-tectonic earthquakes, and very-low levels of everything else. In March 2003, the level of rockfalls and long period earthquakes were the highest yet recorded at SHV.

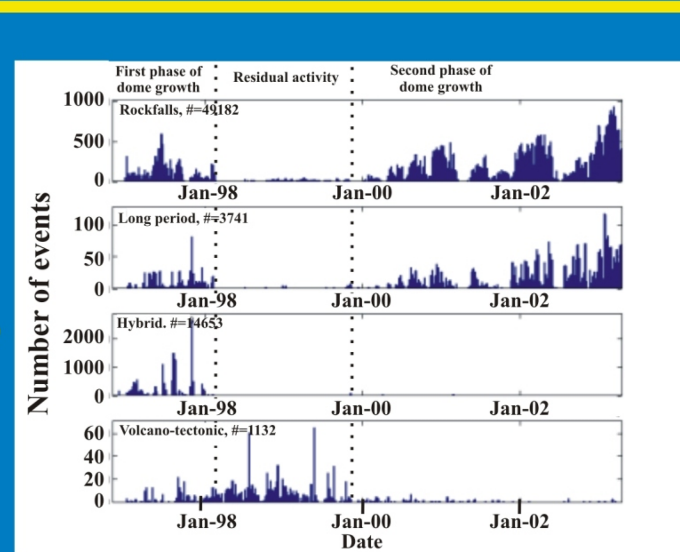

Figure 9: Daily counts of events detected by the digital seismic network with an equivalent magnitude, M > 1.0 (in 7 day bins), for the period November 1996-March 2003. Events are broken down by subclass: rockfalls (first panel), long-period earthquakes (second panel), hybrid earthquakes (third panel) and volcano-tectonic earthquakes (fourth panel). Total number of events M > 0.7 is shown in the top left-hand corner of each panel (e.g. 49182 rockfalls).

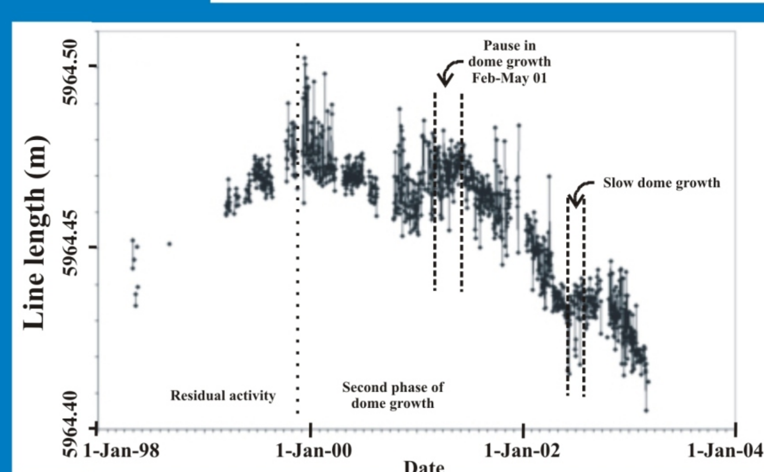

Figure 10: All HARR-SOUF permanent GPS site baseline data from early 1998 onwards. In 1996 and 1997, HARR was occupied only on rapid static campaigns; SOUF was installed in early 1998.

Deformation data (Figure 10). The main method of deformation monitoring during the second phase of dome growth used six permanent GPS stations at various locations around the volcano. The most interesting data are derived from line lengths across the volcanic edifice (*e.g.*, Fig. 10). The HARR-SOUF line (see Fig. 1 for locations) shows strong expansion during non-eruptive periods (Mar 1998 to Nov 1999, late-Feb to mid-May 2001) at around 1.7 mm/month, slight expansion during sluggish parts of the eruption (June to mid-July 2002) at around 0.8 mm/month, contraction at 1.4 mm/month in early part of phase 2 dome growth, and more rapid contraction during 2001, most of 2002 and early 2003 around 1.9 mm/month. In addition the closest site (HERM; Fig. 1) shows gradual subsidence during both dome growth and non-eruptive periods.

Gas data (Figure 11). The long time series of data shows that the magnitude of SO_2 emissions has remained similar through periods of both dome growth and non-eruption. SO_2 is thought to originate from mafic magma intruding the andesitic upper crustal reservoir. Variations are seen on time-scales of minutes to months, and these have been interpreted as a result of changes in permeability in the upper conduit and dome (Edmonds *et al.* 2003). HCl is derived mostly from the andesite and emission rates closely follow lava extrusion rate (Edmonds *et al.* 2001).

