PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

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THE ROYAL SOCIETY

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The 1995–1998 eruption of the Soufrière Hills volcano, Montserrat, WI

By R. E. A. Robertson[1], W. P. Aspinall[2], R. A. Herd[3], G. E. Norton[4], R. S. J. Sparks[5] and S. R. Young[3]

[1]*Seismic Research Unit, University of the West Indies, St Augustine Campus, Trinidad*
[2]*Aspinall & Associates, 5 Woodside Close, Beaconsfield HP9 1JQ, UK*
[3]*Montserrat Volcano Observatory, Mongo Hill, Montserrat*
[4]*British Geological Survey, Keyworth, Nottingham NG12 5GG, UK*
[5]*Department of Earth Sciences, University of Bristol, Bristol BS8 1RJ, UK*

Eruption of the Soufrière Hills volcano began on 18 July 1995 after three years of elevated seismic activity. Four months of increasingly vigorous phreatic activity culminated in mid-November 1995 with the initiation of dome growth. Growth rates increased unevenly through early March 1996, with fluctuations on time-scales from hours to months. Since March 1996, gravitational collapse of the unstable dome flank has affected an ever-increasing area with pyroclastic flows, surges and ashfalls. Major collapse of the eastern flank on 17 September 1996 resulted in a sub-Plinian explosive eruption later that day. By February 1997, the dome had outgrown the confines of the crater and begun to spill into the surrounding valleys. A large collapse on 25 June 1997 caused pyroclastic flows and surges on the northern flanks and resulted in the only deaths of the eruption. In August, September and October 1997, vulcanian explosions followed further collapses on the western and northern flanks. The largest event of the eruption occurred on 26 December 1997 with failure of the southwestern flank of the volcano producing a debris avalanche and large dome-collapse pyroclastic flows. Dome growth ceased in early March 1998, but residual volcanic activity has continued and consists of ash venting, mild explosions and dome-collapse pyroclastic flows.

Keywords: volcanic eruption; volcanic hazards; volcano monitoring; crisis management

1. Introduction

Montserrat (latitude 16° 45′ N, longitude 62° 10′ W) lies towards the northern end of the Lesser Antilles island arc (figure 1). The island consists of four volcanic centres (Silver Hill, Centre Hills, Soufrière Hills and South Soufrière Hills), which range in age from Pliocene to Recent (MacGregor 1938; Rea 1974; Wadge & Isaacs 1988; Harford *et al.* 2000). The youngest of these centres is the Soufrière Hills volcano (SHV), which consists of five andesitic lava domes: Gages Mt, Chances Mt, Galway's Mt, Perches Mt and Castle Peak. Before July 1995, the youngest dome, Castle Peak, occupied the horseshoe-shaped English's Crater (figure 1).

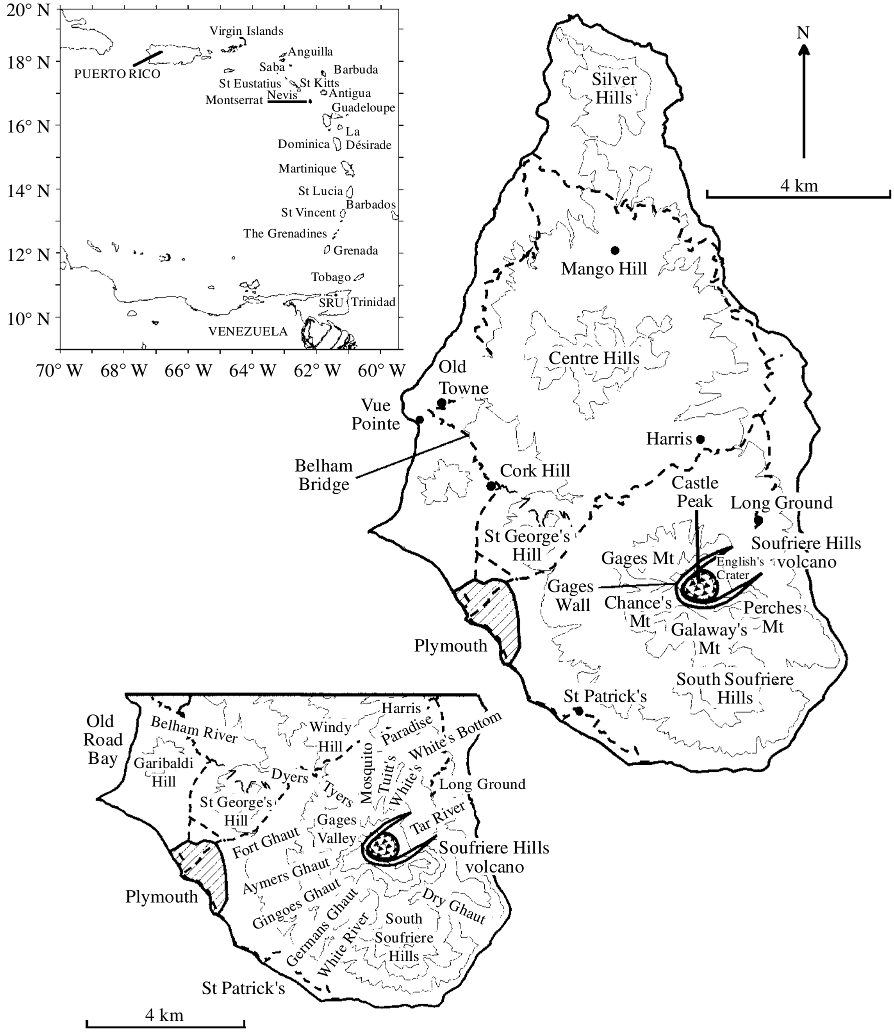

Figure 1. Map of Montserrat showing its location within the Eastern Caribbean and the main place names used in the text.

The Soufrière Hills is a Peléen-type volcano with andesitic magmas of relatively narrow compositional range (58–64 wt% SiO_2). Lava domes and pyroclastic flows are the typical eruption products. Recent stratigraphic work by Roobol & Smith (1998) indicates that the volcano was particularly active between 31 000 and 16 000 years BP, when block and ash flows and surges were erupted. Resumption of activity in *ca.* 4000 years BP resulted in the formation of English's Crater by sector collapse. The last eruption before the 1995–1998 event appears to have been about 350 years BP (i.e. *ca.* AD 1625), when there were small eruptions of dense andesite (Young *et al.* 1996).

Despite the lack of eruptive activity during the past 200 years, the Soufrière Hills volcano has not always been quiet. Three volcano-seismic crises have occurred during the past 100 years: 1897–1898, 1933–1937 and 1966–1967 (MacGregor 1938; Perret

1939; Shepherd *et al*. 1971). All were accompanied by enhanced fumarolic activity and may be regarded as failed attempts by magma to rise to the surface. The most recent crisis (1966–1967) was interpreted as injection of a relatively small volume of magma from a depth of more than 10 km into a complex system of cracks and fissured rocks located below the volcano (Shepherd *et al*. 1971).

