Montserrat Volcano Observatory:

Summary of volcanic activity and monitoring data, with particular emphasis on the second phase of dome building November 1999 to June 2003

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1. Eruption chronology up to the beginning of the second phase of dome growth

The reader is referred to Kokelaar et al., a review; and Watts et al., a chronology of dome emplacement, in: The eruption of Soufrière Hills Volcano, Montserrat, from 1995 to 1999, edited by T H Druitt and P Kokelaar, Geological Society Memoir no. 21, 2003.

1.1 Precursory activity

Volcanic unrest began in 1992, when an intense earthquake swarm occurred beneath Montserrat, followed by another intense swarm in late 1994 (Aspinall *et al*., 1998). Similar swarms had occurred frequently during the last two centuries, with seismic crises recorded in 1897, 1933 and 1966 (Perret, 1939; Shepherd *et al*., 1971; Robertson *et al*., 2000). The most recent (1992-1994) seismic crisis comprised 15 episodic swarms of volcano-tectonic earthquakes located at around 10-15 km depth beneath Montserrat (Aspinall *et al*., 1998) and culminated in November 1994, when some events were felt locally (Robertson *et al*., 2000). A study of fumarole compositions in 1988-1989 did not register any significant changes (Chiodini, unpubl. data), although in March 1995 Galway's Soufrière showed a marked magmatic signature in $^3He/^4He$ and δC^{13} (Hammouya et al., 1998).

1.2 Phreatic phase

Eruptive activity began on 18 July 1995, when a steam vent opened on the side of Castle Peak dome (770-200 years BP), inside English's Crater (thought to have formed after a sector collapse c. 4000 years BP). Phreatic explosions with steam and ash columns up to 4 km high continued for 4 months, frequently associated with cold base surge ash clouds (Gardner and White, 2003). No juvenile material was erupted at this time (Young et al., 1998). Seismicity was dominated by shallowing volcano-tectonic earthquakes (Aspinall et al., 1998) and hybrid swarms and tremor (White et al., 1998). Sulphur dioxide emission rates of >300 t/d in July 1995 decreased exponentially to <50 t/d by the end of August 1995 (figure 13). At the end of September, a small, dome-like mass of non-juvenile material was erupted on the west side of Castle Peak dome.

1.3 The first phase of dome growth

Juvenile material was first erupted in mid-November 1995 and it accompanied localised deformation in the crater area (Jackson et al., 1998), measured by Electronic Distance Meter (EDM). The early dome growth was slow and discontinuous (Sparks et al., 1998; Watts et al., 2003). Dome growth occurred at a rate of around 0.1-0.5 m^3/s until February 1996 and dome growth was characterised by whalebacks and spines, created by the highly viscous, crystal-rich andesite lava (Watts et al., 2003).

A strong volcano-tectonic earthquake swarm from 20-22 July 1996 marked the beginning of a more vigorous phase. Banded tremor (figure 1; Table 1) emerged in the following days, which became intense by 28 July 1996 (when extrusion rates were as high as 10 m^3/s) and continued in association with small dome collapses and energetic pyroclastic flows over the following weeks. This period of activity culminated in a sustained collapse and sub-Plinian explosion on 17 September 1996 (Robertson et al., 1998).

Up to May 1997, a broadly increasing (albeit unsteadily) extrusion rate gave rise to the extrusion of shear lobes and blocky lava and frequent dome collapses, interspersed with episodes of endogenous growth (Watts et al., 2003). By June 1997, extrusion rate was greater than 5 m^3/s and cyclic seismicity (Table S1), tilt and pyroclastic flow activity on the time scales of 6-14 hours were occurring (Voight et al., 1998; Baptie et al., 2003). The long-term increase in extrusion rate, overlain by higher time frequency variations, have been interpreted to be linked to the intrusion rate of mafic magma at depth and the feedback mechanisms induced by crystallisation kinetics in the top few hundred metres of the conduit (Sparks et al., 2000; Melnik and Sparks, 2003a, b).

Periods of sustained explosive activity in August and September 1997 associated with cyclic seismicity (Table S1) involved sequences of vulcanian explosions with column collapse and radial pyroclastic (pumice) flows (Druitt et al., 2003). A sector collapse on 26 December 1997 involved a large portion of the southern flank, incorporating wall rocks, basement and lava dome material in a debris avalanche, followed by a lateral blast and surge (Sparks et al., 2003; Voight et al., 2003; Richie et al., 2003; Woods et al., 2003; Mayberry et al., 2003).

Dome growth recommenced shortly after this event and continued up to mid-March 1998, when lava extrusion ceased. The volume of the dome at this time was c. 113 x 10^6 m^3 and the maximum height (a spine) was 1031 m.a.s.l and the average summit height was ~1000 m.a.s.l.

1.4 A prolonged non-eruptive period

The extrusion of lava ceased or was at a very low rate from mid-March 1998 until mid-November 1999 (Norton et al., 2003). On 3 July 1998, a large dome collapse, during a period of heavy rainfall, involved c. 25 x 10^6 m^3 lava and basement rock, focussed on the eastern flank of the dome (MVO Special Report 7). Pyroclastic flows and associated surges occurred in the Tar River Valley. After this event, a large scar marked the eastern part of the dome, deeply incising into the basement rock around the vent area.

After the collapse, SO_2 emissions were very high and then decayed exponentially throughout August and September 1998 (Oppenheimer et al., 2003; Edmonds et al., 2003). During October 1998 to January 1999, a number of smaller dome collapses occurred, steadily incising a deep canyon running from east to west, through the remaining dome structure. Pyroclastic flows arising from these events occurred in Fort, German's and Gingoes Ghauts and the Tar and White River Valleys.

Small gas-rich explosions occurred regularly every 2-6 days during April to June 1999, associated with cyclic gas emissions (Edmonds et al., 2003), but there was very little seismicity.

1.5 The beginning of the second phase of dome growth

A series of phreatic explosions in October 1999 were followed by an intense hybrid earthquake swarm from 3-8 November 1999 and small magmatic explosions. These explosions involved small amounts of juvenile ash and dense material. In mid-November fresh lava was observed inside the collapse scar in the heart of the dome complex. Banded tremor (Table 1) accompanied the lava dome growth and this continued throughout the remainder of the year and into January 2000.

2. Volcanic activity during the second phase of dome growth

2.1 Volcanic activity during 2000

Volcanic activity throughout 2000 was dominated by the continued growth of the new lava dome. The extrusion rate early in the year was 2-3 m^3s^{-1}. Banded tremor and gas emissions accompanied dome growth during January 2000 (Young et al., 2003). Banded tremor continued until mid-February (Table 1).

2.1.1 Dome collapse on 20 March 2000

A major dome collapse occurred to the east down the Tar River Valley on 20 March 2000 (figure 5). This occurred during a period of intense rainfall, and removed most of the new growth (around 20 x 10^6 m^3) that had occurred over the previous 4 months. This event culminated in a small vulcanian explosion and light ashfall across the island (MVO Special Report 8; Carn et al., in review).

2.1.2 Resumption of dome growth end-March 2000

Dome growth resumed immediately after 20 March. The growth rate immediately after 20 March was estimated to be 5-6 m^3s^{-1}. Resumption of dome growth was accompanied by cyclic seismicity (banded tremor, rockfalls and hybrid earthquakes) lasting for about 4 weeks (Table 1).

During April to August 2000, occasional small pyroclastic flows occurred in the Tar River to the east, some reaching as far as the sea. Minor rockfall activity also occurred to the northeast, northwest, south and west. The dome growth rate was around 3 m^3s^{-1}. An underlying three-month periodicity occurred in rockfall seismicity, which increased in May, declined in July, increased again in August, declined again in mid-October, then increased again in mid-November (figure 2). SO_2 emission rates were high at the beginning of September and declined from >2800 t/d on 4 September down to ~400 t/d by the end of September (figure 13). Variable SO_2 emission rates of 100-1200 t/d were recorded in October. SO_2 emission rates increased on 26 October to >2000 t/d, steadily decreasing to <360 t/d by 22 December (figure 13).

As the dome continued to grow, rockfall activity became more frequent in Tuitt's Ghaut, although the focus of growth and activity remained towards the east. A small pyroclastic flow in Tyre's Ghaut in November 2000 raised concerns about the safety of the Belham Valley, but further activity was not seen in that area.

2.2 Volcanic activity during 2001

2.2.1 Dome growth during January and February 2001

In January and February 2001 the dome continued to grow on the eastern side above the Tar River Valley, and the accumulation of rockfall debris almost completely buried the northeast buttress. SO_2 emission rates had declined to low levels of 100-400 t/d by the end of January (figure 13). Tremor was recorded on 21 February 2001, and was followed by a hybrid earthquake swarm over the next few days. SO_2 emission rates increased on 23 February to ~1000 t/d. Sustained low-level pyroclastic flow activity took place on 23 and 24 February, with many small flows developing in the upper reaches of Tuitt's Ghaut. This was due to the extrusion of a large lobe directed to the northeast, which repeatedly collapsed as it grew. SO_2 emission rates then rapidly decreased to ~100 t/d on 26 February (figure 13). The direction of growth then switched to the south overnight, and was accompanied by a small collapse occurred on 25 February with pyroclastic flows travelling down the White River Valley to the fan at the mouth of the valley. The collapse is estimated to have had a volume of less than 1 million cubic metres. An intensification in the hybrid earthquake swarm occurred on 26 February, accompanied by a sharp drop in SO_2 emission rates to ~100 t/d (figure 13), and the development of strong banded tremor (Table 1), which peaked on 28 February (figure 3).

2.2.2 *Pause in extrusion March – mid-May 2001*

The hybrid earthquakes and banded tremor associated with the activity at the end of February 2001 ceased on the 3 March, coinciding with a peak in SO_2 emission of ~1500 t/d (figure 13). Seismicity was at a very low level from 3 March onwards, until mid-May (figure 4). SO_2 emission rates had dropped to 200 t/d by 6 March and averaged 200 t/d until the beginning of April and then dropped further to a daily average of ~100 t/d until 8 May 2001 (figure 13). No changes were visible on the dome during this period and the rate of dome growth was inferred to be low or zero.