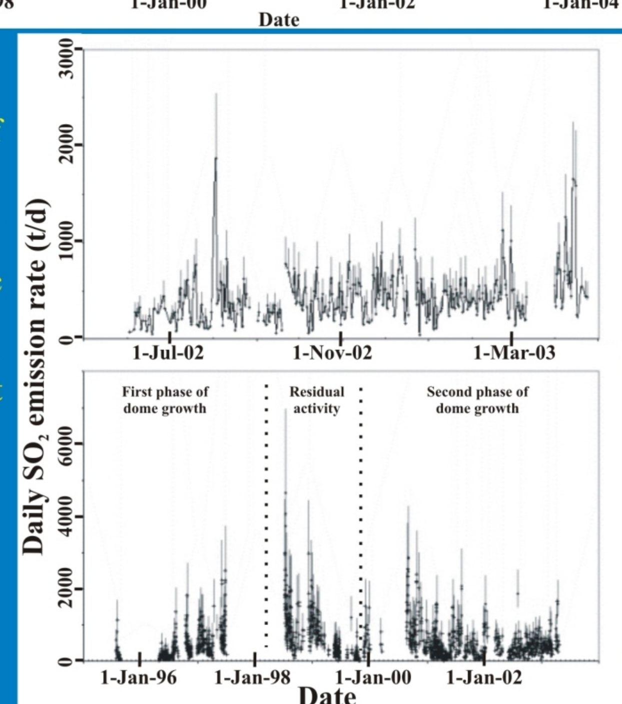

Figure 11. Sulphur dioxide emission rate: June 2002 to April 2003 in tonnes per day (top) and for the entire eruption, July 1995 to April 2003 (bottom). The data are derived from COSPEC measurements up to January 2002 (errors +40%, -30%) and from the Scanspec network (utilising DOAS for retrievals) from January 2002 to April 2003 (errors +36%, -20%).

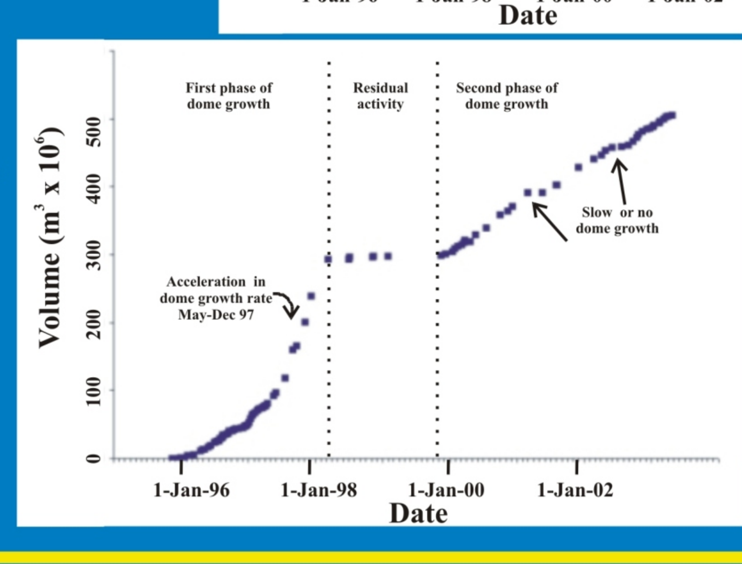

Figure 12. Total erupted volume over time, m^3 x 10^6. (Note surge in output Sept to Oct 2002 following quiet period in summer reminiscent of Oct 96 to Jan 97).

Volcanological data (Figure 12). The main observation in the second phase of dome growth is that the rate of extrusion has been relatively constant. In the late part of the first phase (May to December 1997), the extrusion rate accelerated, resulting in explosive behaviour, and regular dome collapses. In phase 2, there have been some relatively minor fluctuations in extrusion rate, and therefore, fewer dome collapses and no extended periods of explosions have resulted. Analytical work has shown that there has been little change in the chemical composition or gross petrology of the lava erupted, although there have been some minor variations in the geochemistry of some minerals (Devine *et al.* in press).

Discussion

This poster documents a second phase of magma extrusion at Soufrière Hills Volcano, Montserrat. There are some similarities, but some major differences, between the period described here and the first phase of dome growth in 1995-98.

- *Similarities.* **1.** The long-term average extrusion rate is similar in both phases of dome growth. **2.** The overall SO_2 emission rate has been constant through the whole eruption. **3.** The petrology of the andesite has changed little over the whole eruption. **4.** Cyclic activity, particularly manifested as hybrid earthquake swarms and tremor bands, has been common in both phases of activity, although less vigorous in phase 2. **5.** The GPS data show that, in both phases, when the dome is extruding, there is associated deflation of the volcanic edifice. Equally when the extrusion ceases, inflation occurs.
- *Differences.* **1.** In phase 2 there have been fewer periods of rapid extrusion, and two periods of very slow or no dome growth. **2.** There have only been two major dome collapses in phase 2, both of which were probably related to intense rainfall. In phase 1, dome collapses or explosive eruptions occurred every 8 to 10 weeks. **3.** In phase 2, the dome has grown to a volume almost twice the maximum size attained in March 1998. **4.** There have been no periods of cyclical explosive activity in phase 2, and the only explosions observed have followed immediately after very large dome collapses.
- The change in style of eruption from a very dynamic dome with rapidly fluctuating extrusion rate to a relatively steady state dome with minor changes in growth rate has major implications for hazard assessment on Montserrat. A major explosive eruption now appears to be less likely, although the potential size of dome collapse pyroclastic flows is now much larger, and could travel further towards inhabited areas. Such a dome collapse is also more likely to be triggered by intense rainfall, and less likely to be forced by internal pressurisation of the magmatic system.

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