The latest eruption of the Soufrière Hills volcano began with phreatic explosions on 18 July 1995 (Young *et al*. 1997, 1998*a*). The eruption was preceded by a period of elevated seismicity (Ambeh *et al*. 1998), which began in January 1992. After the initial phreatic phase, most of the eruption has consisted of the emplacement and disintegration of a viscous lava dome. There have also been periods of explosive activity associated with rapid extrusion rates and major dome collapses. The eruption has caused tremendous disruption to the lives of the local population, who had established a viable community on the fertile pyroclastic deposits on the flanks of the volcano. Volcano monitoring and crisis management responses have had to be adapted to a challenging environment in which the resolve of scientists and population has been both tested and strengthened by a protracted and evolving eruption.

This paper reviews the eruption, outlining the chronology of events, the techniques used in monitoring, and briefly discusses crisis management. It highlights the most important elements of the crisis.

2. Eruption chronology

(*a*) *Pre-eruptive seismic activity (January 1992–July 1995)*

Between January 1992 and July 1995, seismic stations on Montserrat and surrounding islands recorded 15 episodic swarms of small earthquakes in the vicinity of the island. These originated at depths of 10–15 km and were particularly intense in July 1994. This prompted installation of additional seismic stations by the Seismic Research Unit (SRU) of the University of the West Indies, the agency responsible for regional volcano monitoring. During November–December 1994, the events again became intense and some were felt locally. Monitoring operations were further improved by the establishment of a local subnetwork with processing capability (November 1994), regular checks on conditions at active fumaroles (December 1994) and re-occupation of dry tilt stations (February 1995) (see figure 2). Collaboration with the Institut de Physique du Globe through the Observatoire Volcanogique de La Soufrière, Guadeloupe, enabled sampling and analysis of gases and condensates from active fumaroles in early 1995. By February 1995, data from six seismic stations were being telemetered to the Emergency Operations Centre in the capital, Plymouth, where the earthquake traces were examined and possible events sent to the SRU for further analysis. The signals from two of the stations were also transmitted directly to Trinidad using leased circuit telephone lines.

(*b*) *Start of eruption: the phreatic phase (July–October 1995)*

The eruption began on 18 July 1995 with mild explosions and ash and steam emission from a vent excavated on the NW flank of the Castle Peak dome. Subsequent explosions opened further vents on 28 July, 20, 22 and 28 August (figure 3) and prompted the evacuation of the nearby village of Long Ground. Activity at this time consisted mainly of sustained periods of vigorous steaming with periodic explosions

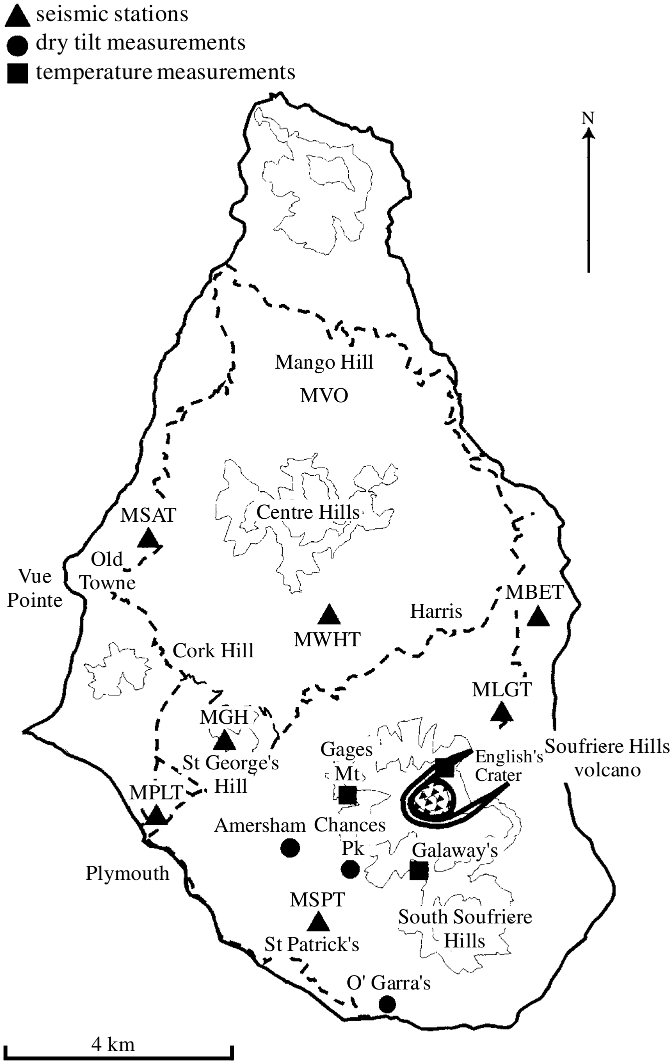

Figure 2. Pre-eruptive volcano monitoring programme operated by the Seismic Research Unit in Montserrat.

from the 18 July vent. Ash samples collected were andesitic and interpreted to be pulverized portions of the old dome. Seismic activity was similar to that experienced during earlier volcano-seismic crises in Montserrat (Powell 1938; Shepherd *et al*. 1971), and consisted mostly of swarms of volcano-tectonic earthquakes diffusely scattered around southern Montserrat. A few long-period events and tremor episodes associated with steam venting were also recorded (Aspinall *et al*. 1998; Miller *et al*. 1998). Measurement of SO_2 flux by correlation spectrometer (COSPEC), averaged 300 t d^{-1}, with maximum values associated with vigorous periods of ash and steam venting (Young *et al*. 1998*b*). SO_2 tubes established in Plymouth since December 1995 showed low levels in inhabited areas. Sampling of gases and condensate from the three active fumaroles continued to show no changes (Hammouya *et al*. 1998).