2.2.3 *Dome-growth towards the south beginning mid-May 2001*

A gradual increase in rockfall and long-period earthquake events began on 10 May and visual observations suggested a slight change in dome morphology on the southern part of the dome complex, where most of the rockfalls were concentrated. During the week of 11-18 May a new lobe of lava was observed directed to the south, although the rate of growth appeared low. A weak swarm of hybrid events occurred from 19-21 May and high-levels of long-period earthquake seismicity were recorded for the remainder of the month (figure 4). The GOES satellite-mounted infra-red spectrometer detected a strong hotspot in the summit area on 21 May. SO_2 emission rates had increased to ~700 t/d by 21 May (figure 13). Visual observations showed some more changes in dome morphology on the southern flanks of the dome with the formation of a lobe headwall and a large accumulation of talus at the head of the White River Valley by 24 May. Growth on the south side of the dome continued throughout June and July and was accompanied by near continuous rockfalls that added to the broad apron of talus, which by then extended completely around the southern and eastern flanks of the active dome. A small amount of rockfall debris also spilt to the west, building the talus apron in that direction, and in mid-June rockfalls started to spill down the Gages chute into the upper reaches of Fort Ghaut. On 30 June a small collapse of about 0.5 x 10^6 m^3 of lava occurred on the northeastern side of the dome, producing small pyroclastic flows in the Tar River Valley. A few small pyroclastic flows also occurred in the Amersham and Gages areas on 4 July, prompting a decision to close the Day Time Entry Zone (DTEZ). Examination of the deposits showed that these particular flows were not very hot and were extremely altered, produced by the collapse of remnants of the older dome that had been extruded in 1997 above the Gages wall. In the second half of July, rockfall activity escalated on the active lobe on the south side of the dome, and pyroclastic flows occurred on the eastern flank, in the upper reaches of the Tar River Valley. SO_2 emission rates were variable during this time, ranging from 200-1500 t/d. The dome had reached a volume in excess of 160 x 10^6 m^3 and was the largest it had been since the eruption began in 1995.

2.2.4 *Major dome collapse 29 July 2001*

A major collapse of the eastern flank of the dome occurred on the 29 July, following a day of torrential rainfall and mudflows. Low-energy, near-continuous pyroclastic flows down the Tar River Valley began in the afternoon (MVO Special Report 9). The collapse escalated around 6.00 pm coinciding with the most intense rainfall (figure 6) and pyroclastic flows were observed to travel 1-2 km across the sea. Extensive areas around Long Ground were affected by pyroclastic surges, and minor pyroclastic flows also occurred in the upper reaches of White's, Tuitt's and Fort Ghauts; and on the southern flanks of the dome in the upper reaches of White River. There was significant ash fall, producing up to 5 centimetres of wet, compacted ash in the Salem - Old Towne area, and up to 12 centimetres in the Fox's Bay – Richmond Hill area. There were also two large vulcanian explosions, which resulted in rock fragments up to a few centimetres (largest measured 6 cm) in length being deposited in populated areas between Salem and St Peters. These explosions occurred at 7:51 and 10:05 pm (figure 5) and were imaged by the GOES and MODIS satellites. The distribution of rock fragments was controlled by high-level winds blowing from the south. The ash plume generated by the eruption reached heights estimated to have been between 20,000 and 35,000 feet. Strong south-easterly winds at low levels carried the plume to the northwest, depositing ash as far away as Puerto Rico and the Virgin islands. The ash plume caused serious disruption to air traffic during the eruption, and the deposition of ash resulted in the closure of several airports, including the major hub of San Juan, where 139 international flights were cancelled. The TOMS satellite-mounted UV spectrometer detected a cloud containing 2kt SO_2 over Puerto Rico two days after the collapse event.

The collapse lowered the height of the general summit region of the dome by about 150 metres and produced a complex amphitheatre-shaped scar over 200 metres deep incised into the dome and open to the east at the head of the Tar River valley. "Walls" of talus material remained to form the collapse scar rims at the heads of White River in the south and Gage's Valley in the west. Around 45 x 10^6 m^3 of the dome were removed during the collapse, making this the second largest event during the history of the eruption.

2.2.5 Continued dome growth between August and December 2001

On 3 August a new dome was observed growing within the collapse scar. SO_2 emission rates were high immediately after the dome collapse, reaching around 1000 t/d on 2 August and over 2000 t/d on 10 August (figure 13). During August and September the new dome grew at an average extrusion rate of 2.6 m^3/s, and in late September had a volume exceeding 12 x 10^6 m^3. In early August, soon after the collapse, seismicity was dominated by weak cyclic seismicity (mainly rockfalls, but also hybrids/tremor), which lasted until early November (Table 1). SO_2 emission rates were moderate and variable throughout this period (figure 13), ranging from 100-700 t/d.

By late September 2001 the active dome began to generate small but energetic pyroclastic flows in the upper reaches of the Tar River Valley. On the 4 and 5 October there were two periods of sustained pyroclastic flow activity each lasting several hours, during which flows reached the sea at the Tar River delta.

A small collapse occurred on 14 October following a day of torrential rainfall and mudflows. This involved several million m^3 of older unconsolidated talus on the southeastern flanks of the older dome that had accumulated between March 2000 and July 2001. The collapse lasted for about 6 hours and produced low-energy pyroclastic flows down the Tar River valley to the sea. Ash from this event was blown to the northwest and deposited over residential areas. A similar collapse of unconsolidated talus of the pre-29 July dome occurred on the southern flank on 16 October. This produced numerous pyroclastic flows in the White River Valley.

The active dome continued growing at a moderate rate throughout the final months of the year. Seismic activity was at a low level during the first half of November but the dome continued growing during this time, albeit slowly. A weak swarm of hybrid earthquakes began on 14 November and reached a peak on 21 November. When the visual observations were made on 19 November, the general summit region had increased in altitude to about 940 metres, and had several large spines reaching in excess of 970 metres. At this stage most rockfall activity occurred on the western and southern flanks. By the end of November the dome had reached a height of 960 metres (260 metres above the floor of the July collapse scar) and growth was strongly focused on the west, producing rockfalls that accumulated in the trench against the backwall of the July 29th collapse scar. SO_2 emissions dropped sharply in the middle of November, averaging ~100 t/d from 19 November to 19 December (figure 13).

For much of December the dome was not seen because of cloudy weather. Rockfall seismicity escalated during this period (figure 7), and towards the end of the month, when the dome was next seen, growth had switched once more to the east. During the final week of the year, spectacular incandescent rockfalls were seen at night on the eastern flank of the dome above the Tar River area. On 27 December the rockfall seismicity became cyclical and the SO_2 emission rate increased to around 700 t/d. On the following afternoon a small but sustained collapse occurred on the northeast flanks of the dome. This lasted for about 1.5 hours and produced pyroclastic flows down the Tar River Valley to the sea.

2.3 Volcanic activity during 2002

2.3.1 Dome growth 1 January to beginning April 2002

In early January 2002 the summit of the lava dome was broad and blocky with an extrusion lobe directed to the northeast. The level of activity was generally high at this time and several energetic pyroclastic flows reached the sea down the Tar River Valley. Activity gradually declined over the second half of the month, but increased again in February when several pyroclastic flows reached the sea. At this stage the summit of the dome was occupied by a series of large spines. The general summit area had an altitude of around 990 metres, although a 90 metre high spine, extruded overnight on the 25 and 26 February, reached a height of 1080 metres. The estimated volume of the active dome at this stage was 38 million m^3, which was equivalent to an average extrusion rate of 2 m^3 per second since the collapse on 29 July 2001. A temporary lull in rockfall seismicity occurred in late-February and early-March but reached high-levels again by 8 March and remained high for the remainder of March with numerous pyroclastic flows occurring in the Tar River Valley.

2.3.2 April 2002 switch in direction of dome growth

The level of activity remained high throughout April. Since December 2001, growth had been focused on the northeast side of the dome, but in the second week of April there was a switch in the direction of extrusion to the southeast. The northeastern lobe stagnated at a height of just over 1000 metres. The new southeastern lobe of the dome grew steadily throughout May, although compared with previous months the level of activity was considerably lower. During the second week of the month small pyroclastic flows occurred in the upper reaches of Tuitt's Ghaut, having overtopped the 29 July 2001 collapse scar in this direction.

2.3.3 Stagnation in activity in mid-2002

Activity declined abruptly at the very beginning of June and visual observations suggested that the growth of the dome had almost stagnated. Photographs taken by the remote digital camera at White's Yard indicated that almost imperceptible extrusion continued. The level of rockfall and long-period seismicity declined to low levels throughout June and early July (figure 7) and SO_2 emissions dropped to daily averages of 100-200 t/d. Ground deformation monitoring recorded a significant inflation throughout this quiet period, suggesting that this was a temporary hiatus and that activity was likely to resume, possibly at a high level. At this stage, the upper surface of the active lobe had the form of a smooth whaleback shear lobe, directed towards the southeast. The top of the extrusion lobe had a height of 1048 metres.

2.3.4 Resumption and switch in the direction of dome growth in late July 2002

SO_2 emission rate increased over several weeks from 5 to 19 July, reaching a daily average of 760 t/d on 19 July, which decreased sharply the following day to <200 t/d and remained low until 2 August (figure 13). Hybrid and volcano-tectonic earthquake swarms during 19-21 July, coinciding with the resumption of high-levels of long-period seismicity, indicated a switch in the direction of dome growth was underway. On 21 July visual observations indicated that a switch in the direction of dome growth had occurred to the northeast. Growth of this lobe gave rise to increased rockfall and pyroclastic flow activity on the eastern and northeastern flanks, in the Tar River Valley and Tuitt's Ghaut. On 23 July, a small collapse produced low-energy pyroclastic flows continuously for about an hour.