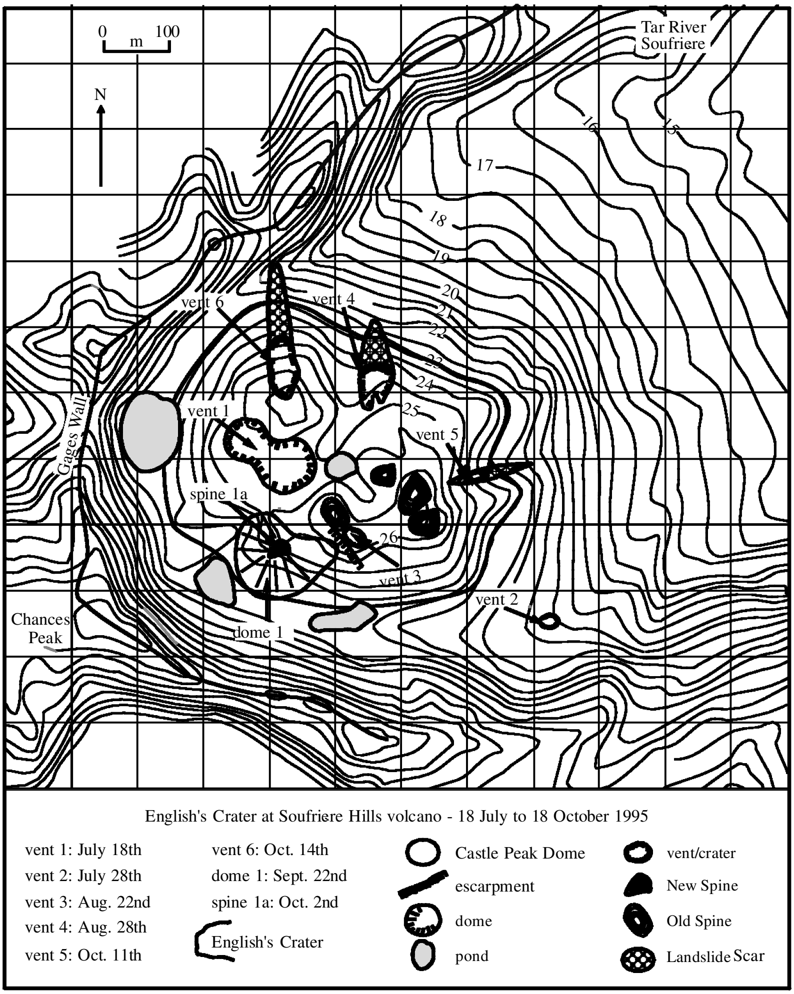

Figure 3. English's Crater showing its main physiographic features as they existed during the period 18 July–18 October 1995.

Phreatic explosions became larger during August, and on 21 August 1995 the first of several large explosions produced a cold base surge, which blanketed Plymouth and resulted in total darkness for *ca.* 15 min. This event prompted the spontaneous evacuation of Plymouth, which later became an official relocation, lasting two weeks. Large explosions on 31 October, 4 and 9 November also resulted in cold base surges, which caused 15–30 min periods of darkness in southern villages. These eruption columns reached 3 km in height and deposited a few millimetres of ash as far as 5 km downwind from the volcano.

The first unequivocal evidence that magma was rising to the surface at the Soufrière Hills volcano occurred in late September 1995. Clear conditions at the summit allowed observation of a small spine (*ca.* 40 000 m^3) on the SW part of Castle Peak dome (figure 3). The first intense swarm of hybrid earthquakes (Miller *et al.* 1998), which occurred from 22 to 29 September, preceded and accompanied the emplacement of this spine. Phreatic explosions became larger and more frequent during October, producing thick deposits of fragmented rock on the upper flanks of the volcano.

(c) *Early dome growth (November 1995–June 1996)*

The onset of continuous dome growth occurred on or around 14/15 November, when high rates of ground deformation accompanied an intense swarm of repetitive hybrid earthquakes. Poor visibility prevented confirmation of extrusive growth until 30 November, when incandescent material was observed in the enlarged 18 July vent. Increased concern for public safety, due to the presence of fresh magma at the surface, prompted the second evacuation of southern Montserrat on 1–2 December 1995. The evacuation lasted until 1 January 1996, by which time it was established that the dome growth was non-explosive and did not pose an immediate threat to communities in the south of the island.

Quiet dome growth continued at *ca.* $0.5\ m^3\ s^{-1}$ for the remainder of 1995 and early 1996. The material progressively filled the phreatic vents and began to cover Castle Peak. Dome instability caused rockfalls, which produced minor ash plumes up to 2000 m and millimetre-thick ash deposits downwind of the volcano. Dome samples collected during early January 1996 indicated that the new andesite was similar in composition to older andesites from the Soufrière Hills volcano (Rea 1974; Devine 1987; Wadge & Isaacs 1988; Murphy *et al.* 2000). The andesite (*ca.* 59–61 wt% SiO_2) was porphyritic and contained phenocrysts of plagioclase, hornblende, orthopyroxene, titanomagnetite and minor ilmenite and apatite (Devine *et al.* 1998). Fine-grained mafic inclusions were found to form a widespread but minor (*ca.* 1–2%) component of the andesite (Murphy *et al.* 1998). The inclusions were generally phenocryst-poor and had basaltic to basaltic–andesite bulk compositions similar to the older (*ca.* 125 ka) mafic lavas of the South Soufrière Hills centre. The textures and mineral chemistry of phenocrysts from the andesite and from melt inclusions provided evidence for reheating of the andesite magma due to influx of mafic magma and the triggering of the eruption by magma mixing (Murphy *et al.* 2000).

Dome growth continued at an increasing rate during the first three months of 1996, and larger sections of the dome became unstable. During late January, a swarm of repetitive hybrid earthquakes, which lasted for two weeks, accompanied an increase in growth rates to $2\ m^3\ s^{-1}$ that continued until late July. Rapid extrusion rates in early February produced two elongate ridges oriented SW to NE, which resembled whalebacks and were mirror images of each other (figure 4). This contrasted with the more common mode of dome growth in this period, which involved extrusion of slab-shaped masses of lava (spines), which grew rapidly (5–20 $m\ d^{-1}$) to *ca.* 25 m before collapsing and adding to the talus slopes covering the flanks of the dome.

The first pyroclastic flows occurred during late March, as the size of the dome (by then $6.3 \times 10^6\ m^3$) and the growth area (NE) were such that material spilled into the upper Tar River valley. These flows were discrete events produced by gravitational collapse of unstable parts of the dome. Vigorous ash venting and high dome-gas pressure were first evident in early April. With continued dome growth, the runout distances of these flows increased, and on 3, 6 and 8 April a series of flows travelled as far as 2.4 km from the dome and generated ash plumes up to 9 km in altitude. These deposited ash on communities to the west as a result of the prevailing easterly

Figure 4. Photograph of English's Crater taken in February 1996 showing the SW whaleback (a); the NE whaleback (b); collapsed spines and talus forming the bulk of the dome (c); the Gages gap (d); Chances peak (e); and Plymouth in the background (f).

winds. Concern regarding the potential hazards caused by these flows and the risk to surrounding areas prompted the third evacuation of southern Montserrat in early April 1996. Periodic shifts in the locus of growth became a characteristic feature of dome growth and allowed short-term forecasting of the direction of pyroclastic flow activity.