2.3.5 Switch in the direction of dome growth at the beginning of August 2002

On 1 August, an observation flight indicated that the direction of dome growth had moved around to the north. On 2 August, SO_2 emission rate increased sharply, to1870 t/d. For much of the rest of the month a well-developed shear lobe continued to grow in this direction, spilling rockfalls and small pyroclastic flows into the upper parts of Tuitt's Ghaut and White's Ghaut and rockfalls onto the northern and northwestern flanks and into the head of Tyre's Ghaut. By the third week of August the northeast buttress (an older dome remnant that erupted in June 1997) had been completely buried by rockfall talus from the active extrusion lobe. A small collapse down the Tar River Valley was triggered by intense rainfall on the 21 August. This consisted of older talus material accumulated on the slope below the (inactive) southeastern lobe that had been active earlier in the year. By the end of August growth of the active lobe had become re-focused slightly more towards the northeast, with numerous rockfalls and small pyroclastic flows occurring in Tuitt's Ghaut and the Tar River Valley.

2.3.6 Switch in direction of dome growth to the northwest in late September 2002

Activity intensified during September and by the second week of the month most rockfall and pyroclastic flow activity was occurring on the northern side of the Tar River Valley, suggesting that the focus of extrusion had shifted around to a more easterly direction. On 18 September SO_2 emission rate was very low, <100 t/d. Unfortunately, the plume was out of range of the spectrometer network for the next two days. On 19 September a weak hybrid swarm occurred, and coincided with an increase in rockfall and long-period seismicity, which suggested that another switch in the direction of growth could have been in progress. On 21 September the SO_2 emission rate had increased, up to 780 t/d (figure 13). Poor weather conditions associated with tropical storm Lili obscured the summit region until 26 September, when it was apparent that there had been a switch in the direction of growth and a large extrusion lobe had developed on the northwestern side of the dome complex above the northwest buttress. Numerous rockfalls and pyroclastic flows occurred off the northern face of the lobe. Most were channeled northeastwards across the top of Riley's Estate and into Tuitt's Ghaut, although a number of small but energetic flows occurred to the west, in the upper reaches of Fort Ghaut. By 27 September, the direction of growth had become strongly focused towards the northwest and the SO_2 emission rate remained fairly high, at 730 t/d. A 4-hour period of intense activity took place in the afternoon and evening of 27 September. Semi-continuous pyroclastic flows spilled off the northern flanks and were channeled north eastwards into the upper reaches of Tuitt's Ghaut and White's Ghaut. A small collapse occurred on the north – northwestern flanks of the dome on the evening of 29 September. For several hours pyroclastic flows were channeled northeastwards, across the northern flanks, into Tuitt's Ghaut and White's Ghaut, reaching the sea at Spanish Point. Heavy ash fall accompanied this event in the Salem – Old Towne – Olveston areas.

At midday on the 2 October a brief period of intense rainfall occurred prior to a collapse on the eastern flank of the dome. This involved older talus material that had accumulated earlier in the year when the dome had been active on the southeast side. For six hours, continuous low-energy pyroclastic flows passed down the Tar River Valley to the sea, and heavy ash was blown to the northwest, depositing up to 9 mm in the Salem – Old Towne area.

Throughout October and the beginning of November, growth of the dome was focused towards the north and northwest. During this period the accumulation of talus from rockfalls and pyroclastic flows gradually buried the pre-existing topography on the northern flank. Most of the pyroclastic flows off the northern flanks were channelled across the top of Riley's Estate and into Tuitt's Ghaut, although on the 8 and 10 November several flows entered Tyre's Ghaut and reached as far as the lower part of Riley's Estate. Flows also occurred along the northern side of the Tar River Valley, and to the west in the upper reaches of Fort Ghaut. For much of November cloudy conditions prevailed and the summit of the dome was not seen. SO_2 emissions averaged 400 t/d throughout October and November 2002 (figure 13).

2.3.7 Switch in dome growth back to the northeast in November 2002

Visual observations on 29 November indicated that a well-developed, north-northeasterly directed extrusion lobe had established itself. This active lobe produced pyroclastic flows in White's and Tuitt's Ghauts and along the northern edge of the Tar River Valley, although material continued to spall off the northern flank, building up a large apron of debris above the area of Riley's Estate and Farrell's Plain.

Activity escalated in December. On 8 December a significant collapse occurred down White's Ghaut with hot, energetic pyroclastic flows reaching the sea at Spanish Point. This event involved approximately 5 million cubic metres of material. A spurt of rapid lava extrusion ensued, and in less than two weeks, the collapse scar was completely filled. On the 18 December a period of increased pyroclastic flow activity occurred on a broad sector of the dome extending from the east around the northern flanks to the west. Pyroclastic flows occurred in the Tar River Valley, White's Ghaut, Tuitt's Ghaut, Tyre's Ghaut and Fort Ghaut. Very vigorous steaming was observed throughout the 18 and 19 December on all flanks of the volcano. During an observation flight on 19 December mudflows were observed in White River, Dry Ghaut, Tar River Valley and Fort Ghaut, although there was no apparent rainfall. SO_2 emission rate reached a peak of 930 t/d on 22 December (the highest emission rate recorded since 2 August 2002). Activity increased to a very high level during the last week of December. Most of the pyroclastic flows at this stage spilled off the front of the active extrusion lobe and passed down White's Ghaut, Tuitt's Ghaut and the Tar River Valley. Many large rockfalls and small pyroclastic flows also spilled northwards across the upper part of Riley's Estate and several flows occurred in Tyer's Ghaut. During this period the daily average SO_2 emission rates was 360 t/d. At the end of December the summit of the dome had a broadly rounded top with a height of about 1050 metres, although a large spine was extruded in the last week, which may have exceeded 1100 metres. The overall volume of the entire dome complex at this time had reached about 190 million m^3. This is equivalent to an average extrusion rate of about 1.6 m^3 per second since the 29 July collapse. SO_2 emission rate averaged 480 t/d throughout December 2002.

2.4 Volcanic activity during 2003

2.4.1 Dome growth from January to March 2003

The frequency and size of pyroclastic flows and rockfalls decreased slightly around 2 January 2003, but the level of activity remained elevated until the middle of the month, when it declined to a moderate level temporarily. Although generally directed towards the north-

northeast, much of the growth was fairly central causing the summit area to increase in height and bulk-out on all sides. Throughout January, most pyroclastic flows and rockfalls occurred on the northeastern face of the active lobe and passed down the northern side of the Tar River Valley, White's Ghaut and to a lesser extent, Tuitt's Ghaut. From time to time, material also spalled off the northern side of the summit, producing rockfalls and small pyroclastic flows onto Farrell's Plain and into Tyre's Ghaut, and occasionally to the west into the Gages chute. The largest flow in Tyre's Ghaut occurred on 10 January. This surged across the top of Farrell's Plain and drained northwestwards down Tyre's Ghaut, stopping just short of the bridge at Dyer's Village. Throughout January 2003, the average daily SO_2 emission rate was 380 t/d.

By late January, long-period seismicity had again recommenced at high-levels, and coincided with a gradual increase in rockfall seismicity (figure 7). Throughout February, growth continued to build the central part of the summit of the dome. Most pyroclastic flows were directed northeastwards down the Tar River Valley and White's Ghaut. There were also periods of activity on the northern flank producing rockfalls and small pyroclastic flows in Tuitt's Ghaut and onto the top of Farrell's Plain. High daily average SO_2 emission rates were recorded on 22 and 28 February, of 1120 and 1020 t/d, respectively (figure 13).

By late-February, rockfall seismicity had reached it highest ever level, and remained very high throughout March. In the first week of March, activity was focused on the northeastern and northern flank of the extrusion lobe, producing small pyroclastic flows, which were mostly channelled into Tuitt's Ghaut. Over the following three weeks, clear observations from the air indicated that lava was being extruded into the central part of the summit area and growth of the dome was not focused in any particular direction. At this stage, rockfalls and pyroclastic flows mainly occurred in the Tar River Valley, although periods of activity continued on the northern and western flanks, with occasional flows occurring in the upper reaches of Tyre's Ghaut. Measurements on 20 March indicated that the dome had reached a height of 1098 metres, which was at its highest recorded to date. A period of increased pyroclastic flow and rockfall activity lasting 4 to 5 hours occurred on the northern and northwestern flanks of the dome on 25 March. This appears to have been triggered by a brief but intense rainstorm.

2.4.2 Switch in direction of growth towards the east-southeast at the end of March

A weak swarm of volcano-tectonic earthquakes occurred late at night on 25 March, possibly indicating a switch in the direction of dome growth. The following day, visual observations suggested that most rockfall and pyroclastic flow activity was occurring on the south side of the Tar River Valley. Observation flights on the 27 and 28 March indicate that a well-developed extrusion lobe had established itself on the eastern – southeastern side of the summit area and that rockfalls and small pyroclastic flows had begun to spill off the southern flanks of the dome. A large vertical spine was extruded on the southern side of the summit at this time. The general summit area of the dome had an altitude of around 1090 m, and the top of the spine had an altitude of 1163 m, which was the highest point measured so far. Over the following weeks, activity was mainly directed towards the east and southeast within the Tar River Valley and on the southern flank of the dome. Occasional small flows continued to occur on the northern and northwestern flanks.

2.4.3 Switch in direction of growth towards the east-northeast at the beginning of May

During the last week of April and first few days of May there was a marked increase in long-period earthquake activity and sulphur dioxide emission rates were also high. On 5 May activity escalated to a high level with numerous hot, energetic pyroclastic flows directed down the northern side of the Tar River Valley. Observations indicated that the direction of dome growth had changed slightly and throughout May a well-developed whaleback shaped extrusion lobe grew on the eastern side of the summit area, the axis of which was aligned between 70 and 80 degrees (north of east). Rockfall and pyroclastic flow activity ceased on the southern side of the dome, and most activity was directed down the central and northern side of the Tar River valley for the rest of the month, and to a lesser extent in White's Ghaut and Tuitt's Ghaut. From time to time there were periods of elevated activity on the northern and northwestern flanks, with rockfalls and small pyroclastic flows occurring on the top of Farrell's Plain and in Tyre's Ghaut. In the first week of June, activity rapidly declined to a low level.

3. Summary and salient features of activity during the second phase of dome growth

The second phase of dome growth began in November 1999 and still continues at the time of writing in early June 2003.