By April 1996, production of acid aerosols from volcanic gas emission had caused extensive damage to vegetation within 3 km downwind of the volcano. However, SO_2 tubes established in Plymouth since December 1995 showed only low concentrations at ground level in inhabited areas. Measurement of SO_2 flux restarted in April 1996 and gave an average of 200 t d^{-1} (Young *et al*. 1998*b*) with low SO_2:HCl ratios (Oppenheimer *et al*. 1998). Rapid shortening of line lengths on the electronic distance meter (EDM) network on the east and south sides of the volcano, which had been going on since measurements were started in late September 1995, slowed considerably in early May 1996 (Jackson *et al*. 1998). Hybrid earthquakes, rockfall events and low-amplitude volcanic tremor were the most common types of seismic events recorded during this period (Miller *et al*. 1998).

Numerous large spines, which typically grew at a few metres per day, were extruded during May and June 1996. After a few days of rapid extrusion, these eventually stopped growing and then collapsed. On 12 May, pyroclastic flows reached the sea for the first time, *ca.* 2.6 km from the dome, at the mouth of the Tar River valley. These deposited *ca.* 0.2×10^6 m^3 of new material (Cole *et al*. 1998), most of which was involved in the creation of a small coastal fan. Most of the flows during this period were discrete events that occurred in the Tar River valley and had runout distances of less than 3 km. Dome growth switched to the northwest sector during early June, and led to the material just over-topping the Gages wall above the capital Plymouth. Then the growth area switched location again, and by mid-June was concentrated on the northern sectors of the dome.

(*d*) *Increased activity and explosive eruption (July–September 1996)*

High numbers of shallow non-repetitive hybrid earthquakes, preceded by swarms of small volcano-tectonic earthquakes, began to occur on 20 July, the first time since dome growth began. These were accompanied by a marked change in deformation rate on the Eastern EDM triangle from 1 to 6 mm d^{-1} (Jackson *et al.* 1998). The area of active growth switched at this time to the eastern flank. The average rate of dome growth increased to *ca.* 4 m^3 s^{-1} with brief periods (29–31 July and 12–17 August) when extrusion rates may have been even higher (Sparks *et al.* 1998). High magma production rates led to major dome collapses and pyroclastic flows in the Tar River on 29 July, 11 and 21 August and 2–3 September. The flows generated ash that fell over most of the island and extended the coastal fan (400 m east–west by 1 km north–south), at the mouth of the Tar River valley.

The removal of 11.7×10^6 m^3 (DRE) of the dome during a 9 h period of sustained pyroclastic flow activity on 17 September 1996 unroofed the pressurized interior of the dome and conduit, and led to the first magmatic explosion of the eruption (Robertson *et al.* 1998).† A major ash plume rose to *ca.* 14 km, and *ca.* 600 000 t of ash, pumice and lapilli were deposited in southern Montserrat. Pyroclastic flows in the Tar River valley substantially extended the coastal fan and ballistic projectiles were thrown out up to 2 km to the NE of the volcano, causing fires in Long Ground village. A large U-shaped scar formed on the eastern side of the dome. Immediately after this event, seismicity reduced drastically and there was little evidence of volcanic activity for the remainder of September.

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(*e*) *Continued dome growth and SW crater wall instability (October 1996–April 1997)*

On 1 October 1996, new growth began at the base of the scar left by the September explosion. Growth continued and the scar rapidly became filled with new material (figure 5). Shallow, non-repetitive hybrid earthquakes restarted during late October and continued until early December. From November to early December, eight prolonged earthquake swarms accompanied deformation of the steep SW crater wall (Galway's wall), possibly caused by intrusive activity (Miller *et al.* 1998). Numerous landslides occurred from the outside face of the wall during these swarms and large fractures developed on the surface. In contrast, during the aseismic periods between swarms, activity was dominated by rockfalls on the main dome, when magma reached the surface through the central conduit and the dome grew strongly. As the Galway's wall became more degraded and deformed, concern about the possibility of a major sector collapse increased.

Exogenous growth restarted in the SW of the crater around 12 December 1996, accompanied by a reduction in crater-wall deformation. The growth area increased rapidly, exceeding the height achieved by the 1 October dome, and causing pyroclastic

† DRE: dense rock equivalent.

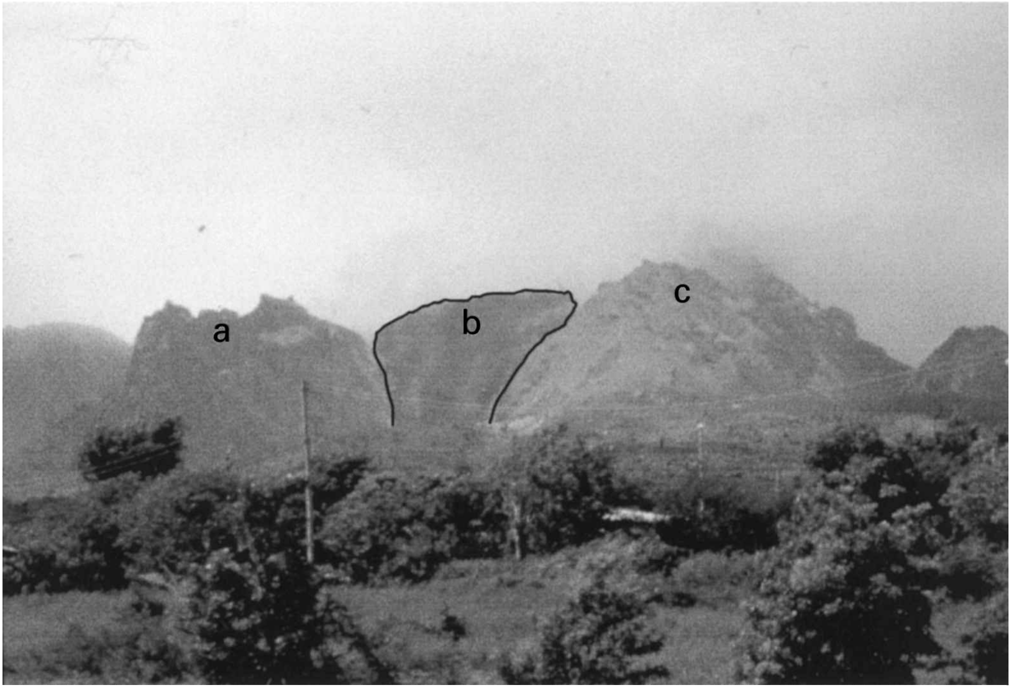

Figure 5. Tar River valley during October 1996 showing the pre-existing Castle Peak dome (a); new growth in the 17 September collapse scar (b); and the November 1995–September 1996 dome (c).

flows down the south side of the Tar River valley. The locus of growth then switched back to the 1 October dome, following partial dome collapse and the production of the first pumiceous pyroclastic flows in mid-December. About 24 December a new lobe spread rapidly across the top of the dome which had erupted during October. Between 24 December and early January, the new lobe expanded to the east over Castle Peak, which started to erode away as rockfalls went over and around the Peak. Cyclic inflation and deflation of the dome (with periods of 6–8 h), as measured by tiltmeters on the crater rim (Voight *et al*. 1998, 1999), was first recognized at this time. These episodes were accompanied by another phase of hybrid earthquake swarms and tremor associated with rapid dome growth (Miller *et al*. 1998). Growth continued at a steady rate in January with occasional moderate pyroclastic flows to the east in the Tar River valley. These flows were especially intense in early and mid-January, and on 20 January a short-duration collapse excavated the SE part of the dome. Fresh dome growth started immediately, forming another lobe within the collapse scar.

Hybrid earthquake swarms lasting 2–4 h were common in January and February 1997. Further degradation of the SW crater wall occurred in early February, allowing dome material to collapse over Galway's wall for the first time. Rapid growth occurred in the southern sector at the end of March, producing the first sizeable pyroclastic flows to the south into the White River valley. From late March to early April, sustained collapses occurred over Galway's wall, generating further pyroclastic flows with runouts of up to 4 km down the White River valley (Cole *et al*. 1998). No hybrid earthquake swarms accompanied this period of elevated activity (Miller *et al.* 1998). However, global positioning system (GPS) and EDM measurements indicated increased rates of deformation from mid-March. The total volume of magma erupted by late March 1997 was estimated to be *ca.* 77×10^6 m^3 (DRE).

(*f*) *Continued dome growth with pyroclastic flows to north and west (May–July 1997)*

Hybrid earthquake swarms began in mid-May 1997 accompanied by further distinct inflation and deflation cycles recorded by tiltmeters on the crater rim (Voight *et al.* 1998, 1999). The locus of growth shifted to the north and northeastern face of the dome, and the rockfalls spilled into Tuitt's Ghaut for the first time. By late May, the first pyroclastic flows entered the ghauts on the northern slopes of the volcano, and in June larger flows reached further than 3 km down Mosquito and Tuitt's Ghauts, which feed valleys leading to the east coast. At that time the average discharge rate of the dome increased to above 4 m^3 s^{-1} and was sustained at a high level for the remainder of the dome-growth phase of the eruption. By mid-June, there had been significant changes in Mosquito Ghaut, as large volumes of pyroclastic flow material accumulated 500 m down the Ghaut. Debris from small rockfalls started to spill over Gages wall in mid-June, and pyroclastic flows travelled to *ca.* 1.6 km down the Gages valley. The volume of the dome in late June 1997 was estimated to be 70×10^6 m^3.

Collapse of *ca.* 5×10^6 m^3 from the dome on 25 June 1997 led to sustained pyroclastic flows, which reached *ca.* 6.5 km to the east down the Mosquito Ghaut. These flows reached to within 50 m of the terminal buildings at Bramble Airport and devastated central and eastern villages, causing 19 deaths and extensive property damage. Repetitive episodes of hybrid earthquake swarms over several days, synchronized in time with remarkable periodic inflation–deflation cycles on the electronic tilt stations at Chances peak, preceded this event (Voight *et al.* 1998, 1999). These two strongly correlated indicators were used to anticipate increased pyroclastic flow activity, which, at the time, almost invariably accompanied peaking in the inflation cycle. The generation of a secondary pyroclastic flow, which detached from the main avalanche on 25 June and reached close to the village of Cork hill down the Belham River valley to the west of the volcano, prompted a complete evacuation of all communities in southern Montserrat.

Volcanic activity reduced immediately following the major 25 June collapse event. However, minor explosions in late June and early July gave evidence of continued high internal dome pressures. Increased extrusion rates (5–10 m^3 s^{-1}) resulted in rapid refilling of the collapse scar and caused more pyroclastic flows to the north and west. These filled the northern ghauts and created a wide debris fan at the top of the Gages valley, where flow activity was concentrated at the end of this period.

(*g*) *Major flows to west and southwest and vulcanian explosions (August–November 1997)*

Cyclical behaviour resumed in early August with episodic hybrid swarms being followed by pyroclastic flows. Major pyroclastic flows into Plymouth preceded a remarkable period of 12 repetitive vulcanian explosions between 3 and 12 August (figure 6). These explosions generated eruption columns up to 15 km in height and

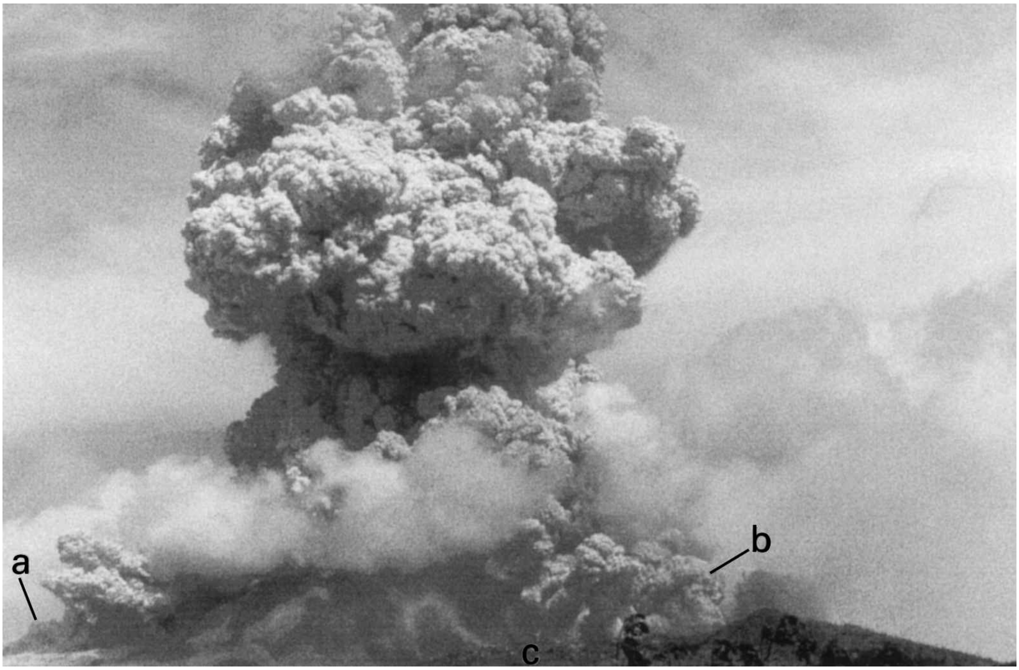

Figure 6. Photograph taken from Old Towne of a vertical eruption plume from one of the August 1997 explosions. Pyroclastic flows have developed radially by column collapse and are seen descending Mosquito and Tuitt's ghauts (a) and into the Gages valley (b) just south of St George's Hill (c).

column-collapse pumice flows into all the valleys radiating from the volcano. They also excavated a large vent over the Gages area, on the northwest side of the dome.