Growth rates have generally been relatively steady during the second phase of the eruption, and have been similar to the long-term average for the entire eruption, with extrusion rates of approximately 2 to 3 m^3/s.

The second phase of dome growth has been less dynamic than the first phase and collapses have been less frequent. The largest collapses, of 20 March 2000 and 29 July 2001, were triggered by intense and prolonged rainfall. These events involved the collapse of about 20 million and 45 million m^3 of material respectively. Several other smaller collapses were also coincident with intense rainfall, such as those of 14 October 2001, 2 October 2002 and 22 October 2002. The mechanism of rainfall-triggered collapses is not well understood, but appears to begin with mudflow activity, which probably removes talus on the lower flanks of the dome, so undermining the upper active part of the dome, leading to collapse and the generation of pyroclastic flows. These were prolonged events lasting 8-9 hours in the case of the 29 July 2001 collapse, and were characterised by continuous large-scale pyroclastic flows that were very erosive and able to erode through the dome down into the underlying basement.

Smaller scale endogenous type collapses have also occurred during the second phase of dome growth. These involve the collapse of hot, recently extruded lava of the active extrusion lobe on the summit area and have had volumes of less than a million up to a few million cubic metres. Such events have produced hot, energetic pyroclastic flows, which in some cases have been strongly erosive into the dome, as for example the 8 December 2002 event, which involved the removal of 4-5 million m^3.

Following the major collapses of 20 March 2000 and 29 July 2001 extrusion continued unabated and the dome began to re-grow immediately. Extrusion rates tend to be relatively high immediately following large collapses. These initial periods of re-growth have also been characterised by weak cyclical (banded) seismicity consisting mainly of rockfalls, but also hybrid earthquakes and weak tremor. This cyclical seismic activity lasted for about 4 weeks after the 20 March collapse and about three months following the 29 July 2001 collapse.

There have been several pauses or periods of stagnation during the second phase of dome growth. These were from the beginning of March to mid-May 2001 and again from the beginning of June to late July 2002. At the time of writing the growth of the dome also appears to have stagnated. During these pauses or periods of stagnation rockfall and seismic activity diminished to very low levels and sulphur dioxide emissions were also well below average. Swarms of hybrid and long-period earthquakes and sharp increases in sulphur dioxide emissions marked the end of these pauses and renewed extrusion and dome growth.

A switch in the direction of growth followed each pause in extrusion. There have also been several switches in the direction of growth not associated with pauses but usually following periods of relatively low rates of extrusion. Following switches and the resumption of growth, well-developed, strongly directional whaleback-shaped extrusion lobes form and are initially characterised by increased rockfall and pyroclastic flow activity caused by lava spalling off the free face of the lobe. With time lobes have tended to become less directed and to bulk out on all sides and to pile up vertically, before eventually stagnating and or switching direction once more.

4. Resources for further information

Geophysical Research Letters v 25, nos. 18 and 19, 1998.
Geological Society Memoir no. 21, 2003.
MVO web page, publications,
MVO Open File and Special Reports
MVO Weekly Activity Reports
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Tables:

Table 1: Episodes of cyclic seismicity (e.g. banded tremor) at the Soufriere Hills Volcano. This table was created by Glenn and last revised in November 2001. Needs updating!

Start date	End date	Number of cycles	Mean interval (hours)	Mean cycle amplitude (cm^2)	Maximum cycle amplitude (cm^2)	RSAM stations
28-Jul-1996	13-Sep-1996	123	7	1.5	5.0	MLGT (22 Jul – 15 Sep?)
12-Dec-1996	8-Feb-1997	92	10	1.3	5.1	MLGT (particularly 2-6 Jan)
23-May-1997	2-Sep-1997	116	12	1.1	4.6	MWHZ (particularly 22 May – 10 Jul, 31 Jul – 5 Aug, 10-20 Aug
4-Feb-1998	25-Feb-1998	33	11	0.7	2.5	MLGT (31 Jan – 25 Feb)
25-Mar-1999	29-Mar-1999	3	15	0.8	1.2	MLGT (what about 21-25 May?)
12-Oct-1999	13-Oct-1999	3	8	0.6	0.9	MLGT
1-Nov-1999	20-Feb-2000	151	9	0.4	2.0	MLGT Particularly 19-31 Dec, 1-6 Jan
22-Mar-2000	16-Apr-2000	82	7	0.3	1.3	MBWH Particularly 23-26 Mar, 1-9 Apr
26-Feb-2001	03-Mar-2001	9	12	2.3	4.8	"
13-Aug-2001	08-Nov-2001	39	13	0.6	1.5	"
ALL		**651**	**10**	**1.0**	**5.1**	

Data from March 2000 onwards are from MBWH.
Data from May-Sep 1997 are from MWHZ, scaled by 0.65.
All other data are from MLGT, scaled by 0.5.

Figures

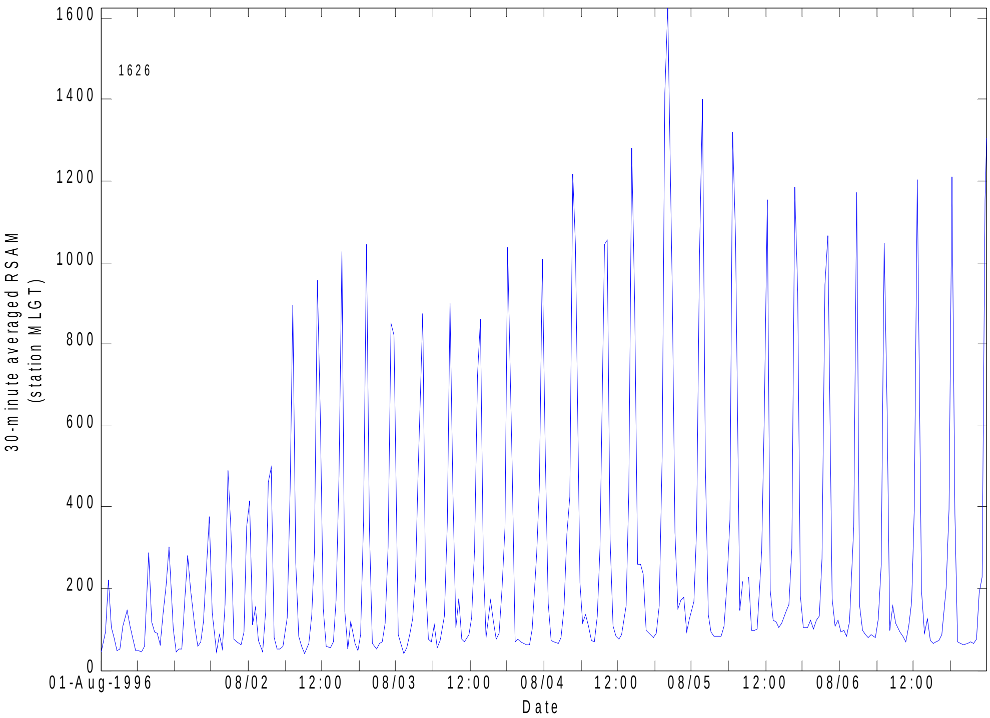


Figure 1: RSAM data from Long Ground seismic station recorded in August 1996 showing the phenomenon called "banded tremor". Bands of volcanic tremor lasting 1-2 hours are separated by quiet periods. Banded tremor first emerged after a volcano-tectonic earthquake from 20-22 July 1996, and continued until a large explosive collapse event on 17 September 1996. At other times during the eruption, hybrid swarms have occurred in bands, and eventually this has developed into banded tremor or vice versa (e.g April 2000). This indicates that tremor is a sequence of hybrid earthquakes overlapping closely in time, and that banded tremor is a special case of cyclic hybrid swarms. Each cycle consisted of several hours of intense seismic activity, separated by longer periods of inactivity or relative inactivity. The peaks in the cycles of seismicity were associated with heightened rockfall and pyroclastic flow activity and the venting of ash.

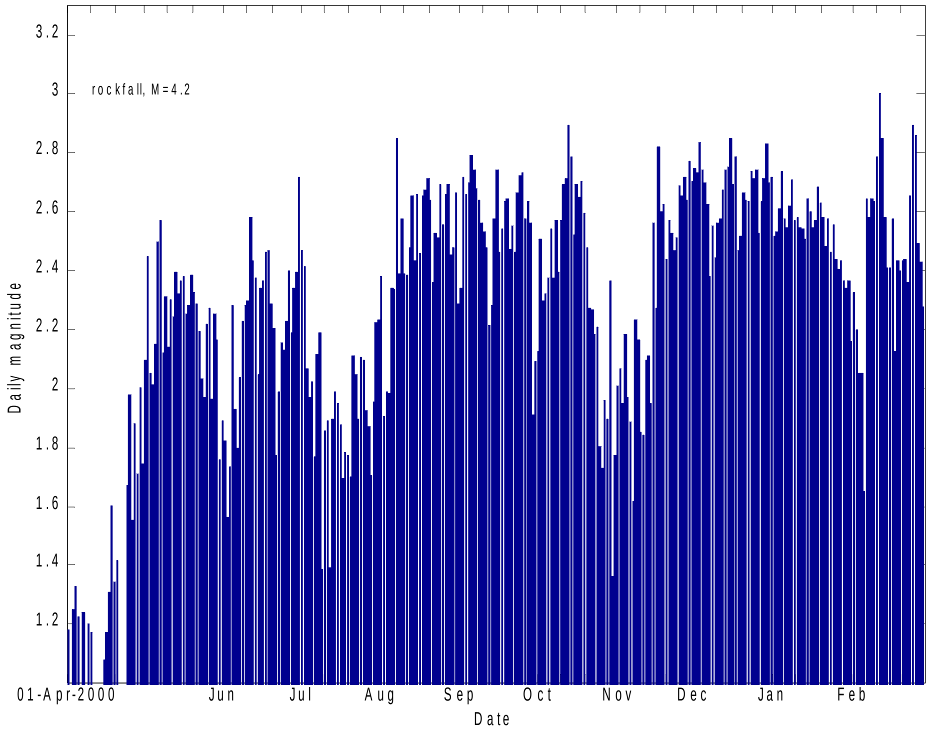


Figure 2: Daily rockfall seismic energy (expressed in terms of its equivalent magnitude) for the period April 2000 – February 2001. Escalations in rockfall seismicity occurred in early May 2000, early August 2000, mid-November 2000, suggesting an overall 13-14 week cycle. The last 4 weeks of each cycle are marked by much lower levels of rockfall seismicity. This allowed MVO to predict a further escalation in rockfall seismicity in mid-February 2001.