Renewed growth of the dome accompanied by hybrid earthquake swarms began immediately after these explosions and continued into September 1997. The total dome volume (including talus accumulations) was estimated at this time to be 85×10^6 m^3 (DRE). Increased concern over the risk to Old Towne and surrounding areas from potentially larger explosions prompted the relocation of Montserrat Volcano Observatory to a new facility at Mongo Hill in the north.

A major dome collapse (*ca.* 8×10^6 m^3) occurred on 21 September 1997, avalanching out to the NE of the volcano and causing further destruction to eastern Montserrat. This resulted in mass unloading of the dome and led to a second series of 75 vulcanian explosions that lasted for one month and occurred regularly, at intervals of *ca.* 10 h. Unlike the August explosions, there was no clear precursory activity. Eruption columns reached 6–13 km in height and deposited ash and pumice fragments over the entire island and other parts of the northeastern Caribbean. Column-collapse pumice flows accompanied most of these explosions and extended up to 6 km radially, with ballistics thrown up to 1 km from the volcano. A large explosion crater (*ca.* 300 m in diameter) was excavated in the northern part of the dome (Young *et al.* 1998*a*).

Rapid regrowth of the dome in the crater excavated by the explosions occurred during October 1997. Renewed growth in the south and rapid extrusion rates (*ca.* 7–8 m^3 s^{-1}) resulted in partial dome collapses in early November and several large pyroclastic flows in the White River valley. These further infilled the White River valley and extended the delta 400 m out to sea. Hybrid earthquake swarms and rockfall signals dominated the seismicity during this period. Seismic energy release from a few of the larger hybrids was sufficiently strong to propagate to surrounding islands and was recorded by seismometers as far away as Dominica (*ca.* 160 km).

(*h*) *Sector collapse and regrowth (December 1997–February 1998)*

By 25 December, the dome had reached a volume of 110×10^6 m^3 and the total erupted volume since November 1995 was 240×10^6 m^3 (DRE). Growth during November and December had extended a lobe laterally over Galway's wall (Sparks *et al.* 2000). A large hybrid swarm began on 24 December 1997 with events every 20 min, and this increased in intensity the following day. This culminated in the failure of the hydrothermally altered SW crater wall and generation of a debris avalanche (*ca.* 40–45 $\times 10^6$ m^3) on 26 December 1997. The collapse triggered the failure of *ca.* 55–60 $\times 10^6$ m^3 of the lava dome, which generated a high-energy pyroclastic density current that devastated *ca.* 10 km^2 of southern Montserrat (Sparks *et al.* 2000). The avalanche and flows reached the coast at the mouth of the White River and produced a 14 km-high ash plume.

Rapid dome growth accompanied by low seismicity restarted almost immediately in the upper of the two bowl-shaped scars left by the collapse. An increase in seismicity in mid-January 1998 was accompanied by periods of continuous rockfall and ash venting. These produced ash plumes up to 2 km in height and small pyroclastic flows down the White River valley. Periodic swarms of volcano-tectonic and hybrid earthquakes coincided with increased rockfall activity and moderate ash fall in the north of the island in early February.

(*i*) *Cessation of dome growth and relapse into dome disintegration (March–September 1998)*

The summit of the lava dome in early March 1998 was measured at 1011 m above sea level (ASL) and consisted of a small number of short spines. One of these developed into a large broad-based feature, which reached a maximum height of 1027 m by 9 March. Dome growth ceased abruptly during the second week of March, and visual observations made after this time indicated no major changes in dome morphology. Minor degradation of the upper parts of the dome began in late March and created deep rockfall chutes on the eastern and southwestern flanks. Several small pyroclastic flows occurred in the Tar River valley. An area of fumarolic activity developed in a V-shaped cleft located on the eastern side of the dome. Surveys of the dome conducted on 10 and 30 March, and revised again on 16 April, indicated that the total volume was 113×10^6 m^3. This figure incorporated 29×10^6 m^3 for the talus slope and 84×10^6 m^3 for the dome itself. Several mudflows were generated during June; most of them travelled down Dyer's River towards the NW, into the Belham River valley.

There was a sudden increase in activity on 3 July 1998 with the collapse of *ca.* 15–20% of the dome to the east down the Tar River valley. The event occurred without precursory activity and generated an ash plume, which reached a height of 13 km and drifted to the ENE at high level. Pyroclastic flows reached the sea in the Tar River valley and ballistic blocks observed *ca.* 1 km from the volcano suggested that there may have been an explosive component to the event.

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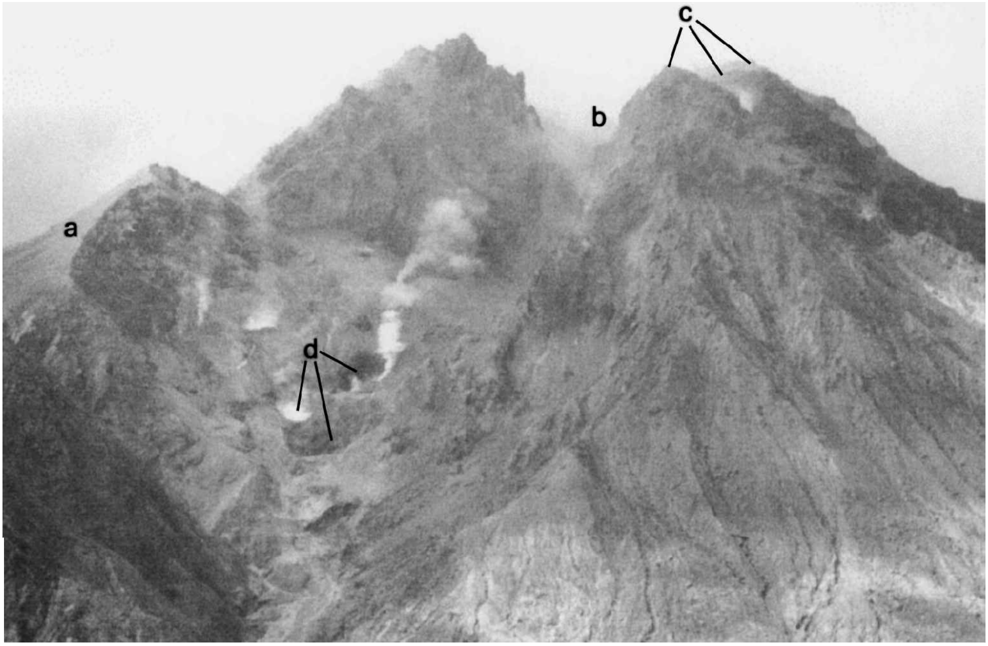

Figure 7. Photograph of the dome taken in January 1999. The main features labelled are the Galway's crater wall (a); the east–west trending gorge developed in the dome following dome collapse during July, October and November 1998 (b); the northern buttresses of the dome (c); and explosion craters and fumarolic vents active during this period (d).