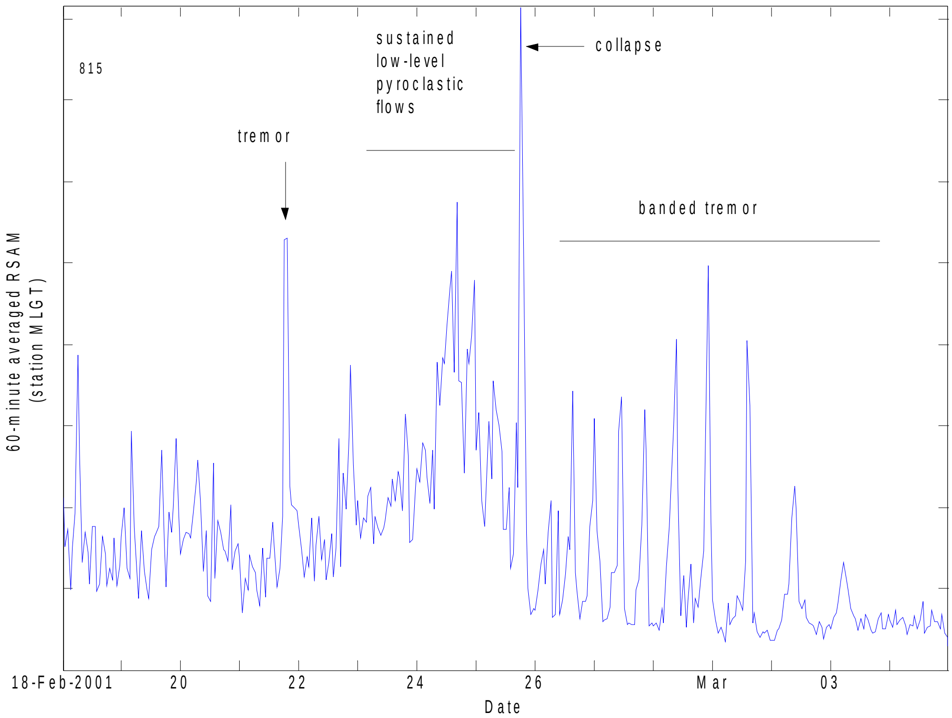


Figure 3: RSAM data from Long Ground seismic station recorded 18 February – 5 March, 2001. A period of high activity began on 21 February with volcanic tremor. An increase in the level of rockfalls and pyroclastic flows occurred in the following days, culminating in a collapse down White River on the evening of 25 February. Strong banded tremor then developed, but rapidly died out in March.

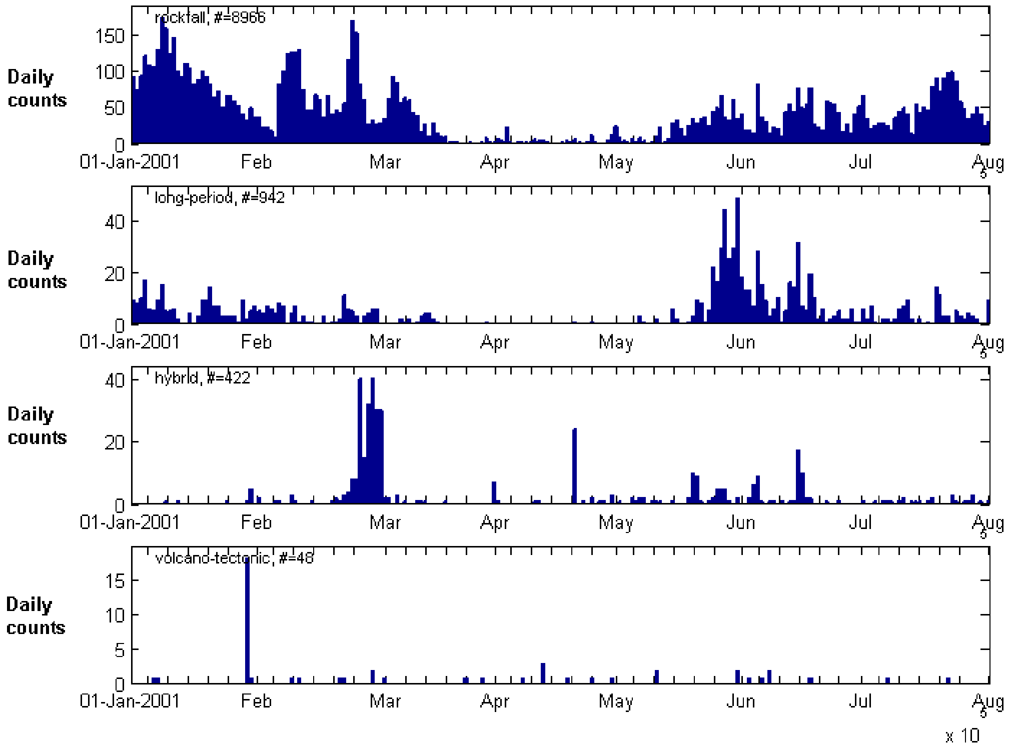


Figure 4: Daily counts of events detected by the digital seismic network with an equivalent magnitude of 0.7 or above for the period January-July 2001. Events are broken down by subclass: rockfalls (first panel), long-period earthquakes (second panel), hybrid earthquakes (third panel) and volcano-tectonic earthquakes (fourth panel). Note the decline in rockfall seismicity throughout commencing mid-January, two sharp increases in rockfall seismicity in February, hybrid swarms in late-February 2001, and particularly the low levels of seismicity throughout March, April and early-May. An increase in rockfall seismicity in late-May was accompanied by high-levels of long-period earthquakes, and sporadic hybrid swarms. Rockfall seismicity continued at moderate levels until the major collapse on 29 July 2001.

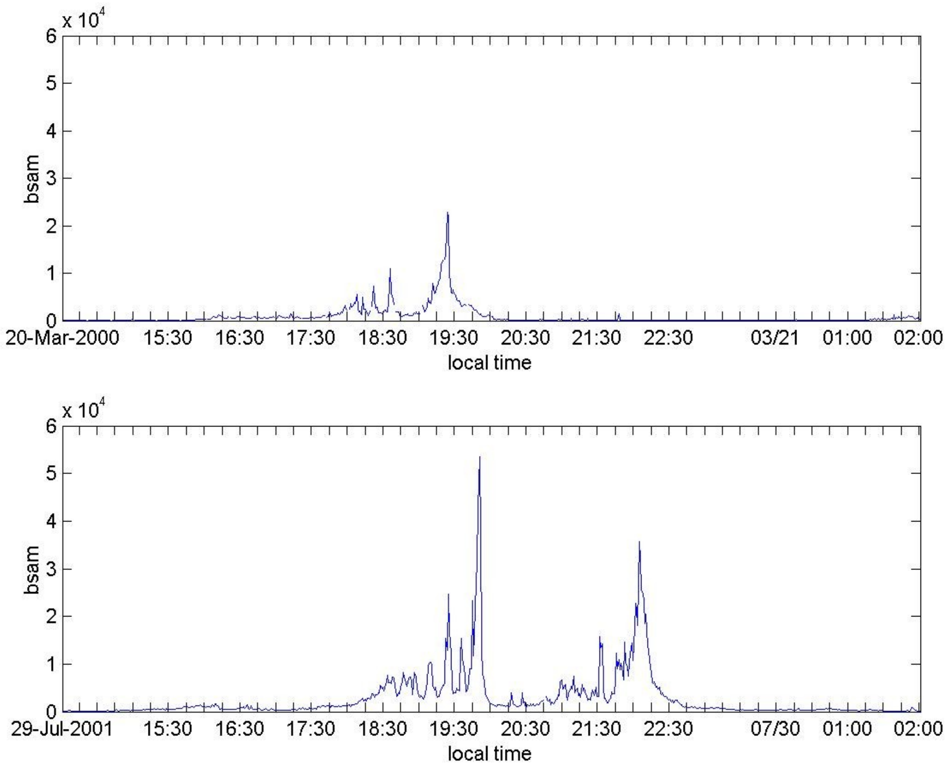


Figure 5: Seismic amplitude data showing (top panel) the 20 March 2000 collapse and (bottom panel) the 29 July 2001 collapse. The x and y scales are identical on each plot to aid comparison. Each collapse was preceeded by intense rainfall and mudflows, escalated over a period of 2-3 hours, was characterized by pyroclastic flows approximately every 5 minutes, culminated in an explosive event, and was followed by a rapid decline to background levels. The 29 July 2001 event was in effect two such collapses, with explosive events marked by peaks in seismicity at 1951 and 2205 local time.