The SO_2 flux measured after the event was elevated but declined steadily throughout the rest of July to an average of 1000 t d^{-1}. Significant pulse-like ash and steam venting continued for two to three weeks, although there were low levels of rockfall activity and few earthquakes. An intense volcano-tectonic swarm during late July had no apparent effect on activity at the surface. Fumaroles were active in the 3 July scar and on the south and north flanks of the dome.

Activity during August and September 1998 was dominated by several small dome-collapse events into the White River and the Tar River valley. There were also periods of enhanced steam and ash venting, which were correlated with low-amplitude seismic tremor and increased gas fluxes. SO_2 flux varied from above 1000 t d^{-1} in mid-August (1457 t d^{-1} on 19 August) to less than 1000 t d^{-1} in late September (407 t d^{-1} on 30 September). Heavy rain associated with Hurricane Georges on 20–21 September produced large-volume mudflows down all flanks of the volcano. The Belham River valley below the bridge (*ca.* 5 km from the volcano) was totally inundated with water and debris. Mudflow deposits a few metres thick were also deposited on the airport runway and in Plymouth, where a deep gully was eroded along the former course of Fort Ghaut.

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(*j*) *Increased dome collapses with ash venting and minor explosions (October 1998–June 1999)*

Small-volume dome-collapse events increased in frequency during October and November 1998. These caused pyroclastic flows in most sectors of the volcano and were followed by vigorous periods of ash venting, which lasted for a few minutes to several hours. Ash plumes associated with these events reached altitudes of *ca.* 8 km and drifted to the W and NW of the volcano. Progressive degradation of the dome culminated on 12 November in the erosion of a deep channel, *ca.* 150 m deep and *ca.* 30 m wide, which bisected the dome between the Tar River and Gages valley (figure 7).

Heavy rain during late September to December resulted in extensive mudflows down all flanks of the volcano. Up to 1 m of new material was deposited on the Belham Bridge, and there was further deposition in Plymouth and on the airport runway.

A spectrum of activity was experienced from December 1998 to mid-1999. This varied from brief episodes of weak steam and ash venting to extremely vigorous pulse-like ash venting, commonly following dome collapses or small explosions. Some of the explosions generated substantial ash clouds (up to *ca.* 6 km in height) and were followed by episodes of ash venting lasting a few minutes to several hours. Small-volume pyroclastic flows occurred periodically, the majority generated by dome collapses. Some flows may have been generated by fountain collapse during small explosions. Very few mudflows occurred during this period. However, overnight mudflows in early December caused the delta at Old Road Bay to be extended as far as the jetty.

The dome volume in late January 1999 was 76.8×10^6 m^3, with its highest point located at the top of the White River valley at 977 m ASL. The scar from the 12 November 1998 event had cut up to 100 m deep into the pre-1995 crater floor and had removed a minimum of 5.4×10^6 m^3 of old rock from this area. The northern part of the dome—which comprised three main buttresses above Gages, the northern flank and Tar River—then contained two-thirds of the total dome volume.

During March 1999, a total of 23 small, explosive and ash-venting episodes occurred, with the largest producing ash clouds reaching *ca.* 6 km in height and with associated lightning and ashfall. These occurred at an average rate of just less than one per day, with the time-interval between events decreasing towards the end of the month. Volcano-tectonic earthquakes and rockfall signals continued to be the dominant aspect of seismicity during this period, with no seismic build-up before the ash venting and explosive events. Deformation rates continued to be low and gas emissions were moderate.

From late April to June 1998, small explosions and ash venting continued at lower rates than during May. An intense volcano-tectonic earthquake swarm on 22 May was followed within 24 h by a dome collapse down the Tar River valley to the sea. A small dome collapse (*ca.* 1.5×10^6 m^3) on 5 June from above Tuitt's Ghaut produced pyroclastic flows to the sea in the Tar River valley and also into White's Bottom Ghaut and Tuitt's Ghaut to *ca.* 2 km from the dome.

3. Monitoring

Prior to the onset of phreatic activity at the Soufrière Hills volcano in 1995, the monitoring programme had consisted of six seismic stations, three single set-up dry tilt stations, and temperature measurement and condensate sampling at all active fumaroles around the volcano (figure 2). This work was undertaken by the SRU of the University of the West Indies, the agency responsible for regional volcano monitoring. The seismic network was improved in late July and August 1995 by the installation of new short-period seismic stations and deployment of an automated data acquisition and analysis system. In addition, SO_2 monitoring with a correlation spectrometer and installation of electronic tiltmeters at three sites on the volcano increased the level of surveillance. These latter improvements were conducted with the involvement of scientists from the USGS Volcano Disaster Assistance Program (VDAP), who joined the monitoring team in late July 1995. Volcanic hazard assessment was also improved with geological investigation of the pre-existing deposits from the volcano, as well as geochemical analysis of ash samples from the initial phreatic explosions.

Once the eruption was underway, the monitoring strategy used at the Soufrière Hills volcano had to be developed proactively, in a challenging environment and under difficult and dangerous conditions. Although a formal hazard assessment had been done for the volcano (Wadge & Isaacs 1988), there had been no historic eruptions and no precedents upon which to base short-term forecasts. The monitoring system needed to be flexible enough to enable a rapid response to any sudden developments at the volcano, while providing scientific stability by using established techniques with long time-lines. The volcano monitoring strategy, therefore, evolved in parallel with the state of volcanic activity and so ensured that a variety of geophysical, geodetic and geochemical techniques were eventually used in the surveillance effort.

Concern regarding the stability of the western crater wall above the Gages valley (overlooking the capital town, Plymouth), led to the introduction of measurements using a Leica TC 1100 Total Station and the improvement of the ground-deformation programme. Before this, GPS measurements, started by the University of Puerto Rico during August 1995, allowed determination of wide field deformation at the volcano. With the onset of dome growth in mid-November 1995, a programme of mapping (December 1995) and volume assessments (January 1996) began, using photographs from fixed locations, theodolite measurements and, later, GPS and laser range-finding binoculars. SO_2 diffusion tubes were deployed in populated areas and rainwater was sampled to determine the environmental impact of volcanic gases. Petrological investigation of the lava dome began with the collection of dome samples in early 1996. Before this, and throughout the eruption, ash samples were routinely collected and sent overseas for analysis.