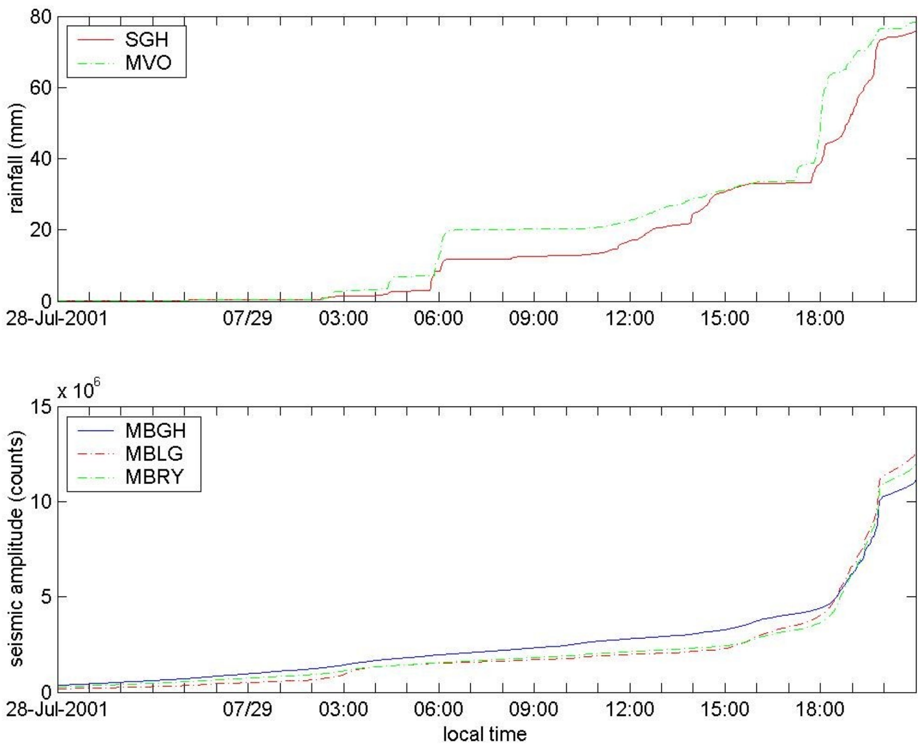


Figure 6: Remarkable correlation between cumulative rainfall (top panel) and cumulative seismic amplitude (bottom panel). The sharpest change in each is observed between 1800-1900h local time, suggesting the rainfall triggered the escalation towards a catastrophic collapse.

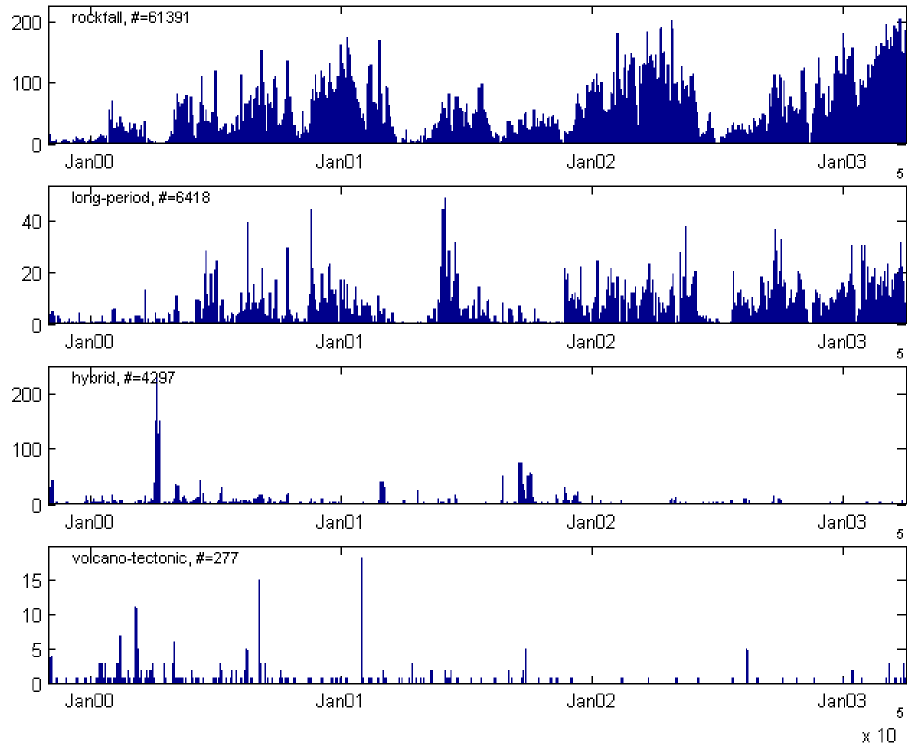


Figure 7: Daily counts of events detected by the digital seismic network with an equivalent magnitude, M > 0.7 for the period November 1999-March 2003. Events are broken down by subclass: rockfalls (first panel), long-period earthquakes (second panel), hybrid earthquakes (third panel) and volcano-tectonic earthquakes (fourth panel). Total number of events M>0.7 is shown in the top left-hand corner of each panel (e.g. 61391 rockfalls).

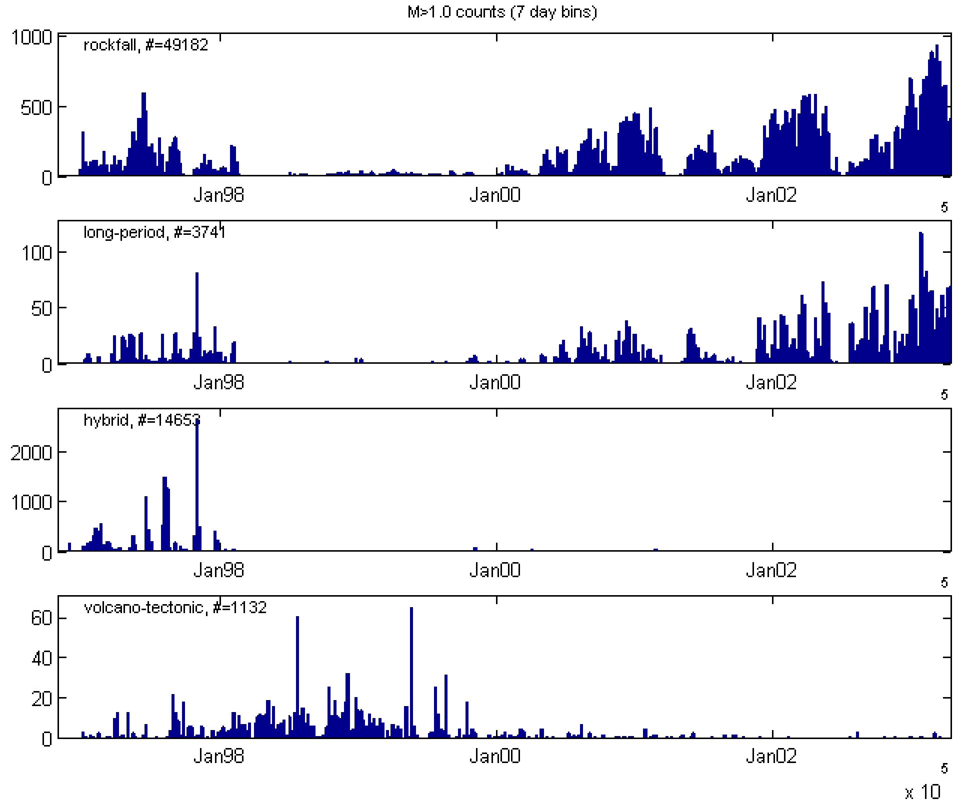


Figure 8: Daily counts of events detected by the digital seismic network with an equivalent magnitude, M > 1.0 for the period November 1996-March 2003. Events are broken down by subclass: rockfalls (first panel), long-period earthquakes (second panel), hybrid earthquakes (third panel) and volcano-tectonic 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). Periods of dome growth are characterised by rockfall and long-period seismicity, with occasional hybrid swarms (generally marking switches in dome growth, but not shown here). In contrast, the period of little or no dome growth from March 1998 to October 1999 was characterised by higher levels of volcano-tectonic earthquakes, and very-low levels of everything else. Note that rockfall and long-period seismicity in February/March 2003 were at their highest levels ever.

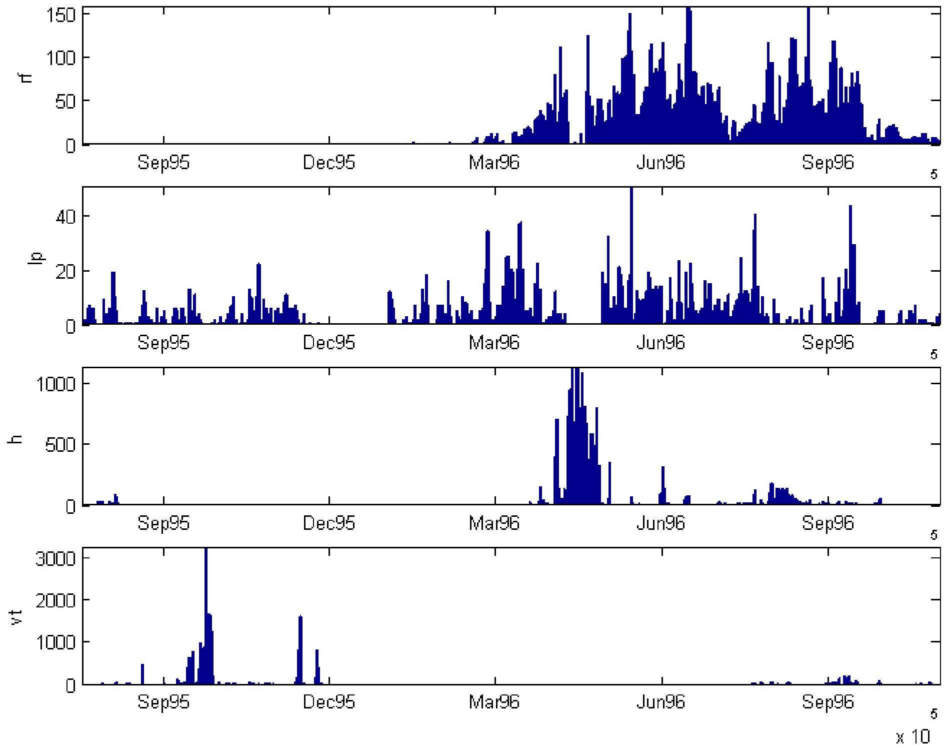


Figure 9: Daily counts of events (any size) detected by the analog seismic network, 18 July 1995 – 31 October 1996. Panels show from top to bottom: rockfalls, long-period earthquakes, hybrid earthquakes and volcano-tectonic earthquakes. This data is shown because the digital seismic network did not start operation until November 1996. There are many data gaps which are not indicated here.