Attempts to resolve changes in line lengths recorded by the Total Station into vertical and horizontal components led to the introduction of a Leica system 300, dual-frequency differential GPS in April 1996. Gravimetry using static and dynamic gravity techniques and open-path Fourier-transform infrared spectroscopy (OP-FTIR) were also introduced at this time. The next major change in monitoring activities occurred in October 1996 with the installation of a network of three-component broadband seismometers utilizing 24-bit digital telemetry. Concern over stability of the Galway's crater wall led to the introduction of extensiometers and new electronic tiltmeters on Chances peak during late 1996.

In support of urgent needs for appraisal of particular threats, finite-element modelling of crater-wall deformation and computer simulations of pyroclastic flows, surges and ashfalls have been undertaken. Extensive experimental petrology on the products of the eruption has also been undertaken (Barclay *et al.* 1998). Throughout the crisis, detailed documentation of eruptive activity has been carried out using 35 mm still photography, video cameras and satellite imagery, supported by numerous field sketches and notes made by members of the scientific team in the field.

The full range of monitoring efforts that have been applied in Montserrat, had to be undertaken eventually by a multinational, multi-institutional team of scientists drawn mainly from the Caribbean, the UK and the USA, all functioning under the auspices of the Montserrat Volcano Observatory.

4. Crisis management

At the start of the eruption, the close proximity of populated areas to the Soufrière Hills volcano, combined with the lack of local experience and limited knowledge of volcanism, presented some very difficult challenges for the crisis-management team. The official policy on risk was one of zero casualties. However, in the absence of resources and alternative infrastructure, there was a desire to maintain a viable and relatively normal life in the established communities, despite their close proximity to an erupting volcano. This placed tremendous pressure on the scientific team monitoring the volcano to provide accurate short-term forecasts to guide mitigation efforts. In addition, the initial desire to prevent adverse publicity led to some public distrust of official government releases. Consequently, the word of the scientists, who were perceived by most as unbiased, was given considerable credibility and led to their increasing involvement in public outreach efforts.

Despite the challenges, mechanisms were established early in the crisis for scientific briefing of local administrators. The scientific team gave daily briefings, which provided short-term forecasts and hazard assessments, to the civilian administrators. As the crisis evolved and eruptive activity became better understood, the briefings were reduced in frequency to biweekly events. A series of contingency plans were drafted by the emergency department for action to be taken in case of certain types of activity. These were tied directly to a customized alert system, which was prepared in late 1996 and replaced the pre-existing generic plan, which did not cater to the unique conditions on Montserrat. These were all linked directly to hazard and risk assessments, which were prepared routinely by the scientific team. The major assessments were formalized in late 1997 with the organization of six-monthly scientific reviews that examined the state of the volcano and provided best estimates of short-term and medium-term activity. The latest developments in techniques for structured elicitation of expert judgement were utilized by the scientific team to provide rapid consensus positions for the most urgent mitigation decisions, for the formal risk assessments and for the routine alert-level evaluations.

As the importance of public education was realized, a great deal of effort was expended in outreach activities. A spectrum of techniques was used including radio and television interviews; live phone-ins and situation updates on the local radio; written articles for the local press; specialized publications and newsletters; video documentaries; public displays and posters; and public lectures.

5. Discussion

The eruption of the Soufrière Hills volcano has been a challenging experience for both the scientific team and the civilian administrators. The documentation of an andesite dome-building eruption and integration of a variety of monitoring and hazard-mitigation techniques in ongoing crisis management has been unique. The eruption was unusually long with an irregular, punctuated increase in the magnitude and intensity of eruptive events with time. This posed several problems for disaster-management officials who had no prior experience of volcanic activity and, in any event, were accustomed to dealing with discrete events on much shorter time-scales (e.g. hurricanes). Scientists monitoring the volcano and civilian administrators alike were on rising learning curves throughout the eruption. For the decision makers, the situation was not ameliorated by the unavoidable scientific uncertainty, which attends such emergencies, particularly in respect of the timing and scale of dangerous events. For instance, the Galway's wall flank failure, which was foreseen early on, only occurred one year after it was first suggested as a possibility, while the secondary fluidized pyroclastic flow, which occurred on 25 June 1997, was a new type of activity and could not have been specifically predicted. These events had a direct impact on decisions to evacuate areas at risk and on public trust in both scientists and civil authorities. By contrast, the recognition of distinctive cyclical patterns in seismic and tilt monitoring signals allowed short-term forecasts of strong eruptive activity to be made (Voight *et al*. 1998), which protected the safety of scientists and essential workers in the exclusion zone, and improved public faith in the monitoring programme. Despite the cessation of dome growth in early March 1998, impressive, and occasionally dangerous, activity at the volcano has not yet ended, and the people of Montserrat and the volcano-monitoring team continue to be enthralled by the volcano.

There are many lessons to be learnt from the experience of monitoring and crisis management during the 1995–1998 eruption of the Soufrière Hills volcano on Montserrat. There is clearly a need for long-term baseline measurements of essential volcano parameters to be obtained before onset of an eruption. The use of a variety of monitoring techniques improves short-term forecasting and assists in volcanic hazard and risk assessments. The building of a responsible, cohesive and dedicated team, at the expense of individual scientific opportunism, was essential in achieving the best possible outcome for the population at risk and greatly enhanced the effectiveness of the entire volcano-monitoring effort. In the complex political structure of Montserrat, a British Dependent Territory, it was found by experience that there was a need for clearly defined lines of reporting and responsibility to be established and maintained for best scientific involvement. Public information and education must be ongoing and should include a mechanism to gauge the effectiveness of the message, but, above all, such outreach must seek to reinforce and optimize the partnership between the public administrators and scientists, as they confront jointly the threat of an erupting volcano.

The people of Montserrat, so badly affected by the disaster in their island, have given wholehearted support to the work done at the MVO, and their encouragement and expressions of confidence have been greatly appreciated by all the scientists involved. The MVO has also benefited from the goodwill and hard work of a large number of persons; particularly the local staff, who have all contributed unstintingly towards its development during a period when they themselves had to confront great personal difficulties caused by the eruption. The input of staff from the Seismic Research Unit, the British Geological Survey, the USGS Volcano Disaster Assistance Program, the French Observatories in Martinique and Guadeloupe, the University of Puerto Rico, Lancaster University, Bristol University, The Open University, Brown University and numerous other institutions have all contributed to the work of the MVO and, hence, the publication of this paper. Funding for the MVO has been provided by the Government of Montserrat and by the British government through its Department for International Development. This paper is published with the permission of the Director, British Geological Survey (NERC).

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