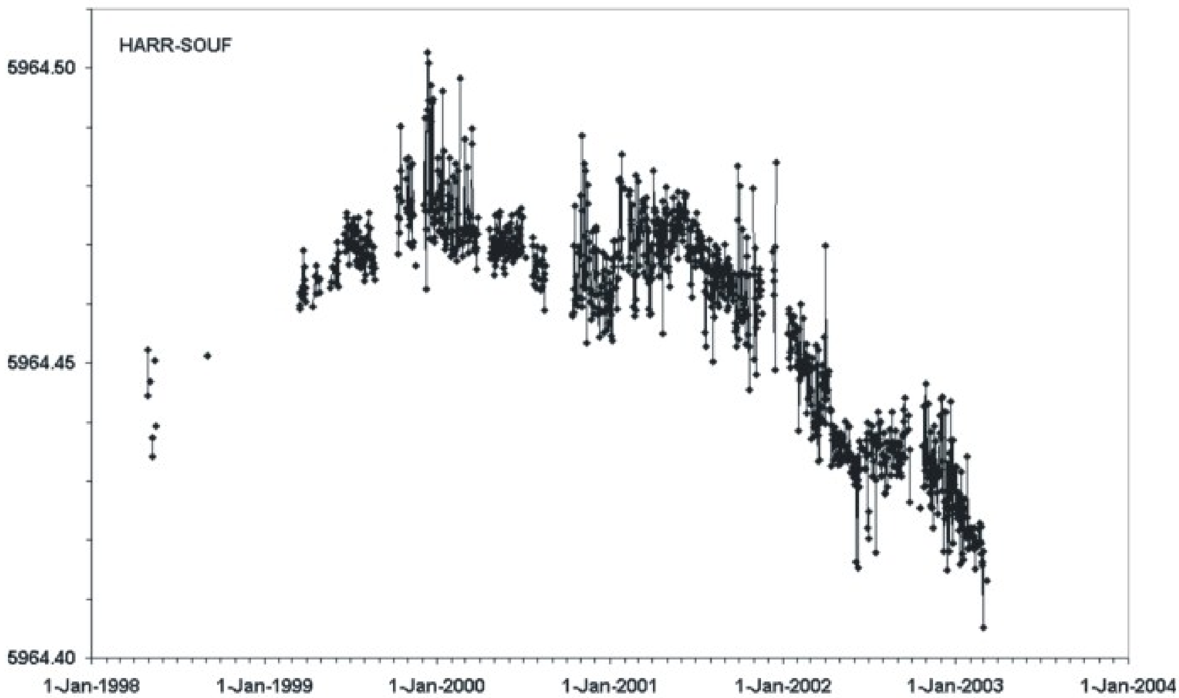


Figure 10: HARR-SOUF baseline showing strong expansion during non-eruptive periods (Mar 1998 – Nov 1999, late-Feb – mid-May 2001) at around 1.7 mm/month, slight expansion during sluggish parts of the eruption (June – mid-July 2002) at around 0.8 mm/month, contraction at 1.4 mm/month in early Phase II, and more rapid contraction during 2001, most of 2002 and early 2003 around 1.9 mm/month.

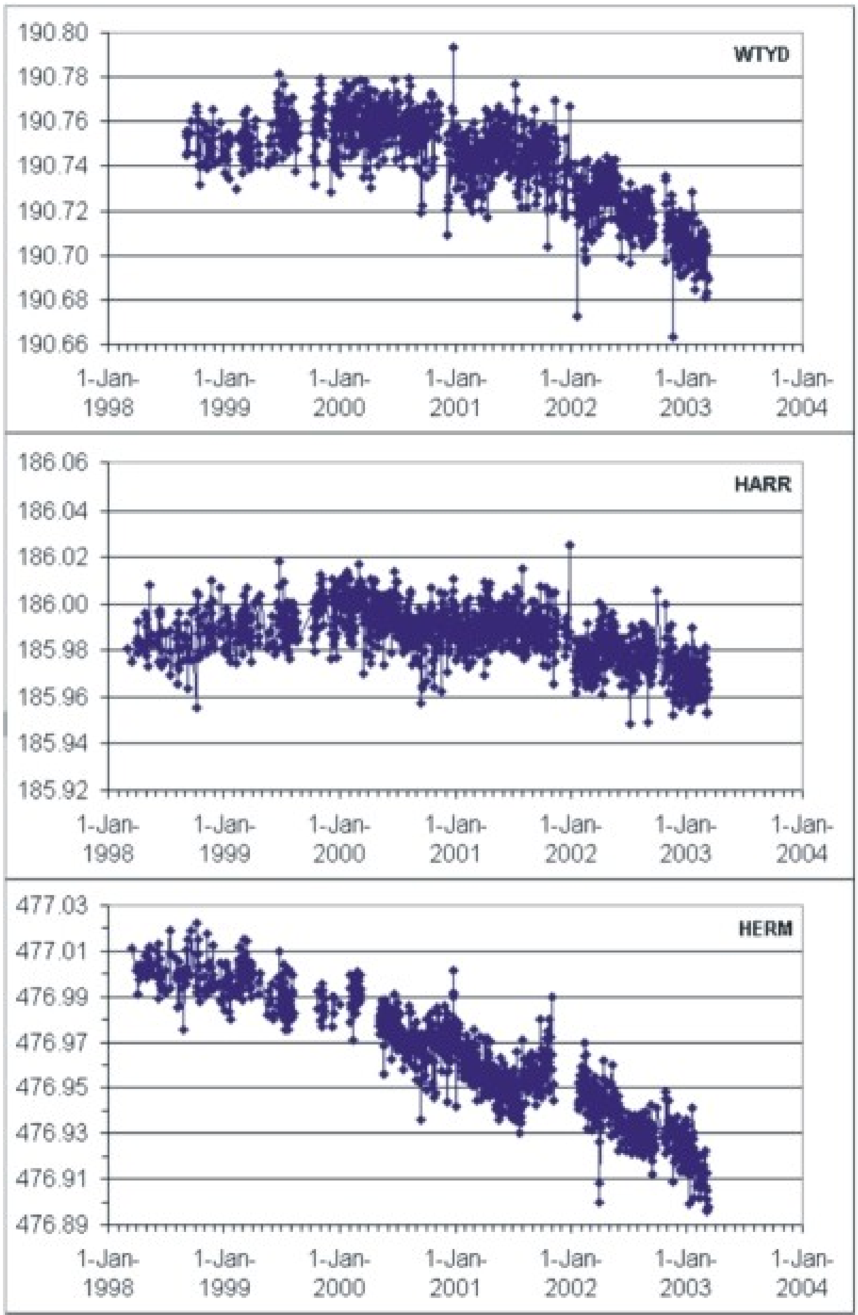


Figure 11: Height of three sites in metres above sea level w.r.t. MVO1 (in the north of Montserrat).

WTYD: uplift until late-99, followed by strong subsidence with small uplift March-May 2001.

HARR: similar pattern to WTYD although much weaker. The cause of the dislocation early-2002 is not known.

HERM: persistent subsidence of the site during eruptive and non-eruptive periods. The 3cm uplift in mid-2001 followed the July 29th collapse with the removal of 107 tonnes of rock from a few hundred metres from the site.

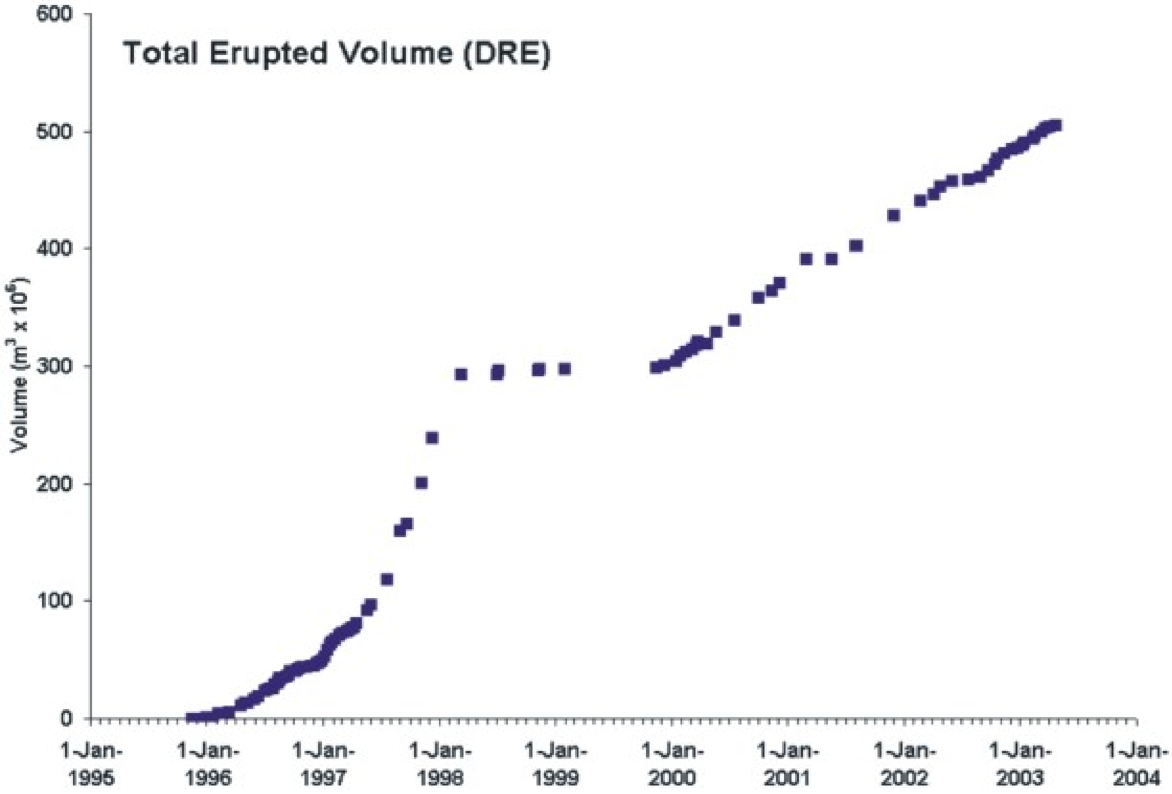
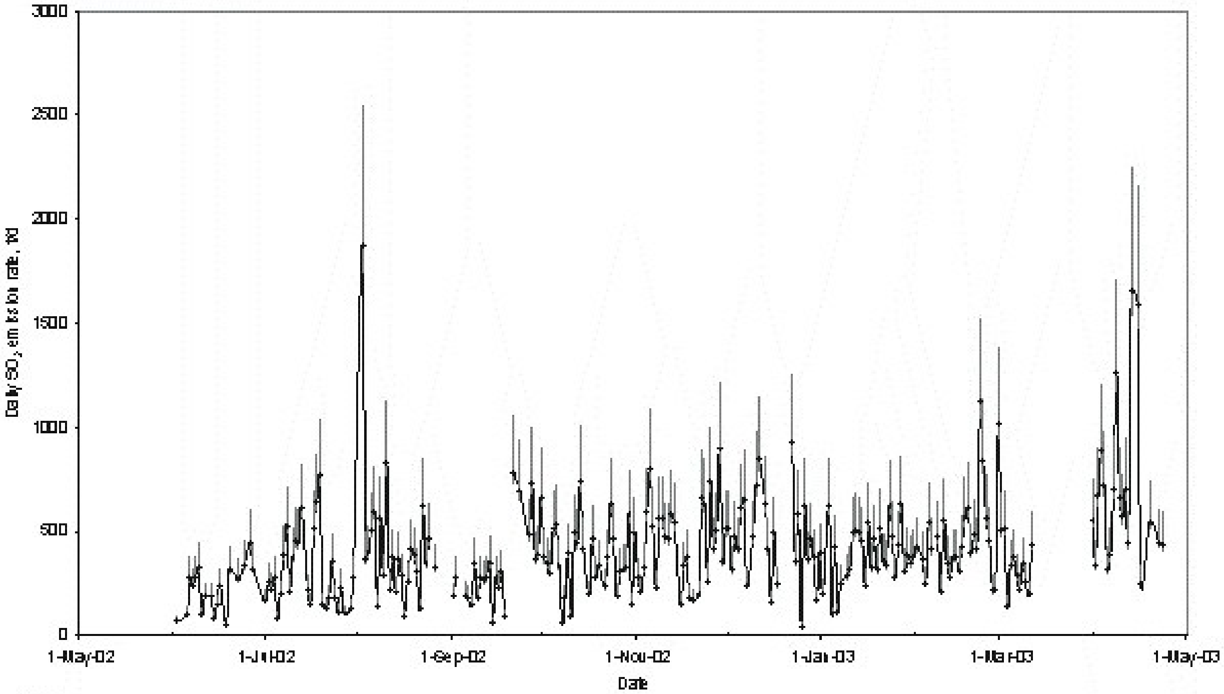


Figure 12: Total erupted volume over time, $m^3 \times 10^6$. (Note surge in output Sept-Oct 2002 following quiet period in summer – reminiscent of Oct 96 – Jan 97).



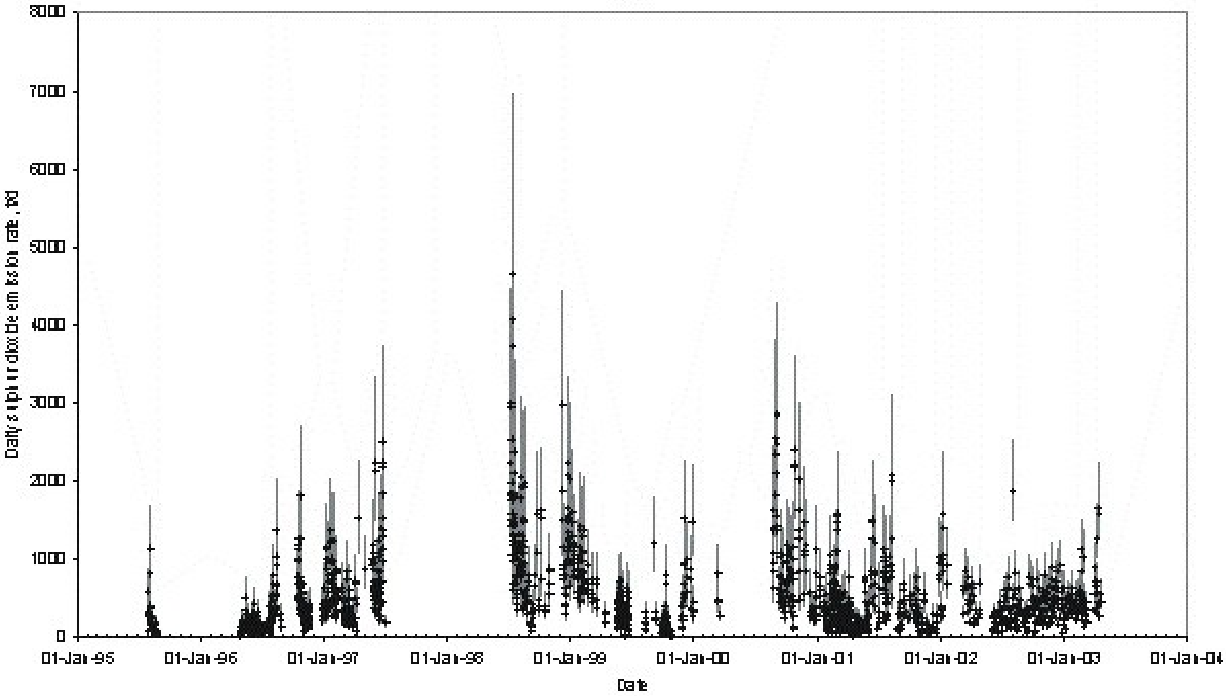


Figure 13: Sulphur dioxide emission rate June 2002 to April 2003 in tonnes per day (top) and for the entire eruption, July 1995 to April 2003 (bottom). The data are derived from COSPEC measurements up to January 2002 (errors +40%, -30%) and from the Scanspec network (utilising DOAS for retrievals) from January 2002 to April 2003 (errors +36%, -20%).

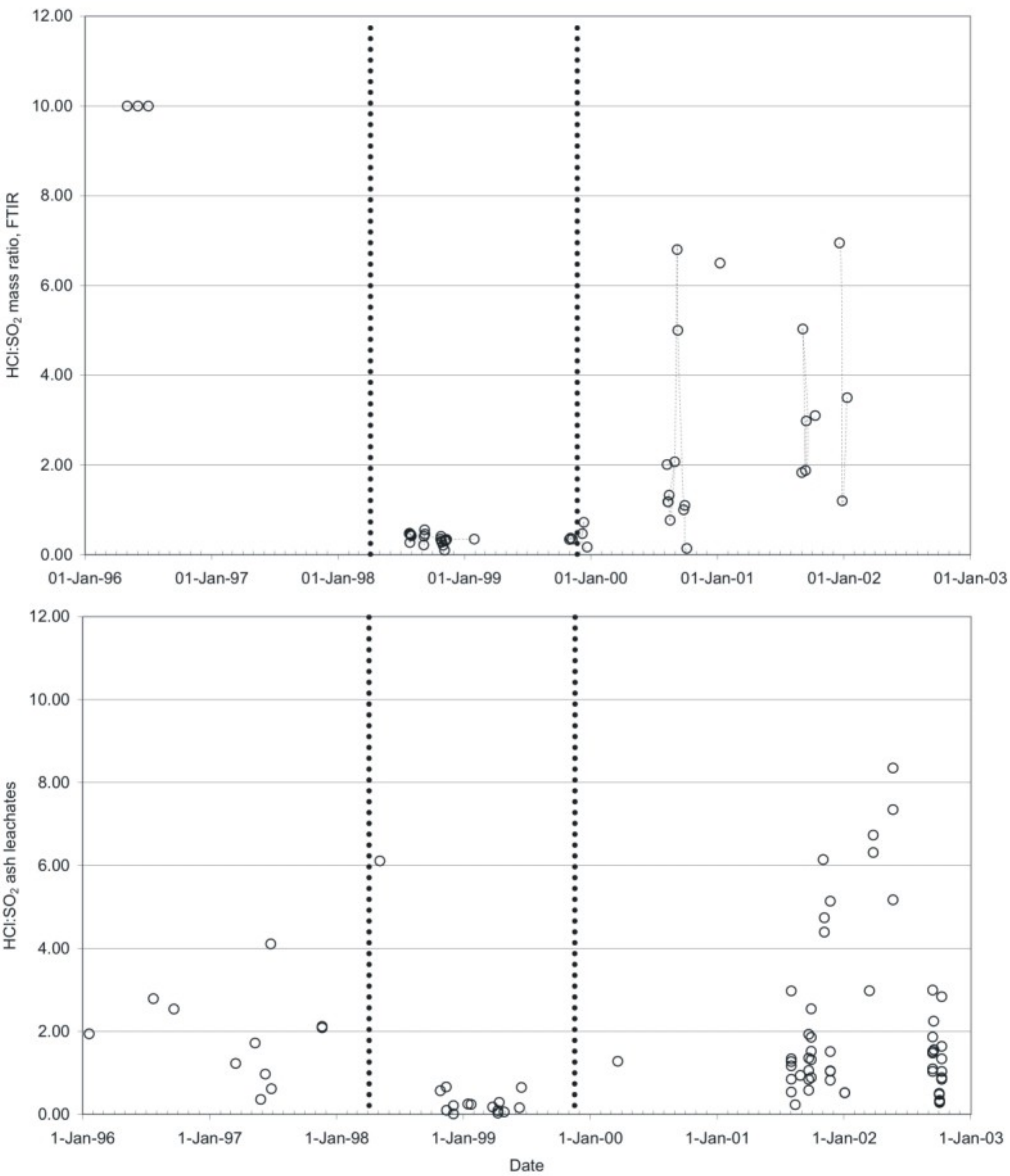


Figure 14: HCl:SO_2 mass ratio in the volcanic plume measured by **open path Fourier Transform Infrared Spectroscopy** (top) and **analysis of the chemistry of ash leachates** (bottom) from 1 January 1996 to January 2003. The first dashed line marks the cessation in dome growth in March 1998. The second dashed line marks the onset of the second phase in dome growth in November 1999.